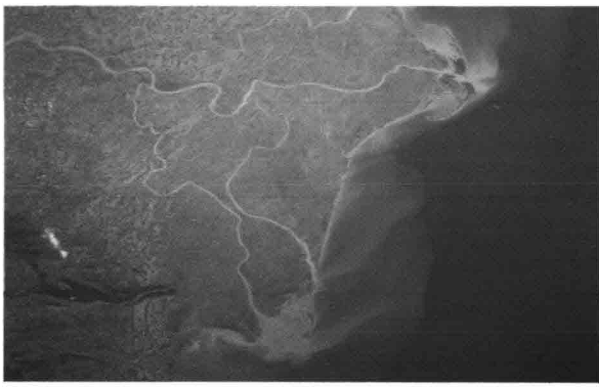
Prlarczyk

International Institute for
Infrastructure, Hydraulic
and Environmental Engineering

COASTAL MORPHOLOGY

A CASE STUDY IN PROVINCE OF NAM DINH, RED RIVER DELTA, VIETNAM



MSc. Thesis in Hydraulic Engineering

You have shown that you have learn how to use the modern tools for wave and morphological simulations. It is of great importance to you, your further carrier, and for your country, where these (research) instruments are still rather scarce. But, on the other side, what is the practical value of this. Do you feel that this study brought us closer to understanding the problem, ? underline understanding of problem because in my opinion we are still far away from finding a proper solution.

Luong Giang Vu

June 2003

What is your opinion hereabout?

Crenulate-shaped / spiral (silhouette) bay shape / headlands

COASTAL MORPHOLOGY

A CASE STUDY IN
PROVINCE OF NAM DINH, RED RIVER DELTA, VIETNAM

Master of Science Thesis
By
Luong Giang Vu

Supervised by
Associate Prof. Dr. R.M.M. Hassan and Dr. Ir. Jan van de Graaff

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This thesis is done for the partial fulfilment of requirements for Master of Science degree at the International Institute for Infrastructural, Hydraulic and Environmental Engineering, IHE Delft, The Netherlands,

Delft
June 2003

Preface

This thesis work was done as a part of the MSc program of the Faculty of Hydraulic Engineering, UNESCO-IHE Delft, the Netherlands and was carried out IHE from October 2002 to June 2003. The whole MSc. program in IHE lasts 20 months (from October 2001 to June 2003) included courses, field trips, group works, and the thesis.

I would like to acknowledge my sponsors: NFP, Bloom Foundation, the Lamminga Fund, and D.W.W for the financial support, and the graduation committee for their guidance and judgement.

I owe special words of thanks to: Mr. Marco Pluijm from Boskalis for his help to bring me to this course, Mr. Krystian Pilarczyk from D.W.W for his concern and assistance with so much warmth and care, Dr. Randa Hassan - my mentor- for her constant support during my study at IHE, My supervisor Mr. Jan van de Graaff for his patience, enthusiasm, directed and valuable advice, Mr. Bas Wijdeven for sharing his data and ideas, Mr. Nguyen Sy Nuoi and Mr. Le Duc Ngan from DDMFC for arrangement of pleasant and interesting site visit to province of Nam Dinh, Mr. Nguyen Khac Nghia from CECE for sharing data from his PhD study, Mr. Holthuijsen for his valuable advice in wave modelling, Mr. Nguyen Kim Nhan and his family for pleasant visit in Budapest, Mr. Kyle Robertson for his help in reviewing English of this study, Mr. Ortman from Haskoning and his wife for their warm welcome and friendship, and Jan Willem for his friendship and help.

My high appreciation goes to all the teachers who have taught and armed me with such a valuable knowledge to my future career; IHE staffs, friends and my classmates for their support, assistance and for making my stay here filled with joys and memories.

I would like to keep the great thank to my parents and my parents in law, my sister and brother, my brother in law for their great support and always being source of encouragement and energy, my wife and my little son for their long wait with such faith and love.

IHE - Delft, June 2003

Luong Giang Vu

Abstract

COASTAL MORPHOLOGY
A case study in Province of Nam Dinh, Red River Delta, Vietnam

Carried out by: Luong Giang Vu

Supervised by: Associate Prof. Dr. R.M.M Hassan, and Dr.Ir. Jan van de Graaff

Vietnam has about 3260 km of coastline, primarily consisting of low-lying coastal areas. More than 165 km of this coastline are within the Red River Delta, a densely populated region which experiences substantial dynamic changes and destruction due to frequent intense impacts from the river (floods) and the sea (typhoons, changes in sea level, currents, etc.).

The study area for this thesis is the province of Nam Dinh, which constitutes part of this dynamic coastline within the Red River Delta, which alters very often due to erosion and accretion processes. Since the beginning of last century, about 30 km of the coastline of Hai Hau district has been facing erosion with estimated erosion rates of about 10-20m per year causing damages to the local economy housing, and loss of land, etc.

In recent years a number of studies have been done in order to understand the problem and find the solutions to mitigate these losses. Due to the lack of data, and design tools the results of these studies somehow are still limited, and the problem is still poorly understood.

Advanced mathematic models - SWAN, a 2D wave model which is developed by TU Delft and Delft Hydraulics, and UNIBEST a 1D morphology model developed by Delft Hydraulics - are used in this thesis to run and analyse the data in search of better results for understanding the erosion problems at Nam Dinh coast. By doing this study the necessary engineering knowledge and study skill to solve a problem in practice are also achieved.

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Chapter 1
INTRODUCTION

1.1 BACKGROUND

Vietnam, as shown in Figure 1.1, has about 3260 km of coastline, which primarily consists of low-lying coastal areas. More than 165 km of this coastline are within the Red River Delta, densely populated regions which experiences substantial dynamic changes and destruction due to frequent intense impacts from the river (floods) and the sea (typhoons, changes in sea level, currents, etc.).

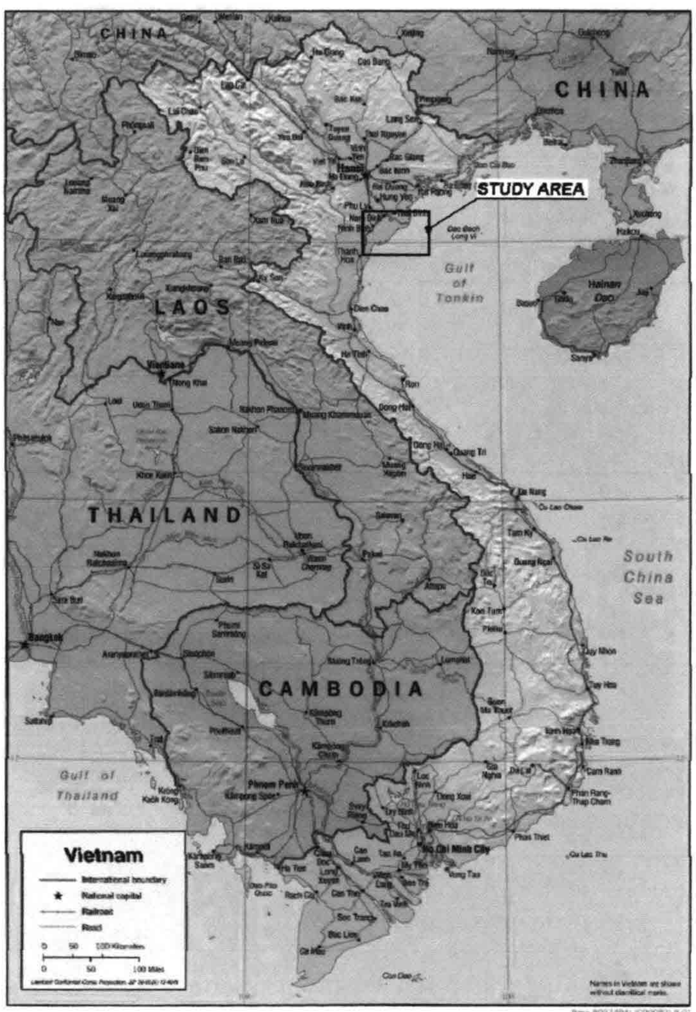


Fig. 1.1: General location of Vietnam

There is so [illegible]

– Halan

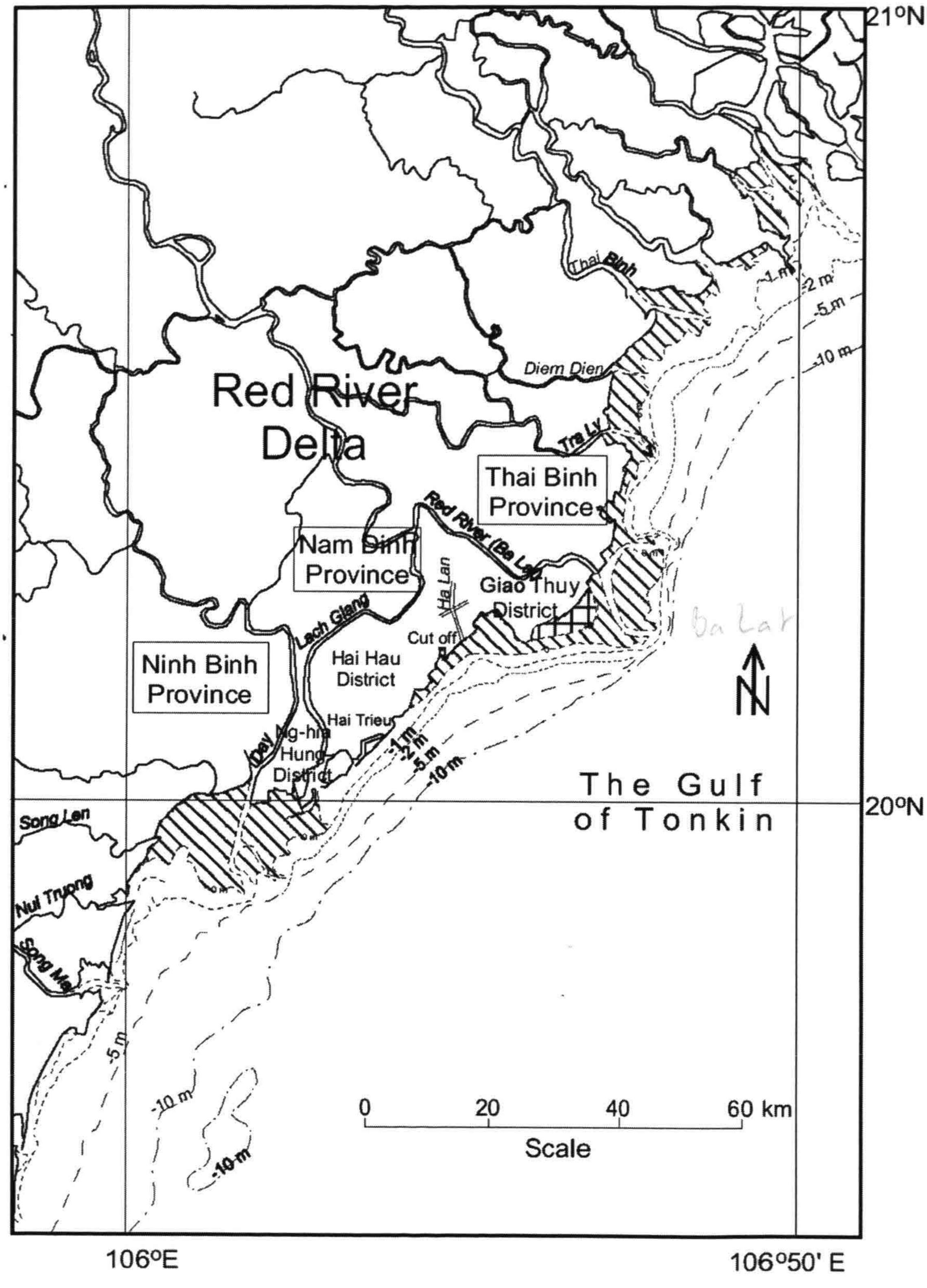


Fig. 1.2: The study area

much attention is paid to longshore transport

because of relatively frequent heavy storms
sediment is transported to deep water
and probably not much of it transported to the coast
during calm season

(reduction of cross [illegible] [illegible] cross section
may reduce the erosion [illegible]

The study area for this thesis is the province of Nam Dinh (Fig1.2) that constitutes part of this dynamic coastline within the Red River Delta, which alters very often due to erosion and accretion processes. The two alluvial grounds in the Giao Thuy and Nghia Hung districts within Nam Dinh were claimed to accrete and enlarge by hundreds of meters every year resulting from the large volumes of silt supplied by the rivers. On the contrary, about 30 km of the coastline of Hai Hau district is facing erosion with estimated erosion rates in order of 10 to 20m per year.

According to public data of the People Committee of Nam Dinh province in year 2000, the province has a total population of 2 million people, which is considered to be one of the most densely populated areas in the world. The average density is more than 1000 people per km^2, and in Nam Dinh city the density can reach 5000 persons per km^2. The main income is derived from agriculture and aquaculture, salt mining, and tourism. Therefore beach erosion has resulted in many severe consequences to Nam Dinh. For example, some consequences with the data come from Nam Dinh Dike department are listed bellow:

- Beach erosion, dike breach due to typhoons, storm surge, and wave actions caused retreat of about 3000m of the shoreline during the last 100 years. Total area of land loss is approximately 15,000 ha (nearly as big as the current area of the Hai Hau district).
- Strong storms: which have wind with Beaufort strength from 9 to 12 cause houses to collapse, killing people and huge property loss. In the 20 years from 1976 to 1995, storms took away 4,028 houses, 6 fishing ships sank, and 25 people died and 34 people were injured.
- Dike breach: seawater overflow into to the hinterland resulted in flooding and salt in cultivated land. Practical statistics showed that 38,273 ha cultivated land was impacted by salt, and 76,474 tons of food was lost. Salt mining fields, and shrimp hatching ponds were also heavily damaged.
- Due to storms and wave actions, water set-up combined with high tide the sea dike system in Nam Dinh gets damaged almost every year. During the preriod from 1976 to 1995 about 934,000m^3 of earth and 30,400 m^3 of stone were taken away from the sea dikes in Nam Dinh. Therefore the expenditure on maintenance is very large (in order of millions of Euro).

It is apparent that the coastline erosion has a bad effect on the economy and social life in the area. In response the central and local authorities have organised some efforts in order to restrain the possible adverse consequences. However, due to budget constrains and the lack of strategic and long-term solutions, such efforts still remain limited to reactive and temporary measures.

Following figures (Fig. 1.3 - Fig. 1.5) are the recent photos at Hai Hau coast. The photos show some impressions view about the erosion problem and its effect to the area.

Fig 1.3: A damaged dike section

Fig 1.4: Hai Trieu Village in 1995

Fig 1.5: Abandoned Hai Trieu Village, 2001 due to dike breach in 1999

[illegible] B[illegible] [illegible] growing? [illegible] [illegible] [illegible])

What about reducing/[illegible] B[illegible] → less possibility [illegible]

1.2 OBJECTIVES OF STUDY

This study mainly focuses on the erosion problem along Hai Hau district of Nam Dinh province. The erosion is so critical that part of the outer protecting dike has been damaged. This has caused seawater intrusion to destroy, among others, agriculture land, aquaculture and fishing areas, salt production activities, and village and other residential areas, while threatening a lot more. (Pruszak et al., 2001)

The problem becoming more acute to these low-lying Vietnamese coastal areas due to the potential climate changes (sea level rise). Such study on the accelerated sea level rise (ASLR) by Mimura and Harasawa (2000) which forecasts about 50 cm SLR within the coming 100 years is a pertinent concern. Evident increase of typhoons (with an annual average of 4.7 typhoons/year) and violent storms striking the coast of Vietnam every year as highlighted by Pruszak et al. (2001) is yet another disturbing climatic extreme to be acknowledged.

Generally, the two common initial hypotheses for the cause of erosion especially at Hai Hau beach were the construction of a large dam upstream the Red River Delta (i.e. at Hoa Binh) and the closing of a river branch (Ha Lan) that used to supply sediment to the beach. (Hung et al., 2001). However, it is interesting to note that the above-mentioned dam was constructed in 1986 and closure of the Ha Lan River has taken place in 1955, which are fairly much recent events. While on the other hand, Pruszak et al. (2001) has described that the erosion was even much greater at the beginning of the 20th century as compared to the recent estimates. Although there is less likelihood for a direct correlation between the influences of the above earlier hypothesis to the actual cause of the erosion problem, the dam construction and the closure of Ha Lan river may have further contributed to the erosion problem. Even though adaptation of the natural environment to the changed morphological condition was used by Pruszak et al. (2001) to substantiate the recent decreasing erosion rate within the area, the problem still persist and necessitate immediate attention.

In response to that, the preliminary assessment of the available information as well as few previous studies that were carried out such as the latest by Hung et al. (2001) revealed that the erosion at Hai Hau beach is mainly due to the prevailing waves generated by the winter monsoon in combination with the local shoreline orientation. While Bas Wijdeven (2002) stated that the main causes of erosion problem at the study area are due to abandoning of So River and development of Ba Lat estuary.

Based on the acquired understanding about the phenomena of the erosion problem being addressed, it can be deduced that the two main inter-related components that contribute to the erosion at the project area are gradient in longshore transport and cross-shore transports.

This argument is more or less in line with the comments made by Pruszak et al. (2001), which also relates the development of the Red River Delta further towards the sea to the resulted imbalanced sediment budget in other eroded sub-areas. Their findings, based on field observations and results of other studies, that only part of the sediment from the estuaries (Ba Lat, Lach Giang and Day) retained in the nearshore zone (30%) while a larger portion of it is transported offshore into the deeper sea (70%) further explained the large deficit of sediment in the study area. The influence of the seaward development of the Red River Delta can thus be summarised as the alteration of the sediment transport pattern downcoast of the delta.

In short, it can be deduced that the erosion problem at Hai Hau beach has been progressing for at least almost one hundred years ago. Even though there are various scales of erosion rates reported by several earlier investigators, it is still apparent that the shoreline retreat is very alarming. The beach has been receding with some parts reaching the first (or outer) dike line and with some stretches has been completely breached. The situation becoming more critical as the erosion caused the beach at the toe of the dike to become much deeper. This has not only endangered the overall safety of the dike due to possible undermining, but also promotes impacts by larger waves due to the larger water depth.

Thus, it can generally be comprehended that the various possible inter-related phenomena that may contribute to the erosion problem at Hai Hau beach may also include:

- The potential climate changes (sea level rise).
- Increase of yearly typhoons and violent storms striking the coast of Vietnam.
- The construction of a large dam upstream the Red River Delta (i.e. at Hoa Binh)
- Natural change of sediment discharge distribution of Red River branches.
- The closing of a river branch (Ha Lan) that used to supply sediment to the beach.

to explain the reason of [illegible] you have to take into account both:

longshore

cross-shore [illegible]

- The prevailing waves generated by the winter monsoon in combination with the local shoreline orientation.
- The longshore sediment transport gradients caused by the interaction between the prevailing wave climate and the bottom topography.
- The development of the Red River Delta further towards the sea, which resulted in an imbalance of sediment budgets in other eroded sub-areas.
- The large deficit of sediment in the study area which main portion (70%) of the sediment from the Red River system transported offshore.

Even though a more thorough assessment can be carried out covering all the above aspects, the scope of the study has been limited to cover only the predominant inter-related phenomena. Thus, the assessment emphasises the main causes of the erosion at the project area, which was hypothetically contributed by the gradient in longshore transport and cross-shore transport.

It is thus the task of this study to investigate these inter-related phenomena in order to ascertain and quantify the contributing factors to the erosion problem in Hai Hau district. The preliminary findings established from the various previous studies have been further explored and established. The understanding achieved regarding the morphological behaviour of the area has enabled appropriate outlining and evaluation of the potential mitigation measures for the erosion problem being analysed.

In summary the main objectives of the study can be outlined as follows:

- To undertake a comprehensive analysis of the erosion problem with particular attention to wave climate and longshore sediment transport at Hai Hau District, Nam Dinh province.
- Possible mitigation measures are discussed to give an overview of how to adapt a suitable defence strategy for the study area.

1.3 APPROACH OF STUDY

The approach of this study is structured based on the proposed objectives of the investigation concerning the erosion problem along the Hai Hau coast in Nam Dinh province in relation to the Red River systems. The main thrusts of the study involve modelling work using SWAN (a version integrated with Delft-3D) and UNIBEST that were developed by Delft Hydraulics. Generally, the following approach forms the methodology in undertaking the overall study:

(i) Collect all possible data from different sources covering among others, the main geographical and hydrographical features of the study area, soil and geological characteristics, meteorological and oceanographical data (hydraulic parameters, tides and water levels, currents, winds, waves, sediment transport etc). This shall also include the information about morphodynamic process within the study area.

(ii) Review and analyse all the data collected and gathered and pursue further data acquisition where necessary.

(iii) Review previous related studies, recent and existing mitigation works within the study area as well as the historical changes/development of the shoreline condition.

(iv) Describe the overall system by means of the sediment balance for the study area.

(v) Carry out relevant literature study concerning erosion, coastal defence and other technical information for the study area.

(vi) Study and understand the potential use of the SWAN and UNIBEST modelling systems and their appropriate applications for the study.

(vii) Prepare model set-up, schematisation and boundary conditions for the required modelling works.

(viii) Carry out model calibration where practicable.

(ix) Model study and analyse model results

(x) Define all possible coastal engineering solutions for the problem.

Outline overall conclusions and recommendations.

Chapter 2

NATURAL CONDITIONS OF THE STUDY AREA

2.1. GENERAL DESCRIPTION ABOUT STUDY AREA

The coastal zone of Nam Dinh is roughly 80,000 hectares in size with about 70 Km of coastline. The area is naturally divided into 3 sections by 4 large estuaries: the Ba Lat (Red River), Ha lan (So River – has been cut-off), Lach Giang (Ninh Co River) and Day (Day River), from north to south the sections are:

- Section 1: from Ba Lat estuary to So estuary belongs to Giao Thuy district, about 27 Km long.
- Section 2: from So estuary to Ninh Co estuary, belongs to Hai Hau district, 27 Km Long.
- Section 3: from Ninh Co estuary to Day estuary, belongs to Nghia Hung district, 16 Km long.

The erosion or accretion rate on each section varies depending on the position that faces to the sea or the proximity to the estuary. (See Fig. 2.1)

a) *<u>Accretion at the estuaries:</u>* Accretion takes place at the estuaries area

- Ba Lat estuary: The accretion at the Ba Lat estuary has been forming for about 30 - 40 years. Firstly this accretion is only one big alluvial ground connected to a section of sea dike belonging to the Giao Thuy district, forcing the Red river to run northward via the Lan mouth to the sea. The accretion ground grew bigger, year after year, then flood flow from the Red River has divided the ground into 3 parts: the inner ground (next to the former sea dike), Con Ngan ground (in the middle), and Con Lu ground on the outer area facing the sea.
- Day estuary: Alluvial ground at Day estuary - named Con Xanh ground - belongs to Nghia Hung district. This new delta has been formed by the Day river, the delta is growing very fast, since 1975 the delta has encroached about 8 Km seaward. From 1931 to date there has been 2 series of dikes, which were constructed for land reclaimation, and a new commune (named Nam Dien) was formed with an area of 1,2000 ha.

- Lach Giang estuary: this is also an accretion estuary and the delta here is not as big as the other ones mentioned above but this is one of the main national channels connecting the seaway to the inland waterway system. Lots of sand has been dredging in order to maintain the shipping channel.

b) *Erosion problem:* Beside the accretion areas, at the locations far from the estuary that face the sea the erosion problem is quite alarming. The erosion is happening along the coastline from the southern coastline of Giao Thuy district through to the coastline belonging to the Hai Hau district and part of northern coastline of the Nghia Hung district. At the erosion locations the beach width is now only 100 - 200m at the low tide. According to records of the Dike department in Nam Dinh, the retreat speed during some periods can be summarised as follows:

- From 1900 to 1954: about 35m to 50m per year,
- From 1954 to 1973: about 15m to 25m per year,
- From 1973 to 1990: about 8m to 10m per year.

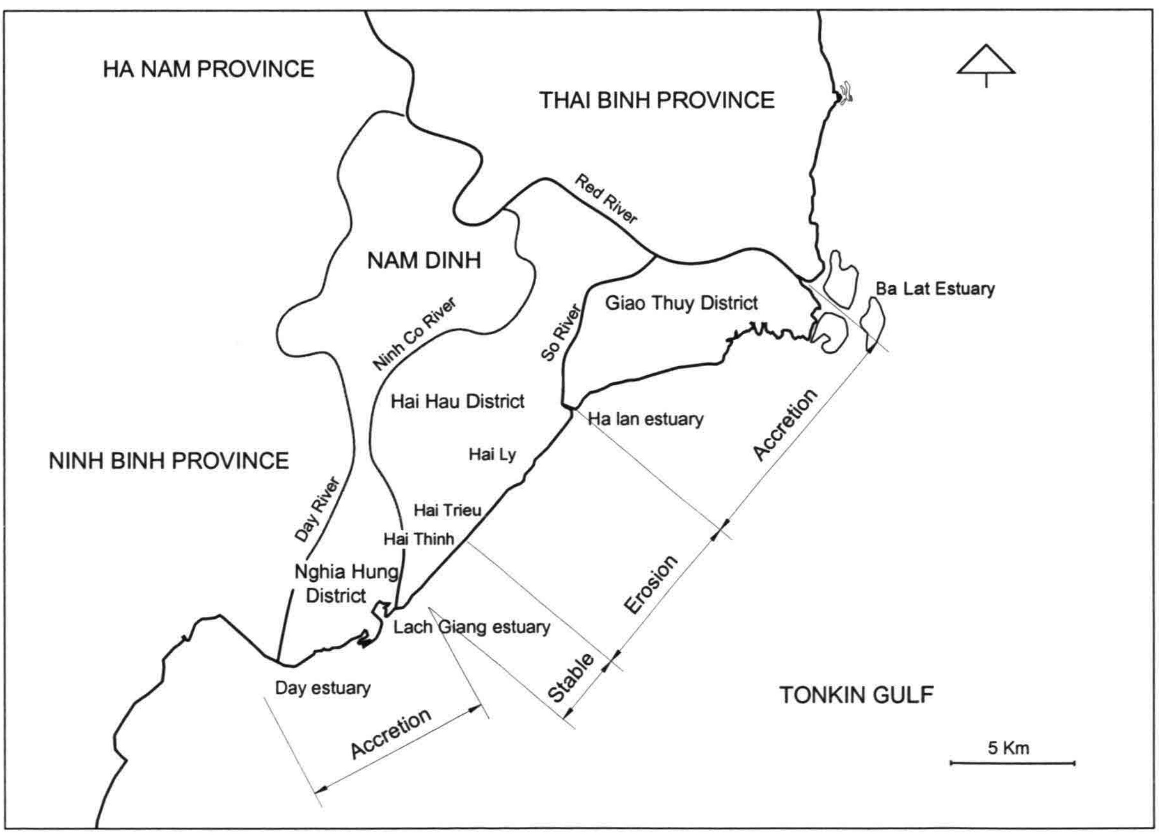


Fig. 2.1: Coastal zone of Nam Dinh

2.2. DELTA TOPOGRAPHY

According to Le, Ngoc Le, (1997), the delta (Fig. 2.2) has flat topography, gradually sloping from northwest to southeast with an altitude vary from 10-15m to mean sea level over a distance of 150 Km. During the mid and late Holocence period, the mountainous bottom of the Tonkin Gulf filled up with alluvium. In the middle of the delta, mountains and hills can be found, linked to the geological formation under the alluvial sequences. The delta can be subdivided to three parts: (1) the Rim Plain, (2) the Central Plain, (3) and the Coastal Plain. The Rim Plain was not submerged in the mid-Holocene period and it is covered with ancient alluvium and dotted with sparse hills and mountains, which form part of underlying geological foundation. The area is elevated 3 m above mean sea level. The Central Plain is the area built with new alluvial from the Red River and the Thai Binh River and it was submerged in the mid-Holocene period and has been impacted by both rivers and the sea (Le, Ngoc, Le, 1997). The area elevates 1-3m above mean sea level and its topography is one of low-lying lands with mountains and hills. The Coastal Plain consists of young alluvial deposits. The topography is flat, varying from 1m below mean sea level to 1 m above mean sea level with the presence of beach ridges. The pro-delta zone (the most seaward portion of the subaqueous delta) has a depth of 20-30m covered with silt and red silty clay (Hoi and Tuan, 1994).

Upstream, in the mountainous area surrounding the delta, the Red River is confined to a straight narrow northwest-southeast aligned valley (Fig. 2.2), produced by the Red River Graben (a sunken area between two roughly parallel faults, the faults converge toward one another below the surface, so that they look like the letter "V" in cross section). This major tectonic structure can also be traced southeastwards deep beneath the Quaternary sediments of the delta plain and into the Tonkin Gulf. It acts as a major sediment trap (Fontaine and Workman, 1978).

Recent studies about geology and geomorphology of the Red River Delta have confirmed that there's no relation between the tectonic activities and the erosion problem at coastline of Nam Dinh.

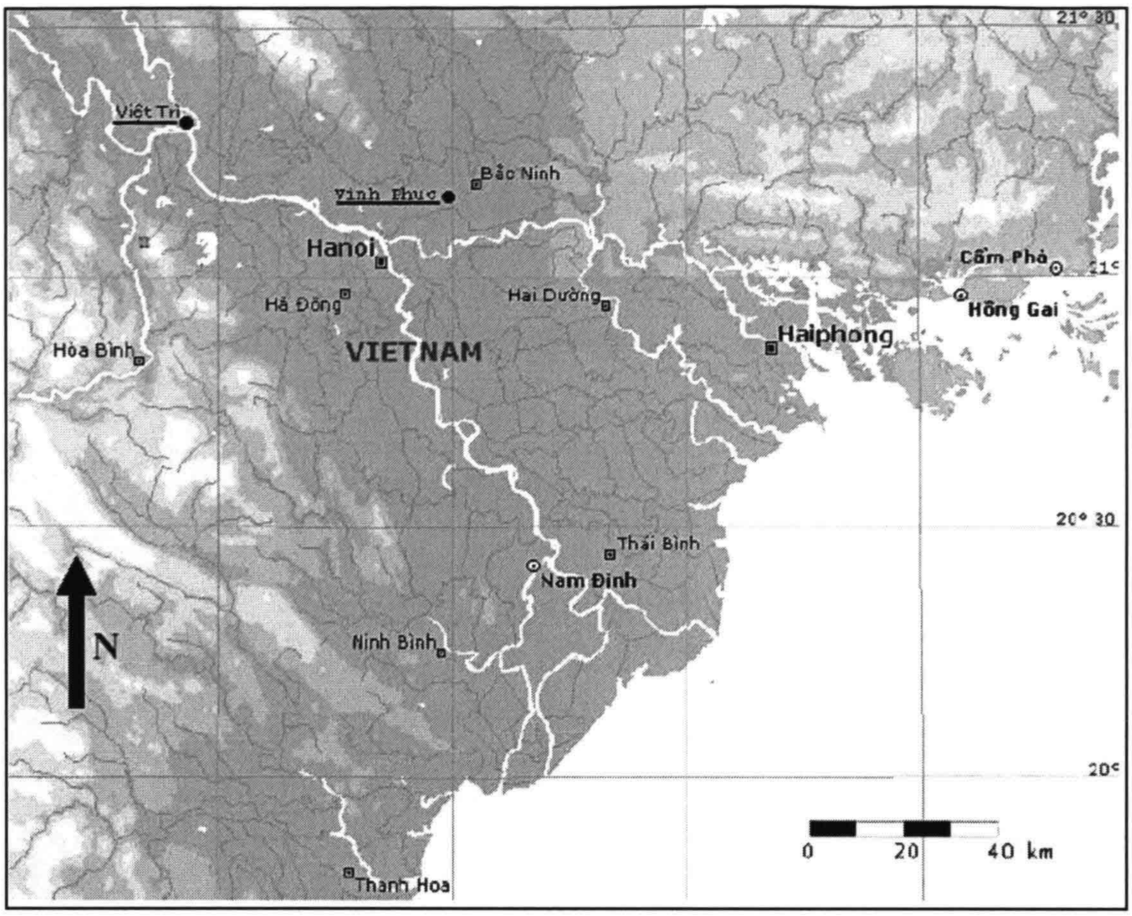


Fig. 2.2: Extension of Red River Delta

2.3. MAIN SOIL AND GEOLOGICAL FEATURES

Nam Dinh province has been formed by the rivers in Red River system, soil in Nam Dinh has alluvial characteristics. Outside the sea dike, the coastline has been shaving due to action of waves and tide current, the erosion is taking away the small grains causing the coarsening of the grain size of the beach.

According to geology the investigation document of the Hydraulics engineering Survey and Design Service of Nam Dinh, strata structure of Nam Dinh coast has 3 following layers:

- The upper layer is sand, covering all over the beach with a thickness range from 0.5m to 2.0m. Grain size ranges from 0.1mm to 0.15mm.
- Under the upper layer is a clay layer with thickness ranging from 0.5m to 1m. This is the original clay layer of the beach, in plastically flabby state.

- The third layer is a coarse sand layer with a thickness of more than 5m.

With this structure of the strata we can easily realise that Nam Dinh has a vulnerable beach. If the upper layer is washed away the stability of the dike will be seriously threatened.

2.4. SEDIMENT TRANSPORT CONDITIONS

The shoreline of Nam Dinh is not protected by islands or large tidal barriers. The sediment supplied by rivers is accumulated in the near shore zone close to the river mouth and is not transported along the shore in any significant amounts. Therefore, sections of the beach situated relatively far from the river mouth in the range of ten kilometres are not nourished by river sediment.

The beach slope is rather gentle with average value that fluctuates from 1:150 to 1:300 along the coast. But near the dike in a distance of about 300m seaward from the dike toe, the beach is relatively steeper; the slope here varies from 1:50 to 1:100.

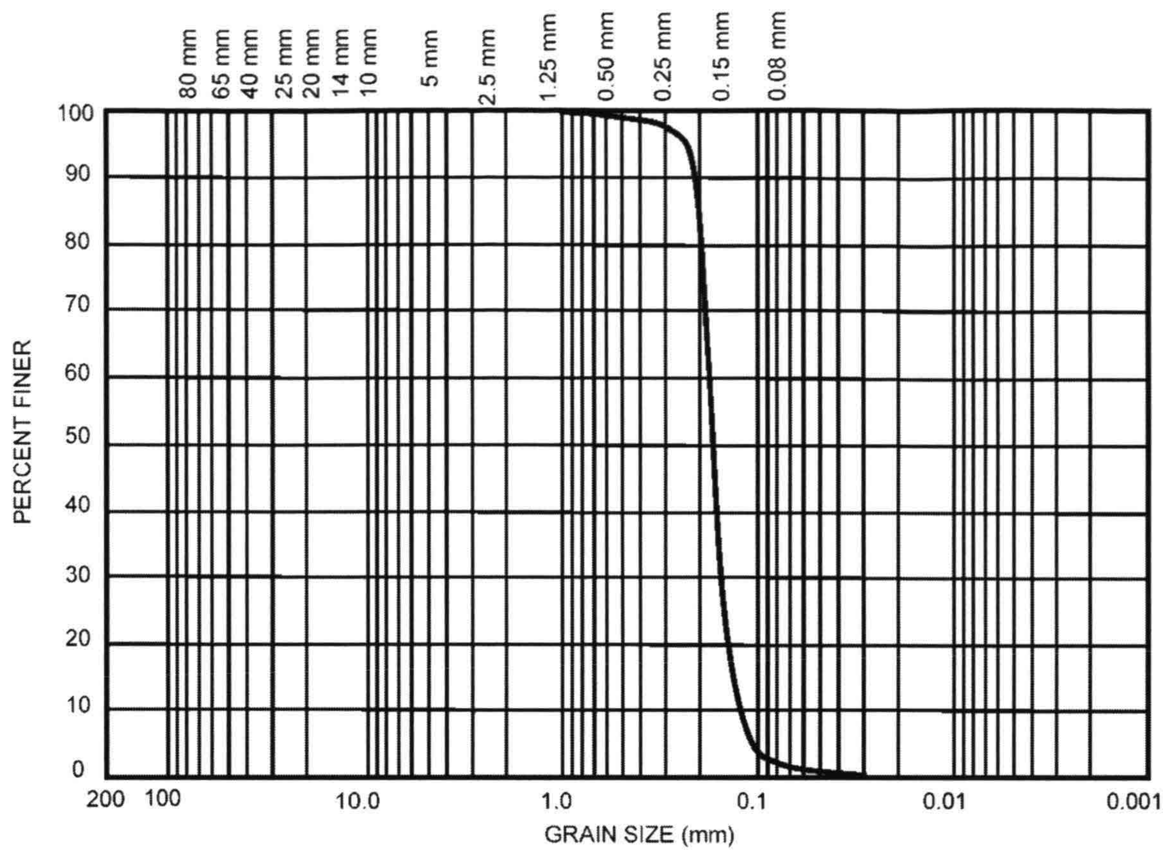
Table 2.1: Sediment load composition on the shoreline

	Sand	Aleurite	Clay
Percentage	22%	64%	14%

[source: Pruszak et al. 2001]

Figure 2.3 illustrated a different approach to particle size distribution on the coast as referred to Hung et al. (2001).

A rough assessment of longshore sediment transport in the coastal area of the Red River estuary indicated that the total annual longshore sediment transport is about 5% of the whole annual Red River sediment discharge that remains in the near shore zone, Pruszak et al. (2001). During the winter monsoon the longshore sediment transport is directed southwest. In the summer period it reverses to the northeast. A general scheme of sediment flux showing the rate of sediment discharge to the sea by the main Red River branches together with the division of the coastline area into three parts is presented in attached Figure 2.4.



Test	% +3"	% GRAVEL	% SAND	% SILT	% CLAY
1	0.0	0.0	98.0	2.0	

LL	PI	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_C	C_{LF}
		0.199	0.167	0.157	0.138	0.121	0.113	1.01	1.5

[Source: Sea Dyke service Department, Dec. 2001]

Fig. 2.3: Sieve curve of beach material in Hai Hau coast

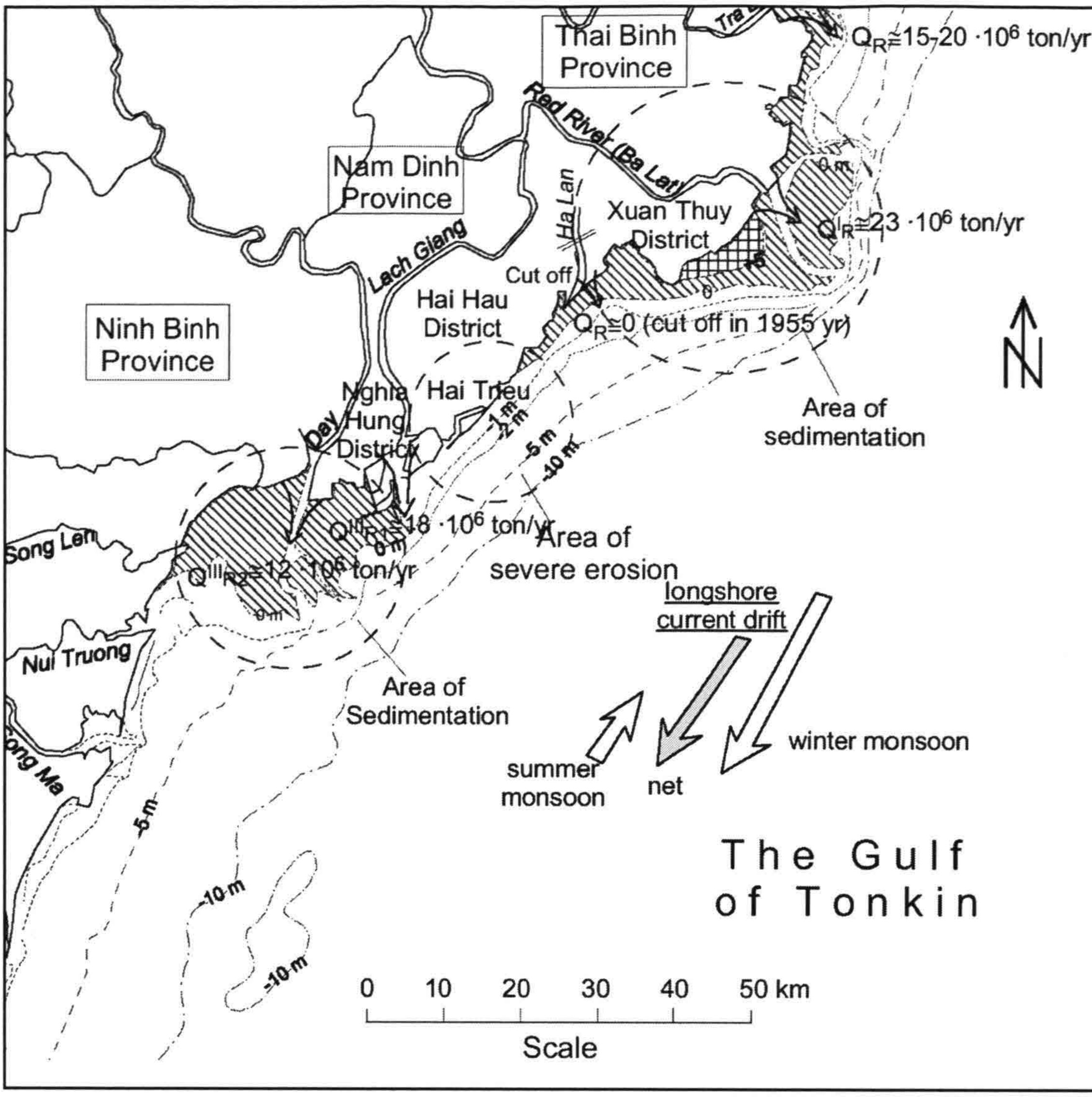


Fig. 2.4: Local sediment budget at Nam Dinh coast (Pruszak et al. 2001)

2.5. CLIMATE AND METEOROLOGY

The climate of Nam Dinh is tropical with a pronounced maritime influence. The average annual rainfall is 1600 to 1800 mm, 85% of which occurs during the rainy season (April to October). The heaviest rainfall occurs in August and September, causing intensive flooding in the delta due to overflow of the riverbanks.

The winter is cool and dry, with mean monthly temperatures varying from 16°C to 21°C. Fine drizzle is frequent in early spring, after which the temperatures rise rapidly to a maximum of 40°C in May. The summer is warm and humid, with average temperatures varying from 27°C to 29°C. The prevailing winds are Northeast in the winter, and South and Southeast in the summer.

Typhoons and tropical storms are frequent between July and October. During the period from 1911 to 1965 the region withstood 40 typhoons. However, the frequency of storms and typhoons appears to have increased in recent years. Typhoon storms usually come from the west pacific, through the Philippines or Eastern Sea. They then shoot into the coastal areas of South China and Vietnam. Among the typhoons that occurred from 1954 to 1990, strong winds with grade 12 were observed for 31 cases. The annual average number of typhoons is about 5, but more than 10 were observed in 1964, 1973 and 1989. The severe latest typhoon hitting Nam Dinh province was Nikki in 1996, causing a surge of 3.11m at the Hai Hau distric coastal area.

Typhoons also bring about periods with heavy rains, (over 100 mm/day, possibly 300-400mm/day) causing severe flooding. The rains, which affect areas in radius of 200 – 300 km, may become terrible natural calamities. When such storms break over the main land, a huge amount of water is released, damaging the sea dikes (rainfall erosion), and flooding the coastal areas.

2.6. SEDIMENT TRANSPORT IN MAIN RIVERS

Most of the river sediments are discharged into the sea through the six different branches (Thai Binh, Diem Dien, Tra Ly, Ba Lat, Lach Giang, Day, Ha Lan-cut off). In general, the accumulation occurs in the vicinity of the branches, at a rate depending on the local sediment discharge on each branch. The most intensive accumulation is recorded at Ba Lat estuary situated at the north of Hai Hau beach, followed by the Day River mouth on the south of this beach. However, simultaneously with accumulation, high rates of erosion have occurred at the Hai Hau beach (Hung et al. 2001).

The morphological system of the Red River Delta is very dynamic. During the summer monsoon season, 80 % of annual sediment load is discharged to the sea, resulting in huge deposit volumes being situated close to the main branches of Red River mouths. Due to the dominant wind wave direction at this time, the sediment is deposited mainly on the eastern and northeastern side of the Red River branches (e.g. Thai Binh or Ba Lat). During the winter monsoon, the sediment is redistributed in southwesterly direction due to strong southwest current (Pruszak et al. 2001).

Also, the total amount of sediment discharge by the Red river mouths to the sea in the Thai Binh and Nam Dinh province is assessed at about 75 million tons per year. The mentioned sediment transport is distributed among its branches as is showed in Table 2.2.

Table 2.2: Sediment Transport at Red River Branches.

Branch	Thai Binh	Tra Ly	Ba Lat	Lach Giang	Day
Sediment (mil. tons/year)	15 - 20	12 - 15	23	18	12

[Source: Pruszack et al. 2001]

This amount of the sediment is distributed irregularly over the year, with 91.5 % annual volume in the flood season and 8.5% in the dry season.

Furthermore, up to about 30 % of the total sediment load, which consists of 48% sand 43% aleurite (sand and clay) and 9% clay, remains in the near shore zone and develops sandy ridges and tidal flats (depth below 2 m). The remaining material (about 70%) of mainly clayey material remains suspended, passes the inter-tidal plain and goes offshore to deep water areas (depths of 2 – 30 m). The mean annual concentration of suspended sediment in Red River reaches nearly 1000 g/m^3.

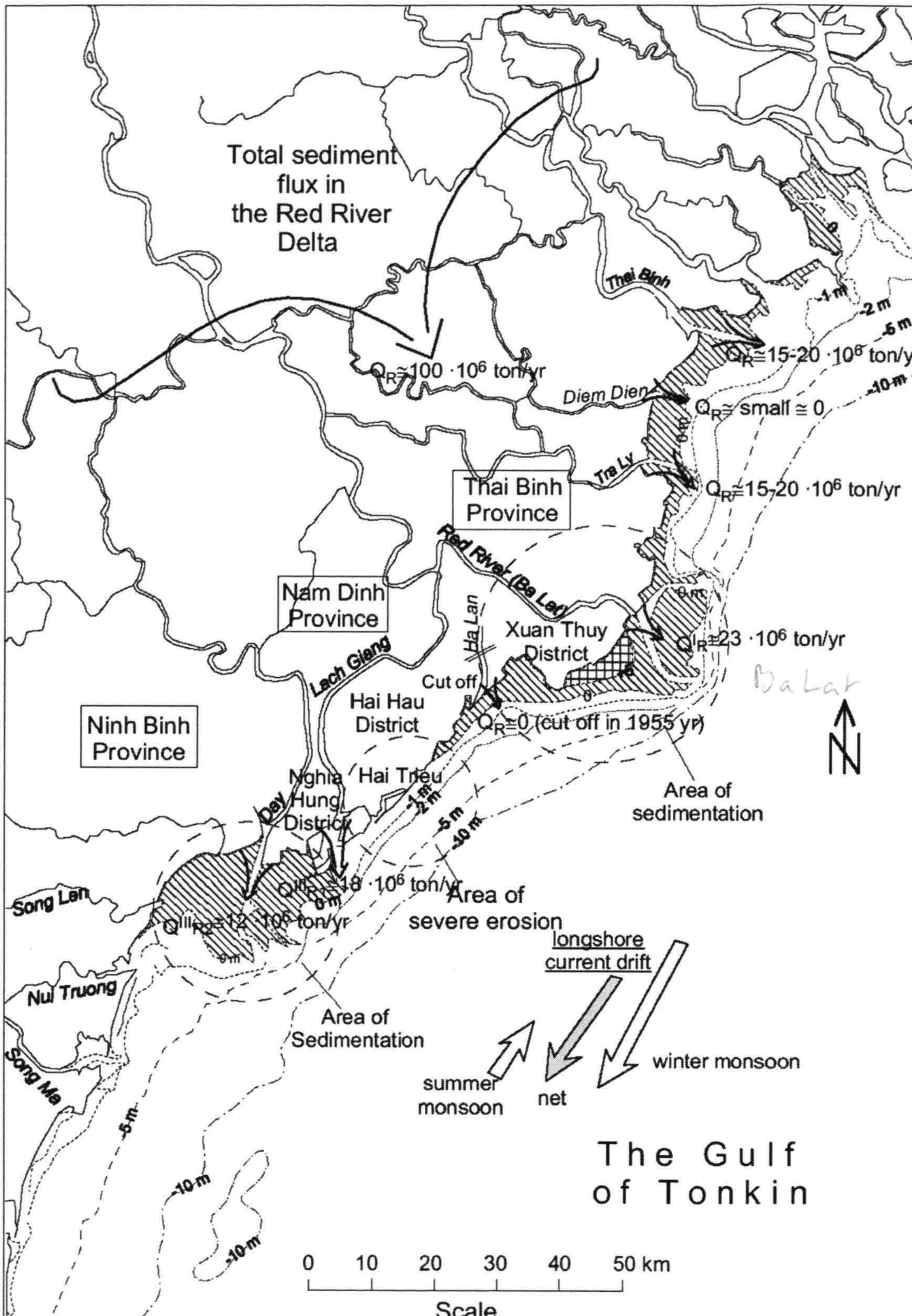


Fig. 2.5: Red River system and its sediment discharge (Pruszak et al. 2001)

2.7. OCEANOGRAPHY

2.7.1. Tide

According to tidal map of Vietnam, Tide at Nam Dinh is diurnal with tidal range varying from 3 - 4m. Records at Van Ly gauging station show that tide and water level at Van Ly is similar to Hon Dau gauging station. The tidal table of the General Department of Hydrometeorology reveals that the water level at Van Ly station can be deduced from the data at Hon Dau station with coefficient of 0.95.

Observation at Hon Dau station shows that tide in this area is purely diurnal, there is one spring tide and one neap tide every month (period more or less 25 days) and one high tide and one low tide a day. Tidal range in is about 3.0m in the spring tide.

Table 2.3: Extreme tidal water level in period of 19 years at Nam Dinh coast

No.	Location	MSL (cm CD)	Max. HW (cm CD)	Min. LW (cm CD)	Tidal range (cm)
1	Ba Lat	185.60	346	-7	353
2	Ha Lan	185.30	345	-7	352
3	Van Ly	185.00	344	-7	351
4	Lach Giang	185.00	345	-8	351

[Source: Vietnamese Water Resources Institute, 2002]

According to the tidal model of the Vietnamese Hydraulic Institute the tidal current at Nam Dinh is irregular diurnal. The diurnal character of the tidal current decreases southward, even at Lach Giang estuary the tidal current already is irregular semi-diurnal. This means that the variation of tidal level does not coincide with the tidal current.

Table 2.4: Extreme tidal current in period of 19 years at Nam Dinh coast

No.	Location	Flood tide		Ebb tide	
		Velocity (Cm/s)	Direction (Dgr. N)	Velocity (Cm/s)	Direction (Dgr. N)
1.	Off shore Ba Lat	59	348	57	174
2.	Off shore Van Ly	45	310	37	159
3.	Off shore Lach Giang	26	355	41	145

[Source: Vietnamese Water Resources Institute, 2002]

2.7.2. Currents

According to field observations done by Hung et al. (2001), wave-induced longshore currents have average value of 0.2 to 0.4 m/s and maximum of 0.7 to 1.0 m/s at depth of 2.5m. These figures include the tide current velocity (Hung et al. 2001). Longshore wave-driven currents are southwestward in the winter and northeastward in summer.

According to the Vietnamese Hydraulic Institute, a current at the Nam Dinh coast always exists due to winds, this current flowing in direction northeast to southwest. The current is stronger in the winter time (November to March), and he average wind current in winter is about 30 cm/s to 40 m/s, while in summer it is only 10 to 20 cm/s.

2.7.3. Wind

Since there is no offshore island, and it has relatively flat and low-lying topography, Hai Hau is an area exposed directly to the open sea, the area is subject to the winds generated from every direction. In the winter time (from October to March) the dominant wind directions are north, northeast and east. In summer (from May to August) the dominant wind directions are south, southeast and southwest. April and September are considered to be transition times.

In this study the observed wind data at Bach Long Vy Island was used (Tonkin Gulf, 20.133° latitude; 107.72° longitude).

Table 2.5: Wind data at Bach Long Vy Island (observation: 1975 - 1995)

Class (m/s)	Calm	N	NE	E	SE	S	SW	W	NW	Sum
1-5		843	3,103	2,843	1,875	1,858	578	277	320	**11,697**
6-10		505	5,160	1,378	810	3,440	530	77	108	**12,008**
11-15		156	2,013	73	79	1,043	65	6	9	**3,444**
16-20		90	863	11	23	77	4	2	19	**1,089**
21-25		16	27	0	2	5	1	0	5	**56**
26-30		3	4	0	1	2	3	0	3	**16**
31-35		3	1	1	0	4	0	0	0	**9**
36-40		1	0	1	1	0	0	0	1	**4**
Sum	536	1,617	11,171	4,307	2,791	6,429	1,181	362	465	**28,859**

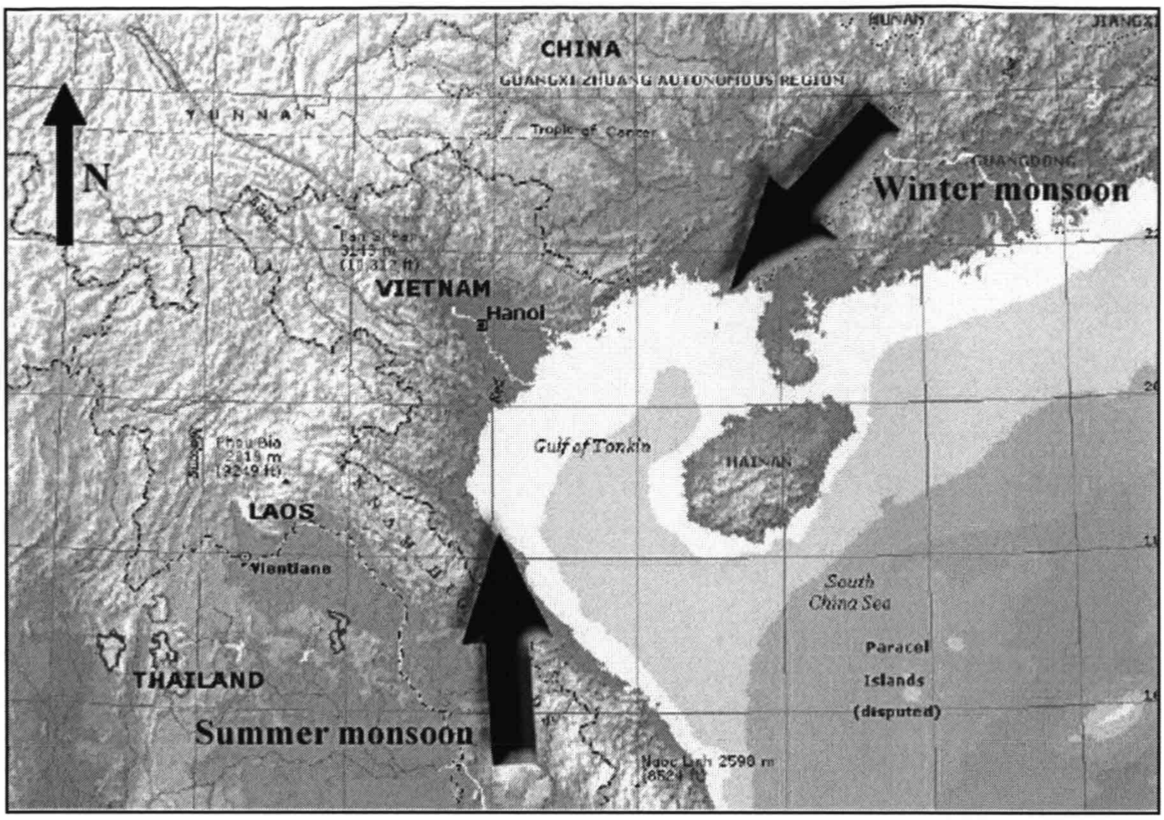


Fig.2.6: Main wind directions in northern Vietnam

Storms/Cyclones: As referring to the topographic map, the beach of the study area has a very gentle slope, which creates a relatively wide zone for wave transformation and energy dissipation. Apparently, only monsoon waves, severe storms or typhoons, with high rainfall, extreme wind speed, high wave and storm surges, cause severe threats to the local natural beach and the existing coastal structure.

In the study area, according to the weather observation record, there were about 4 typhoons occurring in a year on average. August and September are the most critical periods to encounter floods and storms. In August and September, storm winds are generated from NE with velocities of 20 m/s, and in some cases even up to 48 m/s. Typhoons are normally accompanied by storm surges. See Table 2.6

Table 2.6: Storm surge at Nam Dinh coast

Surge level (cm)	0 - 50	50 - 100	100 - 150	150 - 200	200 - 250
Frequency related to number of storms (%)	35	38	17	8	3

[Source: Vietnamese Water Resources Institute]

2.7.4. Waves

The Sea at Nam Dinh area is open (there is no offshore island) so the wind fetch is long enough for wave growth and approaches the shoreline without any obstacles, which can cause considerable damage to shoreline and sea dikes. According to observation in period from 1975 to 1987 waves at Nam Dinh had following characteristics:

- In winter (from September to March): In the winter, the sea was much more rough sea than in the summer. Wave height is about 0.8m – 1.0m, with periods varying from 7 to10 seconds. At times higher waves were observed. Predominant wave direction was northeast, and makes angles of about 30° to 45° with the shoreline. In this season - often in the October and November - waves sometimes combined with high spring tide causing high water levels that threatened to the dikes.
- In the summer (from April to August): In the summer there are less rough sea days but strong storms usually happen in this season causing severe damage to the dike system. Average wave height varies from 0.65m to 1.0m with period ranging from 5 to 7 seconds. The prevailing wave direction is south and southeast.

2.8 SEA DEFENCE SYSTEM IN NAM DINH PROVINCE

Sea dikes play a dominating roll concerning shoreline defence structures in Vietnam, and for the Hai Hau district dike systems are totally prevailing. The defence strategy regarding construction, maintenance and rehabilitation is overall governed by the Ministry of Agricultural and Rural Development (MARD) but is operationally run by the Department of Dike Management and Flood Control (DDMFC), which handles more than 3,000 km of coastal and estuarine dikes (Pilarczyk and Vinh, 1999). The main objective for DDMFC is to secure communities in coastal areas from erosion and flooding and thus increase agricultural production and income.

Construction of new dike systems and upgrading of old ones is a continuous process. In Van Ly, for example, the average annual coastline retreat has resulted in one destroyed dike line every 10 years. Due to the lack of proper equipment, upgrading and repair (in case of breach) of the front dikes are rarely possible and the land behind the dike is lost to the sea. Dike maintenance costs are extensive and in Hai Hau district they represent nearly 70 percent of the total sea defence budget (VCZVA, 1996).

The normal design wave height is based on an annual frequency of exceedance of 5 percent of time, which is determined by both investment costs and levels of protection. The dikes are fundamentally constructed to withstand concurrent design events, which are reflected in the employed dike crest elevation formula given by $z_{crest} = z_{tide} + z_{storm\ surge} + z_{wave\ run\text{-}up} + z_{free\ board}$, where z is elevation and the subscripts are self-explanatory. However, funding problems and shortage of equipment for example vehicles have affected the construction of the dikes and thus resulted in both weak structures and serious overtopping (salinity intrusion). In the future the economical development in the coastal zone will expand and thus it is expected that investments will increase and more money will be put into erosion control, i.e. better defence systems. The Vietnamese design standards are somewhat out of date and must be revised in order to meet contemporary international knowledge (Pilarczyk and Vinh, 1999).

The eroding impact from waves is in particular severe on beaches with steeper bottom slopes since waves hereby can propagate closer to the shore before breaking takes place. According to Vinh et al. (1996), the bottom slopes in Hai Hau district ranges from 1:40 in eroding areas to 1:200 in other areas. At present, 75 per cent of the Hai Hau coastline is deteriorating and it is a major problem that has attracted wide attention, both domestically and internationally. The dike system at Hai Hau beach is characteristically positioned as shown in Figure 2.7 and Figure 2.8.

When a breach takes place, the section dikes help to limit flooding and the second dike will be the new first line of defence. In general, the second dike is mainly made of soil (no true revetment) and thus it is weaker than the first. However, these dikes must and will be reinforced when the water reaches them; otherwise they will not last long. The distance between the dikes vary but is roughly 200-250 meters. The land areas between the dikes are also divided into sections varying between several hundred meters up to 3 km. The division into sections causes only limited areas to be flooded when a breach occurs at the front dike and without sections greater land areas would have been destroyed at once. Recent photos of the front dike reveal major erosion problems and clearly show the earth core of the dike as seen in Figure 2.9. The photo also illustrates the casuarina tree, which is frequently planted and used to reduce wind speed and bind the shoreline soil. The tree is common not only at Hai Hau beach but in Vietnam in general.

According to the VCZVA (1996), the front slope of the dikes in Nam Ha province is normally 1:3 and the crest elevation lies around 5 meters above mean sea level (MSL). The earth core consists of material from local sand and clay resources, which strongly affects the durability of the dikes since the fine soil is easily flushed out to sea. On top of the dike, revetments made from limestone cobbles are positioned on a layer of clay. A characteristic dike cross-section is shown in Figure 2.10. In total, dikes protect 75 per cent of the Hai Hau coastline. Finally, it is imperative to realize that the defence strategy in Hai Hau district is commonly known as a retreat strategy. This means that the rate of erosion is slowed down, not stopped.

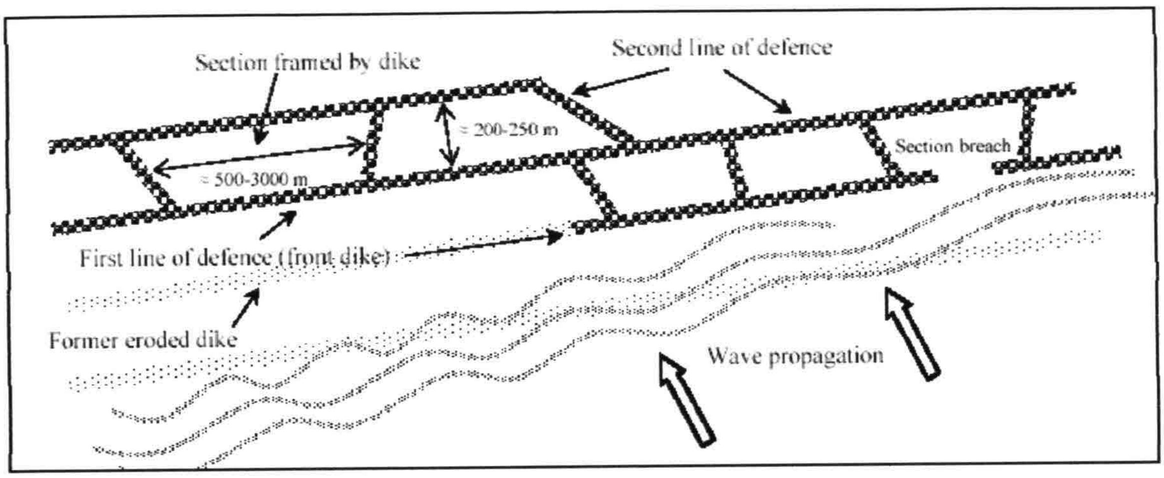


Fig. 2.7: Sketch of double dike system at Hai Hau beach

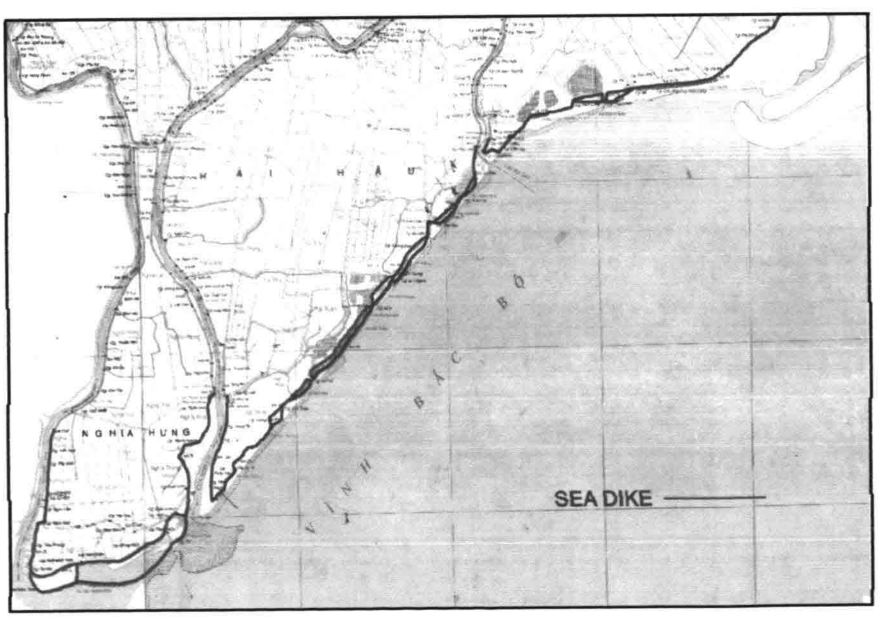


Fig. 2.8: Sea dike system in Nam Dinh province

Fig. 2.9: Severely eroded dike with planted casuarina trees at Hai Hau beach.

Fig.2.10: Characteristic cross-section of an eroded dike near Van Ly village

Chapter 3
OVERVIEW OF PREVIOUS RELATED STUDIES

During centuries, coastline in Nam Dinh province has experienced some changes due to accretion and erosion. However, in the last 100 years, severe erosion has taken place in this area, especially in Hai Hau district. Observation has shown that nature/climate changes and man-made structures built in the area could be the reason of these processes.

The aim of this chapter is to deal with primary assessment of coastline change in the past. Generally, in order to do that, there are three approaches that can be used, including: Comparison of a set of data (it could be photographs, topographical maps, satellite imageries, aerial photographs and bathymetry survey), review on previous studies and interviews of local Authorities and residents. However, due to lack of data available, for the time being, the analysing and comparison would only concern the first two approaches. The topographical map, satellite imageries, photographs and some related previous studies would be investigated in this report.

3.1 HISTORICAL CHANGES OF NAM DINH COAST

Thousands of years ago people in Hai Hau district tried to gain land by building dikes around the land. This is known then as “Reclamation system”. The coastal defence consists of two parallel dikes with a distance of about 250m in between. So far it is not yet clear about until what the reclamation system is built.

The severe erosion in Hai Hau district has taken place for 100 years. Observation has shown that nature/climate changes and man-made structures built in the area could be the reason of these processes. In the following figures and data, changes of Nam Dinh coast during last century are shown briefly.

To estimate the historical coastline change maps from several different years have been used along with satellite images. The maps and the satellite photos were scanned and thereafter the coastline was digitised. The resulting graph of all the digitized coastlines is shown in Figure 3.1. The figure displays an expected pattern of erosion in the two southern districts (Hai Hau and Nghia Hung) in Nam Ha province and strong accretion in the northern district (Xuan Thuy) and outside the river mouths.

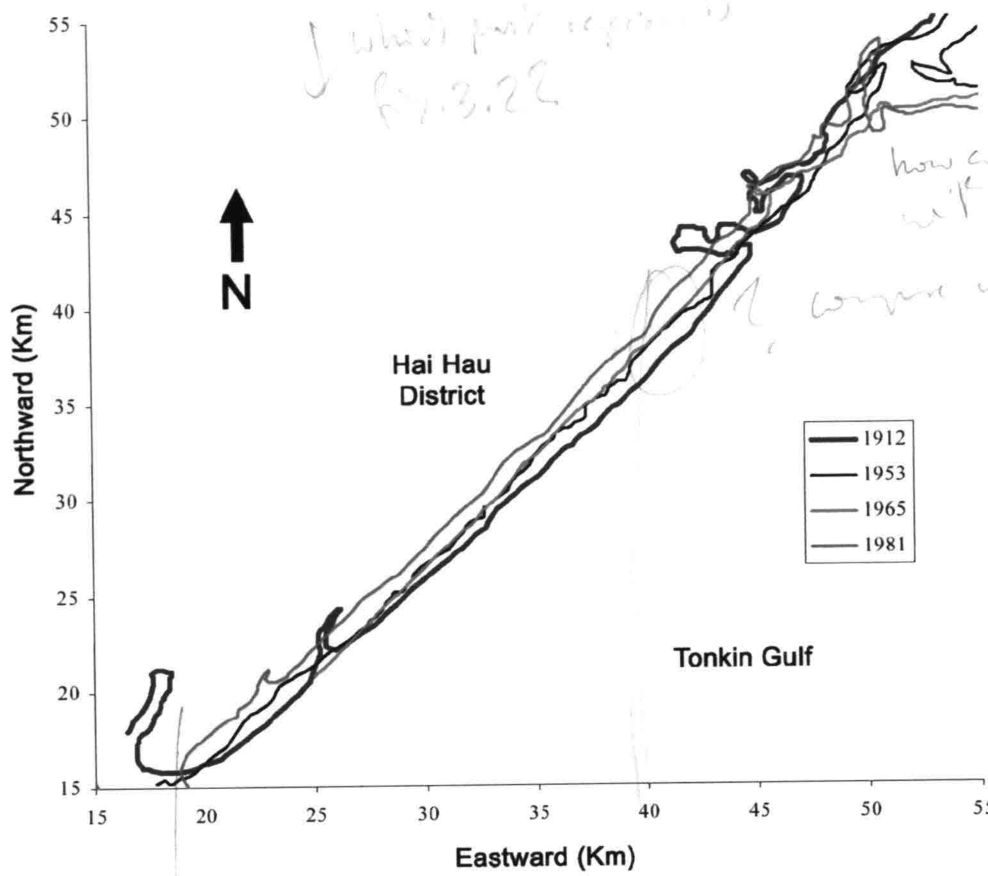


Fig. 3.1: Coastline change at Nam Dinh province from 1912 to 1981

From the shorelines in Figure 3.1, the retreat at Hai Hau beach for the period 1912-1981 has been estimated at approximately 2 km. Hence, the yearly erosion rate over these years equals 24 m, which is similar to 29 m as stated by Vinh et al. (1996). A more detailed view of the coastline change at Hai Hau beach is given in Figure 3.3. The coordinates in Figures 3.2 and 3.3 are not the same and the shorelines can therefore not be compared directly.

From Figure 3.2 the conclusion can be drawn that the erosion rate has slowed down over the last 40 years (the pattern is also supported in Figure 3.1. The average erosion rate, estimated from this figure, is approximately 29 m/year.

One should note that the coastline in Figure 3.1 and 3.2 is deduced from the sea chart map at the area with small scale (order or 1/100,000). These maps are not detailed enough to visualise the sea dike system at the study area. It means that there will be errors contribute in erosion rates that are deduced from this method. However this kind of analysis give us an overview about the evolution trend of the study coast.

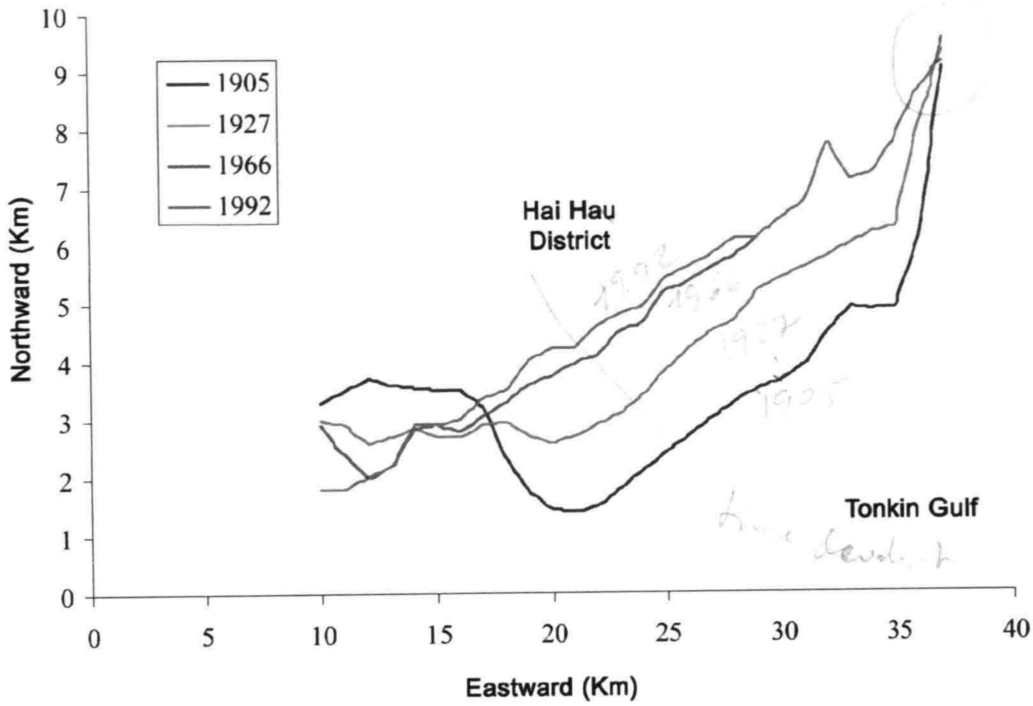


Fig. 3.2: Coastline change at Hai Hau beach from 1905 to 1992 (Hung et al., 2001)

Figure 3.3 shows a recently satellite image of Nam Dinh coast. The figure shows that sediment distribution is concentrated in Ba Lat, Day, and the Lach Giang river mouth. However, it was observed that some material was transported between Ba Lat and Day and Lach Giang

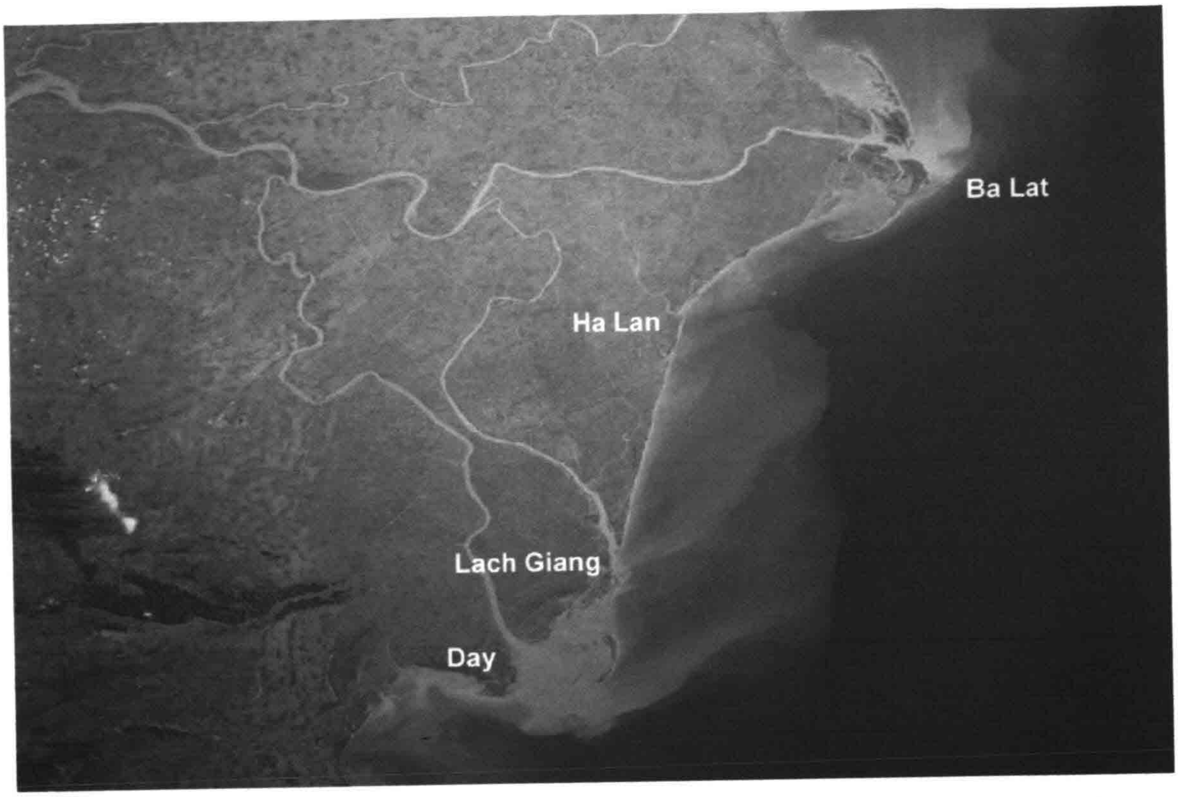


Fig. 3.3: Satellite image of study area

Figures 3.4, 3.5 and 3.6 show the condition of the Hai Hau beach in 1995 and 2000 by means of photographs. It is clearly indicated in the photos that the beach has suffered from erosion. The hydraulic structures that exist in the area, such as dikes and groynes, are not functioning. All of this structure is in poor condition. So, it is necessary to do remedial work as soon as possible.

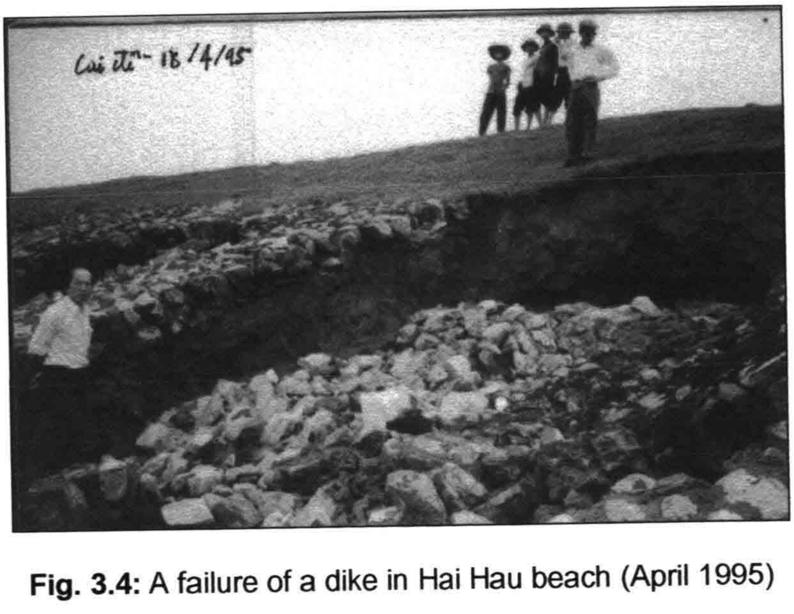


Fig. 3.4: A failure of a dike in Hai Hau beach (April 1995)

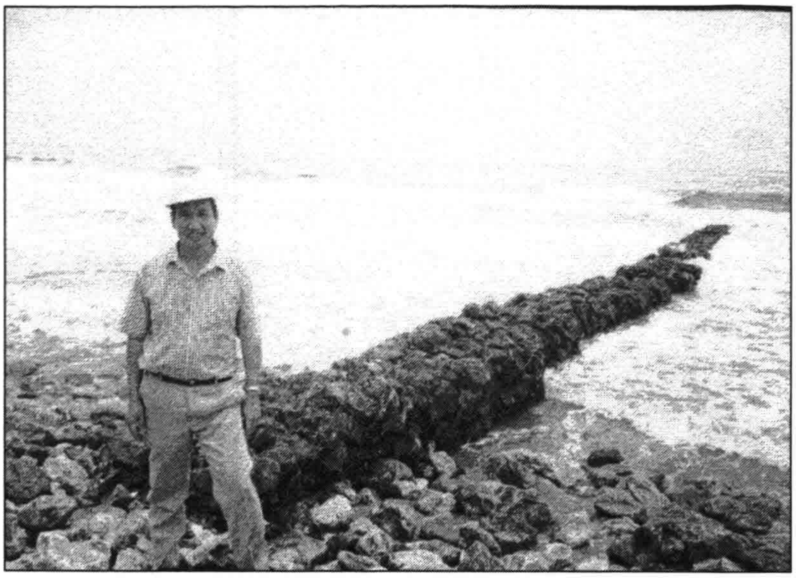


Fig. 3.5: A groyne in Hai Hau beach (High water, April 1995)

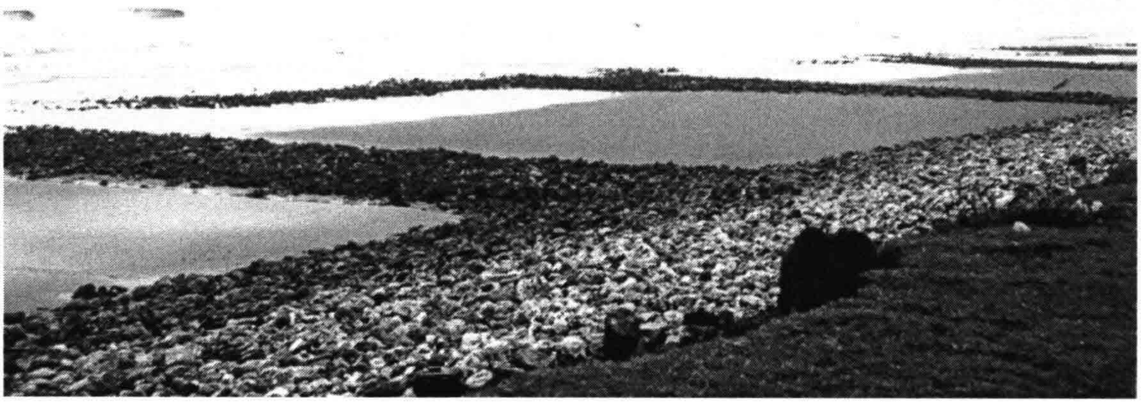


Fig. 3.6: Groynes with insufficient impact on the longshore sediment transport

Especially as can be seen at pictures of the groynes (Fig 3.5 and 3.6) at Hai Ly commune, which were built to prevent the erosion problem due to longshore transport. But due to lack of budget, groynes were not built with design length (they were made shorter). As the result, the groynes do not have significant impact to longshore transport and the erosion still going on.

Hanoi Hydro-geographic Survey Department provided this Figure 3.7 showing the map of Hai Hau district with the coastline change from 1972 to 1996. The grey area in the coastline of the map represents the deficit of the beach in the period of time from 1972 to 1996. Table 3.1 presents the results of measurement of erosion rate of Hanoi Hydro-geographic Survey Department map.

As shown in Table 3.1, the erosion rate was different in each commune. The average erosion rate from Hai Dong in the north to Hai Thinh in the south was about 16 m/year. The overall trend of erosion rate was decreased to the south. A maximum erosion rate was located in Hai Ly (Van Ly), which is located in the northern part.

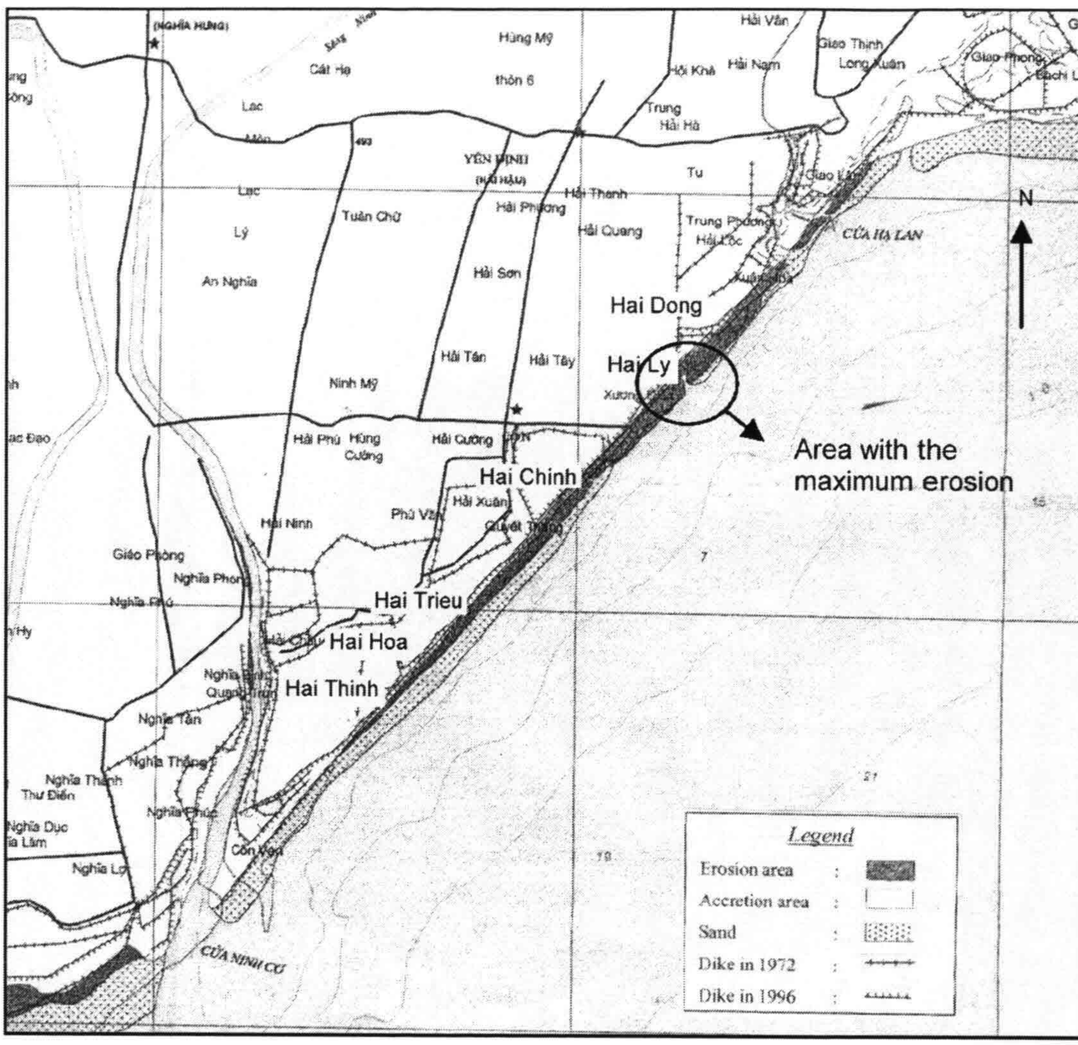


Fig. 3.7: The erosion map of Hai Hau district in the period from 1972 to 1996

Table 3.1: Summary of erosion rate from 1972-1996

Location	Erosion distance (m)	Erosion rate (m/year)
Hai Dong	600	25
Hai Ly	720	30
Hai Chinh	360	15
Hai Trieu	300	13
Hai Hoa	180	8
Hai Thinh	100	4

3.2 OVERVIEW OF PREVIOUS STUDIES

Some research has already been undertaken to come across an explanation of the phenomena that has happened in this area over the last few decades. The finding of some recently related studies follows:

i) ***" Research on Prediction and Prevention of Shoreline Erosion at Northern Part of Vietnam"**, Oceanography Sub-Institute in Hai Phong, Vietnam (2000).*

The research was carried out in order to determine the reasons of erosion at the northern coast of Vietnam – Including Nam Dinh province. Therefore, prediction of coastal evolution and defence strategy can be made. Some conclusions about erosion problem in Hai Hau district were issued:

- *Indirect reason:* Erosion of Hai Hau beach is related to natural evolution of Red River Delta and human activities that can cause reduction of sediment supply to the sea. / to the coast
- *Direct reasons:*
  - + Combination of longshore and cross-shore transport is a direct reason that causes erosion problem in this area.
  - + Closing of Ha Lan estuary (So river) also contributes to the erosion process. Due to this closure, there is some reduction of sediment transport to the sea.

In this report, there are also some general proposed solutions for erosion problems along the beach of Nam Dinh. It was suggested to build a groyne system for Hai Hau beach.

ii) ***" Coastal Processes in the Red River Delta Area, Vietnam"*** *Pruszak et al. 2001*

The study was conducted to analyse the evolution of the Nam Dinh coastline by means of using UNIBEST software. The study is concentrated in one segment of coastline that is most vulnerable to destruction, that of the Hai Hau beach. For this modelling, 20 year-recorded waves in the depth of 20m is used. Thus, the wave analysis used Krynov spectral method. The result indicated gradually smoothing-out of the shoreline configuration and reduction of the intensity of erosion.

It was concluded that the reason for the erosion in Hai Hau area is the changes in climate and complexity of topography that influence the sediment transport surrounding area. However, it is predicted that the erosion would be decreased due to improvement of hydraulic structures along the beach and equilibrium of the coast. See Fig.3.8

iii) ***"Regional Wave Transformation and Associated Shoreline Evolution in The Red River Delta"*** *- Hung et al., Mechanics Institute, 2001*

The aim of this study was to analyse the regional wave transformation that caused shoreline evolution in the Red River Delta. The regional wave transformation was divided into those that were offshore wave, and the nearshore waves. For offshore waves the data used is 20 years-recorded data at Bach Long Vi Station, which was calibrated using 20 years of visual observed data carried out in the same place. Based on this data the dominant wave direction was from the northeast and south. The nearshore wave transformation was analysed using a numerical 2D random wave transformation model. The results indicated that the wave height decay and energy dissipation in the middle and southern part of the Red River Delta, particular in the area where significant erosion has been observed. Based on this wave analysis, the sediment transport was calculated.

It was concluded that the governing factor of erosion are gradients in longshore sediment transport due to wave climate and its interaction with the nearshore topography. The other factors highlighted in their report were dam construction in the upstream of Red River, Hoa Binh in 1980's and the closing off So river - a branch of Red River, in 1955.

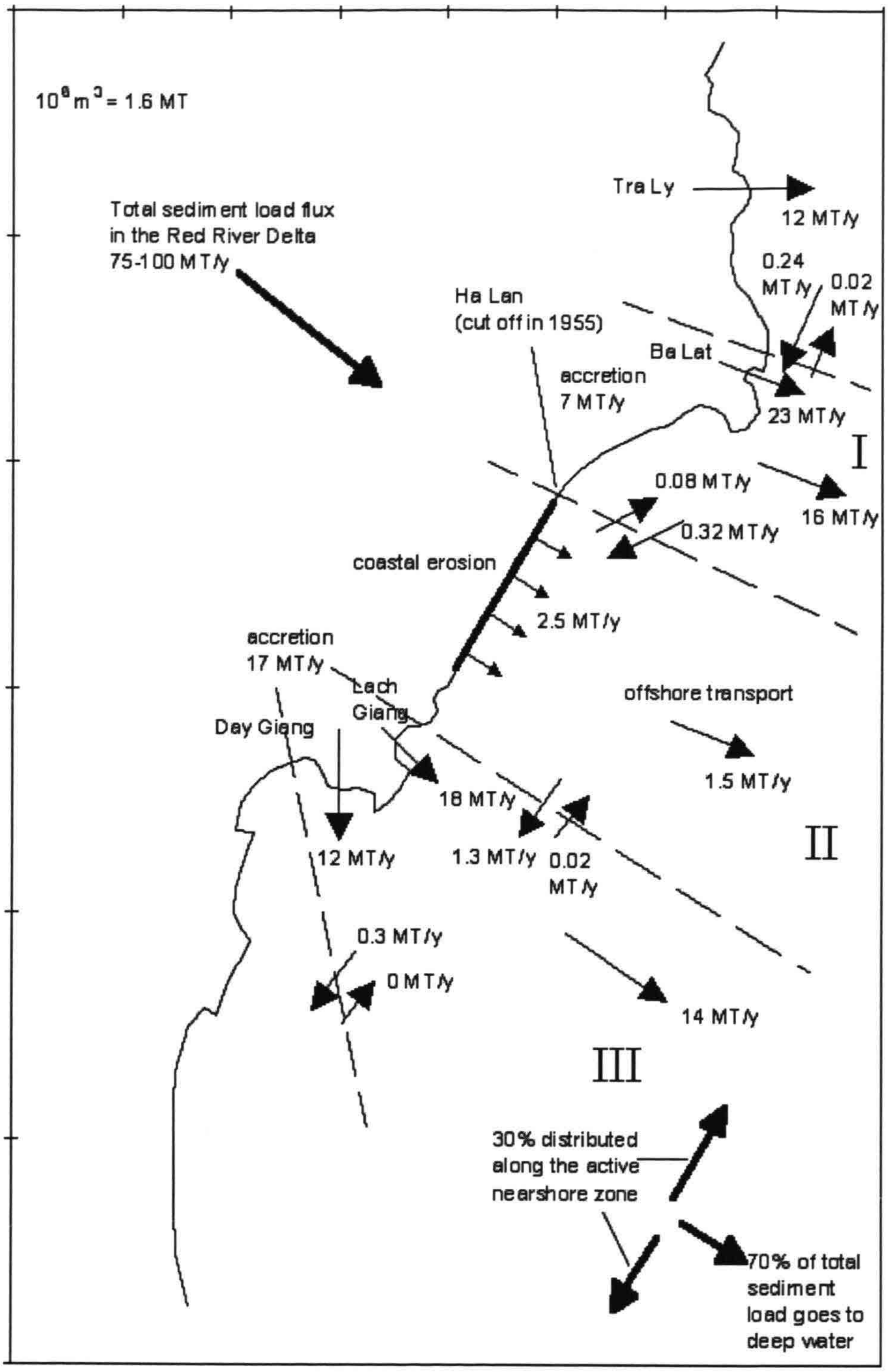


Fig.3.8: Sediment transport along the Nam Dinh coast - Pruszak et al. 2001

iv) ***"Coastal Erosion on a Densely Populated Delta coast – a Case study in Nam Dinh province, Red River Delta, Vietnam"*** *– Bas Wijdeven, TU Delft, 2002.*

This is a Master of Science thesis of a Dutch student. The main objectives of this study were to create an overview of historical and future coastal development of the coastline of Nam Dinh and to simulate the coastline behaviour over the past 100 years and its interaction with the coastal defences. Thereafter, possible future problems of dike erosion were predicted and mitigating measures were proposed.

The study was carried out based on data and information of some previous studies and reports. A 1D modelling package (WATRON) and UNIBEST packages for longshore sediment transport and coastline dynamics modelling (developed by WL | Delft Hydraulics) were used. Some main conclusion of the study follows:

- The main causes for erosion were found to be in the changing geometry of the Red River system and morphological mechanisms that characterise river mouth development: the abandoning of So river, and the development of the Red river mouth to its present shape.
- The cyclic mechanisms of the Red River mouth cause cyclic alteration of supply and non-supply of sediment of river mouth to downdrift located beaches.
- Construction of Hoa Binh dam on Da river, which is responsible for 53% of the total discharge of Red River system, is the most plausible cause for decrease in sediment supply to the coast.

In the study also discussed in depth about delta forming, side effect of dam construction and deforestation at the upstream of Red River to the erosion problem at Nam Dinh coast.

v) ***"SWAN Prediction of nearshore wave climate at Nam Dinh coast in Viet Nam"*** *- Nguyen Thu Huong, IHE-Delft, 2003*

This most recent study was done as a MSc. Thesis at IHE. The study aimed to improve the wave climate simulation at Nam Dinh coast.

Bas Wijdeven (2002) stated that the due to limitations of 1D wave model the nearshore wave climate was not good enough for sediment transport calculations. With the wave climate derived at water depth of 11m a wrong direction of sediment transport at Nam

Dinh coast was calculated. This is the main reason for this study to improve the nearshore wave climate with 2D wave model.

The Author used 2D wave model SWAN (*(acronym for **S**imulating **WA**ves **N**earshore)*, which was developed by Delft University of Technology, for study nearshore wave climate at Nam Dinh coast. The model was set-up based on rectangular computation grid with size of 500m. Offshore wave boundary is the results that were derived from 1D wave model, which was carried out earlier by Bas Wijdeven (2002).

The study has succeeded in surmounting the limitations of the 1D model. The study also concluded that the application of SWAN in a wave study for the Nam Dinh coast is acceptable. However due to lack of sufficient data for set-up boundary conditions and insufficient calibration data the results should be used with care. Causes of erosion problem at Hai Hau coast were not discussed in this study.

Table 3.2: Summary of findings from the previous studies

Name of study	Rate of erosion	Cause of problem	Solution
i) Research on Prediction and Prevention of Shoreline Erosion at Northern Part of Vietnam	1905 - 1927: 34.7m/year 1927 - 1966: 18.7m/year 1966 -1992: 3.6m/year	- Gradient in long shore transport - Changes in climate	No solution offered
ii) Coastal Processes in the Red River Delta Area, Vietnam	1905 - 1927: 40m/year 1927-1966: 20 m/year 1966 - 1992: 5.7m/year	- Gradient in long shore transport - Dam construction in upstr. Red River - Closing of So river	No solution offered
iii) Regional Wave Transformation and Associated Shoreline Evolution in The Red River Delta - Hung et al. 2001	1930 - 1965: 3.4m/year 1965 - 1991: 9.6 m/year 1991 - 2000: 14.5 m/year	- Gradient in long shore transport - Reducing of sediment supply to sea from Red River delta - Closing of So river - Movement of sand from shore to deep water	Structural (groyne system) and non-structural

development

Table 3.2 (continue)

Name of study	Rate of erosion	Cause of problem	Solution
iv) Coastal Erosion on a Density Populated Delta coast – a Case study in Nam Dinh province, Red River Delta, Vietnam - Bas Wijdeven 2002	1912 – 1955: 9.5 m/year 1955 – 1965: 24 m/year 1965 – 1995: 9 m/year	- Changing of Red river system. - Morphological development of river mouths - Cyclic mechanisms of Red river mount - Construction of Hoa Binh dam	- Reopen the So river - Relocation people in the risk area - Upgrade dike - Set-up a long-term management program
v) SWAN Prediction of nearshore wave climate at Nam Dinh coast in Viet Nam - Nguyen Thu Huong, IHE-Delft, 2003	Introducing nearshore wave climates by using 2D wave model (SWAN).		- No solution

3.3 DISCUSSIONS

The issue of erosion rate mentioned in this section varies. Pruszak et al. mentioned that the erosion rate from 1966-1992 was about 3.6 m/year whereas Hung et al. mentioned that from 1966-1992 the erosion rate was about 5.7 m/year. However both reports have the same trend of erosion rate, which was decreased in the last 26 years. Both reports also have almost the same figures of erosion rate during 1905-1992. Conversely, Oceanography Institute reported that the rate of erosion was about 9.6 m/year from 1965-1991. Thus, the trend of erosion rose rapidly to 14.5 m/year during 1991-2000. On the other hand, based on manual measurement from the map of Hanoi Hydro-geographic Survey Department from 1972-1996, the erosion rate was about 16 m/year and the maximum erosion rate was about 30 m/year in Hai Ly commune.

As mentioned above, Pruszak et al., Hung et al. and Bas Wijdeven reports have almost the same results. The erosion rate, sediment transport calculations and other information from these studies were also used for further comparison in this study.

The map from of Hanoi Hydro-geographic Survey Department (Fig. 3.8) is used for calibration of the coastline model. This figure is considered reliable source for the study because it is the latest information available and produced by Authority.

The erosion rates that were deduced from the map analysis should be used with care, because this erosion rates might be included the land loss area. Particularly to the situation at Nam Dinh when behind the sea dike it the low land areas, once the dike breach happened seawater intrudes to the low land behind the dikes, cause abandoning of the land (see Fig. 1.5, and Fig. 2.7). This might explain why the erosion rate at Hai Hau beach was reported so high, such as 30m per year even 50m per year. Since there is no long-term management strategy and monitoring program at the area, it is now very difficult to quantify exactly the erosion rate at the study area

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Fig. 3.10: Area between two dikes is filled with seawater, this area is considered as a erosion area. Hai Dong commune (Nov. 2003)

Chapter 4
WAVE MODELLING

4.1 INTRODUCTION

As discussed in the earlier chapters the erosion problem at Nam Dinh is quite alarming and poorly understood so far, due to a very limited amount of available data on nearshore wave, current and sediment transport data for studying the problem. Thus, the limited amount of available data must be supplemented by calculations in order to develop an understanding of governing coastal process. Waves are a key factor in this kind of study. A good understanding the characteristic of wave climate in the study area can result in good calculation of longshore current, and sediment transport which are the main elements of the coastal processes that might help to explain the causes of problem. This chapter is devoted to study the wave climate for the study area by using numerical wave model in order to: (1) Derive yearly nearshore wave climates for longshore transport calculation; (2) Investigate the influences of development of Ba Lat estuary to the nearshore wave climate for the area.

When modelling wave induced longshore sediment transport capacity patterns along the coastline, a yearly average wave climate is needed as input for these computations. The yearly average climate should be based on a minimum of 10-20 years of data, in order to compute a statistic reliable long-term wave climate. As no long-term time series of wave data (needed for nearshore wave calculation) were available for the Gulf of Tonkin, a method will be presented to estimate the nearshore wave climate. The only data sources of offshore waves were hand-written tables of wave observations. First, time series of offshore winds were calculated on the basis of a 20-year time series of wind speed and wind direction. The calculated offshore climate was verified using hand-written tables with wave data, based on a 19.5-year record of wave observations in the period from 1962 to 1981 (3 observations per day) at Bach Long Vy (Island in the middle of the Gulf of Tonkin). After verification and calibration, the calculated time series of offshore wave height were transformed to nearshore time series of waves. The 2-D numerical model SWAN (WL | Delft Hydraulics) was used to compute the offshore and nearshore wave climate. Background of wave theory and SWAN is given in Annex 1.

4.2 MODEL SETUP

4.2.1 Model area and bathymetry

Due to the limitation of data for offshore wave boundary, a hindcasting method is chosen to predict waves at the study area. Since the calibration point is an island in the middle of Tonkin Gulf, the fetch condition was ensured at the maximum to the hindcast point by making the model area the whole area of Tonkin Gulf. See Figure 4.1

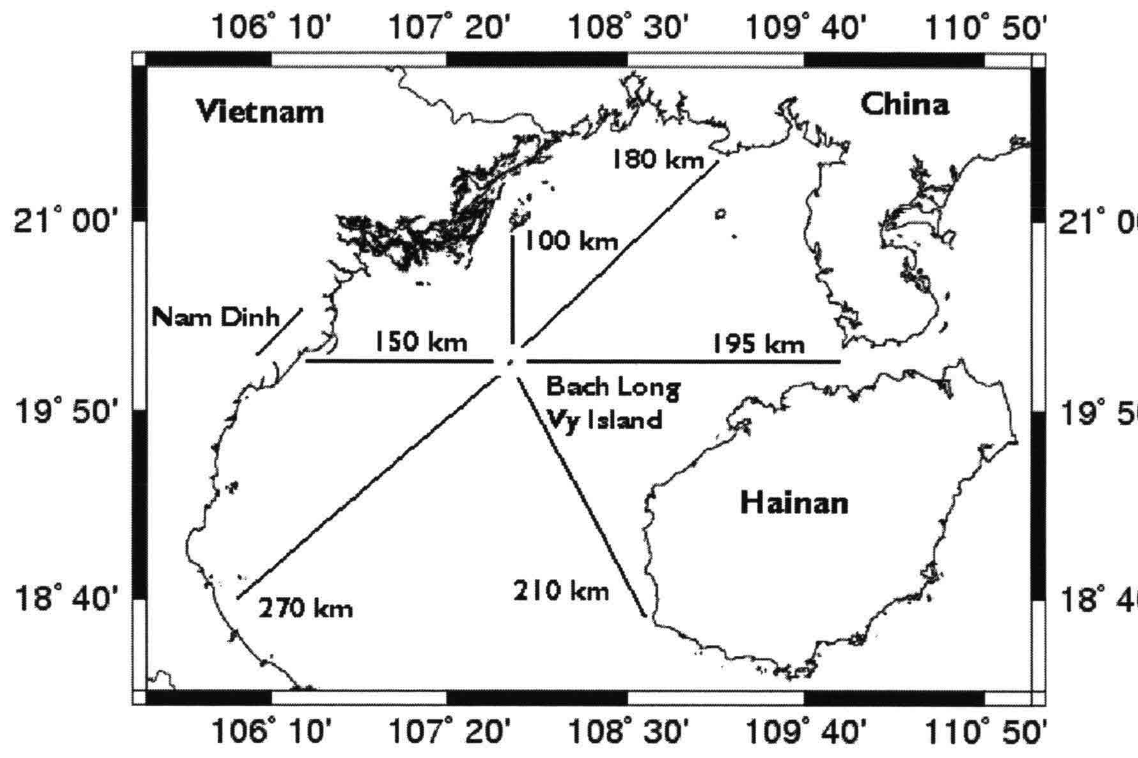


Fig. 4.1: Model area and wave hindcast location Bach Long Vy Island

The bathymetry data of Tonkin Gulf was obtained from Delft Hydraulics. Bathymetry of Tonkin Gulf was schematized by Delft-grid and Delft-quickin (the input tools of Delft3D model - WL| Delft Hydraulics) with curvilinear computation grid. Depending on the interest of the location, grid size varies from 2km - 5km.

4.2.2 Water level

For purpose of calculating nearshore wave climate at water depth of 10m to 11m the Mean Sea water Level (+1.85m CD) was used as the constant water level, which was considered not to have much influence on wave heights at water depth of 10m.

4.2.3 Wind data

Wind is assumed to constantly blow over for the whole model area, with duration varying from 6 hours to 10 hours. Wind data was derived from observation data at Bach Long Vy Island from 1975 to 1995. See Table 2.5 (chapter 2)

4.2.4. Other parameters of model

Other parameters of the model are summarized in Table 4.1

Table 4.1: Model paramaters

Group	Name of parameter	Description/option
Physical parameters	Constants	Gravity: 9.81 m/s^2
		Water: 1025 Kg/m^3
		North: 90 degree
		Minimum depth : 0.05 m
		Convention: Nautical
		Setup: None
		Forces: Wave energy dissipation rate
	Processes	Type of formulation: Third generation
		Bottom friction: Jonswap; coefficient =0.0067
		Depth induced breaking: B & J model, default value
		Nonlinear triad interactions: LTA; default value
	Various	Activate: Wind growth; white capping; quadruplets
		Activate: Refraction and Frequency shift.
Numerical parameters	Geographical space	Default value
	Spectral space	Default value
	Accuracy criteria	Relative change: 0.02
		Percentage of wet grid point: 98%
		Max. number of iterations: 18

Wave observation data at Bach Long Vy Island are summarized in the Table 4.2

Table 4.2: Wave observation at Bach Long Vy Island during period 1962 - 1981

Class (m)	N	NE	E	SE	S	SW	W	NW	Sum
0.25 - 0.50	185	573	448	355	303	97	61	116	2,138
0.51 - 0.75	188	971	677	570	635	158	80	58	3,337
0.76 - 1.00	227	1,452	706	458	963	176	48	41	4,071
1.01 - 1.50	238	2,634	519	280	1,822	213	34	41	5,781
1.51 - 2.00	68	1,631	145	64	827	50	14	14	2,813
2.01- 2.50	68	935	30	91	221	11	2	1	1,359
2.51 - 3.00	23	326	20	25	35	2	0	2	433
3.01 - 4.00	35	148	6	4	31	4	1	5	234
> 4.0	6	30	1	7	3	1	0	1	49
Sum	1,038	8,700	2,552	1,854	4,840	712	240	279	**20,215**

4.3 OFFSHORE WAVE VALIDATION AND CALIBRATION

Due to lack of information on swells at the open boundary at the south of the Tonkin Gulf (Fig. 4.1), the hindcasting was carried out with a zero wave height at the open boundary. Test simulations has showed that only with swells that are higher than 1.5m have noticeable change in wave heights at the study area and the effect is mainly on the waves that are generated by winds that come from southeast, south and southwest. On the other hand, according to wind observation data these winds only predominate in summer times and usually have speed less than 10m/s. This means that underestimate of wave heights at study area due to lack of information on the swells do not have major impact on the yearly nearshore wave climate at the study area and the simulation results without swell are acceptable.

In order to calibrate the hindcast wave model 148 simulations were done according to wind data. In the Table 4.3 shows the significant wave heights, which are extracted from the model results at Bach Long Vy Island for calibration.

Table 4.3: Significant wave heights at Bach Long Vy Island

(Hindcasting results with maximum fetch)

U_{10} (m/s)	Significant wave height - Hs (m)							
	N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
4	0.23	0.29	0.23	0.29	0.29	0.30	0.29	0.29
5	0.38	0.43	0.44	0.43	0.44	0.43	0.42	0.42
6	0.59	0.59	0.60	0.60	0.60	0.60	0.59	0.57
7	0.77	0.77	0.79	0.79	0.79	0.80	0.78	0.75
8	0.99	1.01	1.04	1.02	1.05	1.04	1.00	0.97
9	1.26	1.31	1.31	1.28	1.35	1.33	1.29	1.20
10	1.54	1.60	1.60	1.61	1.66	1.66	1.58	1.48
11	1.82	1.93	1.93	1.92	2.01	2.00	1.89	1.76
12	2.15	2.26	2.26	2.25	2.36	2.36	2.22	2.05
13	2.43	2.61	2.60	2.59	2.76	2.74	2.53	2.32
14	2.74	2.94	2.95	2.96	3.14	3.11	2.84	2.61
15	3.06	3.26	3.29	3.32	3.53	3.49	3.18	2.92
16	3.36	3.62	3.64	3.66	3.93	3.93	3.53	3.19
18	3.96	4.30	4.34	4.39	4.75	4.67	4.23	3.71
20	4.59	4.98		5.15	5.56	5.50		4.31
22	5.16	5.65		5.92	6.39	6.28		4.87
24	5.82	6.32		6.59	7.10	6.97		5.43
26	6.39	6.83		7.26	7.87	7.75		6.05
28	6.86	7.41	7.56		8.48			
30	7.41	7.77	7.97		9.01			
32	8.10		8.53	9.12				7.88

The wave observations are taken as the most accurate reference. The input parameters (for example wind speed-storm duration distribution) were varied in order to test the assumptions that were done. Figure 4.2 shows the difference between the observations and hindcasting results. As can be seen from the Figure 4.2 the hindcasting result curve has shown a good agreement on trend with observation curve. However the hindcasting results give higher values compare to the observations, at a same frequency the maximum difference in the wave height is about 40cm.

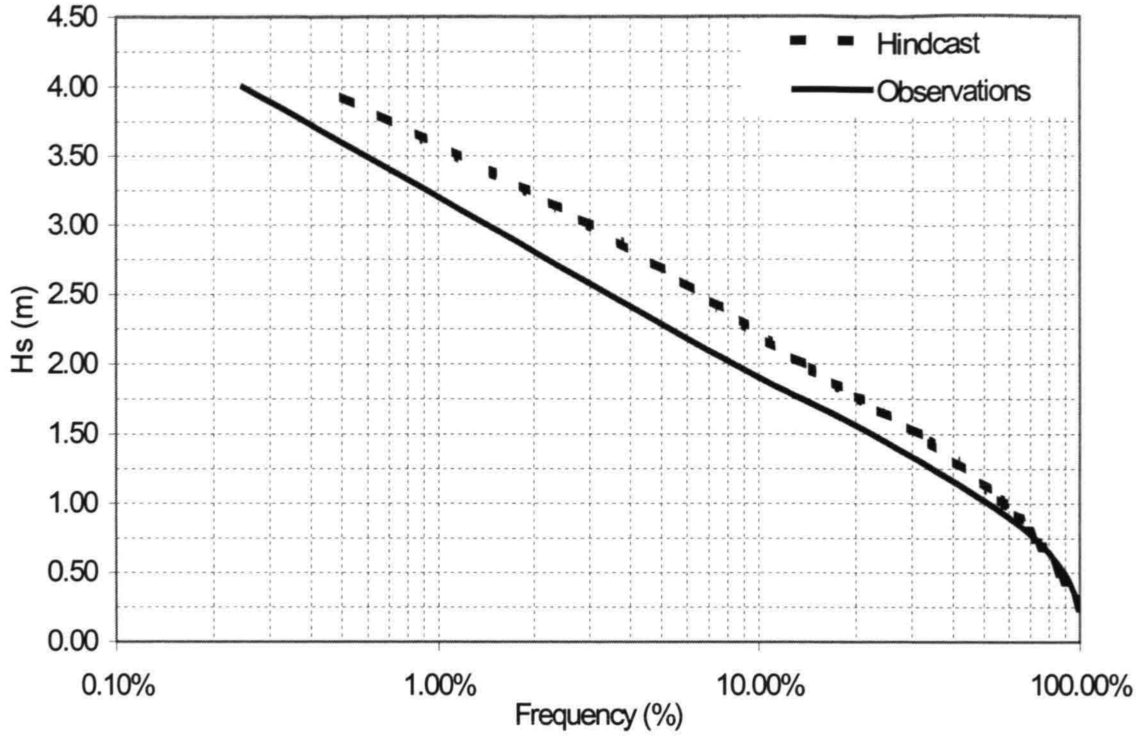


Fig. 4.2: Wave calibration

The difference between the observations and simulation results can be caused from the assumption in wind data. Using a constant wind speed for whole computation grid is not a good solution for hindcasting method. A wind field that describe the variation of wind in speed and direction in the model area should be developed, this is impossible for this case since there is only one observation station for wind at Bach Long Vy Island.

In earlier works done by Bas Wijdeven (2002) with the same wind input data and wave observation, the wave hindcasting was carried out by a 1D model (WATRON), and the calibration has also been done successfully only when using other program to fit the wind data to wave observation data (See Figure 4.3).

Efforts had been done in order to search for more information for better wave simulations, so far these are all the possible data at the area of Tonkin Gulf that can be used for modelling works. However compared with previous studies on wave modelling at Tonkin Gulf the results are acceptable and good enough for further computation. For further study in the next steps wind data wind were fitted to the wave observations.

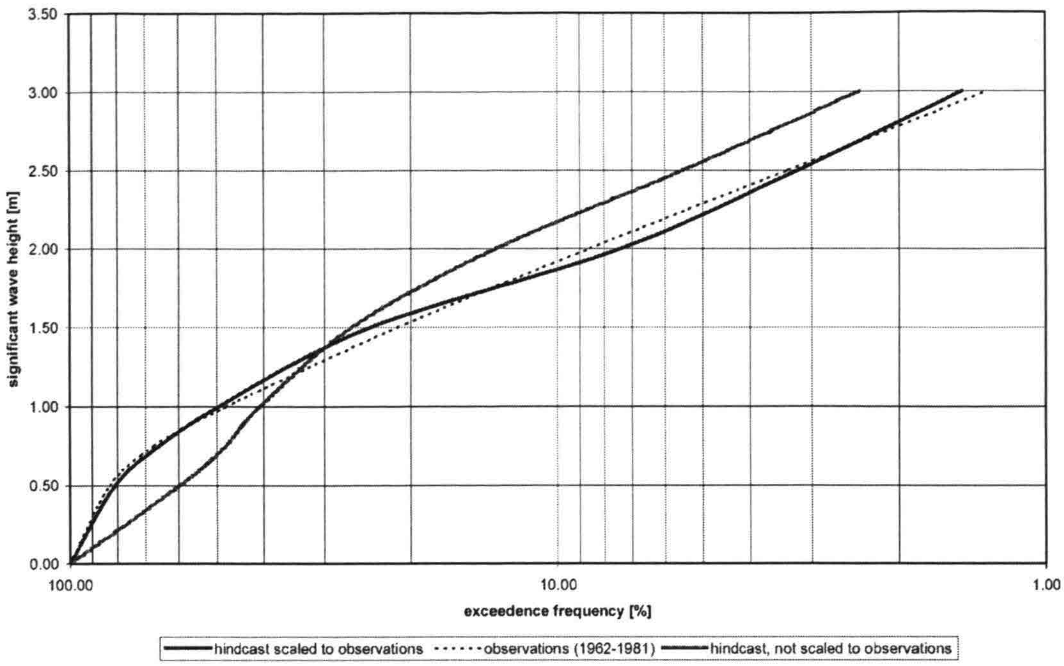


Fig.4.3: Wave calibration at Bach Long Vy Island (Bas Wijdeven, 2002)

4.4 NEARSHORE WAVE CLIMATE AT NAM DINH COAST

It is reported in the previous studies that development of Ba Lat estuary might alter the wave field at Hai Hau beach and cause the changes in gradient of longshore current resulting the erosion problem at Hai Hau beach. The purpose of modelling work in this section is to:

- Examine the influences of the development of Ba Lat estuary to the wave field at the study area.
- Extract the nearshore wave climate for sediment transport computation from the simulation results.

Average year nearshore wave climates will be extracted at 9 points along the coastline at the study area for comparison and examination. The position of the points are described and illustrated in the Table 4.4 and Figure 4.4

Table 4.4: Location of the points for extracting nearshore wave climate

Location	Name	Co-ordinate (UTM-48)		Depth (m)	Wave directions
		X (m)	Y (m)		
Giao Thuy district	GT	656786	2230440	10.6	NE, E, SE, S, SW
So (Ha Lan) estuary	HL1	647862	2226360	10.3	NE, E, SE, S, SW
	HL2	645532	2224320	10.5	NE, E, SE, S, SW
Hai Hau district	HH1	643264	2222270	10.9	NE, E, SE, S, SW
	HH2	640971	2220140	11.5	NE, E, SE, S, SW
	HH3	638665	2218000	11.6	NE, E, SE, S, SW
	HH4	636288	2215110	12.4	NE, E, SE, S, SW
Nghia Hung District	NH1	631188	2210610	11.0	NE, E, SE, S, SW
	NH2	621408	2197440	10.1	NE, E, SE, S, SW

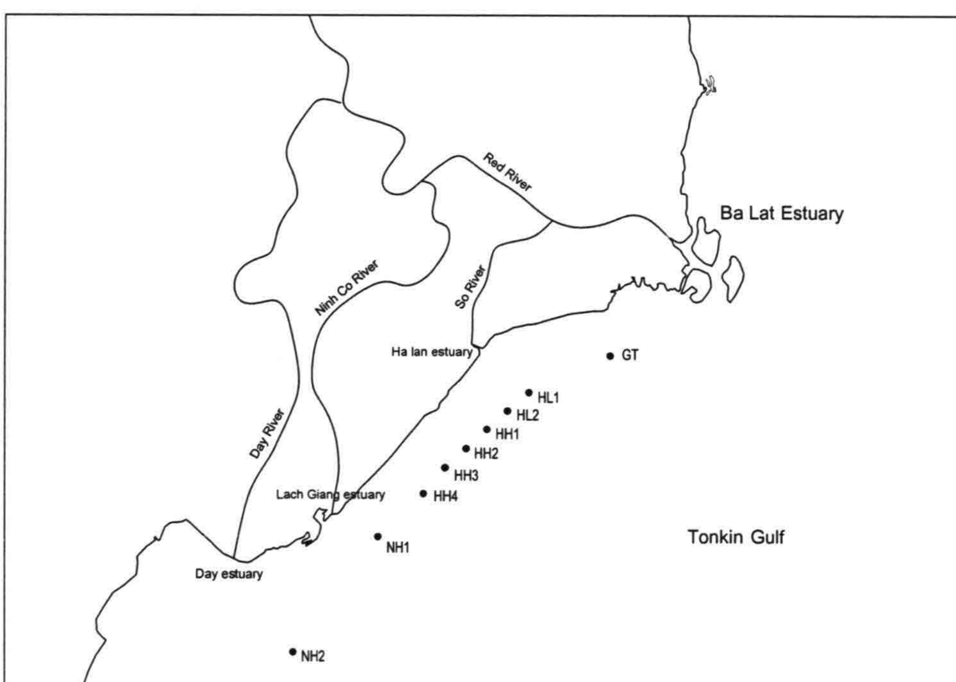


Fig.4.4: Nam Dinh coastline and location of the extracted points.

Three scenarios of the coastline with different forms of Ba Lat estuary are used to simulate the wave field at the study area. The study area is nested in the Tonkin Gulf model (see Fig. 4.5 and Fig. 4.6).

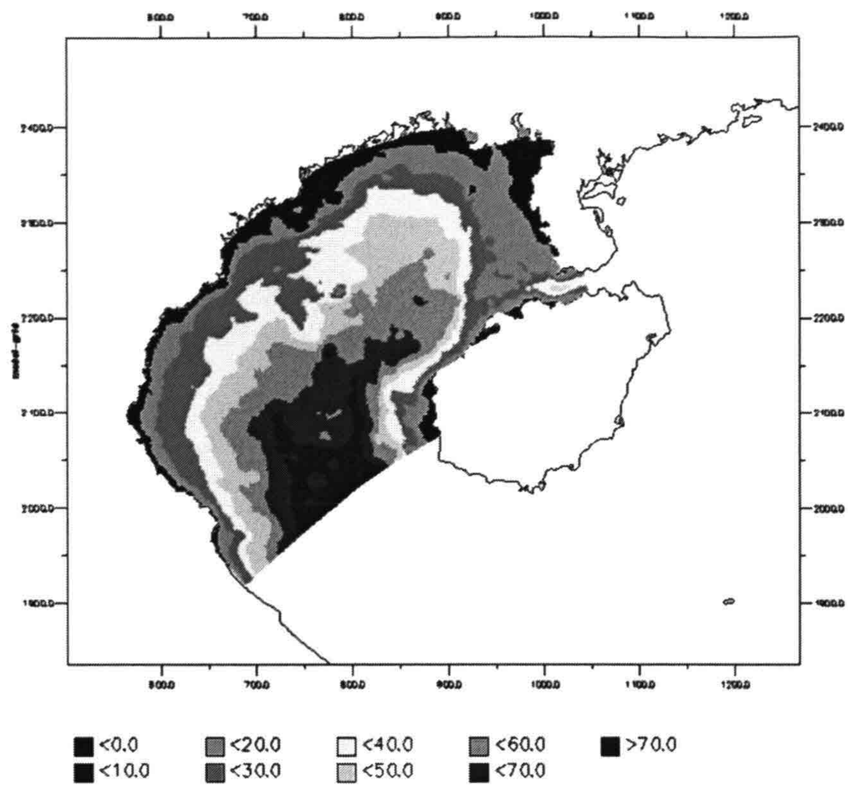


Fig. 4.5: Bathymetry of Tonkin Gulf - Model area in Delf3D

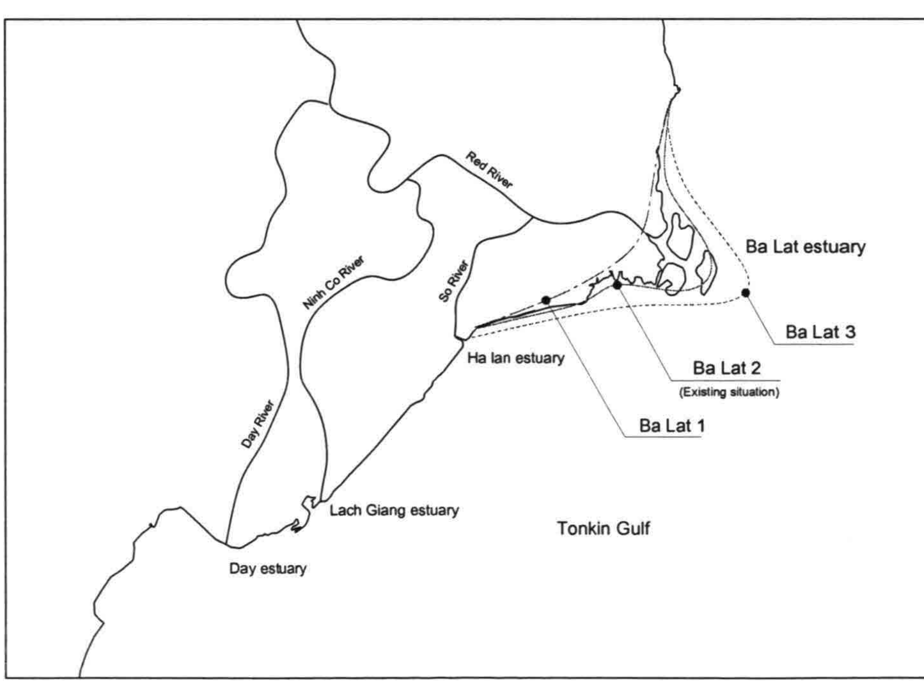


Fig. 4.6: The study area with different developments of Ba Lat estuary

- Scenario 1 (Ba Lat 1): The Ba Lat estuary is schematized without the spits; this more or less looks like the situation in the 1950s,
- Scenario 2 (Ba Lat 2): This is the existing situation of the Ba Lat estuary,
- Scenario 3 (Ba Lat 3): Assume the spits going seaward about 3Km compared to the existing condition.

In the three scenarios above when assuming the form of Ba Lat estuary, the bathymetry at Bat Lat is modified in such a way that the contour lines at the estuary area still have the same trend, their position is only shifted.

The wave hindcasting is carried out for wind directions and speed with occurrence frequency as mentioned in the Table 4.5. The wind data here is the data deduced from the wind data at Bach Long Vy Island after using Bestfit program to fit with the wave observation data.

Table 4.5: Wind data for wave hindcasting

Wind Sp	N	NE	E	SE	S	SW	W	NW
5 m/s	0.915%	2.835%	2.216%	1.756%	1.499%	0.480%	0.302%	0.574%
7 m/s	2.053%	11.986%	6.841%	5.085%	7.905%	1.652%	0.633%	0.490%
9 m/s	1.177%	13.030%	2.567%	1.385%	9.013%	1.054%	0.168%	0.203%
11 m/s	0.336%	8.068%	0.717%	0.317%	4.091%	0.247%	0.069%	0.069%
12 m/s	0.336%	4.625%	0.148%	0.450%	1.093%	0.054%	0.010%	0.005%
14 m/s	0.114%	1.613%	0.099%	0.124%	0.173%	0.010%	0.000%	0.010%
16 m/s	0.173%	0.732%	0.030%	0.020%	0.153%	0.020%	0.005%	0.025%
18 m/s	0.010%	0.109%			0.010%			
22 m/s	0.005%	0.030%		0.020%				0.005%
24 m/s		0.010%	0.005%	0.015%		0.005%		
28 m/s	0.005%							
32 m/s	0.010%							
SUM	**5.135%**	**43.037%**	**12.624%**	**9.171%**	**23.938%**	**3.522%**	**1.187%**	**1.380%**

See Annex 2 for the whole set of simulation results.

4.5 DISCUSSIONS

From the simulation results we can draw some following conclusions about the nearshore wave climate at the Nam Dinh coast:

- Nearshore wave climate at Nam Dinh coast consists of waves coming from NE, E, SE, S and SW directions,
- Nearshore wave climate at Nam Dinh is strongly predominated by waves that come from the NE and E directions. According to observation these waves have more than 50% exceedance frequency in the whole year wave climate and they are also strong waves because they are generated by winter wind.
- For the waves that come from NE and E (see Fig. 4.7 and Fig. 4.8): in the distance about 27km (from GT to HH4 - see Fig. 4.4) - most of this part belongs to Hai Hau district - wave height increases steadily. In the next section from HH4 to NH2 (km 27 to km 35) - the Lach Giang estuary area - wave height seems stable then picks up again in the last section (Day estuary area.
- The seaward development of Ba Lat does not have a strong influence on the wave heights of the waves that come from NE and E directions; especially in the first two cases (Ba Lat 1 and Ba Lat 2) the difference in the wave height is very small. Only in the last scenario (Ba Lat 3) wave heights are smaller than the previous scenarios. From the results the biggest difference in wave heights can be seen at the Ba Lat estuary (Giao Thuy district). The difference in wave height here (at Giao thuy district - point GT1) in order of 10cm and this difference is getting smaller southward, finally at the Day estuary (point NH3) there is no difference in the wave heights among 3 scenarios. See Fig. 4.7 and Fig. 4.8

In these plots U_{10} = 11m/s has been used as an example. Similar results are found for other wind speeds.

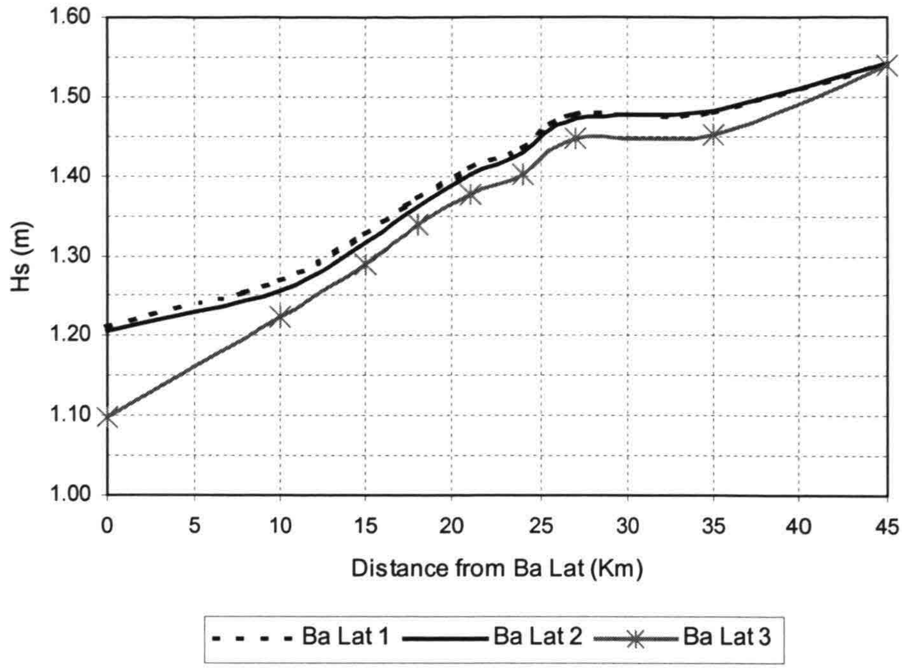


Fig. 4.7: Wave height distribution along the coast (Northeast wind, U_{10} = 11m/s)

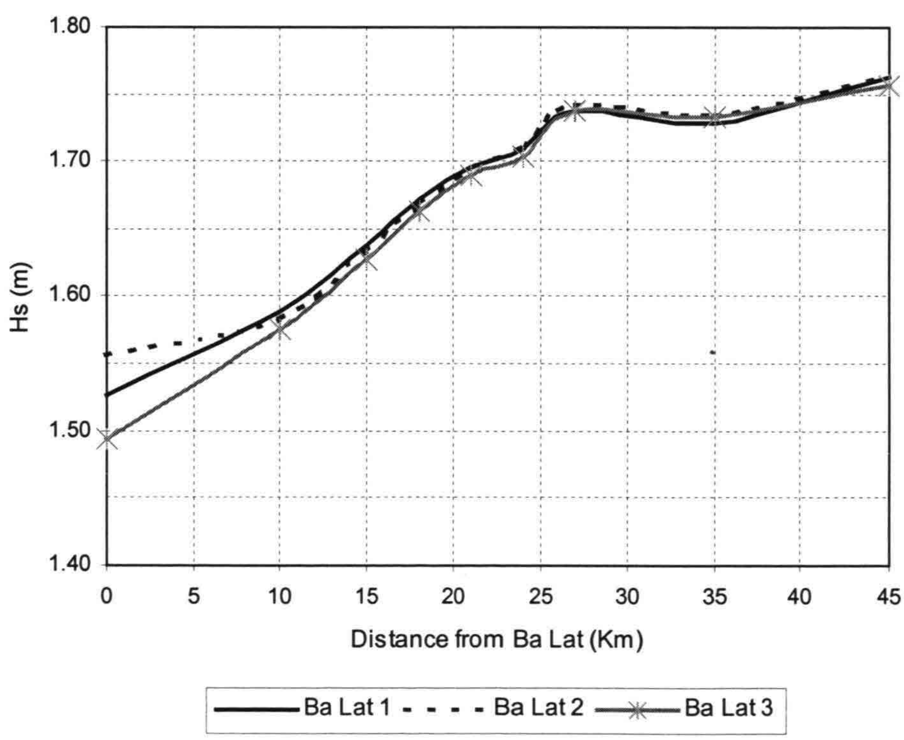


Fig.4.8: Wave height distribution along the coast (East wind, U_{10} = 11m/s)

- For the waves that come from the southeast direction (see Fig. 4.9), in general, it is also more or less the same trend for the waves from northeast and east mentioned above. The main difference is that the gradient of wave height is very small: 10cm/27 Km coastline compared to 35cm/27km.
- The development of spits at Ba lat estuary does not have any influence on the wave heights of the waves coming from southeast.

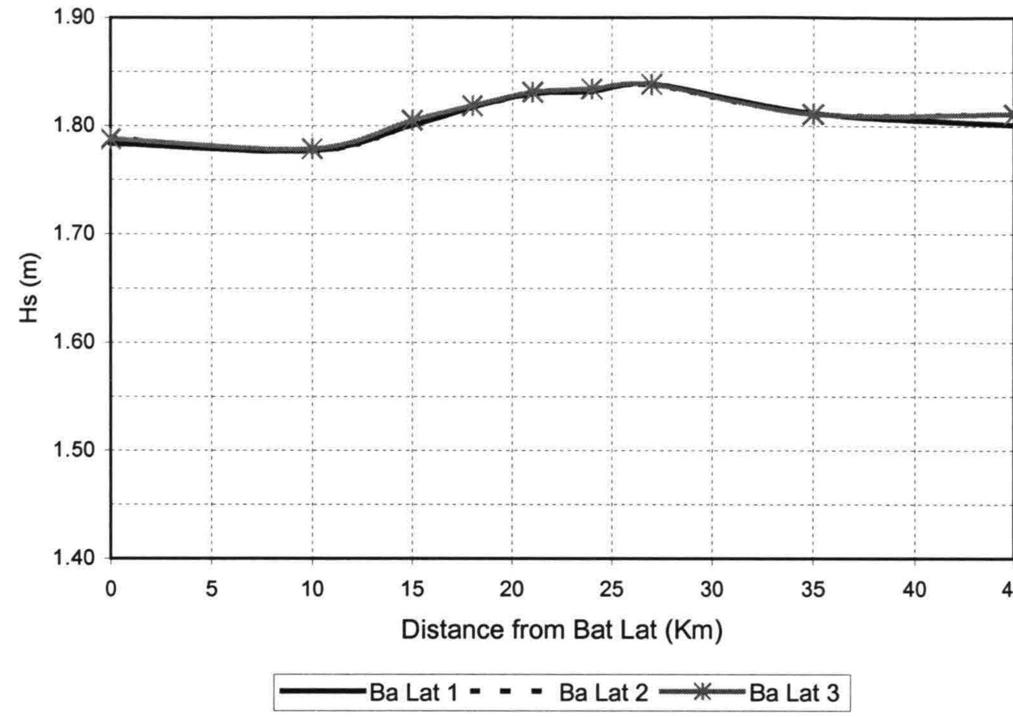


Fig. 4.9: Wave height distribution along the coast (Southeast wind, U_{10}=11m/s)

- For the waves coming from the south and southwest directions (see Fig. 4.10 and Fig. 4.11). We can see from Figure 4.10 and Figure 4.11 that these waves are not affected by the development of the spits at Ba Lat. Wave heights slightly increases from south to north.

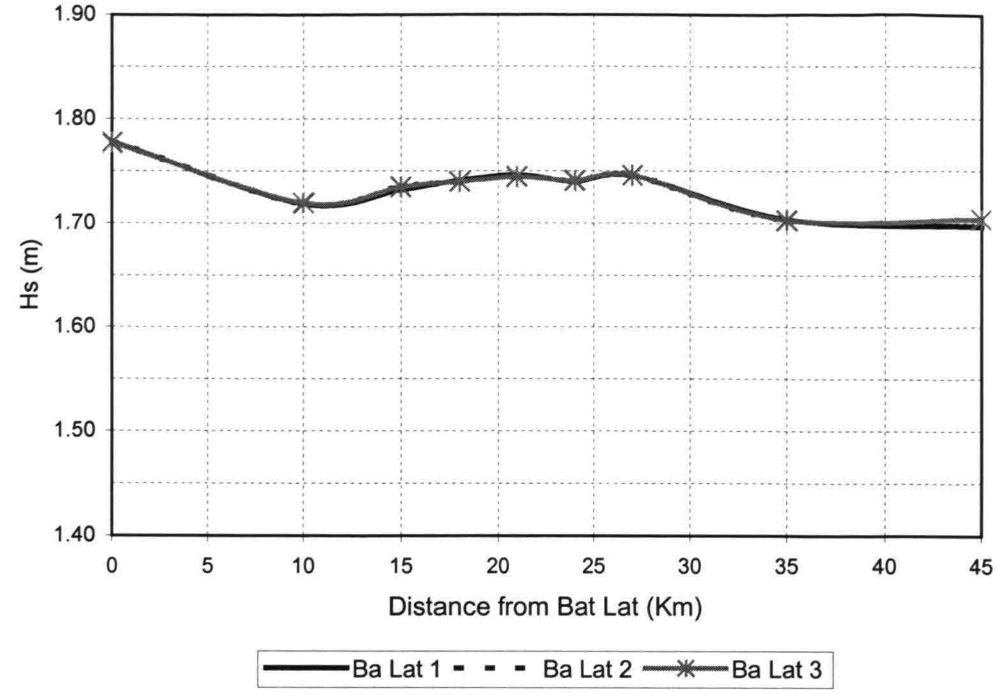


Fig. 4.10: Wave height distribution along the coast (South wind, U_{10} = 11m/s)

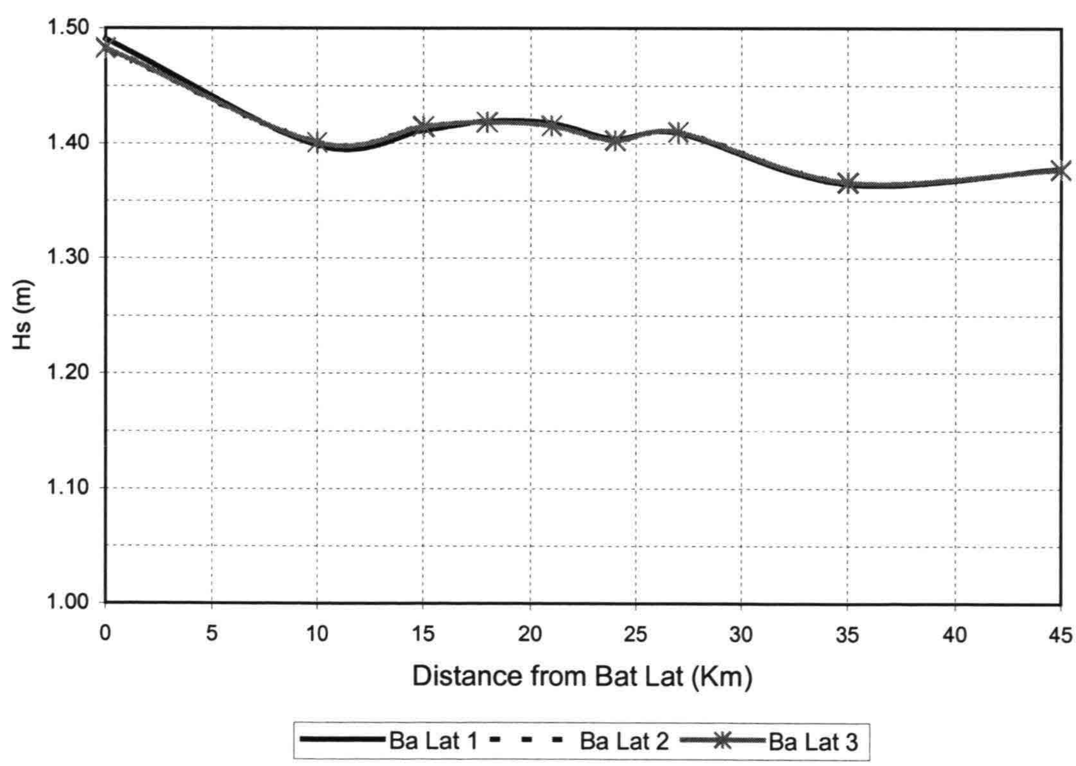


Fig 4.11: Wave height distribution along the coast (Southwest wind, U_{10}=11m/s)

- In general the development of spits at Ba Lat estuary has only a minor influence on wave heights of waves come from northeast and east.
- The waves coming from the northeast and east are dominant in the year wave climate. With wave heights increase southward, these waves may be the main reason for causing the longshore current and sediment transport going to the south.
- Although waves that come from the south also occur quite often in the yearly wave climate (about 30% of the time) the gradient of the wave height is not large. So the northward longshore sediment transport is not a dominant factor in the erosion process. This coincides to the observations at Nam Dinh coast.
- These findings show difference results with the previous studies, which say that the development of spits at Bat Lat might alter the nearshore wave climate causing the erosion at the Hai Hau beach.

Chapter 5
SEDIMENT TRANSPORT MODELLING

5.1. INTRODUCTION

Littoral processes are the results of the interaction of winds, waves, currents, tides, sediments, and other phenomenon in the littoral zone. Shore erodes, accretes or remains stable, depending on the rates at which sediment is supplied to and removed from the shore. The littoral transport is classified in onshore-offshore transport and longshore transport. Onshore-offshore transport has an average net direction perpendicular to the shore, while longshore transport has an average net direction parallel to the shoreline.

In this section the longshore transport is subjected to study with support of UNIBEST - a numerical model developed by Delft Hydraulics (Background of the UNIBEST model, the reader is referred to Annex 3).

Comparing the 42 degrees orientation of Hai Hau beach with the dominant wind directions (N, NE, S), it is clear that on this coastline, the wave climate is an important parameter, influencing coastal changes (Bas Wijdeven, 2002). This hypothesis is also supported by Hung et al. (2001), who poses the hypothesis that the erosion on Hai Hau beach mainly occurs due to the prevailing waves generated by winter monsoon in combination with the Nam Dinh coastline topography. Its interaction produces longshore sediment transport gradients (Hung, 2001).

5.2. INPUT DATA FOR LONGSHORE TRANSPORT COMPUTATION

5.2.1 Nearshore wave climate

For these calculations 9 different yearly nearshore wave climates are used for 9 calculation profiles (see Fig.5.1). Nearshore wave climates were derived form the results of wave modelling. The sediment transport calculations are made for the existing situation of Nam Dinh coast (based on data of year of 2000). So wave climates refer to the results of the wave model Ba Lat 2 (see Annex 2 for yearly nearshore wave climates).

5.2.2 Tide conditions

The tidal velocity, assumed to follow a Chezy relation, is implicitly defined in the longshore momentum equation by the tidal surface slope longshore. In practice this means that a tidal velocity has to be given for a certain reference depth. The current velocity distribution over the dynamic profile is extrapolated from this reference point. In this particular situation with a rather wide dynamic zone (more than 1 km offshore, bounded at 6m to 7 m water depth) this yielded unrealistic tidal velocities, and thus a domination of tide to waves (Bas Wijdeven, 2002). Therefore, in the modelling procedures, just the effect of wave driven currents on the longshore transport was modelled, slightly underestimating the total transport induced by waves and tide.

Table 5.1 summaries the vertical tide parameters used in UNIBEST calculations.

Table 5.1: Tide parameters

Tidal height [m] relative to mean sea level	Frequency [%]
0,25	9
0,75	17
1,25	22
-0,25	12
-0,75	11
-1,25	29

5.2.3 Beach profiles

Beach profiles, which are used here, refer to beach profiles measured in 2 years (1999 and 2000) and nearshore bathymetry scale 1/2500 carried out by the Center for Estuary and Coastal Engineering - Hanoi (CECE). See Figure 5.1 and 5.2. According the inspection of the CECE on cross-shore profiles at Nam Dinh coast the closure depth of cross-shore profiles is chosen at 6m deep. The onshore part of the profiles was extended to level 2.5m CD. At the cross-shore profiles that there is no beach infront of sea dike, it is assumed the sea dike is a sand dune.

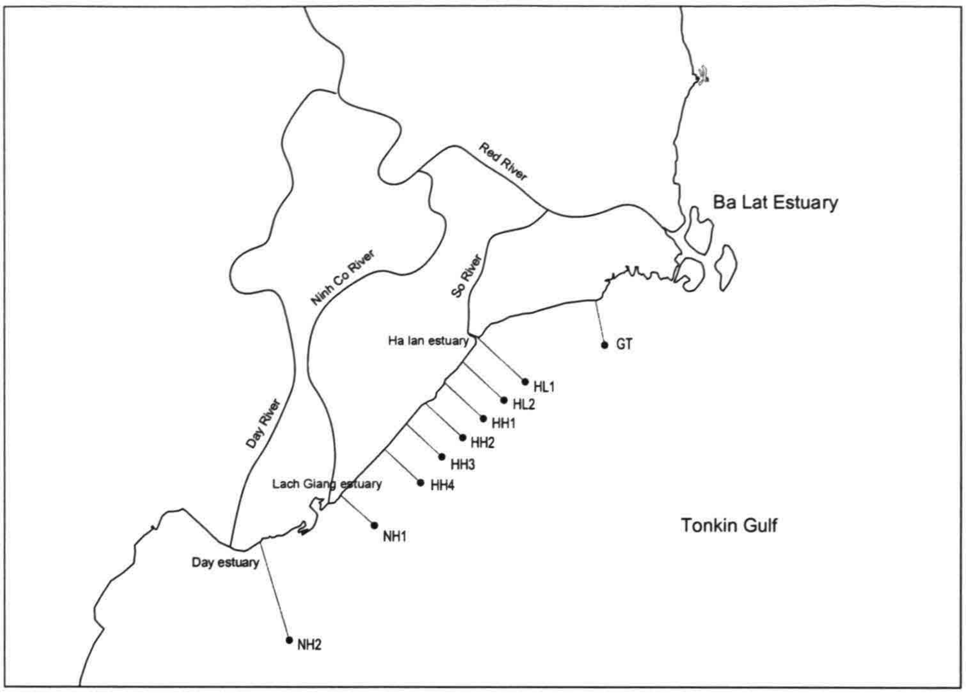


Fig. 5.1: Cross-shore profiles, which are used to calculate longshore sediment transport along the study area.

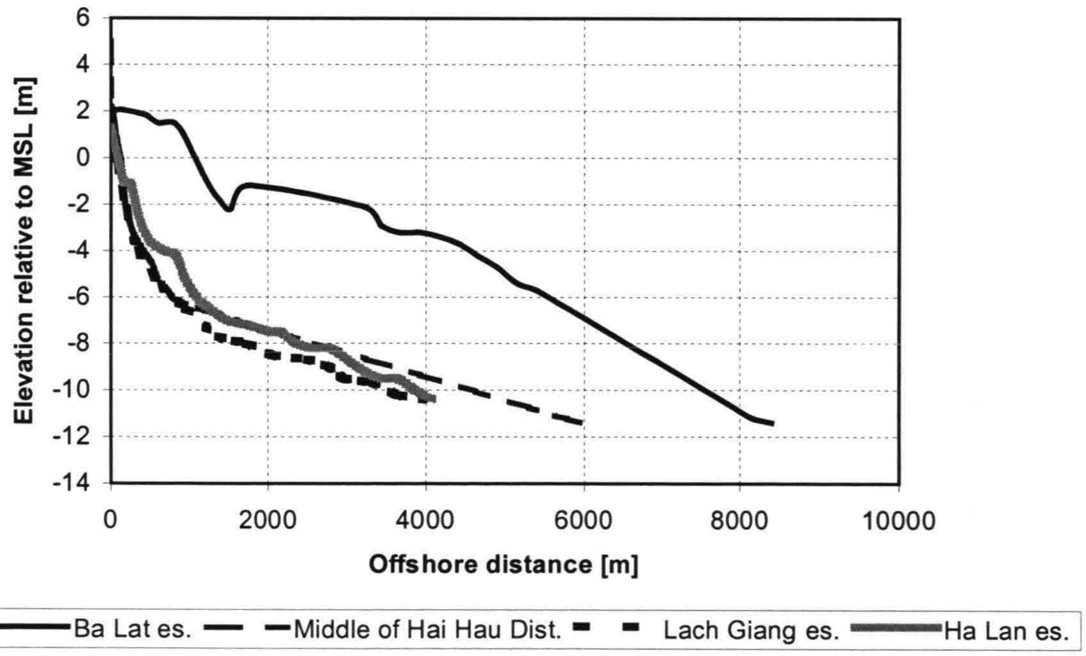


Fig. 5.2: Cross-shore profiles (source: CECE, N.K Nghia 2000)

The nearshore wave climates were derived at a water depth of 10m, so the cross-shore profiles should be extended to the same water depth. The nearshore available bathymetry, which was mentioned above, just extends a to water depth of 6m. The addition information on bathymetry from water depth of 6m to 10m was achieved from the sea chart at Nam Dinh area scale 1/100,000 published in 1981 by the Vietnamese Mapping Bureau.

5.2.4 Sediment information

There are several different data on particle size of sediment such as: d_{50} = 140μm (Pruszak et al., 2001), Sea Dike Service Department posed d_{50} = 150 μm, while CECE introduced a quite small value of the d_{50} = 100μm. The longshore sediment transport was computed with Bijker formulae, CERC formulae, and Van Rijn formulae. There is no requirement on sediment size for CERC formulae. For the Bijker formulae and Van Rijn formulae some input parameters on characteristics of sediment are needed, these parameters are given in Table 5.2 and 5.3

Table 5.2: Sediment parameters for Bijker formulae

D50, median (50%) grain diameter	140 [μm]
D90, 90% grain diameter	200 [μm]
Bottom roughness	0.01 [m]
Sediment's fall velocity	0.013 [m/s]
Deepwater criterion Hsig/h	0.07
Coefficient b on deep water	1
Criterion shallow water, Hsig/h	0.6
Coefficient b shallow water	6

Table 5.3: Sediment parameters for Van Rijn formulae

D50, median (50%) grain diameter	140 [μm]
D90, 90% grain diameter [μm]	200 [μm]
Sediment density	2650 (kg/m^3)
Current related bottom roughness [m]	0.01 [m]
Wave related bottom roughness	0.03 [m]
Sediment's fall velocity	0.013 [m/s]
Viscosity	$1x10^{-6}$ [m^2/s]
Correction factor	1
Relative bottom trans. layer thickness	0.01 [m]
Porosity	0.4

5.2.5 The coefficient for energy decay calculation

The coefficients for the energy decay, which are used in the UNIBEST-LT module calculation, include breaking index, the bottom roughness and the friction coefficient. The value of these coefficients is shown in Table 5.4.

Table 5.4: The coefficients for the energy decay calculation

Coefficient for wave breaking (γ)	0.8
Coefficient for wave breaking (α)	1.0
Coefficient for bottom friction (f_w)	0.008 [m]
The value of the bottom roughness (k_b)	0.01 [m]

5.2.6 Coastal angle

Based on the sea chart map of 1949 which has the latest revision in 1998 the costal angle at each computation profile is as in Table 5.5

Table 5.5: Coastal angle

No.	Name of profile	Coastal angle (Dgr.)
1	GT	170.5
2	HL1	131.4
3	HL2	131.4
4	HH1	131.4
5	HH2	131.4
6	HH3	131.4
7	HH4	131.4
8	NH1	168.5
9	NH2	168.5

Note: The coastal angle is angle, which is measured clockwise from the North to normal vector of the coastline where the profile is defined.

As can be seen from the Table 5.5 that from profiles HL1 to profile HH4 the beach here is straight section. So if the erosion takes place in this section it means that the longshore transport gradient is the main reason.

5.3. LONGSHORE SEDIMENT TRANSPORT

5.3.1 Selection of sediment transport formula

The LT-module has a number of transport formulae. The sediment transport formulae for sandy beach are the Bijker formula, Van Rijn formula and CERC formula. These formulae are used for calculation of the longshore sediment transport for the 9 cross-sections and the results are given in Table 5.6.

Table 5.6: Longshore sediment transport

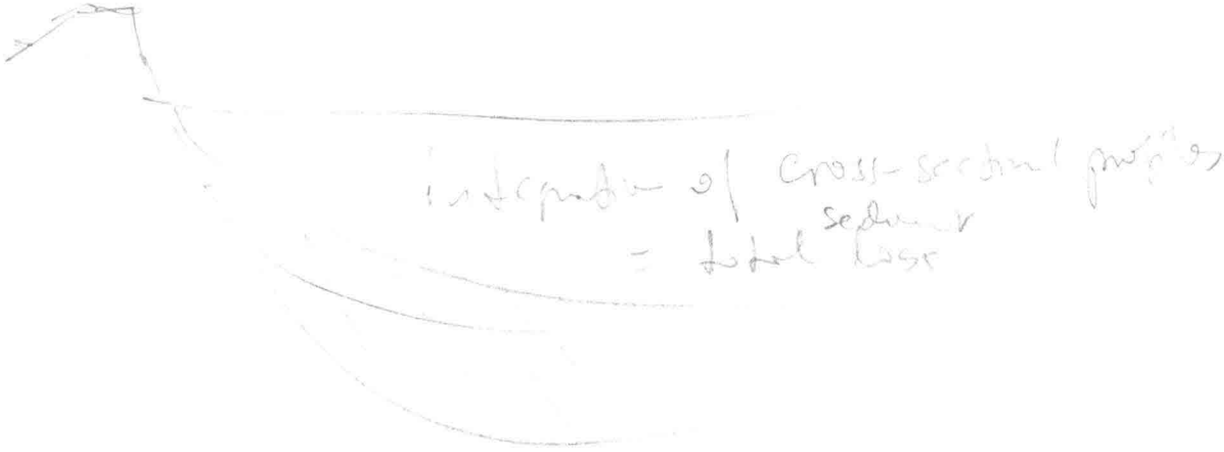
Section	Sediment transport [$10^3(m^3/y)$]			Equilibrium angle (dgr.) (Respected to the original coastline)		
	CERC	Van Rijn	Bijker	CERC	Van Rijn	Bijker
GT	+284.0	+211.4	+189.4	7.73	6.27	4.33
HL1	+178.1	+47.9	+118.7	10.94	4.48	6.20
HL2	+291.1	+122.9	+199.7	16.07	10.90	10.06
HH1	+465.1	+342.9	+460.3	25.65	19.94	24.57
HH2	+616.0	+728.5	+728.6	33.57	28.09	36.04
HH3	+680.1	+883.8	+801.2	36.00	33.39	37.23
HH4	+717.1	+861.7	+853.0	35.31	39.34	39.67
NH1	+327.3	+441.5	+390.7	10.35	11.12	9.15
NH2	+202.7	+281.3	+228.7	6.57	7.32	5.47

Notes: "+" Transport from north to south
" -" Transport from south to north

From Table 5.6 it can be concluded that the net direction of the longshore sediment transport of 3 formulae have good agreement with the observation; Bijker and Van Rijn formulae have close results, while CERC formulae gives a slightly lower values.

5.3.2 Sediment balance

Figure 5.3 illustrates graphically the results in Table 5.6. As we can see from this figure there is loss of sediment from section HL1 to section HH4, these sections belong to Hai Hau district. This also means that the erosion takes place in this area. We also can realize that there will be accretion at between the section from GT to HL1 and from HH4 to NH2. One should notice that it is very difficult to quantify the volume of sedimentation at the accretion areas, because these areas are proximity to the estuary



Can you superpose the graph on
position of coastline ↓ →

Fig 5.1

the same cross-section?

Can you make simulation for example for 10 years
to calculate the shoreline after 10 years?

-> Shoreline is fixed by a dike and revetments

-> if erosion go on -> that means steepening of
coast in front of dikes

-> consequences?

and this computation only take into account the longshore transport due to effect of wave induced current. The erosion beach section is considered relatively far from the estuaries (in order of 10km) so the effect of sediment from river is neglected and can be evaluated. Tables 5.7 and 5.8 give some information on sediment transport at the Hai Hau area according to previous studies and collected data.

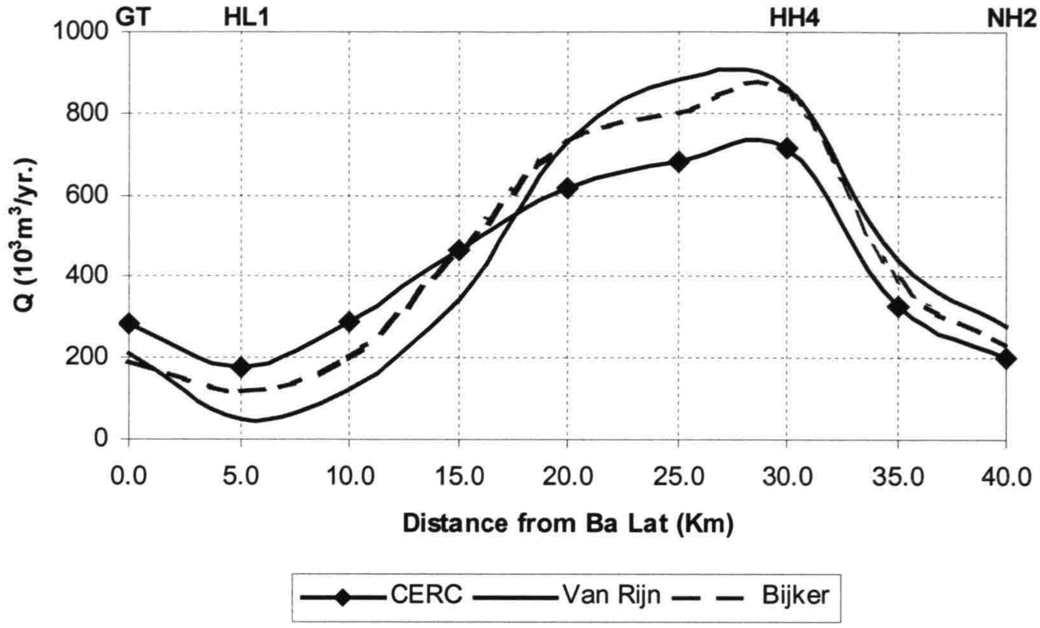


Fig. 5.3: Sediment transport along Hai Hau coast

Table 5.7: Some results form previous studies

Author	Q $_{Loss}$ (10^3 m^3/yr.)	Model	Formulae
Pruszak et al. (2001)	625	UNIBEST	Bijker
Bas Wijdeven (2002)	600	UNIBEST	Bijker
Hung et al (2001)	400	Unknown	CERC
Huong (2003)	120	UNIBEST	Bijker

Table 5.8: Sediment losses according to various sources

From	To	Sediment loss (10^3 m^3/year)
1912	1965	1484
1971	1986	1247
1985	1995	971

Source: Bas Wijdeven, 2002

Compared to the results from the previous studies, results of this study have shown closer values to the collected data in Table 5.8. Although results form previous studies are quite scattered the results from the studies of Pruszak et al. (2001) and Bas Wijdeven (2002) were quite good because of updated information and good data processing and analysis as well as design tools applied. However the authors of these reports had to admit that due to limitations of 1D wave model, and UNIBEST, the results were still somehow smaller than in practice. Therefore it can be concluded that with the wave climates derived from the 2D wave model in this study the results of sediment transport calculation were improved, though due to the lack of information quantifying of results is still very difficult.

5.4 SET UP A COASTLINE MODEL (UNIBEST-CL)

5.4.1 Data Requirement

A coastline model was set-up from the Ha Lan estuary (So River) in the north of the project to Lach Giang estuary (Ninh Co River) in the south. The required data input include:

The basic model defines the coastline position by x, y coordinates and the grid point for transport rays with grid spacing between the basic points ranging from 80m to 150m. The real coordinates of coastline in 1972 from So river to Ninh Co river were inputted into the basic model. The active area of coastline is bounded at a water depth of 6m. The basic model is shown in Figure 5.4.

Note that all coastal structures, which have been already constructed in project, are neglected due to insufficient information model input. This might affect to the results of the model. The beach at Hai Hau is not really uniform beach according to survey map scale 1/12500 carried out by CECE, 2001 and site visit in November 2002 the existing condition of beach at Nam Dinh can be described as follows:

(1) Section form Ha Lan estuary (So River) to Hai Chinh commune: this is the most severe erosion section. Beach is not uniform, the first former dike was damaged heavily and a new sea dike was built behind acting as an official front defence. At some places the first former sea dike is still working and exposed to the sea with no beach infront. See Fig. 5.5

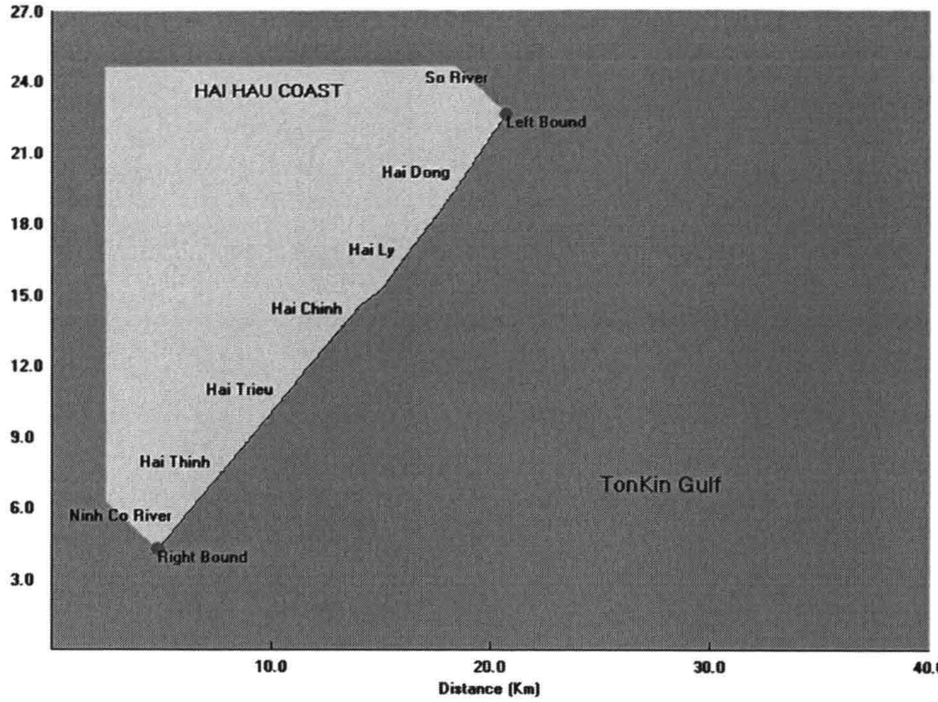


Fig. 5.4: Basic model of coastline from So river to Ninh Co river

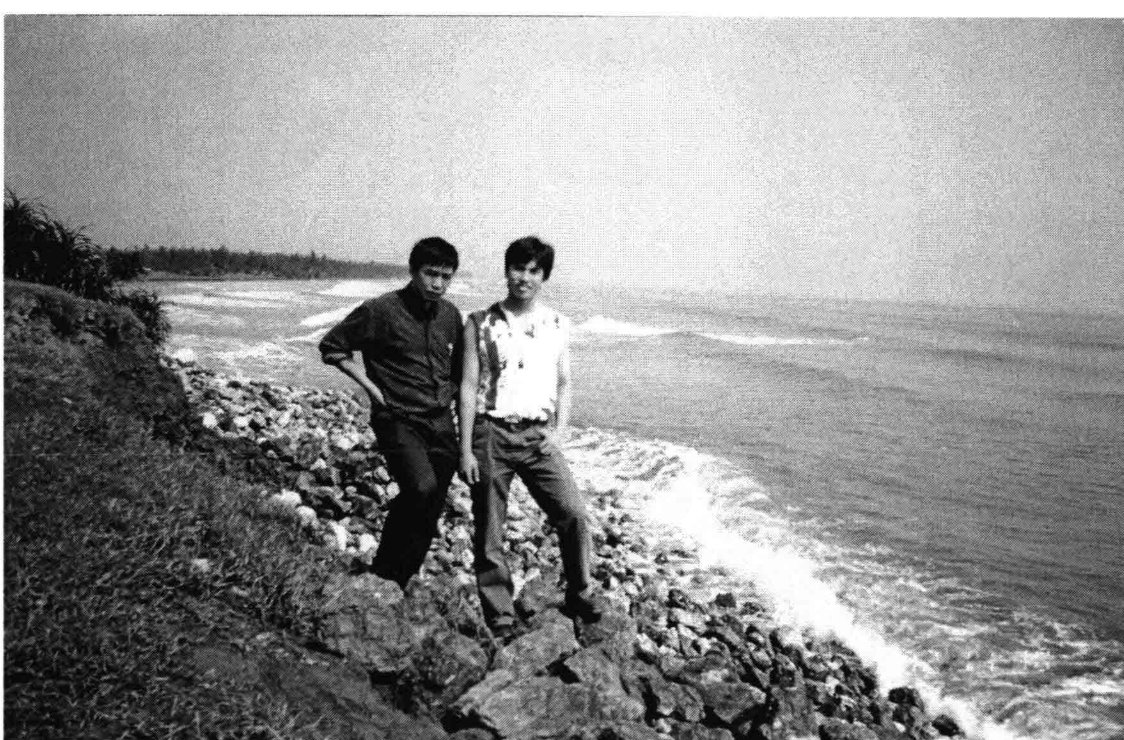


Fig. 5.5: An old damaged dike section near Ha Lan estuary (Nov. 2002)

(2) Section from Hai Chinh commune to Hai Trieu commune: Erosion problem here is less severe than the previous section but the first former sea dike was almost completely destroyed. The new sea dike funded by PAM project is acting as the first line defence. The beach in this section is more or less uniform beach, although at some places the sea has reached the dike at the high tide. (Fig.5.6).

(3) Section from Hai Trieu commune to Lach Giang estuary: The beach becomes a uniform beach again in this section. Erosion is not so serious here and the erosion rate is zero at Hai Thinh commune.

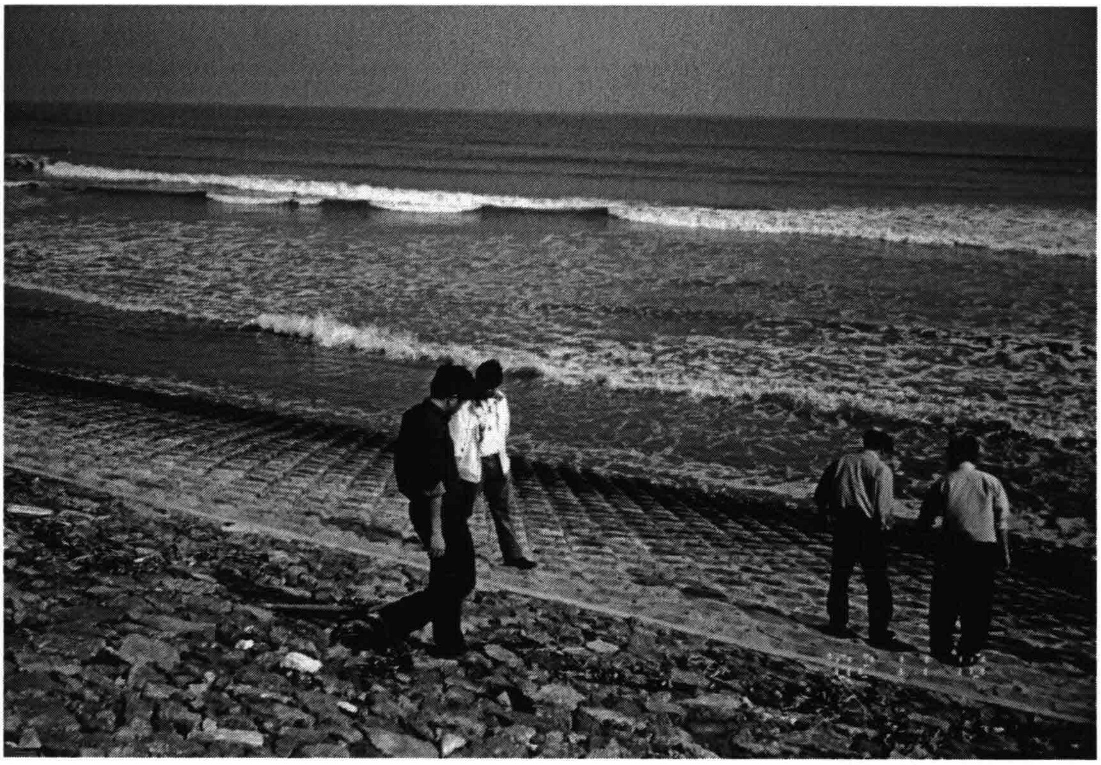


Fig.5.6: Sea has reached the new dike at high tide (Nov. 2002)

The global transport defines the position of 6 transport rays (HL1, HL2, HH1, HH2, HH3, and HH4), which was computed by UNIBEST-LT module, along the coast from So river to Ninh Co river.

The boundary conditions are defined at the left and right model boundaries. These boundaries can be defined in term of coastline position, the transport Qs, or the coastal angle. There are four options:

- The coastline position "y" remains constant
- The coastal angle remains constant

- The transport Qs is a user-defined constant value
- The transport Qs is a user-defined function of time

In this case, the boundary on the left is defined as the coastal angle remains constant, and the right boundary is Y constant

5.4.2 Simulation of coastal evolution

The coastline model was used to simulate shoreline evolution during a period of 24 years starting from 1972. The direction of the net longshore sediment transport shown in Fig. 5.7

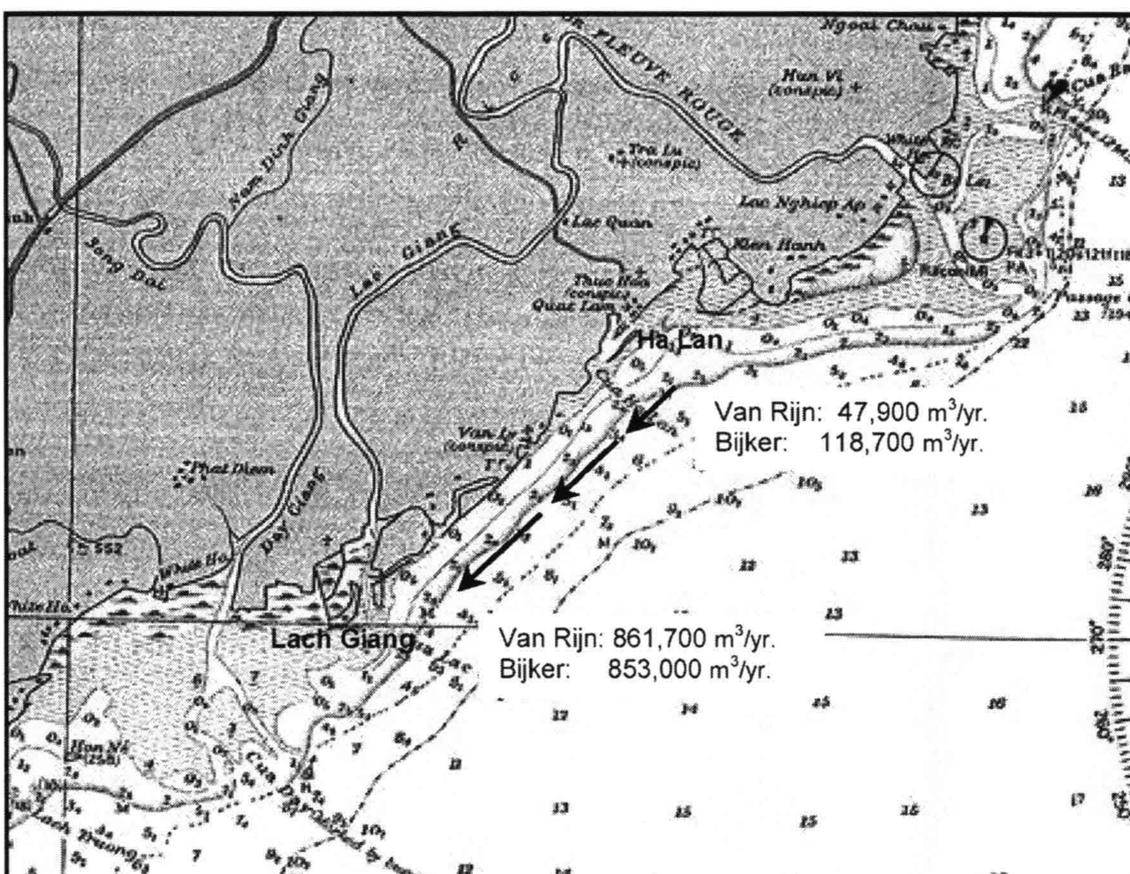


Fig. 5.7: Net longshore sediment transport direction in the project area

According to the modelling output, the net sediment transport direction is from north to south along the coastline. Obviously, the whole project areas are subject to erosion. The maximum erosion rate is at Hai Ly, which is situated in the northern part of the project, and then the erosion rate decreases southward. With Van Rijn formulae the maximum erosion rate is about 13.5 m/year while with Bijker formulae maximum erosion rate of 11.4 m/year is found. The results are slightly different between two formulas.

In order to calibrate the coastline model the simulation results are compared with the data, which were deduced from the erosion map in period 1972 - 1996 (See Fig. 3.8 and Table 3.1). The comparison is shown in the Table 5.9.

Table 5.9: Comparison between modelling results and measurement from the erosion map from year 1972 to 1996.

Location	Erosion rate (m/year)		
	Modelling results		Map (Nature)
	Bijker	Van Rijn	
Hai Dong	9.8	10.7	25
Hai Ly	11.4	13.5	30
Hai Chinh	1.7	3.7	15
Hai Trieu	0.6	0.3	13
Hai Hao	0.5	0	8
Hai Thinh	0.3	0	4

From the reference map in Figure 3.8, the coastline has been subject to erosion since 1972 and the significant erosion happened at Hai Ly. The erosion took place severely in the northern part of the project area and reduced effects are noticed more southward. For the modelling, the result shows that there is a lot of erosion taking place in the northern part and reducing southward. It can be seen that the trends of shoreline change of both modelling and map are similar. But when looking at the values of erosion rates, there is a significant difference between these two results. The results of modelling are much less than the results of measuring from the map.

It has to be mentioned that calibrating the model, in reality, is very difficult and important. There are a lot of factors involving the calibration of the model in this project making the calibration more complicated and impossible, such as:

- The reliability of sources used for calibrating. In this study, the map has been selected because it was published by Hanoi Hydrographic Survey Department, which is a rather reliable source. Besides, there were lots of disagreements among data that were mentioned in previous studies.

- There is one more component, which might play an important role on this area, which is the possible offshore transport. UNIBEST-CL+ is the mathematical modelling used for model shoreline change due to the gradient of longhsore sediment transport only. Moreover, Pruszak et al. (2001) believed that there was an offshore sediment transport occurring in this coastline, and the ratio of the offshore sediment to longshore sediment is about 1:2.
- The situation in Nam Dinh beach is not really good for applying UNIBEST-CL+ to simulate the coastal evolution. Because the beach in Hai Hau district is not uniform beach. In places there is no beach at all, the front dyke is facing the sea. This also might have a major influence on the modelling results.
- It also may be noticed that, the erosion rates that were deduced from the map, are in fact the retreat rates of the shoreline in which the area of loss land was included. An example is the former Hai Trieu village, which was relocated due to dike breach in 1999. In that case the land loss was considered as the erosion area “at once” an erosion of about 250m was reported. The problem was clear when the author interviewed Mr. Le Duc Ngan (Manager of Nam Dinh Dyke Department) during his visit of the site in November 2002.

Comparing the results from Van Rijn and Bijker formula, in the longshore transport calculation as well as coastline change simulations they both give the close results. Therefore both Bijker formulae and Van Rijn are proposed to apply for longshore sediment transport at Nam Dinh coast.

5.5. DISCUSSIONS

Some conclusions can be drawn about longshore transport and erosion problem:

- Longshore transport calculations have improved with wave climates that were derived from the 2D wave model.
- Calculations also proved that application of Bijker formulae is quite suitable for the longshore transport computation at Nam Dinh coast.
- Erosion takes place at the straight beach section. From the wave modelling results we can say that gradient of longshore transport that were characterized by wave

climates at the study area is the key factor that causes the erosion problem at study area.

- Comparing the results of longshore transport computation of this study with the collected data about sediment loss in the study area, we also can say that it is the longshore transport plays an important role in erosion problems at Nam Dinh coast. The offshore transport only occupied about 10 percent to 15 percent of the yearly total sediment loss.
- Due to the complexity of the beach, and lack of reliable information about the coast change, applying the uniform coastline model such as UNIBEST to predict the changes of Hai Hau beach is difficult and not correct.

what next? else?

Mutual development

Spiral of liberation?

Chapter 6
MITIGATION MEASURES

Apparently the beach at Hai Hau is suffering from erosion problems, so mitigation measures should be carried out to control and minimize the possible losses due to erosion. The measures can be non-structural or structural methods. Selection of a mitigation measure also has to depend on the long-term or short-term strategy. It's not the main objective of this study to find a mitigation solution for erosion problem at Hai Hau coast. However, as part of this study the author would like to introduce and discuss some possible measures, which might be applied for the Nam Dinh coast. A thorough study about mitigation measures for the Hai Hau beach section would be a good subject to study.

6.1 ZERO OPTION

The easiest and cheapest method for avoiding problems in future is to do nothing and leave the area, which has the problems (Van der Velden - Coastal Engineering, 1995). Apply this method for the Nam Dinh coast it implies a loss of about 1,000,000 m^3/year of sand due to longshore sediment transport only.

One should note when applying this measure provisions have to be made to relocate or compensate the inhabitants of the area. Also a good policy of coastal management is needed to avoid future problems. A set back line should be established and managed. According to Verhagen, 1999 questions (and resulting actions) should be raised when discussing the need for erosion control. See Fig.6.2

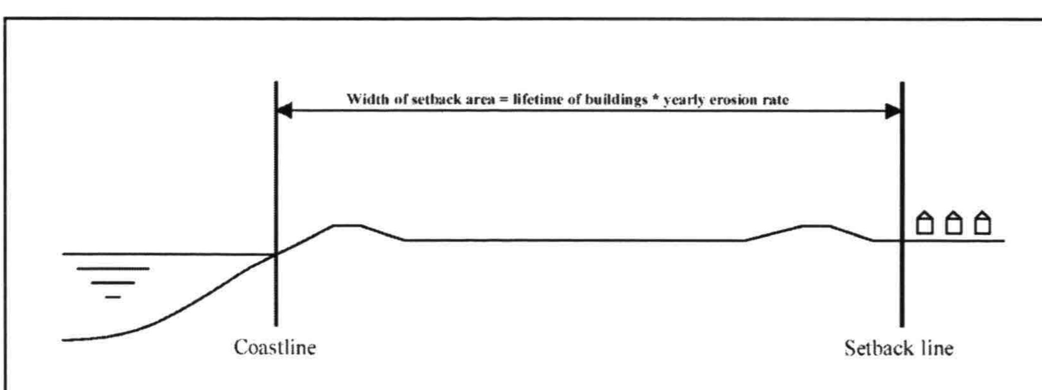


Fig.6.1: Definition of setback line

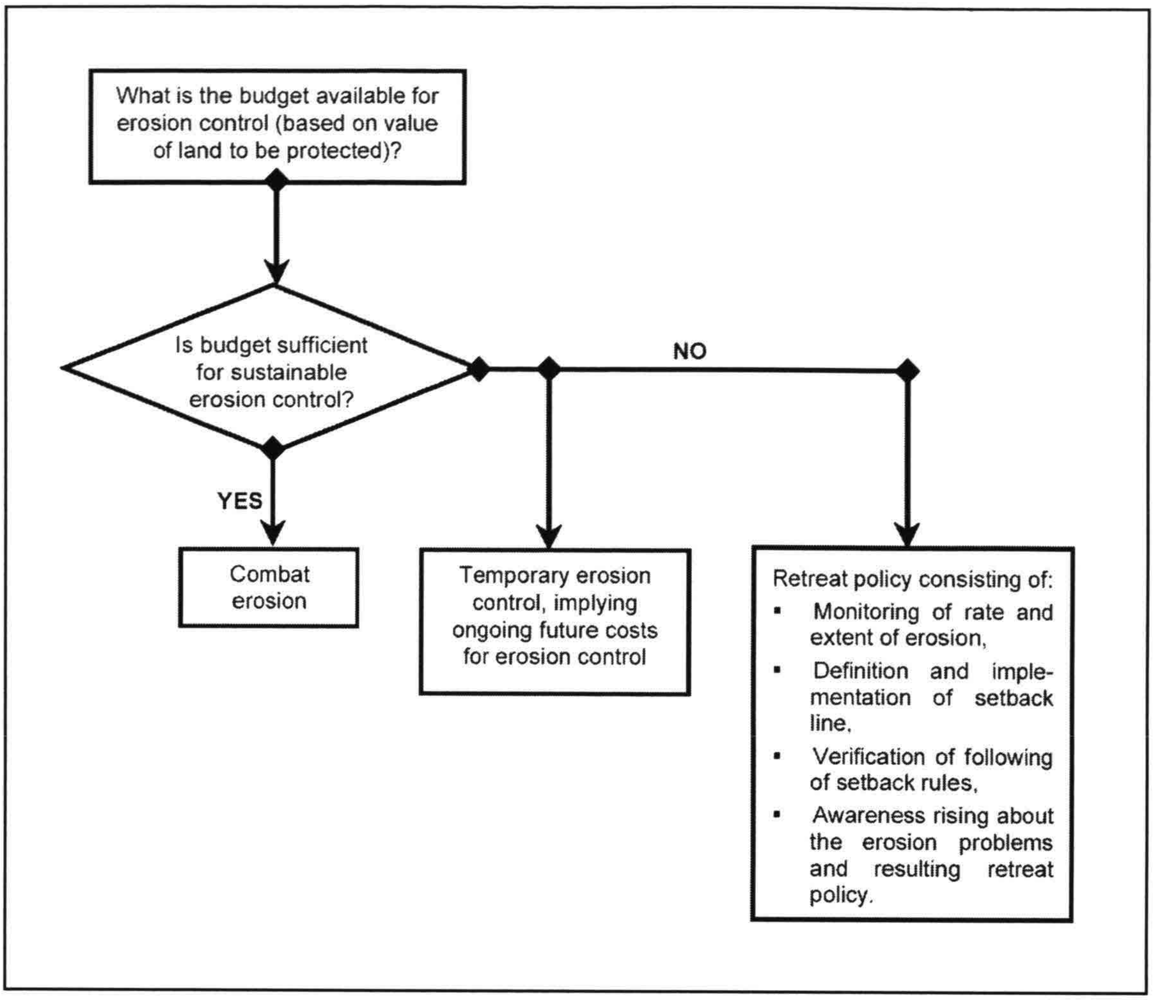


Fig.6.2: Framework for decision process on erosion control (Verhagen, 1999)

6.2 BEACH NOURISHMENT

A potential measure for the erosion problem is beach nourishment. Artificial beach nourishment is known as one of the appealing soft measures for erosion problems due to its flexibility, natural pleasing and economic attractiveness. It is simply the introduction of sediment onto a beach to supplement the diminishing supply of natural sediment.

Beach nourishments can be described into various types depending on the type of classifications. Generally, beach nourishment involves the placement of large quantities of sand or gravel in the littoral zone to advance the shoreline seaward, to create a new shore or to recover the existing one that is lost by erosion. The main objective of the proposed beach nourishment (i.e. sand) is to offer a potential source of material for the existing eroding coastline. It is important to note that nourishment material is sacrificial in nature and thus requires periodical maintenance. Such phenomena must be part of the design concept.

As recommended by CUR Report 130 (1987), various aspects should be carefully considered for the design of a beach nourishment scheme to meet the specified requirements. Main aspects or elements related to beach nourishment that need to be considered are described below.

Source of sand

There is two possible sources of sand in the area are:

- Source of fill material is the sediment discharge from Ba Lat river mouth. Historically, the discharge from Ba Lat used to contribute significantly to downdrift sediment transport system. However, the river mouth has been growing over the years such that the seaward delta development has become few kilometers offshore thus substantially reduced the possible longshore sediment supply to the downdrift coast. Hence, one of the proposals is to introduce a by-passing system to promote the sediment supply back the way it was.
- The other one is the sand from dredging material in shipping channel at Day estuary an Lach Giang estuary. These estuaries are on the national waterways transport corridor, maintenance dredging is carried out annually and dredging material was transported and dumped offshore. If possible this should be a very good combination of work with work.

Sediment Size

The general principle for designing a beach nourishment is to apply fill material with the same or slightly coarser median grain size (d_{50}) compared to the native sand. This is important because fill material, which is too fine, will tend to be lost easily.

Placement of Fill Material

There are two main placement methods that normally are considered for beach nourishment: cross-shore and alongshore.

Basically, the cross-shore placement can take place at four possible locations along the beach profile, which includes:

- Placing the fill material on the dune

- Placing the fill material on the berm
- Placing the fill material over the beach profile
- Placing the fill material offshore at the toe of the profile

The criteria for the placement method usually depend on the source of the sand (offshore or inland), the type of equipment available as well as purpose of the beach nourishment.

There are also several options that can be considered for the alongshore placement. Although it partly depends on the source of the fill material, some of the typical designed placement that will be considered in this study includes:

(i.) Placement as a point source at optimum location (from by-passing system)

(ii.) Uniform or direct placement along the stretch to be protected

(iii.) Stock piling at the center or at the beginning (north side) of the stretch to be protected

In option (i) and (iii), the intended concept is in such a way that it allows the action of waves and currents to naturally distribute it along the coastline.

Quantity and Frequency of Beach Nourishment

Quantity of the fill material has to be determined based on the design requirement. The estimated volume has to take into account the design frequency of the re-nourishment. In this case, a reasonable re-nourishment interval of 5 years has been adopted for the project. The design requirement of the fill volume is further elaborated in the subsequent section.

6.3 GROYNES

A groyne, as defined by Fleming (1990), is a relative long and narrow coastal defence structure, oriented approximately perpendicular to the shoreline. Groynes are designed to control the natural alongshore movement of beach material under the action of waves and tidal currents. In order to protect a large area from erosion, a groyne system may be constructed, in that case a series of groynes can act together.

In general, the groynes take effect in the damping of longshore sediment transport, so the shoreline builds up along the updrift side and erodes in downdrift side. It means that a groyne or groyne system will transfer the erosion problem from one place in up coast to another place in the down coast neighbours. In order to visualise of the shoreline change after the groyne is active in a certain period, the following figures are given:

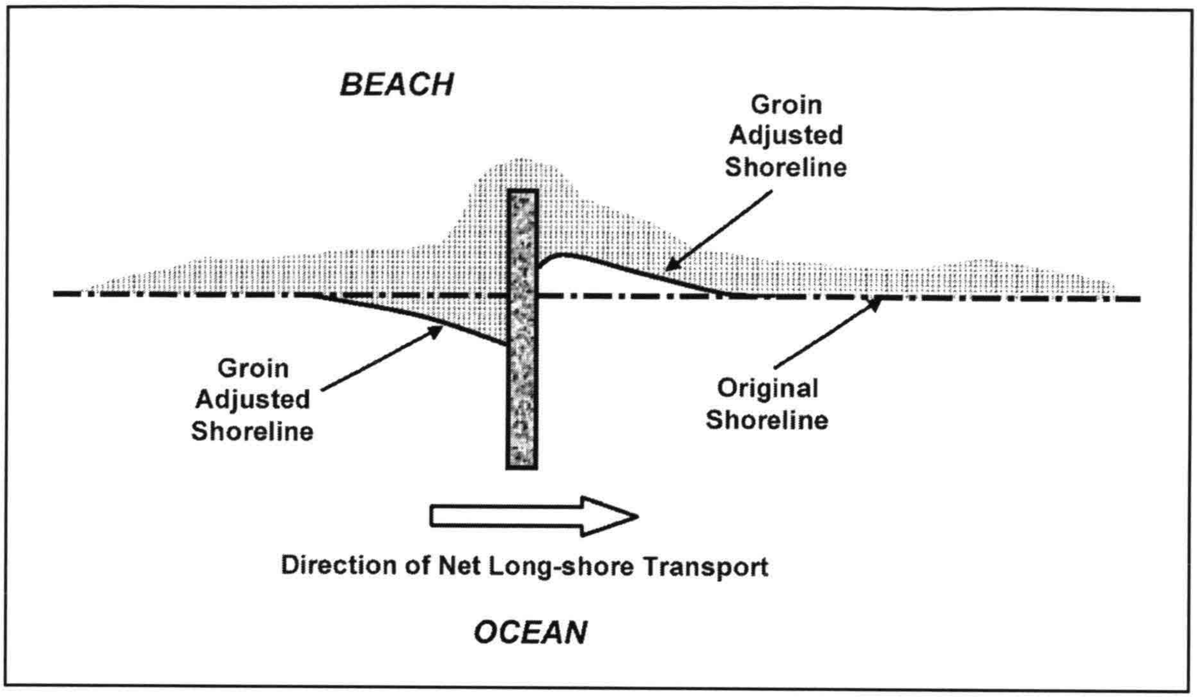


Fig. 6. 3: General shoreline configuration for single groyne

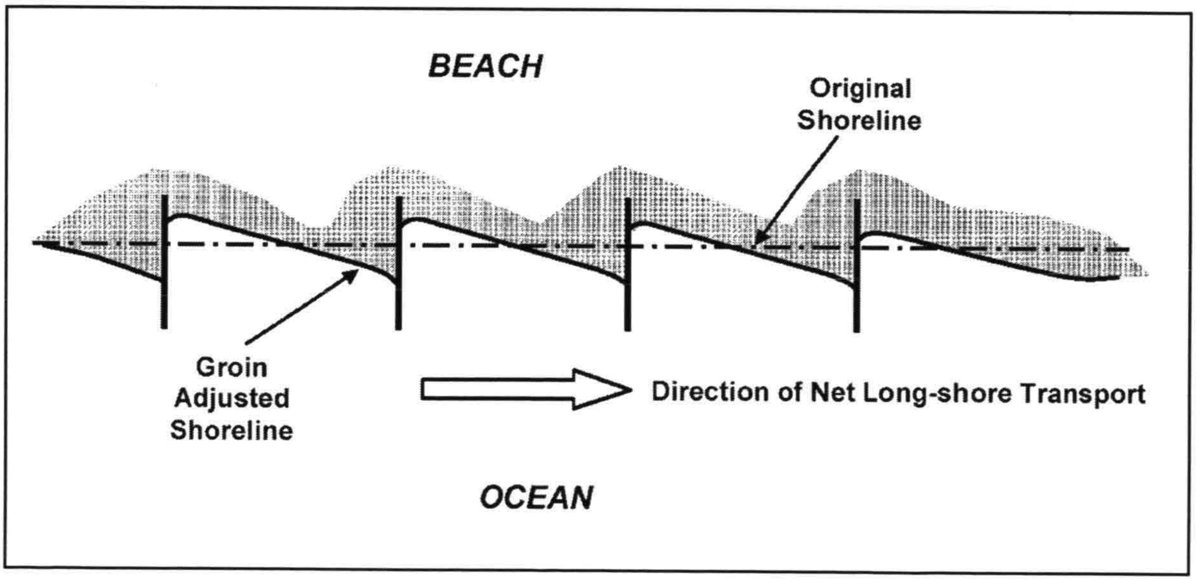


Fig. 6.4: General shoreline configuration for groyne field

The interaction between the coastal processes and a groyne or groyne system is complicated. However, according to "Shore protection manual - Vol. I", there are a few basic principles which can be applied to the design of groyne. These principles are summarised bellow:

- Groyne can only be used to interrupt longshore transport.
- The beach adjustment near the groynes will depend on the magnitude and direction of the long-shore transport in relation to the size of the groyne.
- The groyne-induced accumulation of long shore drift on the foreshore will modify the beach profile, which will then try to re-establish its natural shape.
- Water pushed by waves into a groyne compartment will sometimes return offshore in the form of rip current along the side of groynes.
- The percentage of longshore transport, which bypasses a groyne, will depend on groyne dimension, water level and wave climate.

Design of groyne layout should be carried out by an experienced coastal engineer since some steps need engineering judgments. However, there are some general principles that can be applied to achieve an initial idea for the layout of groyne:

- ***Groyne height***

According to CIRIA report 119, the groyne height is an important parameter that will determine the maximum potential beach depth up drift of groyne. The extreme usually is determined by natural limiting winter and summer beach profile. However the result of physical model test demonstrated the tendency for deep water at up drift of groyne to create rip current which run seaward on the down drift side of groynes. This rip current and the flow at the end of groyne could be quite strong enough to cause erosion channels, which could transport beach material out of the groyne bays. They could also threaten stability of the groyne structure. It means that, increasing groyne height to improve beach level could lead to rip current and erosion gullies. For that reason, it must be considered the real requirement of project in combination with the given data such as beach material, wave, wind climate to decide groyne height.

- ***Groyne length and groyne spacing***

- *Groyne length:* The groyne length is determined depending on the desired trapping effectiveness of the groyne system. One remarkable thing after construction of a groyne field is that lee-side erosion can be expected and this erosion is large in first years. To solve this problem, extension of the root of groyne is important.

- *Groyne spacing:* For a given groyne length, maximum groyne spacing should take into account the resulting variation in beach level at each side of the groyne. According to guideline of "Shore protection manual", the spacing between groynes should be about two or three time their length.

In the situation at Nam Dinh coast, the application of groynes should be concentrated in the most serious erosion section at the Hai Hau district (see Fig. 5.3) in order to bring the longshore transport infront of the erosion section back to constant (Fig.6.5). But once the groynes are applied, it means that the lee-side erosion will take place and the coastline manager should be aware about this and its influence.

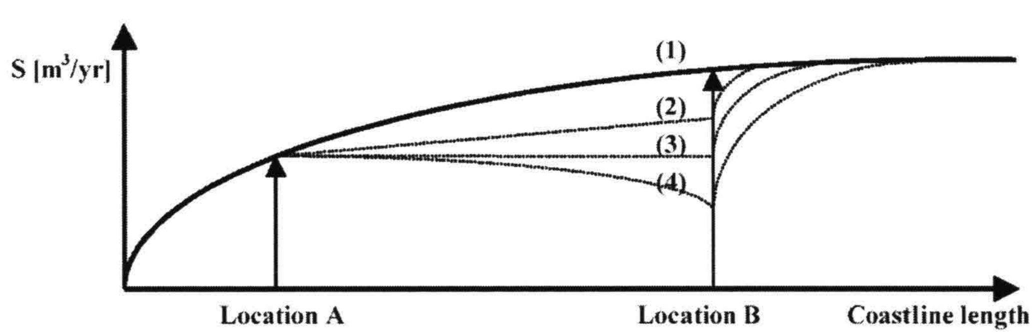


Fig. 6.5: Impact of groyne along the coast

6.4 OFFSHORE BREAKWATER

Offshore breakwaters are quite well known measures among a variety of coastal protection structures that have been implemented worldwide. The offshore, also called detached, breakwaters are generally shore–parallel coastal structures sited at a certain distance away from the shoreline. Their primary objectives are to dissipate wave energy, rearrange waves and currents and, thereby, to redistribute sediment transport patterns and to create desirable beach feature.

There are several mechanisms around offshore breakwaters [Pilarczyk and Zeidler, 1996] (see Figure 6.6):

- Modification of wave energy reaching the protected area by dissipating, reflecting or diffracting incoming waves;
- Generation of local nearshore current systems;
- Modification of both alongshore and onshore sediment movement patterns

Wave diffraction at the ends of the breakwaters, together with their refraction as the curved wave crests cross the bottom contours at an angle, results in a gradient of breaking wave height along the beach. This alongshore gradient causes an alongshore gradient in wave set-up or mean water level in the surf zone. This gradient of mean water level in turn provides the driving force for an alongshore current flowing from the region of high breaking waves outside the area sheltered by the breakwater into the region of low breakers behind it. This process promotes sediment deposition shoreward of the structure.

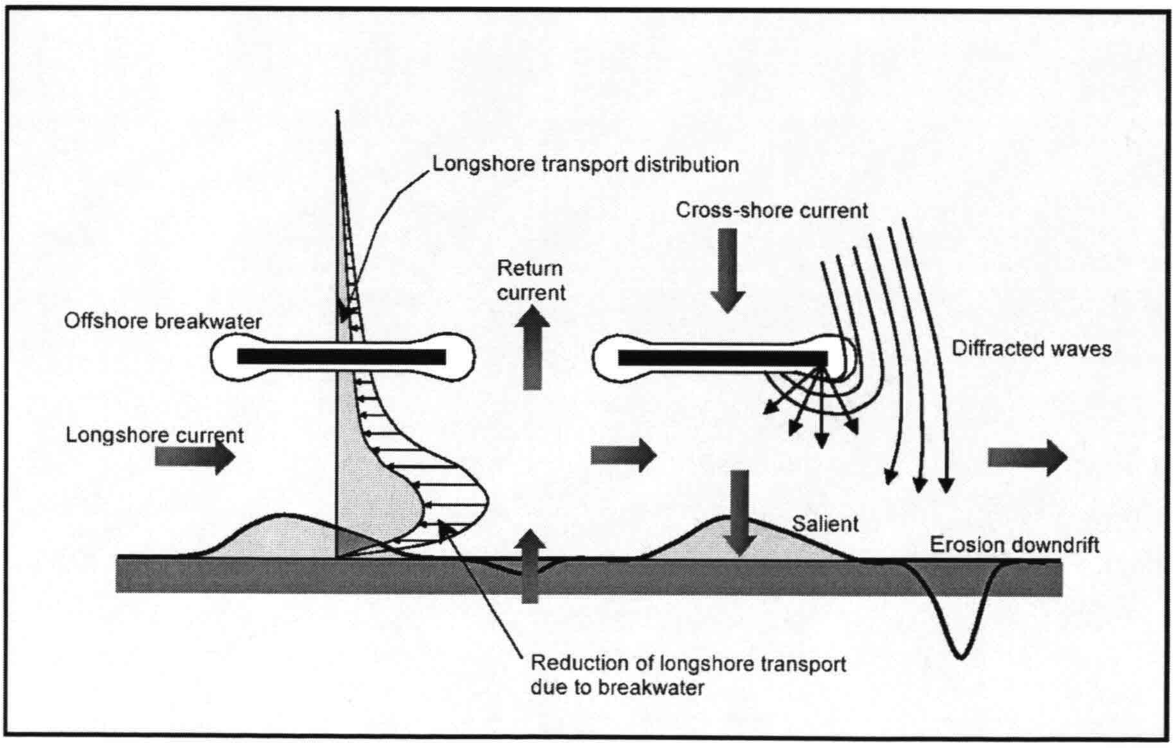


Fig. 6.6: offshore breakwaters and coastal zone behaviour

In addition, offshore breakwaters are considered as a possible implementation to retard erosion of the shoreline of Nam Dinh province because in this area there are conditions suitable for using offshore breakwaters, but one should be aware about the erosion at downdrift.

6.5 REVETMENT

Revetment is known as one alternative among the coastal hard protection measures against erosion. This type of the structure is mainly placed along the shoreline in order to protect the land against the erosion due to the current and wave action. Additionally, one may define a revetment as a sloping surface of stone, concrete or other material used to protect an embankment, natural coast or shoreline against the before mentioned erosion.

According to Pilarczyk (1998), some authors do not recommend to apply revetment for the long term erosion protection because of its detrimental side effects on the coastline, such as:

(1) Accelerating of the erosion of the beaches in front of the structure,

(2) Profile steepening,

(3) Increasing longshore transport capacity that may lead to the total destruction of the protection.

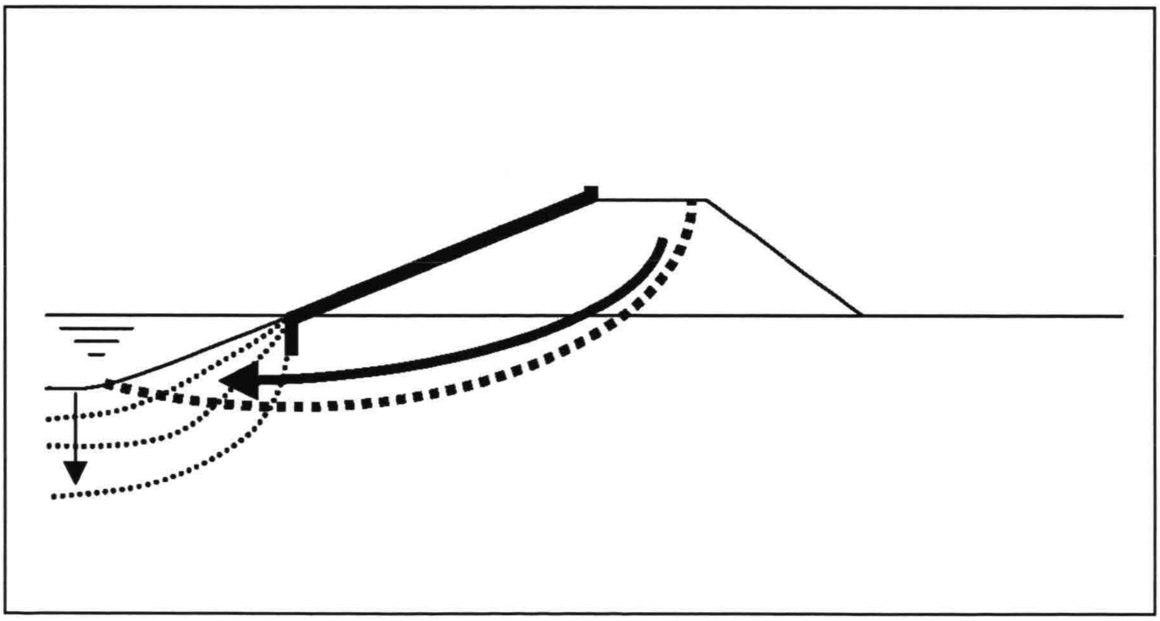


Fig.6.7: Impact of sea dike revetment on an erosion beach

Nevertheless, monitoring and evaluating this problem already claim that there does not exist a real prove that these structures accelerate or enhance the structural erosion of the beaches. Instead of that, it was only found an important difference in beach recovering in post storm conditions (due to cross- shore transport) when there was a deficiency in sediment supply. Moreover, it has been proved that the armouring cause scour in front and at the end of the structure.

So, in order to utilize revetment for shore stabilization, it is recommended to review the historical data on shoreline position, beach profile and littoral processes in the vicinity of the existing sea walls or revetments. In addition, it is necessary to develop a monitoring program to define and to interpret the processes and the responses for each particular context.

Since this coast is not used for recreational activities or any relevant use, it is thus not important to maintain the beach in front of the structure. Then, it is possible to apply a revetment in the area without any concern about the loss of the beach, but one should note that when apply revetment is finally the deep see in front of construction and heavy construction is required to assure the stable of the revetment.

As discussed in the previous chapters, in the project site, there are two dike systems built in the past in order to protect the coastline. To take advantage part of the existing structure (good condition dune), we can consider the first possibility to place in the sea-side of the first row of dunes the revetment to protect and stabilise it, taking in consideration at the same time the criteria that will be used (what is allowed erosion rate from the beach), and it is also possible to evaluate to move the first dune system from its actual position up to the area of interest (seawards). Likewise in order to fulfil its function, the following aspects have to be taken in account during the design process:

- Stability (top layer, sublayer, subsoil, foundation, toe protection);
- Flexibility (possibility of settlement without affect the stability);
- Durability;
- Accessibility (inspection, monitoring damage and repair);
- Overall safety (primary or secondary defence, foreshore geometric, etc);
- Additional functional requirements (roads, reduction of run up, etc)

It is important to mention at this stage, that, in some moment the coastline will reach the structure as a result of the longshore transport gradient. It will firstly erode the beach and then, it will start to erode the bottom of the beach profile up to the ultimate depth until the wave climate cannot affect anymore the new beach profile (more deep).

Likewise the reflection of the waves due to the revetment, combined with the action of the currents present in the area will create some turbulence in front of the structure. The magnitude of this turbulence will depend on the reflection coefficient of the revetment (permeability, slope). This turbulence effect can generate heavy erosion in front of the protected coast (scour), which then requires additional measure such as the design of a heavy and effective toe protection to avoid a sudden failure of the whole structure.

There are some possible solutions in designing a toe protection that can be applied to overcome the problem of scour in front of the revetment as follows:

- The first possibility is to dig in the protection till the expected scour depth (design depth) and to cover it again with the original bottom material.
- Flexible bottom protection like mastic or fascine mattress or a geotextile with concrete blocks attached to it, in order to follow the contours of the scour hole, decreasing its detrimental action.
- Another possible solution is the so-called falling apron that is to store an amount of stones at the toe of the revetment during construction. The scour will then cause the stones to roll down which subsequently prevent further erosion with a slope that is too steep.

Advantages:

- Easy construction.
- Comparatively cheaper initial investment than other hard protection measures.

Disadvantages:

- It prevents further erosion of the local coastline, but does not stop the physical processes, which cause the erosion.
- It often leads to the displacement and expansion of the problem toward down-drift.

- It is usually necessitates additional measures such as beach nourishment, groynes, heavy toe protection, etc.
- Therefore the maintenance costs of an effective revetment can be sometimes very high.

6.6 DISCUSSIONS

By reviewing the possible mitigation measures, the conclusion that can be made hereby is that before these coastal defence structures are implemented, it is necessary to carry out several more studies, such as:

- Full-scale Environmental Assessment;
- Specific Social Impact Assessment, including the project area and adjacent areas, including borrowed area and the downdrift area, which is the subject to erosion after the construction.
- Follow-up monitoring on the efficiency of mitigating measures

In addition, there are several other factors that need to be considered in deriving the proposed optimum solution for the project. This shall include, among others, assessments on the technical aspect, effects to downcoast, expected public response or perception and the environmental issues. In this respect, a score system was developed for the purpose of this evaluation. The following Table 6.3 shows the relative scores for each alternative based on the evaluated criteria.

Apparently, as shown in the above Table 6.3, the beach nourishment yielded the highest total score. Based on the above evaluation, the proposed beach nourishment scheme is thus recommended to be implemented as the mitigation measure for this project. However it is still very difficult to apply beach nourishment in case of Vietnam due to public opinion about this method is still considered as unfeasible and waste of money.

Even though the beach nourishment option seems to be a good measure, a thorough cost benefit analysis should be carried out to provide a more representative investment evaluation for the project site. Such investment analysis shall include the assessment based on the net present value, which considers the 'lost of opportunity' due to unprotected area as well as the additional mitigation measures required to satisfy the social and environmental aspects. Eventually, the overall appraisal will lead to a more optimum solution with a clear phasing, budgeting and implementation of the mitigation works.

Table 6.1: Evaluation of the mitigation measures using scores

Criteria	Zero-option	Beach Nourishment	Groynes	Offshore Breakwater	Revetment
Technical feasibility	5	4	3	1	2
Initial construction cost	5	1	2	4	3
Annual maintenance cost	5	4	3	1	2
Downdrift effects	4	5	3	1	2
Expected Public Response	1	5	3	2	4
Impacts on Environment	1	5	4	3	2
-Physical env.	(1)	(5)	(4)	(2)	(3)
-Biological env.	(2)	(5)	(4)	(3)	(1)
-Social env.	(1)	(5)	(4)	(3)	(2)
Total	**21**	**24**	**18**	**12**	**15**

Note: Score ranges from "1 = very negative" to "5 = very positive"

Qualitative explanation of [illegible]

What is the [illegible] of [illegible]

Chapter 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

In general the author agrees with most of the conclusions about the causes of erosion problems at Hai Hau beach, which was stated in MSc. thesis of Bas Wijdeven (2002). From the results of this study, the author also would like to add some important aspects to those conclusions.

As Bas Wijdeven (2002) stated, the coastal erosion in Nam Dinh province is a problem:

- The reclamation of the flat, low lying inter-tidal coastal areas up until the beginning of the century resulted in occupation of these areas. The population (with average density in the coastal districts of 1700 people per km^2) lived directly behind sea dikes that protect the low-lying land from the treats of the sea.
- The transition of an accumulating coast into an erosive coast implied a retreat strategy that caused an increase in population pressure in the coastal communes and a decrease of the total land for agriculture, aquaculture and salt mining.

Besides the reason of the changing of geometry of the Red River system and the morphological mechanisms that characterise river mouth development, the characteristic of nearshore wave climate at the Nam Dinh coast also is an important factor causing the erosion problem for Nam Dinh coast.

- The yearly nearshore wave climate is dominated by waves that come from northeast and east directions. These waves have more than 50% of the occurrence frequency of yearly wave climate. Moreover, these waves occur in winter due to strong wind, and approach the Hai Hau coast with approximately angle of 45^0 to the shoreline. This implies that these waves contribute a significant part in longshore sediment transport.
- The wave heights of waves that come from the northeast and east increase along the coast of Hai Hau district, create the gradient in longshore current washing the sediment southward.

Sand from La Baie transported to Hai Ham

The study also found down that the development of Ba Lat estuary does not have significant influence on nearshore wave climate at Hai Hau district as mentioned in previous studies.

- The simulation results of 2D wave model SWAN show that the development of Ba Lat estuary just has some minor influences on wave heights of the wave that come from northeast and east.
- For the waves that come from southeast, south and southwest the development of spits at Ba Lat estuary has shown no influence on wave height.

With SWAN - a 2D wave model - the yearly nearshore wave climate has been extracted at water depth of 10m, and used the longshore computation with UNIBEST and the results has shown a good agreement with observations of net longshore transport direction. This is quite an improvement compared to the wave climates of previous studies, which were derived from an 1D wave model.

Thanks to the improved wave climate, the longshore sediment transport computations in this study also get improved with comparison to previous study and observations. The net longshore sediment transport at the Hai Hau district is approximate 900,000 m^3/year while Pruszak et al. (2001) said 800,000 m^3/year and Bas Wijdeven (2002) posed 600,000 m^3/year.

Although still there are limitations, the SWAN model has shown better results in wave study in Nam Dinh coast.

The morphology model UNIBEST -CL+ has shown good results in longshore sediment transport calculation with module LT. But anyway due to many reasons such as the beach is not uniform, not enough information for calibration etc. making the application of UNIBEST-CL+ for coastal evolution in Nam Dinh is still very difficult.

Beach nourishment seems to be a good mitigation measure for erosion problem at Hai Hau beach.

It should be confirmed here re-opening of So river, which was cut off in 1995, will not be a good solution to bring the sediment supply to the erosion beach. This due to the cyclic mechanism of Red River system, So River was cut off when it already lost is important to the system and the discharge through it is not big enough.

7.2 RECOMMENDATIONS

Nevertheless, as discussed earlier, the previous assessment may slightly underestimate the real situation. Thus, it is prudent that few other factors should be further deliberated in order to achieve a more acceptable design expectation. The following considerations are thus recommended:

It is acknowledged that the basic model set-up was not able to accurately reproduce the actual erosion rate inferred from the available maps. If the information from the referred maps is assumed to be reliable, then the result obtained shall be much less than actual. Thus, further study is strongly recommended with additional and refined data and to account for other factors such as the cross-shore sediment transport.

As highlighted in the report, a full Environmental Impact Assessment (EIA) should be undertaken in the detailed engineering design stage. This is to ensure all pertaining issues related to social and environmental aspects are taken into account. The EIA shall serve as part of the tool in achieving a more optimum design while minimising the potential negative impact. Besides the concern on environmentally sensitive living species within the project area, another decisive issue that should be evaluated is the existing and anticipated future land use and socio-economic development in the area against the investment required for such coastal erosion measures.

One should realize that all the difficulties of this study as well as previous studies is the lack of information and reliable sources of information. It is strongly recommended a long-term monitor program should be implemented not only for Nam Dinh coast but also necessary for the whole costal area of Vietnam.

Although the proposed beach nourishment concept was not found to cause any negative effect downcoast, proper construction method is necessary to ensure its full compliance with the design concept.

In order to result in a more comprehensive solution, such study and proposed mitigation measures should be integrated in the overall framework of the existing Vietnam Integrated Coastal Zone Management (VNICZM) for Nam Dinh Province. Depending on the overall planning of VNICZM, the extent of the 'project area' focussed in the present study may eventually be extended in future.

In addition, the final protection scheme shall also be based on a clear policy of VNICZM of Nam Dinh. This is crucial since it will require a long-term strategy, which how to come to the (more or less) final solution will involve specific design criteria and level of urgency. It is imperative to note that the prospect of future maintenance works may be affected by any possible changes in policy in VNICZM. Thus, the maintenance of such proposed solution shall be incorporated in the overall implementation programme.

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Annex 1
NUMERICAL WAVE MODEL SWAN

A1.1 SPECTRAL WAVE MODELING

A1.1.1 Review of wave models

Basically two types of numerical wave models have been developed to simulate the wave evolution in the coastal areas. These are phase resolving and phase averaged wave model.

Phase resolving type:

The phase resolving models are often used for rapidly varying wave conditions. Such models usually reconstruct the sea surface elevation in the absence of generation and dissipation, so the incorporation of wind effect is rather difficult. In addition, these models require high spatial resolutions to calculate wave evolution. These restrictions make these models impractical for wind-wave problem.

Phase averaged type:

In phase averaged wave model, it is assumed that the wave properties vary slowly on the scale of wavelength. In these models the irregular sea surface is described by a spectral energy function. The disadvantage of the phase resolving model can be accounted for in phase averaged model.

Since ***SWAN is a phase averaged wave model***, the discussion will include only the formulation of such models.

The wave propagation in phase averaged model can be described either by a *Lagrangian approach* or by an *Eulerian approach*.

Lagrangian approach: In this method, wave energy propagates from deep water to shore along the wave rays, the change in wave ray direction in response to changes in the bathymetry and current is governed by Snel's law. Propagation of each spectral component is calculated independently of all other components, so that the wave information is only available along the wave rays. This forward tracing of wave rays very often result in chaotic wave rays pattern and caustics, which makes their interpretation rather difficult (Holthuijsen et al 1989). More over the effects of non-linear interactions and white capping can not be implemented in a program developed by the Lagrangian approach. This is due to the fact that these processes require information of $E(f,\theta)$ along a ray which the models with Lagrangian approach can not produce.

Eulerian approach: In this method the wave evolution is formulated in terms of spectral energy on a grid *(see Fig. A1.1)*. Using a wave model that is formulated on a grid avoids the problem of chaotic wave ray pattern and it offers the opportunity to explicitly and efficiently include the propagation, generation, dissipation and non-linear wave-wave interaction of random short crested waves with a spectral formulation.

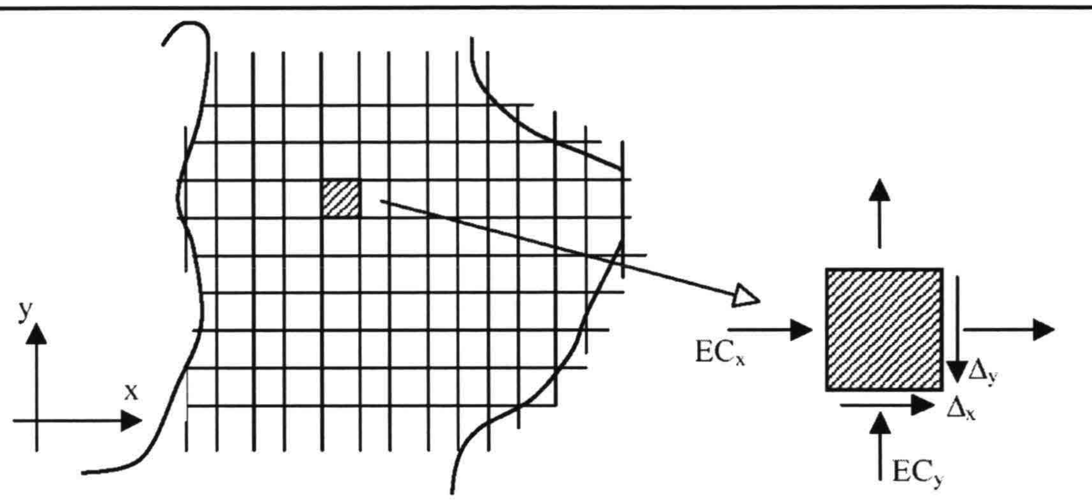


Fig. A1.1: Graphical representation of the Eulerian approach

Since ***SWAN model is developed by Eulerian approach***, more attention will be paid on this approach.

❖ **Mathematical description of Eulerian approach:**

Considering a single grid during time interval Δt over surface area Δx-Δy, the energy balance is given by:

- Stored energy at t=0: $E\ \Delta x \Delta y$

  Stored energy at t=Δt: $E\ \Delta x \Delta y + \partial E/\partial t\ \Delta x \Delta y \Delta t$

  Increase in stored energy: $\partial E/\partial t\ \Delta x \Delta y \Delta t$

- Import of energy in x direction: $C_x E\ \Delta y \Delta t$

  Export of energy in x direction: $C_x E\ \Delta y \Delta t + \partial/\partial x(C_x E\ \Delta y \Delta t)\Delta x$

Net import in X direction: $-\partial/\partial x(C_x E\ \Delta y \Delta t)\Delta x$

Similarly,

Net import in Y direction: $-\partial/\partial y(C_y E\ \Delta x \Delta t)\Delta y$

Local net generation: $S\ \Delta x \Delta y \Delta t$ (S is the source term)

Based on the above, Eulerian energy balance could be written as:

$$\partial E/\partial t\ \Delta x \Delta y \Delta t = -\partial/\partial x(C_x E\ \Delta y \Delta t)\Delta x - \partial/\partial y(C_y E\ \Delta x \Delta t)\Delta y + S\ \Delta x \Delta y \Delta t$$

or $\partial E/\partial t + \partial/\partial x(C_x E) + \partial/\partial y(C_y E) = S$ (1)

By integration this expression numerically it is possible to produce an estimate of $E(\sigma,\theta)$ every where in the model.

A1.1.2 Wave energy spectra

Due to the chaotic nature of waves a description of wave in time domain is rather difficult. An alternative is the description of waves in spectral domain, which enables a ready interpretation with linear wave theory. The spectra analysis decomposes the chaotic ocean waves into harmonic waves having different amplitudes, frequencies and directions. Then it is possible to represent the sea surface elevation as a function of time t and horizontal co-ordinate x-y, the result is two dimensional spectrum *(See Fig.A1.2)*. Two-dimensional spectrum is a summation of a large number of harmonic wave components with different amplitudes, frequencies and directions. The physics of these harmonic waves is thus known within the linear wave theory. Typical two-dimensional spectrum could be characterised by wave parameters such as significant wave height (H_s), mean wave period (T_{mo}) and peak wave period (T_p). Integration of a two-dimensional spectrum with respect to direction results in one-dimensional spectrum giving the variation of energy against frequency *(See Fig. A1.3)*.

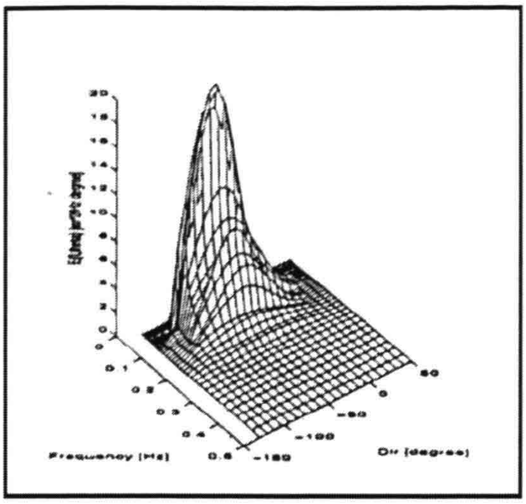


Fig. A1.2: 2D wave energy spectra

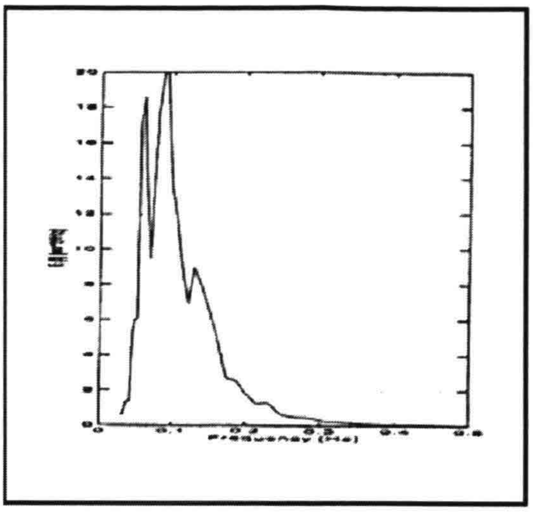


Fig. A1.3: 1D wave energy spectra

A1.1.3 Spectral wave parameters

Spectral wave parameters are expressed as moments of the energy density function *E(f)*. If the n^{th} momentum of the spectrum is m_n, it could be expressed as:

$$m_n = \int_0^{\infty} f^n E(f) df \quad (2)$$

With these moment some commonly applied wave parameters are described:

- Significant wave height: $H_s = 4\sqrt{m_o}$ (3)
- Mean wave period: $T_{m01} = m_0/m_1$ and $T_{m02} = \sqrt{m_0 / m_2}$ (4)
- Peak wave period: $T_p = 1/f_p$ (5)

(Period corresponding to maximum energy density)

- Mean wave direction:

$$DIR = \arctan\left[\frac{\int \sin(\theta) E(\sigma,\theta) d\sigma d\theta}{\int \cos(\theta) E(\sigma,\theta) d\sigma d\theta}\right] \quad (6)$$

A1.2 GENERAL OF NUMERICAL MODEL SWAN

SWAN is the numerical wave model to obtain realistic estimates of wave parameters in coastal area, lakes and estuary from given wind, bottom and current conditions. The evolution of the waves on the SWAN model is based on an *Eulerian formulation* of the spectral discrete wave action balance equation. The model is discrete spectral in frequencies and directions, and the kinematics behaviour of the wave is described with the linear theory of surface gravity waves. Within the SWAN model, the physics are explicitly represented by the state of the art formulation and the model is unconditionally stable due to the use of fully implicit schemes. Functionalities and limitations of the present version of SWAN is stated below:

Functionality:

1. *Wave propagation processes*

- Propagation through graphical space.
- Refraction due to bottom and current variations.
- Shoaling due to bottom and current variations.
- Blocking and reflections due to opposing currents.
- Transmission through sub-grid obstacles.

2. *Wave generation and dissipation processes*

- Generation by wind.
- Dissipation by white-capping.
- Dissipation by depth-induced wave breaking.
- Dissipation by bottom friction.
- Redistribution of energy over the spectrum by non-linear wave-wave interaction (Quadruplets and triads).

Limitations:

- Diffraction is not modelled in SWAN .
- Reflections are not modelled in SWAN.
- Wave induced set up and wave induced current can not calculated simultaneously with wave.
- Propagation is rather diffusive.

A1.3 BASIC EQUATION IN SWAN

In SWAN the waves are described with the two dimensional wave action density spectrum. The evolution of this spectrum for Cartesian co-ordinate is (e.g., Hasselman et al., 1973):

$$\frac{\partial}{\partial t}N(\sigma,\theta)+\frac{\partial}{\partial x}c_xN(\sigma,\theta)+\frac{\partial}{\partial y}c_yN(\sigma,\theta)+\frac{\partial}{\partial \sigma}c_\sigma N(\sigma,\theta)+\frac{\partial}{\partial \theta}c_\theta N(\sigma,\theta)=\frac{S(\sigma,\theta)}{\sigma} \qquad (7)$$

- The term σ and θ denotes the relative frequency and direction respectively.
- The term $N(\sigma,\theta)$ denoting the action density of wave, is the ratio of the energy density $E(\sigma,\theta)$ and the relative frequency σ.
- The term c_x, c_y, c_σ and c_θ represent the energy transport velocity (including the effect of current) in the geographical space (x,y) and the spectral space (σ,θ) respectively.

Different terms in the action balance equation could be briefed as follows starting from the left to right:

- *Term (1)* represents the local rate of change of action density in time.
- *Term (2)* and *term (3)* represent the propagation of action in geographical space (with propagation velocity c_x and c_y).
- *Term (4)* represents the shifting of the relative frequency due to the variation of depth and current (with a propagation velocity c_σ in σ space).
- *Term (5)* represents depth-induced and current–induced refraction (with propagation velocity c_θ in θ space).
- *Term (6)* on the right hand side of the balance equation is the source term in term of energy density representing the effects of generation, dissipation and non-linear wave-wave interactions. This source term could be expressed as the sum of the separate physical processes given by *(8)*.

$$S(\sigma,\theta)=S_{in}(\sigma,\theta)+S_{nl}(\sigma,\theta)+S_{ds}(\sigma,\theta) \qquad (8)$$

Where:

$S_{in}(\sigma,\theta)$ – Generation of wave energy by wind

$S_{nl}(\sigma,\theta)$ – Transfer wave energy due to non-linear wave-wave interaction

$S_{ds}(\sigma,\theta)$ – Dissipation wave energy due to bottom friction, white capping and wave breaking

SWAN computes the variations of energy density by integrating the source terms (i.e. taking into account the local effects like wind, white capping, wave-wave interaction, effects of bottom and currents) and simultaneously propagating these quantities at group velocity on a regular rectangular grid. A brief summary of these physical processes of wind waves will be given in the following section.

A1.4 PHYSICAL THEORY

The physical processes mentioned in above section are addressed separately in the following subsections

A1.4.1 Wave generation

In the presence of wind, the sea surface becomes irregular due to the generation of wind waves. Wind waves are generated as the result of the interaction between the wind and the sea surface. Transfer of wind energy to the waves is described in SWAN with the resonance of two type of mechanisms. The first mechanism is described by Phillips (1957) who considered wave growth that is linear in time due to resonant forcing of free surface waves by turbulent air pressure fluctuations. The second mechanism is described by Miles (1957) who considered growth that is exponential in time due to resonant interaction between the wave induced air pressure fluctuation and the free surface waves. Based on these two growth mechanisms, wave growth by wind is commonly described by the sum of linear and exponential term of a wave component :

$$S_{in}(\sigma,\theta) = A + BE(\sigma,\theta) \qquad (3\text{-}9)$$

in which A describes linear growth (Phillip resonant mechanism) and B describes exponential growth (Miles' feedback mechanism). The linear growth is dominant initially, but the exponential term quickly becomes dominant since some wave energy is present.

A1.4.2 Wave dissipation

Three different dissipation mechanisms distinguished in this study are white-capping, bottom friction and depth-induced wave breaking. Thus, the dissipation term S_{ds} of wave energy is correspondingly represented by the summation of these three contributions:

$$S_{ds}(\sigma,\theta) = S_{ds,w}(\sigma,\theta) + S_{ds,b}(\sigma,\theta) + S_{ds,br}(\sigma,\theta) \quad (3\text{-}10)$$

Where: $S_{ds,w}$ represents the white-capping dissipation

$S_{ds,b}$ represents dissipation due to bottom friction

$S_{ds,br}$ represents depth-induced wave breaking

Each of these processes is addressed separately below.

Whitecappping

The white-capping dissipation source term represents process by which wave energy is dissipated through deep-water wave breaking. It is primarily controlled by the steepness of the waves and is perhaps the least understood in deepwater. Only some empirical expressions are available to represent white-capping, in which the dissipation is proportional to the wave energy, overall wave steepness and (frequency)^2. In SWAN the white-capping formulation is based on the pulse-based model (Hasselmann, 1974), in which the dissipation rate is assumed quasi-linear with respect to the spectral density and depends on an average wave steepness.

Bottom friction

In water of finite depth, the waves start to interact with the bottom boundary layer resulting in wave decay. Wave energy is lost by various wave-bottom interaction mechanisms, they are: bottom friction, motion of soft muddy bottom, percolation scattering on bottom irregularities. An overview of different wave interaction mechanisms and of their relative strength is given by Shemdin et al. (1978). It can be concluded that the first two processes are dissipative and their strength depends on the bottom conditions, while the last one results in redistribution of wave energy by scattering of wave component. It appears that for sandy coastal regions (the most common coast) bottom friction is the most important mechanism.

Depth-induced wave breaking

When wave propagate from deep water to shallow water, shoaling leads to an increase in wave height. If the ratio of wave height over water depth is too large, the wave start to break and wave energy is rapidly dissipated. This process dominate over all other wave related processes in extreme shallow waters. The depth-induced wave-breaking phenomenon is poorly understood especially in relation to spectral distribution. In this study, bore-based model introduced by Battjes and Janssen (1978) is used to calculate the total rate of energy dissipation of random breaking waves.

A1.4.3 Non-linear wave-wave interaction

The basic properties of wave-wave interaction were discovered during the fundamental investigations of Phillips (1960) and Hasselmann (1960,1962). The physical meaning of the interaction is that resonant sets of wave components exchange energy, redistributing energy over the spectrum. For instance, two waves having ideal wavelengths, speeds and directions to satisfy resonance conditions may resonate and produce a third have own pattern. This newly generated wave could resonate with a free surface wave provided that ideal resonance conditions are satisfied. The net result of these wave interactions is redistributed the energy of the spectrum more uniformly over all wave numbers. In deep and intermediate water, this occurs only for three wave components resulting in fourth component. This is referred as quadruplet wave interaction. Whereas in shallow water triad wave interaction becomes important.

Quadruplet-wave interaction

The quadruplet-wave interactions give the main contribution to the evolution of the spectrum in deep water. They transfer wave energy from peak frequency to lower frequencies and partially to higher frequencies. The effect is to stabilise the spectral shape and cause a downward shift of the peak frequency (Young and Van Vledder, 1993). One of the commonly applied numerical formulations to represent the action of quadruplets is the *Discrete Interaction Approximation (DIA, of Hasselmann, 1985).*

Trials-wave interaction

In shallow water the trials-wave interactions become important for steep wave (Beji and Battejes, 1993). These interactions result in sub and super harmonics. The energy transfer in this process can take place over relatively short distance and can dramatically change the wave spectrum and so affect the processes of wave generation and dissipation. The *Discrete Triads Approximation* model *(DTA, Eldeberky and Battjes, 1995)* is one of the common models applied to calculate the triad wave interaction.

- For fully expressions that are used in SWAN for physical processes, reference is made to R.C.Ris (1997).

In summary, the evolution of wave energy spectra in the presence of a wind field is controlled by wind generation, wave-wave interaction and white capping. Evolution of the spectrum in a standard field was first observed by Hasselmann et al. (1973) in the **JONSWAP** project *(**JO**int **N**orth **S**ea **WA**ve **P**roject)*, hence this spectrum was named as a JONSWAP spectrum. In practice, the JONSWAP spectrum is considered as the design wave spectrum for deep water. Figure A1.4 indicates the influence of wave related phenomenon on typical JONSWAP type spectra. It is the energy balance between S_{in}, S_{nl} and S_w that determine the high frequency tail of the spectrum.

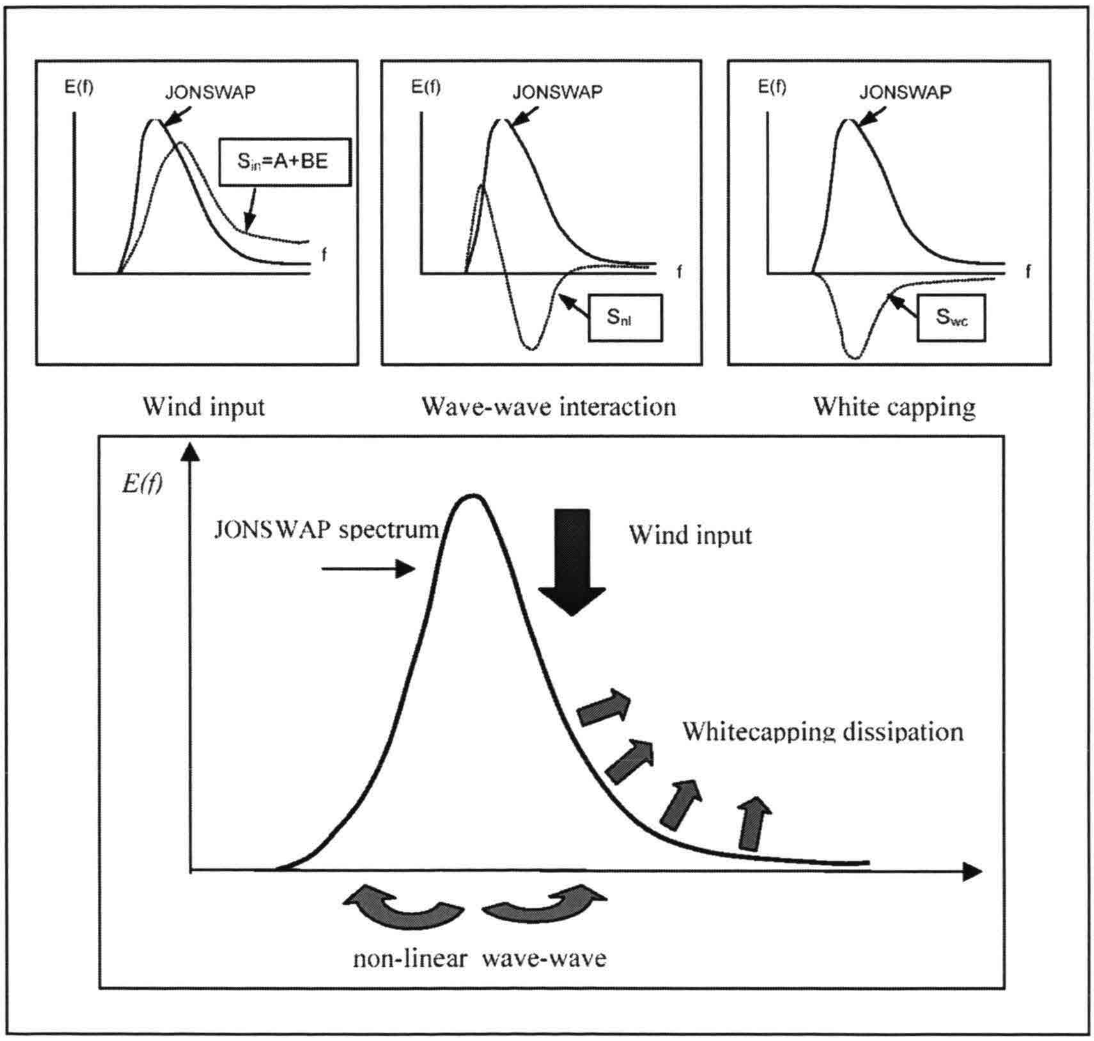


Fig. A1.4: The flow of energy through a JONSWAP spectrum

A1.5 NUMERICAL APPROACH

The basic action balance equation that is implemented in SWAN can be numerically integrated by two methods. These are *Finite Difference Method (FDM)* and the *Finite Elements Method (FEM)*. Which of these is most appropriate for the SWAN model depends on the numerical integration technique that is applied for the propagation term in geographical x, y space. Experiences from previous wave model showed that forward marching technique is very efficient in computation of propagation waves in geographical space. This technique is therefore chosen in SWAN model. However, this forward marching is computationally efficient only if the grid is well structured.. This is the case if each grid point has four and only four adjacent grid points. This condition is generally not satisfied in the FEM, but it can be properly implemented in FDM. Therefore, the ***FDM is selected to numerically integrate the balance equation in SWAN model***. In the FDM, the grid structure is always properly organised so that a forward marching technique can be implemented properly. Based on selected method, the numerical schemes for geographical space, spectral space and for source term in SWAN model are selected and they are described in the following subsections.

A1.5.1 Propagation in geographical space

The numerical schemes that are selected in geographical (and spectral) space are chosen on the basis of robust, accuracy and economy. In SWAN, implicit numerical schemes are chosen to propagate energy in geographical space. Such schemes ensure unconditionally stable propagation (robust) and permit large space steps in the computations since the increments in geographical space *(Δx, Δy)* are independent of those in spectral space *($\Delta\sigma$,$\Delta\theta$)*.

Experience in using the HISWA model (Holthijsen et al 1989) has shown that for an energy based wave model for coastal application, a simple and therefore economical, first-order up-wind difference scheme is accurate enough in geographical space. Such a scheme is also attractive because it suppresses spurious oscillations (avoiding negative action densities). Term (2) and term (3) in equation (7) are accordingly approximated with the following *first-order up wind scheme*:

$$\frac{\partial}{\partial x} c_x N(\sigma,\theta) = \left[\frac{[c_x N]_{i_x} - [c_x N]_{i_x - 1}}{\Delta x} \right] \qquad (11)$$

and

$$\frac{\partial}{\partial y} c_y N(\sigma,\theta) = \left[\frac{[c_y N]_{i_y} - [c_y N]_{i_y -1}}{\Delta y} \right] \qquad (12)$$

in which i_x and i_y are grid counters in x and y space, respectively.

The computation is therefore unconditionally stable for all wave energy propagation directions between the up-wave x and y direction because the characteristics lie within this quadrant (they remain inside domain of dependence). This propagation step is carried out for each grid point in the computation domain. It is therefore forward marching technique for wave components in a 90°-quadrant. The propagation of these components is called sweep 1 in the computation procedure *(See Fig. A1.5)*. By rotating the numerical stencil over 90° and three more to propagate energy over all four directional quadrants (four-sweep technique). This allows wave energy from all directions (four directional quadrant) to propagate over the entire geographical domain. Figure A1.5 displays the numerical stencil for wave energy propagation in geographical space in SWAN with the appropriate directional quadrant indicated per sweep for which wave energies are propagated.

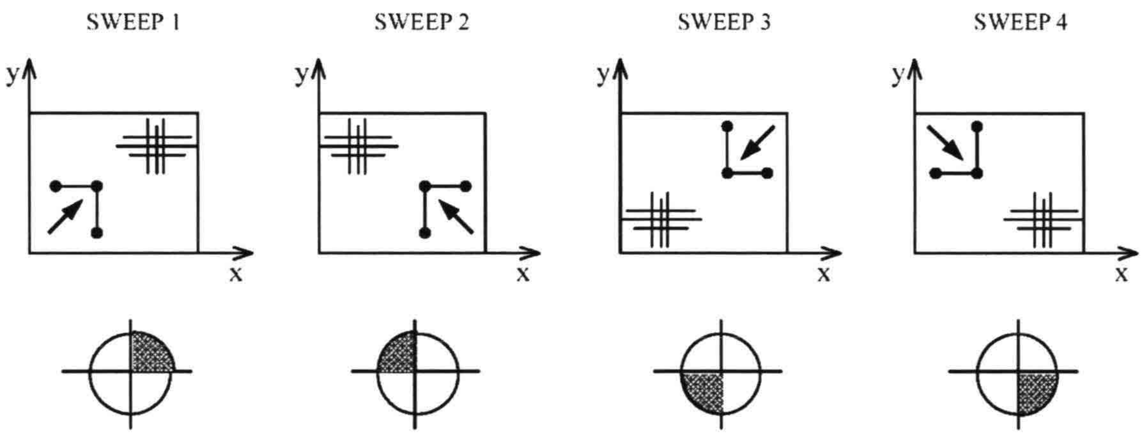


Fig. A1.5: Numerical stencil for wave energy propagation in geographical space

A1.5.2 Propagation in spectral space

Propagation in frequency space

An implicit scheme in frequency space is chosen in the SWAN model. The simplest, most robust and most economical implicit scheme is a first-order up-wind scheme. However, in blocking conditions a second-order central scheme was selected to avoid diffusion for frequencies near the blocking frequency. Therefore, to achieve a robust scheme in situations with (strong) blocking in the one hand and a (more) accurate scheme in situations without blocking (or with weak currents) on the other hand, a first-order up-wind scheme is combined with a second-order central scheme. This allows the user to choose between (or combine) these different schemes depending on the situation that is considered. The fourth term in equation (7) is accordingly approximated with:

$$\frac{\partial}{\partial\sigma}c_\sigma N(\sigma,\theta)=\left[\frac{(1+\mu)[c_\sigma N]_{i_\sigma+1}-2\mu[c_\sigma N]_{i_\sigma}-(1-\mu)[c_\sigma N]_{i_\sigma-1}}{2\Delta\sigma}\right] \quad (13)$$

in which μ is user controlled coefficient. A value of $\mu=0$ corresponds to a central difference scheme which has the highest accuracy (numerical diffusion ≈ 0). A value of $\mu=\pm 1$ (sign of μ depends on the sign of c_σ) corresponds to an up-wind difference scheme which is more diffusive and therefore less accurate but more robust. So, the coefficient μ controls the numerical diffusion frequency space.

Propagation in directional space

To avoid numerical instability in directional space and to allow for large space steps, an implicit scheme is also chosen in θ space.

The selection of the numerical implicit scheme in directional space is the same as in frequency space. So, the fifth term in equation (3-7) is approximated with:

$$\frac{\partial}{\partial\theta}c_\theta N(\sigma,\theta)=\left[\frac{(1+\nu)[c_\sigma N]_{i_\sigma+1}-2\nu[c_\theta N]_{i_\theta}-(1-\nu)[c_\theta N]_{i_\theta-1}}{2\Delta\theta}\right] \quad (14)$$

The coefficient ν plays the same role as the coefficient μ in equation (13) and determines the degree to which the scheme in directional space is up-wind or central.

❖ In brief, implicit schemes are used in both geographical *(x,y)* and spectral space

(σ,θ) which ensure unconditionally stable propagation in all four dimensions.

A1.5.3 Numerical scheme for source-terms

The numerical schemes for source terms that are used in the SWAN model are either explicit or implicit depending on the source term. Experience with the SWAN model shows that an explicit numerical scheme is required for the positive source terms to ensure stable model behaviour at the high-frequency part of the spectrum. Implicit schemes were found to be required for the negative source term to ensure stable behaviour of the model (except for the quadruplet-wave interaction). For reason of computation efficiency the quadruplet-wave interactions are calculated with an explicit scheme.

A1.5.4 Matrix inversion

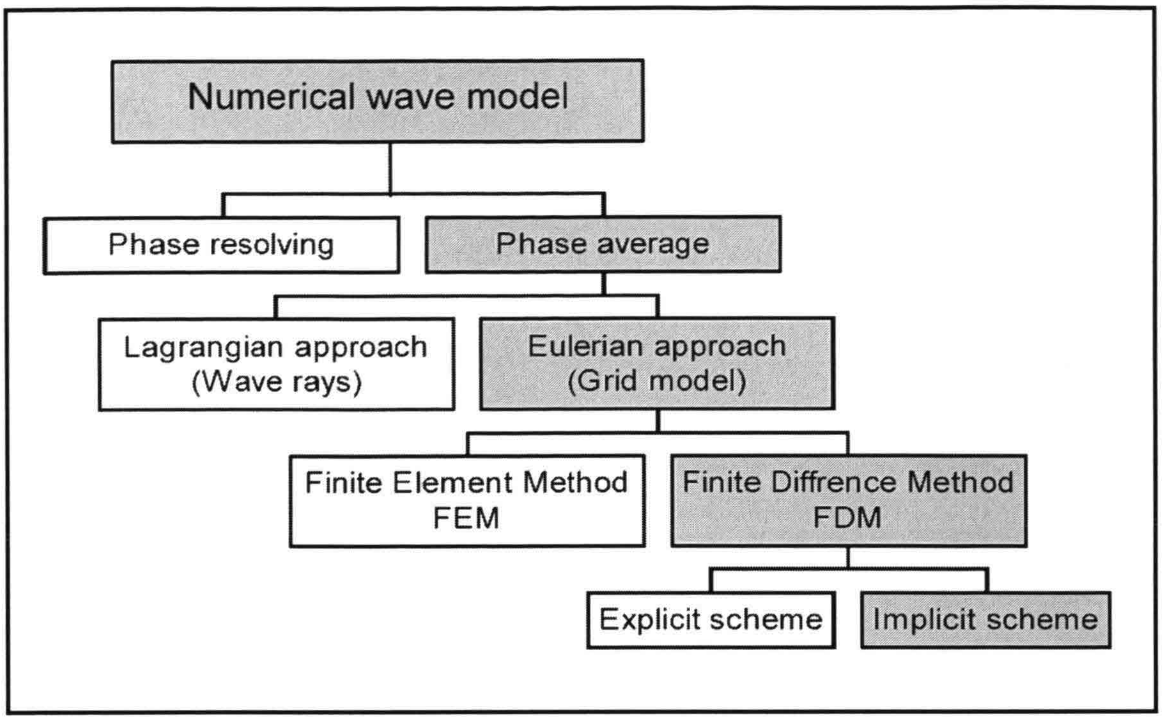
To obtain the new action density in grid point at each iteration, the action balance equation is numerically integrated by solving the following set of linear equations (which constitute a matrix) for each sweep separately:

$$A\,.\,N = b \qquad (14)$$

in which A is a known matrix (with coefficient of the numerical schemes of the propagation terms and the sources terms), N is known action density vector and b is a vector with known values (with coefficient of the numerical schemes of the propagation terms and source terms and the boundary conditions). Depending on the matrix structure, different solvers are used in the SWAN model to invert the matrix. This inversion of one matrix with all terms of the action balance equation implies that the propagation, generation, non-linear wave-wave interactions, dissipation and boundary conditions are treated simultaneously in each iteration in the SWAN models.

❖ In short, the selection of the type of model, the approach used for description of wave propagation, the method applied to numerically integrate the balance equation and the type of scheme in ***SWAN*** model can be summarised in Fig. A1.6.

Since the first time SWAN released on the basis of the above approaches, it has been developed through various generation modes, the evolution of SWAN wave model can be briefly described in the following section.



Note: The grey colour represents the applications for SWAN model

Fig. A1.6: The selections of the approaches used in SWAN model

A1.6 EVOLUTION OF WAVE MODEL

Numerical wave models have been categorised into first, second and third generation models, on the basis of the level of parameterisations of the source term. In the first generation model, which was developed in the 1970's, the non-linear quadruplet interactions are not expressed explicitly. The wave spectrum in these models is allowed to grow to some assume upper limit, which is usually the Peirson-Moskovitz (1964) spectrum with a standard direction distribution.

As a result of the wave growth experiments by Hasselmann et al. (1973), the Joint North Sea Wave Project (JONSWAP), it became clear that to describe properly of growing wind seas, the quadruplet-wave interaction should be taken into account. Second generation was therefor released to remedy this by parameterizing these interactions and by using the JONSWAP spectrum as an upper limit instead of the Peirson-Moskovitz spectrum (Holthuijsen and De Boer, 1988). These changes improved the results of the simulations in second-generation model, as compared to that of the first generation results.

Despite of the improvement of the result in second generation, such models can only be used to estimate the wave conditions for certain classes of wind fields. It was found from a large inter-comparison study of first and second wave models that there were some basic shortcomings in these models and that they lose their reliability in extreme condition. This has led to the development of third generation wave models in which the quadruplet-wave interaction is incorporated explicitly. In third generation models the spectrum is computed by integrating the spectral energy balance equation without any priori restrictions on the spectrum.

The following table briefs the available options in SWAN for the source terms in different generation modes.

Table A1.1. Expression for Source Terms in SWAN

Source terms	Expression	Generation mode of SWAN		
		1st	2nd	3rd
Linear wind growth	*Cavaleri & Malanotte-Rizzoli (1981)* [Modified]	x	x	
	Cavaleri & Malanotte-Rizzoli (1981)			x
Exponential wind growth	*Snyder et al. (1981)* [Modified]	x	x	
	Snyder et al. (1981)			x
	Jassen (1989, 1991)			x
White capping	*Holthuijsen and De Boer (1988)*	x	x	
	Komen et al. (1984)			x
	Jassen (1991), Komen et al. (19940			x
Quadruplet interactions	*Hasselmann et al. (1985)*			x
Triad interactions	*Eldeberky (1996)*	x	x	x
Depth-induced breaking	*Battjes & Jassen (1978) with Nelson (1994)*	x	x	x
Bottom friction	*Hasselmann et al. JONSWAP (1973)*	x	x	x
	Collins (1972)	x	x	x
	Madsen et al. (1988)	x	x	x
Obstacle transmission	*Seelig (1979)*	x	x	x

A1.7 MODEL IMPLEMENTATION

Although SWAN program can be easily accessible through INTERNET, it is still not developed enough to categorise as user-friend package. Therefore when applying SWAN to particular case study, it is essential to familiarise with some other software to carry out pre and post processing of SWAN (e.g. ARC_VIEW and ARC_INFOR), these programs are helpful in term of visualisation for the input and output data. In addition to that, for more convenience in setting up the grid for the model, two packages in Delft3D (From WL | Delft Hydraulic) has therefore been used in the present study too, they are RGFGRID and QUICKIN. Due to the time limited, this report will not go in detail about those program, instead this section will give general introductions to deal with the basic parameters in command file to run SWAN model.

A1.7.1 Co-ordinate system in SWAN

In order to perform the wave computation model accurately, it is essential to have clear picture of the basic co-ordinate applied in a numerical model. In SWAN, two co-ordinate systems must be selected to set up the model.

Co-ordinate systems for geographical locations

In SWAN all geographical locations can be defined in the so called *problem co-ordinate system* according to the two following co-ordinate systems:

- **CARTESIAN:** All locations and distances are in m. Co-ordinate are given with respect to x and y axes chosen arbitrarily by the user.
- **SPHERICAL:** All co-ordinates of locations and geographical grid sizes are given in degrees, x is longitude and y is latitude. Input and output grids have to be oriented with their x-axis to the East, mesh sizes are in degrees. All other distances are in m.

Co-ordinate systems for the directions of winds and waves

There are two options for the convention of the directions of winds and waves in SWAN *(See Figure A1.7)*, they are:

- The **CARTESIAN convention:** The direction to where the vector points, measured counter clockwise from the positive x-axis of this system (in ^{o}).
- The **NAUTICAL convention:** The direction where the wind or the wave comes from, measured clockwise from geographic North.

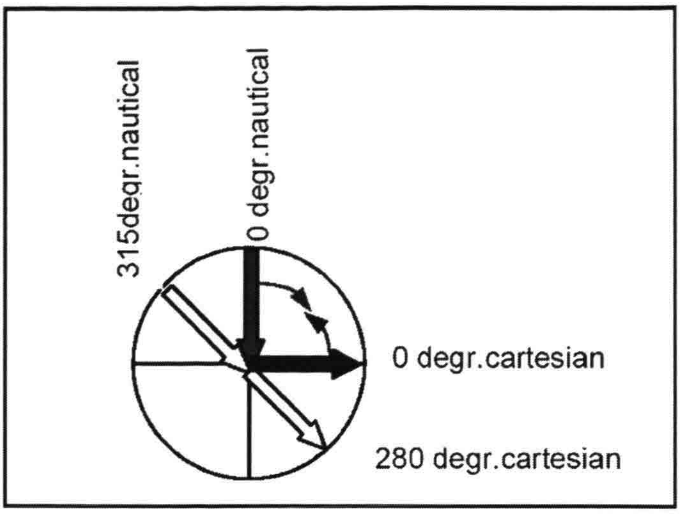


Fig. A1.7: Graphical representation of the two co-ordinate systems

3.7.2 Grid system in SWAN

The grid used in SWAN model may be either curvilinear or rectangular grid. Three grids, which should be defined in SWAN computation, are mentioned below.

Input grid

Input grid is a grid on which the bathymetry, current, water level, friction coefficients and wind field are defined. Input grids can be differ from each other, both in dimension and orientation. The spatial resolution of the input grid depends on the accuracy of the spatial details required. Users should chose the spatial resolutions for those input grids in such way that the relevant spatial details are properly resolved and special care is required in extremely complex coastal area and estuary. However, it should be noted that smaller resolution, more accurate the results will be, but at the same time the required computer space will be increased.

Computational grid

Computational grid is a grid on which model solves action balance equation. In SWAN, users can decide the orientation (direction), the size and the resolution of computational grid system, which include the geographical and spectral grids. These two grids can be defined independent from each other.

- *Geographical grid*

Geographical grid describes the orientation, size and the resolution of the area in which wave computation are to be performed. Generally, three types of grid can be used: a regular rectangular grid (Δx=constant, Δy=constant), an irregular rectangular grid (Δx=variable, Δy=variable) and a curvilinear grid. For the situation in which a higher grid resolution is locally required, grid nesting is optionally available in the SWAN model. In this nesting option the computations are carried out on a coarse grid for a higher area and subsequently on a finer grid for a smaller area. The boundary conditions for the finer grid are obtained from the coarse grid.

The *x, y* resolution and the orientation of the computational grid is defined by the user. The spatial resolution of the computational grid should be selected in such a way that it is sufficient to solve relevant details of the applied wave field. Better results could be obtained by taking the resolution of the computational grid and the input grid approximately equal, by doing such a way the error due to interpolation between grids could be minimised.

In principle the input grid should cover the larger area the computational grid both in space and time. If for some reasons the computational grid exceed the dimensions of an input, for region outside the input grid, SWAN assumes that the particular parameter is identical to the value closer to the boundary.

In addition to the computational grid in geographical space, SWAN calculate also wave propagation in spectral space. To that end for each geographical grid the spectral grid has to be specified as explained below.

- <u>*Spectral grid*</u>

The spectra grid consists of the frequency space and directional grid.

- *Frequency space*

In frequency space, it is simply defined by a minimum and maximum frequency and the frequency resolution is proportional to the frequency itself (common is Δf=0.1f).

- *Directional space*

In directional space, usually the directional range is the full 360° unless when wave travel towards a coast within a limited sector of 180°, it is convenient (less computer time and/or space) to specify the limited directional range. The directional resolution is determined by the number of discrete directions provided by the user. Table A1.2 contains the discretization for each type of grids recommended by the SWAN developers.

Table A1.2: Recommended discretizations for spectral grid

Directional resolution for wind sea conditions	$\Delta\theta$ = 15°-10°
Directional resolution for swell sea conditions	$\Delta\theta$ = 5°-2°
Frequency range	σ_{min} = 0.04 Hz
	σ_{max} = 1.00 Hz
Spatial resolution	Δx, Δy = 50-1000m

Output grid

SWAN can provide outputs on spatial grids that are independent from input grids and computational grids. An output grid has to be specified by the user with care since different in grid resolution among these three grid systems could result in inaccuracies due to interpolation errors. Thus it is wise to keep three grid systems identical, if possible.

A1.7.3 Boundary conditions

It is essential to define the boundary conditions both in the geographical and spectral space to facilitate the integration process of the action balance equation.

Boundary conditions in the geographical space

Some of the important aspects that should be taken into consideration when deciding the orientation, extent and the resolution of geographical grid system. The orientation of the grid can be chosen arbitrary; the boundaries of the computational grid in SWAN are either land or water. In case of land there is no problem. The land does not generate waves and in SWAN it absorbs all coming wave energy. But in the case of water boundary there is a problem. If no wave conditions are known along such a boundary, SWAN then assumes that no waves enter the area and that waves can leave the area freely. This assumption obviously contains errors, which propagate into the model. If the observations are available, they can be used as input at the boundary. However, this usually covers only part of boundaries so that rest of the boundaries suffer from same errors as above. For these reasons, the lateral boundary must be chosen sufficiently far away from the area where reliable computation are needed so that they do not affect the computation result there. This is not the case if the wave condition along the lateral boundaries are specified in segment by the user or such problem occur obviously not is the lateral boundary contain wave information over their entire length, for example, obtained from a previous SWAN.

Special care should be paid when deciding the grid system near the coast where it is often possible to identify an up-wave boundary (with proper wave information) and two lateral boundaries (with no or partial wave information). The affected areas with errors are typically regions with the apex at the corners of the water boundary with wave information and spreading towards the shore at an angle of 30° to 45° for wind sea conditions to either side of the imposed mean wave direction and less for swell conditions. For propagation of short crested waves (wind sea conditions) an example is given in Figure A1.8. For this reason the lateral boundaries should be sufficient far away from the area of interest to avoid the propagation of this error into this area. Such problems occur obviously not if the lateral boundaries contain proper wave information over their entire length e.g. obtained from previous SWAN computation or if the lateral boundaries are coast.

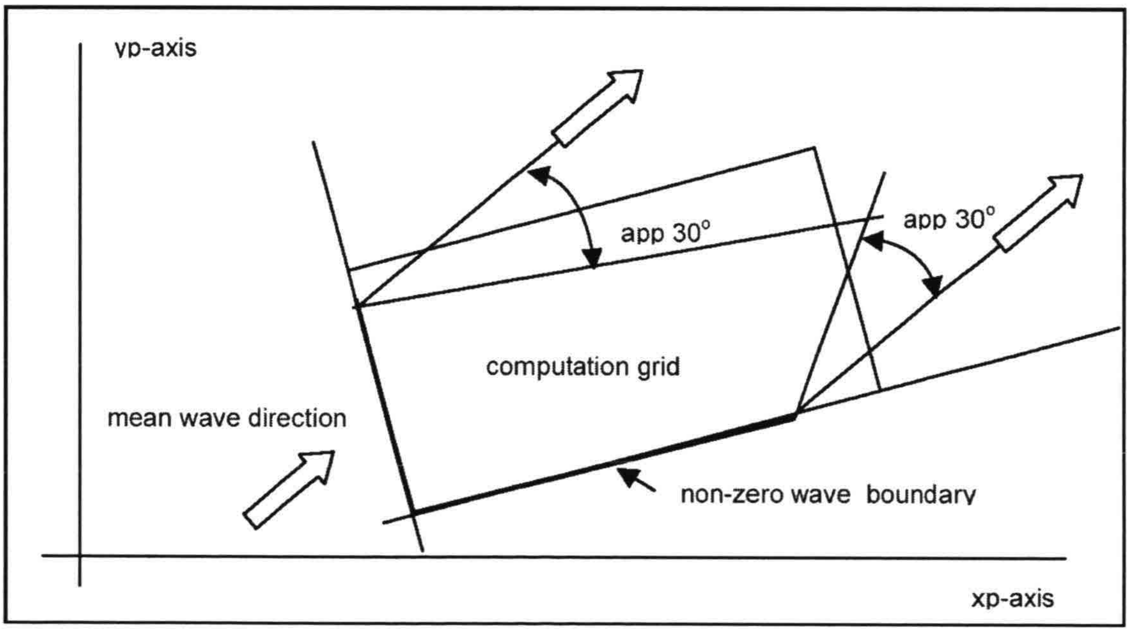


Fig. A1.8: Disturbed region in the computational grid due to erroneous boundary conditions are indicated with shaded areas

Boundary conditions in spectral space

In frequency space the boundaries are fully absorbed at the lowest and highest discrete frequency. So, energy can freely propagate across these boundaries and thus total energy might not be conserved in the presence of current. Since the directional space is a closed circular space, no boundary conditions are needed if the full circle is used. For the reason of economy it is also possible to define directional sectors instead of a full circle. In such cases the boundaries of these sectors are fully absorbed. Therefor action density travelling outside this pre-defined sector will be removed from the model.

Annex 2.
YEARLY NEARSHORE WAVE CLIMATES

Table A2.1: Nearshore wave climate at point GT-1

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Dur. (days)
Hs (m)	Tp (s)	Dir (dg.N)	Hs (m)	Tp (s)	Dir (dg.N)	Hs (m)	Tp (s)	Dir (dg.N)		
0.37	2.71	59.74	0.37	2.40	67.39	0.32	2.40	66.21	2.835%	10.35
0.60	3.08	64.14	0.60	3.08	68.12	0.53	2.71	73.86	11.986%	43.75
0.90	3.48	70.46	0.91	3.48	74.35	0.83	3.48	73.23	13.030%	47.56
1.21	6.50	76.75	1.21	6.50	83.35	1.10	3.95	82.95	8.068%	29.45
1.37	6.50	78.31	1.38	6.50	83.93	1.26	3.95	82.75	4.625%	16.88
1.73	7.37	82.15	1.72	7.37	88.73	1.56	7.37	88.09	1.613%	5.89
2.10	8.35	86.56	2.07	8.35	92.09	1.89	8.35	91.23	0.732%	2.67
2.46	8.35	89.41	2.43	8.35	93.68	2.25	8.35	92.44	0.109%	0.40
3.11	9.46	96.29	3.11	9.46	98.30	2.94	9.46	96.74	0.03%	0.11
3.34	10.71	101.66	3.35	10.71	102.31	3.16	10.71	104.28	0.010%	0.04
0.41	3.08	100.01	0.42	3.08	99.29	0.40	2.71	102.86	2.216%	8.09
0.71	3.95	102.40	0.73	3.95	102.39	0.69	3.95	107.97	6.841%	24.97
1.08	5.07	106.12	1.10	5.07	105.97	1.06	5.07	109.14	2.567%	9.37
1.53	6.50	109.25	1.56	6.50	109.28	1.49	6.50	111.60	0.717%	2.62
1.78	6.50	110.91	1.81	6.50	110.71	1.75	6.50	112.47	0.148%	0.54
2.29	7.37	113.25	2.31	7.37	113.19	2.25	7.37	114.90	0.099%	0.36
2.82	8.35	115.31	2.83	8.35	115.61	2.77	8.35	116.94	0.030%	0.11
4.10	10.71	118.19	4.07	10.71	118.87	4.07	10.71	120.27	0.005%	0.02
0.44	3.08	136.30	0.45	3.48	137.40	0.44	3.48	138.95	1.756%	6.41
0.77	3.95	138.48	0.77	3.95	137.85	0.79	3.95	140.42	5.085%	18.56
1.22	5.07	140.25	1.23	5.07	139.58	1.23	5.07	140.70	1.385%	5.06
1.78	6.50	141.45	1.79	6.50	140.92	1.79	6.50	141.46	0.317%	1.16
2.05	6.50	141.75	2.06	6.50	141.24	2.06	6.50	141.76	0.450%	1.64
2.66	7.37	141.83	2.66	7.37	141.64	2.66	7.37	141.85	0.124%	0.45
3.21	8.35	142.75	3.19	8.35	143.04	3.19	8.35	143.27	0.020%	0.07
4.20	10.71	143.32	4.16	10.71	143.13	4.16	10.71	143.18	0.02%	0.07
4.29	10.71	143.11	4.24	10.71	143.24	4.24	10.71	143.22	0.015%	0.05
0.45	3.08	177.91	0.45	3.08	177.73	0.45	3.08	177.55	1.499%	5.47
0.79	3.95	176.12	0.79	3.95	175.77	0.80	3.95	175.34	7.905%	28.85
1.23	5.07	173.19	1.23	5.07	173.46	1.23	5.07	173.51	9.013%	32.90
1.78	6.50	171.79	1.78	6.50	171.78	1.78	6.50	171.74	4.091%	14.93
2.05	6.50	170.82	2.05	6.50	170.70	2.05	6.50	170.79	1.093%	3.99
2.61	7.37	168.98	2.61	7.37	168.94	2.61	7.37	168.94	0.173%	0.63
3.12	8.35	167.70	3.11	8.35	167.65	3.11	8.35	167.59	0.153%	0.56
3.56	9.46	166.45	3.59	9.46	167.07	3.59	9.46	167.00	0.010%	0.04
4.28	10.71	164.95	4.24	10.71	164.81	4.24	10.71	164.81	0.005%	0.02
0.42	3.08	211.00	0.42	3.08	210.79	0.42	3.08	210.79	0.480%	1.75
0.70	3.95	210.86	0.70	3.95	210.74	0.72	3.95	208.37	1.652%	6.03
1.08	5.07	206.13	1.08	5.07	205.91	1.08	5.07	205.82	1.054%	3.85
1.49	5.74	202.13	1.48	5.74	202.47	1.48	5.74	202.43	0.247%	0.90
1.73	5.74	198.59	1.73	5.74	198.81	1.73	5.74	198.79	0.054%	0.20
2.16	6.50	195.68	2.16	6.50	195.78	2.16	6.50	195.76	0.010%	0.04
2.59	7.37	192.86	2.59	7.37	192.86	2.59	7.37	192.84	0.020%	0.07
3.93	9.46	184.86	3.90	9.46	185.58	3.91	9.46	185.42	0.005%	0.02

Table A2.2: Neashore wave climate at point HL1

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Duration (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.37	2.71	62.55	0.37	2.71	67.88	0.35	2.71	66.65	2.835%	10.35
0.61	3.48	67.42	0.61	3.08	68.11	0.59	3.08	74.64	11.986%	43.75
0.93	3.95	73.38	0.93	3.95	74.48	0.91	3.95	74.90	13.030%	47.56
1.27	5.74	79.63	1.26	4.47	81.87	1.22	4.47	82.94	8.068%	29.45
1.43	6.50	81.06	1.43	6.50	82.37	1.40	4.47	83.68	4.625%	16.88
1.80	7.37	84.69	1.78	7.37	87.08	1.74	7.37	87.89	1.613%	5.89
2.17	8.35	87.90	2.15	8.35	90.31	2.10	8.35	90.79	0.732%	2.67
2.52	8.35	90.76	2.50	8.35	92.60	2.47	8.35	92.95	0.109%	0.40
3.04	9.46	100.03	3.02	9.46	101.18	3.02	9.46	101.63	0.03%	0.11
3.39	10.71	99.63	3.39	10.71	100.45	3.39	10.71	100.85	0.010%	0.04
0.41	3.08	99.75	0.42	3.08	96.93	0.42	3.08	99.29	2.216%	8.09
0.74	3.95	101.28	0.74	3.95	100.81	0.72	3.95	103.91	6.841%	24.97
1.12	5.07	104.15	1.13	5.07	104.43	1.12	5.07	105.19	2.567%	9.37
1.59	6.50	107.24	1.58	6.50	107.72	1.58	6.50	108.34	0.717%	2.62
1.84	6.50	108.42	1.85	6.50	108.43	1.84	6.50	109.27	0.148%	0.54
2.36	7.37	111.02	2.36	7.37	111.26	2.36	7.37	111.74	0.099%	0.36
2.85	8.35	113.84	2.86	8.35	114.18	2.85	8.35	114.42	0.030%	0.11
3.83	10.71	116.62	3.83	10.71	117.12	3.83	10.71	117.47	0.005%	0.02
0.44	3.08	135.49	0.45	3.48	135.77	0.45	3.48	136.49	1.756%	6.41
0.77	3.95	136.75	0.77	3.95	136.68	0.80	3.95	138.03	5.085%	18.56
1.22	5.07	138.37	1.23	5.07	138.40	1.23	5.07	138.49	1.385%	5.06
1.78	6.50	138.71	1.78	6.50	138.65	1.78	6.50	138.68	0.317%	1.16
2.06	6.50	139.07	2.06	6.50	139.02	2.06	6.50	139.09	0.450%	1.64
2.64	7.37	139.40	2.65	7.37	139.40	2.65	7.37	139.40	0.124%	0.45
3.13	8.35	139.72	3.13	8.35	139.75	3.14	8.35	139.65	0.020%	0.07
3.88	10.71	141.05	3.87	10.71	141.03	3.87	10.71	141.05	0.02%	0.07
3.92	10.71	141.11	3.91	10.71	141.15	3.91	10.71	141.13	0.015%	0.05
0.45	3.08	175.78	0.45	3.08	176.19	0.45	3.08	176.53	1.499%	5.47
0.77	3.95	174.37	0.78	3.95	174.54	0.79	3.95	174.06	7.905%	28.85
1.21	5.07	171.28	1.20	5.07	171.27	1.21	5.07	171.27	9.013%	32.90
1.72	6.50	169.14	1.72	6.50	169.25	1.72	6.50	169.19	4.091%	14.93
1.98	6.50	168.22	1.98	6.50	168.28	1.98	6.50	168.27	1.093%	3.99
2.50	7.37	166.15	2.50	7.37	166.18	2.50	7.37	166.17	0.173%	0.63
2.95	8.35	165.16	2.94	8.35	165.11	2.94	8.35	165.12	0.153%	0.56
3.36	9.46	163.61	3.35	9.46	163.65	3.35	9.46	163.64	0.010%	0.04
3.90	10.71	162.70	3.90	10.71	162.50	3.90	10.71	162.50	0.005%	0.02
0.41	3.08	208.67	0.41	3.08	208.61	0.41	3.08	208.61	0.480%	1.75
0.68	3.95	208.76	0.68	3.95	208.96	0.70	3.95	205.94	1.652%	6.03
1.03	5.07	202.87	1.03	5.07	203.07	1.03	5.07	203.08	1.054%	3.85
1.40	5.74	199.55	1.40	5.74	199.49	1.40	5.74	199.49	0.247%	0.90
1.62	5.74	195.77	1.62	5.74	195.86	1.62	5.74	195.86	0.054%	0.20
2.01	6.50	193.13	2.01	6.50	193.19	2.01	6.50	193.19	0.010%	0.04
2.39	7.37	190.58	2.39	7.37	190.76	2.39	7.37	190.76	0.020%	0.07
3.57	9.46	183.29	3.56	9.46	183.58	3.57	9.46	183.47	0.005%	0.02

Table A2.3: Neashore wave climate at point HL2

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Duration (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.38	2.71	61.52	0.38	2.71	65.53	0.36	2.71	65.34	2.835%	10.35
0.64	3.48	66.49	0.63	3.08	67.07	0.62	3.48	72.65	11.986%	43.75
0.97	3.95	72.42	0.97	3.95	73.40	0.95	3.95	73.85	13.030%	47.56
1.33	5.74	78.70	1.32	4.47	80.13	1.29	4.47	81.27	8.068%	29.45
1.60	6.50	77.46	1.50	6.50	80.86	1.48	5.07	81.78	4.625%	16.88
1.89	7.37	83.47	1.87	7.37	85.23	1.84	7.37	85.99	1.613%	5.89
2.27	8.35	86.25	2.25	8.35	88.23	2.22	8.35	88.65	0.732%	2.67
2.64	8.35	89.22	2.63	8.35	90.30	2.61	8.35	90.89	0.109%	0.40
3.23	9.46	98.42	3.20	9.46	99.20	3.24	9.46	98.97	0.03%	0.11
3.58	10.71	99.01	3.57	10.71	98.75	3.59	10.71	100.17	0.010%	0.04
0.42	3.08	98.43	0.43	3.08	95.77	0.42	3.08	98.03	2.216%	8.09
0.75	3.95	99.72	0.75	3.95	99.51	0.73	3.95	102.37	6.841%	24.97
1.16	5.07	102.50	1.16	5.07	102.93	1.16	5.07	103.45	2.567%	9.37
1.64	6.50	105.45	1.63	6.50	105.78	1.63	6.50	106.37	0.717%	2.62
1.90	6.50	106.61	1.91	6.50	106.51	1.91	6.50	107.13	0.148%	0.54
2.44	7.37	109.25	2.44	7.37	109.31	2.44	7.37	109.79	0.099%	0.36
2.97	8.35	111.80	2.97	8.35	111.98	2.97	8.35	112.30	0.030%	0.11
4.15	10.71	115.23	4.15	10.71	115.73	4.15	10.71	115.96	0.005%	0.02
0.45	3.08	135.41	0.45	3.48	135.40	0.45	3.48	135.98	1.756%	6.41
0.78	3.95	136.04	0.78	3.95	136.22	0.80	3.95	137.23	5.085%	18.56
1.24	5.07	137.44	1.24	5.07	137.58	1.24	5.07	137.76	1.385%	5.06
1.80	6.50	137.63	1.80	6.50	137.65	1.80	6.50	137.54	0.317%	1.16
2.09	6.50	137.99	2.09	6.50	137.97	2.10	6.50	138.00	0.450%	1.64
2.68	7.37	138.13	2.68	7.37	138.17	2.69	7.37	138.12	0.124%	0.45
3.20	8.35	138.85	3.20	8.35	138.88	3.20	8.35	138.87	0.020%	0.07
4.17	10.71	139.30	4.16	10.71	139.43	4.16	10.71	139.39	0.02%	0.07
4.24	10.71	139.57	4.23	10.71	139.72	4.23	10.71	139.71	0.015%	0.05
0.45	3.08	175.72	0.45	3.08	176.11	0.45	3.08	176.14	1.499%	5.47
0.78	3.95	174.18	0.78	3.95	174.29	0.79	3.95	173.84	7.905%	28.85
1.22	5.07	171.06	1.22	5.07	171.07	1.22	5.07	171.04	9.013%	32.90
1.73	6.50	168.75	1.74	6.50	168.87	1.73	6.50	168.87	4.091%	14.93
2.00	6.50	167.82	1.99	6.50	167.86	2.00	6.50	167.84	1.093%	3.99
2.52	7.37	165.78	2.52	7.37	165.86	2.52	7.37	165.86	0.173%	0.63
3.00	8.35	164.32	2.99	8.35	164.24	2.99	8.35	164.24	0.153%	0.56
3.37	9.46	162.52	3.36	9.46	162.34	3.36	9.46	162.29	0.010%	0.04
4.18	10.71	161.83	4.18	10.71	161.59	4.18	10.71	161.59	0.005%	0.02
0.41	3.08	209.18	0.41	3.08	208.80	0.41	3.08	208.80	0.480%	1.75
0.68	3.95	208.81	0.68	3.95	208.67	0.70	3.95	206.03	1.652%	6.03
1.04	5.07	203.02	1.04	5.07	203.24	1.04	5.07	203.24	1.054%	3.85
1.41	5.74	199.63	1.41	5.74	199.47	1.41	5.74	199.47	0.247%	0.90
1.63	5.74	195.85	1.63	5.74	196.04	1.63	5.74	196.04	0.054%	0.20
2.02	6.50	193.37	2.02	6.50	193.49	2.02	6.50	193.49	0.010%	0.04
2.42	7.37	191.18	2.41	7.37	191.36	2.41	7.37	191.36	0.020%	0.07
3.70	9.46	182.10	3.69	9.46	182.26	3.71	9.46	182.31	0.005%	0.02

Table A2.4: Nearshore wave climate at point HH1

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Dur (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.39	2.71	60.76	0.39	2.71	64.27	0.37	2.71	64.33	2.835%	10.35
0.65	3.48	66.03	0.65	3.48	66.08	0.64	3.48	71.10	11.986%	43.75
1.00	3.95	71.96	1.00	3.95	72.07	0.98	3.95	72.88	13.030%	47.56
1.37	5.74	77.46	1.36	5.74	78.43	1.34	5.07	79.56	8.068%	29.45
1.55	6.50	78.46	1.56	6.50	79.37	1.53	5.74	80.27	4.625%	16.88
1.95	7.37	82.40	1.94	7.37	83.71	1.92	7.37	84.51	1.613%	5.89
2.35	7.37	85.14	2.34	8.35	86.80	2.31	8.35	87.19	0.732%	2.67
2.74	8.35	88.10	2.73	8.35	89.12	2.71	8.35	89.60	0.109%	0.40
3.34	9.46	97.02	3.38	9.46	96.72	3.31	9.46	98.18	0.03%	0.11
3.72	10.71	98.29	3.73	10.71	98.76	3.73	10.71	99.38	0.010%	0.04
0.42	3.48	97.20	0.43	3.08	95.12	0.43	3.08	96.61	2.216%	8.09
0.76	3.95	98.10	0.76	3.95	98.45	0.74	3.95	101.12	6.841%	24.97
1.18	5.07	101.43	1.18	5.07	101.77	1.18	5.07	102.15	2.567%	9.37
1.67	6.50	104.23	1.67	6.50	104.28	1.66	6.50	104.74	0.717%	2.62
1.95	6.50	105.44	1.95	6.50	105.23	1.95	6.50	105.72	0.148%	0.54
2.50	7.37	107.91	2.51	7.37	108.07	2.50	7.37	108.42	0.099%	0.36
3.04	8.35	110.48	3.04	8.35	110.60	3.05	8.35	110.84	0.030%	0.11
4.33	10.71	114.50	4.34	10.71	114.66	4.34	12.14	114.97	0.005%	0.02
0.45	3.08	134.89	0.46	3.48	134.93	0.45	3.48	135.38	1.756%	6.41
0.78	3.95	135.68	0.78	3.95	135.93	0.81	3.95	136.67	5.085%	18.56
1.25	5.07	136.79	1.25	5.07	136.84	1.25	5.07	137.05	1.385%	5.06
1.82	6.50	136.90	1.82	6.50	136.84	1.82	6.50	136.84	0.317%	1.16
2.11	6.50	137.27	2.11	6.50	137.15	2.11	6.50	137.17	0.450%	1.64
2.72	7.37	137.27	2.72	7.37	137.26	2.72	7.37	137.31	0.124%	0.45
3.28	8.35	137.83	3.28	8.35	137.79	3.27	8.35	137.86	0.020%	0.07
4.32	10.71	137.96	4.33	10.71	138.16	4.33	10.71	138.17	0.02%	0.07
4.42	10.71	138.47	4.43	10.71	138.42	4.43	10.71	138.40	0.015%	0.05
0.45	3.08	175.55	0.45	3.08	175.41	0.45	3.08	175.44	1.499%	5.47
0.79	3.95	174.00	0.79	3.95	174.17	0.80	3.95	173.53	7.905%	28.85
1.22	5.07	170.86	1.22	5.07	170.75	1.22	5.07	170.76	9.013%	32.90
1.74	6.50	168.33	1.74	6.50	168.38	1.74	6.50	168.37	4.091%	14.93
2.01	6.50	167.29	2.01	6.50	167.39	2.01	6.50	167.38	1.093%	3.99
2.54	7.37	165.15	2.54	7.37	165.25	2.54	7.37	165.26	0.173%	0.63
3.01	8.35	163.51	3.01	8.35	163.42	3.01	8.35	163.42	0.153%	0.56
3.35	9.46	161.95	3.35	9.46	161.67	3.35	9.46	161.67	0.010%	0.04
4.32	10.71	160.68	4.34	10.71	160.39	4.34	10.71	160.39	0.005%	0.02
0.41	3.08	209.32	0.41	3.08	209.05	0.41	3.08	209.05	0.480%	1.75
0.68	3.95	208.41	0.68	3.95	208.70	0.70	3.95	206.08	1.652%	6.03
1.04	4.47	203.07	1.04	4.47	203.34	1.04	4.47	203.34	1.054%	3.85
1.42	5.74	199.69	1.42	5.74	199.59	1.42	5.74	199.59	0.247%	0.90
1.64	5.74	195.80	1.64	5.74	196.02	1.64	5.74	196.02	0.054%	0.20
2.02	6.50	193.29	2.02	6.50	193.45	2.02	6.50	193.45	0.010%	0.04
2.42	7.37	191.27	2.41	7.37	191.41	2.41	7.37	191.41	0.020%	0.07
3.75	9.46	180.78	3.69	9.46	180.56	3.72	9.46	180.70	0.005%	0.02

Table A2.5: Nearshore wave climate at point HH2

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Dur (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.39	3.08	60.76	0.40	2.71	63.48	0.38	2.71	63.35	2.835%	10.35
0.67	3.95	65.24	0.66	3.48	66.34	0.66	3.95	70.02	11.986%	43.75
1.03	3.95	71.19	1.02	3.95	71.18	1.01	3.95	72.09	13.030%	47.56
1.41	5.74	76.48	1.40	5.74	77.22	1.38	5.07	78.21	8.068%	29.45
1.60	6.50	77.46	1.60	6.50	78.26	1.58	5.74	79.23	4.625%	16.88
2.01	7.37	81.29	2.00	7.37	82.31	1.98	7.37	82.91	1.613%	5.89
2.42	7.37	84.03	2.41	8.35	85.29	2.38	8.35	85.74	0.732%	2.67
2.82	8.35	86.97	2.81	8.35	87.75	2.80	8.35	88.09	0.109%	0.40
3.53	9.46	93.21	3.54	9.46	93.48	3.54	9.46	93.51	0.03%	0.11
3.86	10.71	97.00	3.87	10.71	97.38	3.84	10.71	98.14	0.010%	0.04
0.43	3.48	96.40	0.44	3.08	94.57	0.43	3.08	95.96	2.216%	8.09
0.77	3.95	97.51	0.77	3.95	97.70	0.76	3.95	100.01	6.841%	24.97
1.20	5.07	100.60	1.21	5.07	100.66	1.20	5.07	101.25	2.567%	9.37
1.70	6.50	103.02	1.70	6.50	103.06	1.69	6.50	103.53	0.717%	2.62
1.98	6.50	104.10	1.99	6.50	104.06	1.98	6.50	104.33	0.148%	0.54
2.55	7.37	106.63	2.55	7.37	106.72	2.54	7.37	106.88	0.099%	0.36
3.09	8.35	109.01	3.09	8.35	109.13	3.09	8.35	109.39	0.030%	0.11
4.53	12.14	113.05	4.53	12.14	113.02	4.53	12.14	113.33	0.005%	0.02
0.45	3.08	134.34	0.46	3.48	134.67	0.46	3.48	134.83	1.756%	6.41
0.79	3.95	135.53	0.78	3.95	135.58	0.82	3.95	136.41	5.085%	18.56
1.26	5.07	136.28	1.27	5.07	136.22	1.27	5.07	136.46	1.385%	5.06
1.83	6.50	135.99	1.83	6.50	136.01	1.83	6.50	136.05	0.317%	1.16
2.12	6.50	136.63	2.12	6.50	136.50	2.12	6.50	136.51	0.450%	1.64
2.74	7.37	136.51	2.74	7.37	136.46	2.74	7.37	136.55	0.124%	0.45
3.31	8.35	136.80	3.30	8.35	136.73	3.30	8.35	136.79	0.020%	0.07
4.51	10.71	136.94	4.50	10.71	136.91	4.50	10.71	136.91	0.02%	0.07
4.65	10.71	137.17	4.64	10.71	137.16	4.64	10.71	137.15	0.015%	0.05
0.45	3.08	175.17	0.45	3.08	175.34	0.45	3.08	175.14	1.499%	5.47
0.79	3.95	173.81	0.79	3.95	173.84	0.80	3.95	173.21	7.905%	28.85
1.22	5.07	170.42	1.22	5.07	170.38	1.22	5.07	170.37	9.013%	32.90
1.75	6.50	167.97	1.74	6.50	167.92	1.74	6.50	167.91	4.091%	14.93
2.02	6.50	166.72	2.01	6.50	166.80	2.01	6.50	166.80	1.093%	3.99
2.55	7.37	164.45	2.55	7.37	164.50	2.55	7.37	164.51	0.173%	0.63
3.02	8.35	162.63	3.02	8.35	162.72	3.02	8.35	162.72	0.153%	0.56
3.53	9.46	161.59	3.53	9.46	161.63	3.53	9.46	161.63	0.010%	0.04
4.52	10.71	159.05	4.52	10.71	158.65	4.52	10.71	158.65	0.005%	0.02
0.41	3.08	209.20	0.41	3.08	208.87	0.41	3.08	208.87	0.480%	1.75
0.68	3.95	208.49	0.68	3.95	208.67	0.70	3.95	205.99	1.652%	6.03
1.04	4.47	203.39	1.04	4.47	203.21	1.04	4.47	203.21	1.054%	3.85
1.42	5.74	199.69	1.42	5.74	199.54	1.42	5.74	199.54	0.247%	0.90
1.63	5.74	195.75	1.63	5.74	195.92	1.63	5.74	195.92	0.054%	0.20
2.02	6.50	193.34	2.02	6.50	193.50	2.02	6.50	193.50	0.010%	0.04
2.40	7.37	191.42	2.40	7.37	191.62	2.40	7.37	191.62	0.020%	0.07
3.74	9.46	179.42	3.72	9.46	179.35	3.76	9.46	179.54	0.005%	0.02

Table A2.6: Nearshore wave climate at point HH3

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Dur (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.39	3.08	60.76	0.40	2.71	62.84	0.38	2.71	62.65	2.835%	10.35
0.68	3.95	65.17	0.67	3.48	65.79	0.68	3.95	68.81	11.986%	43.75
1.04	4.47	70.60	1.04	4.47	70.67	1.03	4.47	71.42	13.030%	47.56
1.43	5.74	75.65	1.43	5.74	76.16	1.40	5.07	76.74	8.068%	29.45
1.63	6.50	76.74	1.63	6.50	77.21	1.62	5.74	78.13	4.625%	16.88
2.05	7.37	80.34	2.04	7.37	81.16	2.02	7.37	81.74	1.613%	5.89
2.46	7.37	83.18	2.45	8.35	84.12	2.43	8.35	84.62	0.732%	2.67
2.87	8.35	86.10	2.87	8.35	86.59	2.85	8.35	87.03	0.109%	0.40
3.60	9.46	91.51	3.56	9.46	92.40	3.56	9.46	92.58	0.03%	0.11
3.94	10.71	95.55	3.93	10.71	96.35	3.93	10.71	96.44	0.010%	0.04
0.43	3.48	96.13	0.44	3.08	94.37	0.43	3.08	94.80	2.216%	8.09
0.78	3.95	96.97	0.77	3.95	97.06	0.77	3.95	98.99	6.841%	24.97
1.21	5.07	99.97	1.22	5.07	99.86	1.21	5.07	100.41	2.567%	9.37
1.71	6.50	102.13	1.71	6.50	102.13	1.70	6.50	102.54	0.717%	2.62
2.00	6.50	102.93	2.00	6.50	102.95	2.00	6.50	103.18	0.148%	0.54
2.56	7.37	105.35	2.56	7.37	105.40	2.56	7.37	105.58	0.099%	0.36
3.09	8.35	107.59	3.10	8.35	107.64	3.10	8.35	107.74	0.030%	0.11
4.58	10.71	111.50	4.58	12.14	111.36	4.58	12.14	111.79	0.005%	0.02
0.45	3.08	134.16	0.46	3.48	134.58	0.46	3.48	134.86	1.756%	6.41
0.79	3.95	135.45	0.79	3.95	135.34	0.82	3.95	136.26	5.085%	18.56
1.27	5.07	135.69	1.27	5.07	135.72	1.27	5.07	135.84	1.385%	5.06
1.83	6.50	135.22	1.83	6.50	135.30	1.83	6.50	135.30	0.317%	1.16
2.12	6.50	136.02	2.12	6.50	135.95	2.12	6.50	136.01	0.450%	1.64
2.73	7.37	135.53	2.73	7.37	135.48	2.73	7.37	135.62	0.124%	0.45
3.30	8.35	135.74	3.30	8.35	135.75	3.30	8.35	135.78	0.020%	0.07
4.54	10.71	135.99	4.54	10.71	135.75	4.54	10.71	135.74	0.02%	0.07
4.70	10.71	135.69	4.69	10.71	135.75	4.69	10.71	135.76	0.015%	0.05
0.45	3.08	174.98	0.45	3.08	175.01	0.45	3.08	174.83	1.499%	5.47
0.79	3.95	173.46	0.79	3.95	173.71	0.80	3.95	172.93	7.905%	28.85
1.22	5.07	169.71	1.22	5.07	169.88	1.22	5.07	169.86	9.013%	32.90
1.74	5.74	167.30	1.74	5.74	167.34	1.74	5.74	167.34	4.091%	14.93
2.01	6.50	166.04	2.01	6.50	166.15	2.01	6.50	166.15	1.093%	3.99
2.53	7.37	163.65	2.53	7.37	163.76	2.53	7.37	163.76	0.173%	0.63
3.01	8.35	161.72	3.01	8.35	161.86	3.01	8.35	161.86	0.153%	0.56
3.54	9.46	160.18	3.53	9.46	160.27	3.53	9.46	160.27	0.010%	0.04
4.55	10.71	157.54	4.55	10.71	157.03	4.55	10.71	157.03	0.005%	0.02
0.41	3.08	209.33	0.41	3.08	208.99	0.41	3.08	208.99	0.480%	1.75
0.68	3.95	208.46	0.68	3.95	208.50	0.70	3.95	205.90	1.652%	6.03
1.03	4.47	203.48	1.03	4.47	203.37	1.03	4.47	203.37	1.054%	3.85
1.40	5.74	199.44	1.40	5.74	199.31	1.40	5.74	199.31	0.247%	0.90
1.62	5.74	195.65	1.62	5.74	195.84	1.62	5.74	195.84	0.054%	0.20
1.99	6.50	193.30	2.00	6.50	193.44	2.00	6.50	193.44	0.010%	0.04
2.37	7.37	191.29	2.37	7.37	191.38	2.37	7.37	191.38	0.020%	0.07
3.61	9.46	176.90	3.63	9.46	177.98	3.67	9.46	178.09	0.005%	0.02

Table A2.7: Nearshore wave climate at point HH4

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Dur (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.40	3.08	59.84	0.40	2.71	61.63	0.39	2.71	62.27	2.835%	10.35
0.69	3.95	64.15	0.69	3.48	64.78	0.69	3.95	67.59	11.986%	43.75
1.07	5.07	69.43	1.07	4.47	69.28	1.06	4.47	70.38	13.030%	47.56
1.48	5.74	74.01	1.47	5.74	74.61	1.45	5.74	74.97	8.068%	29.45
1.68	6.50	75.35	1.68	6.50	75.72	1.67	6.50	76.45	4.625%	16.88
2.12	7.37	78.54	2.11	7.37	79.20	2.10	7.37	79.74	1.613%	5.89
2.54	8.35	81.17	2.54	8.35	81.80	2.52	8.35	82.22	0.732%	2.67
2.96	8.35	83.94	2.96	8.35	84.30	2.95	8.35	84.69	0.109%	0.40
3.68	9.46	89.00	3.61	9.46	90.74	3.69	9.46	89.75	0.03%	0.11
4.10	10.71	91.79	4.10	10.71	92.27	4.09	10.71	92.84	0.010%	0.04
0.43	3.48	95.56	0.44	3.08	93.34	0.43	3.08	94.33	2.216%	8.09
0.79	3.95	96.30	0.79	3.95	96.28	0.78	3.95	97.94	6.841%	24.97
1.23	5.07	98.80	1.24	5.07	98.78	1.23	5.07	99.27	2.567%	9.37
1.74	6.50	100.49	1.74	6.50	100.54	1.74	6.50	100.70	0.717%	2.62
2.03	6.50	101.14	2.03	6.50	101.16	2.02	6.50	101.34	0.148%	0.54
2.60	7.37	103.26	2.61	7.37	103.23	2.61	7.37	103.34	0.099%	0.36
3.15	8.35	105.24	3.15	8.35	105.24	3.15	8.35	105.38	0.030%	0.11
4.76	10.71	108.98	4.76	10.71	109.02	4.76	10.71	109.33	0.005%	0.02
0.45	3.08	133.46	0.45	3.48	134.27	0.45	3.48	134.86	1.756%	6.41
0.79	3.95	135.47	0.79	3.95	135.41	0.83	3.95	136.47	5.085%	18.56
1.28	5.07	134.99	1.28	5.07	135.08	1.28	5.07	135.16	1.385%	5.06
1.84	6.50	134.46	1.84	6.50	134.53	1.84	6.50	134.58	0.317%	1.16
2.13	6.50	134.93	2.13	6.50	134.94	2.13	6.50	135.01	0.450%	1.64
2.75	7.37	134.40	2.75	7.37	134.39	2.75	7.37	134.44	0.124%	0.45
3.33	8.35	134.50	3.33	8.35	134.53	3.33	8.35	134.51	0.020%	0.07
4.65	10.71	134.42	4.66	10.71	134.32	4.66	10.71	134.22	0.02%	0.07
4.91	10.71	133.88	4.89	10.71	133.87	4.89	10.71	133.96	0.015%	0.05
0.45	3.08	175.41	0.44	3.08	175.33	0.44	3.08	175.28	1.499%	5.47
0.78	3.95	173.65	0.78	3.95	173.85	0.80	3.95	173.21	7.905%	28.85
1.23	5.07	169.68	1.23	5.07	169.75	1.23	5.07	169.75	9.013%	32.90
1.75	5.74	167.03	1.75	5.74	167.13	1.75	5.74	167.14	4.091%	14.93
2.01	6.50	166.01	2.01	6.50	166.03	2.01	6.50	166.04	1.093%	3.99
2.54	7.37	163.48	2.54	7.37	163.55	2.54	7.37	163.55	0.173%	0.63
3.03	8.35	161.58	3.03	8.35	161.59	3.03	8.35	161.59	0.153%	0.56
3.55	8.35	159.98	3.55	8.35	160.03	3.55	8.35	160.03	0.010%	0.04
4.65	10.71	156.38	4.68	10.71	156.23	4.68	10.71	156.23	0.005%	0.02
0.41	3.08	209.74	0.41	3.08	209.65	0.41	3.08	209.65	0.480%	1.75
0.68	3.95	208.70	0.68	3.95	208.83	0.70	3.95	206.61	1.652%	6.03
1.03	4.47	204.23	1.03	4.47	204.23	1.03	4.47	204.23	1.054%	3.85
1.41	5.74	200.20	1.41	5.74	200.01	1.41	5.74	200.01	0.247%	0.90
1.63	5.74	196.35	1.62	5.74	196.62	1.62	5.74	196.62	0.054%	0.20
2.00	6.50	194.05	2.01	6.50	194.27	2.01	6.50	194.27	0.010%	0.04
2.38	7.37	192.18	2.39	7.37	192.35	2.39	7.37	192.35	0.020%	0.07
3.65	8.35	178.72	3.62	8.35	178.94	3.65	8.35	179.35	0.005%	0.02

Table A2.8: Nearshore wave climate at point NH1

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Dur (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.39	3.08	59.89	0.40	2.71	61.63	0.40	3.08	62.10	2.835%	10.35
0.69	3.95	63.89	0.69	3.48	64.57	0.70	3.95	67.09	11.986%	43.75
1.07	5.07	69.13	1.07	5.07	69.19	1.07	4.47	69.57	13.030%	47.56
1.48	5.74	73.92	1.48	5.74	74.14	1.45	5.74	74.36	8.068%	29.45
1.68	6.50	75.62	1.68	6.50	75.65	1.68	6.50	75.96	4.625%	16.88
2.12	7.37	78.84	2.13	7.37	79.24	2.11	7.37	79.55	1.613%	5.89
2.54	8.35	81.75	2.55	8.35	81.94	2.53	8.35	82.25	0.732%	2.67
2.94	8.35	84.80	2.95	8.35	84.79	2.95	8.35	84.98	0.109%	0.40
3.62	9.46	90.44	3.58	9.46	90.91	3.57	9.46	91.17	0.03%	0.11
3.98	10.71	90.89	3.98	10.71	91.44	3.97	10.71	91.79	0.010%	0.04
0.43	3.48	94.94	0.44	3.08	93.14	0.44	3.08	93.72	2.216%	8.09
0.79	3.95	96.25	0.78	3.95	95.92	0.78	3.95	97.21	6.841%	24.97
1.22	5.07	98.32	1.23	5.07	98.13	1.23	5.07	98.43	2.567%	9.37
1.73	6.50	100.08	1.73	6.50	100.02	1.73	6.50	100.26	0.717%	2.62
2.02	6.50	100.67	2.02	6.50	100.51	2.01	6.50	100.90	0.148%	0.54
2.59	7.37	102.99	2.60	7.37	102.88	2.59	7.37	103.03	0.099%	0.36
3.12	8.35	104.74	3.13	8.35	104.63	3.12	8.35	104.72	0.030%	0.11
4.43	10.71	107.67	4.44	10.71	107.75	4.44	10.71	107.84	0.005%	0.02
0.44	3.08	132.66	0.45	3.48	134.48	0.45	3.48	134.79	1.756%	6.41
0.79	3.95	135.16	0.79	3.95	135.09	0.82	3.95	136.32	5.085%	18.56
1.26	5.07	134.06	1.26	5.07	134.18	1.26	5.07	133.96	1.385%	5.06
1.81	6.50	133.73	1.81	6.50	133.67	1.81	6.50	133.76	0.317%	1.16
2.10	6.50	133.64	2.10	6.50	133.58	2.10	6.50	133.64	0.450%	1.64
2.70	7.37	133.00	2.70	7.37	132.94	2.70	7.37	132.93	0.124%	0.45
3.26	8.35	132.65	3.26	8.35	132.56	3.26	8.35	132.57	0.020%	0.07
4.36	10.71	132.00	4.36	10.71	131.72	4.36	10.71	131.69	0.02%	0.07
4.50	12.14	131.59	4.50	12.14	131.45	4.50	12.14	131.36	0.015%	0.05
0.44	3.08	175.59	0.44	3.08	175.77	0.44	3.08	175.82	1.499%	5.47
0.77	3.95	173.10	0.77	3.95	173.49	0.78	3.95	172.96	7.905%	28.85
1.20	5.07	168.78	1.20	5.07	168.88	1.20	5.07	168.89	9.013%	32.90
1.70	5.74	165.81	1.70	5.74	165.87	1.70	5.74	165.87	4.091%	14.93
1.95	6.50	164.63	1.95	6.50	164.74	1.95	6.50	164.74	1.093%	3.99
2.46	7.37	161.93	2.45	7.37	161.84	2.45	7.37	161.85	0.173%	0.63
2.92	8.35	159.79	2.93	8.35	159.97	2.93	8.35	159.97	0.153%	0.56
3.34	8.35	156.73	3.39	8.35	158.11	3.39	8.35	158.11	0.010%	0.04
4.31	10.71	155.43	4.34	10.71	154.99	4.34	10.71	154.99	0.005%	0.02
0.41	3.08	209.51	0.41	3.08	209.63	0.41	3.08	209.63	0.480%	1.75
0.67	3.95	209.36	0.67	3.48	209.09	0.68	3.95	207.13	1.652%	6.03
1.00	4.47	204.45	1.01	4.47	203.95	1.01	4.47	204.64	1.054%	3.85
1.36	5.07	200.00	1.37	5.07	200.27	1.37	5.07	200.27	0.247%	0.90
1.56	5.74	195.85	1.57	5.74	196.05	1.57	5.74	196.05	0.054%	0.20
1.93	6.50	193.27	1.94	6.50	193.48	1.94	6.50	193.48	0.010%	0.04
2.30	7.37	190.94	2.31	6.50	191.13	2.31	6.50	191.13	0.020%	0.07
3.53	8.35	176.51	3.47	8.35	175.82	3.52	8.35	176.28	0.005%	0.02

Table A2.9: Nearshore wave climate at point NH2

Ba Lat 1			Ba Lat 2			Ba Lat 3			P (%)	Duration (days)
Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)	Hs (m)	Tp (s)	Dir (dg. N)		
0.41	3.08	56.77	0.42	3.08	58.51	0.41	3.08	59.25	2.835%	10.35
0.71	3.95	60.61	0.72	3.95	60.88	0.73	3.95	63.90	11.986%	43.75
1.11	5.07	65.36	1.12	5.07	65.13	1.11	4.47	65.44	13.030%	47.56
1.54	5.74	69.72	1.54	5.74	69.40	1.54	5.74	69.81	8.068%	29.45
1.76	6.50	70.97	1.77	6.50	70.99	1.76	6.50	70.98	4.625%	16.88
2.22	7.37	74.00	2.24	7.37	73.90	2.23	7.37	73.98	1.613%	5.89
2.65	8.35	76.08	2.66	8.35	76.19	2.66	8.35	76.26	0.732%	2.67
3.07	9.46	79.01	3.09	9.46	78.92	3.09	9.46	78.95	0.109%	0.40
3.66	10.71	82.93	3.73	10.71	83.05	3.72	10.71	83.31	0.03%	0.11
3.87	10.71	81.75	3.96	10.71	82.18	3.96	10.71	82.21	0.010%	0.04
0.44	3.48	93.22	0.44	3.08	92.40	0.44	3.08	92.05	2.216%	8.09
0.79	3.95	94.42	0.79	3.95	94.14	0.80	3.95	94.00	6.841%	24.97
1.23	5.07	94.91	1.24	5.07	94.45	1.24	5.07	94.74	2.567%	9.37
1.76	6.50	95.76	1.76	6.50	96.01	1.76	6.50	96.28	0.717%	2.62
2.04	6.50	96.58	2.04	6.50	96.74	2.05	6.50	96.63	0.148%	0.54
2.62	7.37	98.29	2.63	7.37	98.30	2.63	7.37	98.25	0.099%	0.36
3.11	8.35	99.62	3.18	8.35	99.36	3.18	8.35	99.47	0.030%	0.11
4.04	10.71	100.85	4.15	10.71	101.30	4.15	10.71	101.37	0.005%	0.02
0.44	3.08	132.71	0.45	3.48	134.06	0.45	3.48	134.02	1.756%	6.41
0.78	3.95	135.74	0.79	3.95	135.65	0.82	3.95	136.38	5.085%	18.56
1.25	5.07	133.40	1.25	5.07	133.48	1.25	5.07	133.64	1.385%	5.06
1.80	6.50	133.09	1.81	6.50	133.19	1.81	6.50	133.20	0.317%	1.16
2.09	6.50	132.72	2.10	6.50	132.91	2.10	6.50	132.94	0.450%	1.64
2.70	7.37	132.13	2.72	7.37	132.33	2.72	7.37	132.37	0.124%	0.45
3.23	8.35	130.76	3.22	8.35	130.79	3.22	8.35	130.79	0.020%	0.07
4.03	10.71	130.33	4.15	10.71	130.74	4.15	10.71	130.74	0.02%	0.07
4.08	10.71	129.82	4.18	10.71	130.27	4.18	10.71	130.27	0.015%	0.05
0.44	3.08	177.10	0.44	3.08	176.01	0.44	3.08	175.99	1.499%	5.47
0.76	3.95	174.49	0.77	3.95	174.58	0.78	3.95	174.27	7.905%	28.85
1.19	5.07	170.95	1.20	5.07	171.05	1.20	5.07	171.05	9.013%	32.90
1.70	5.74	168.19	1.70	5.74	168.33	1.70	5.74	168.33	4.091%	14.93
1.93	6.50	167.18	1.94	6.50	167.19	1.94	6.50	167.19	1.093%	3.99
2.43	7.37	164.78	2.45	7.37	164.75	2.45	7.37	164.75	0.173%	0.63
2.90	8.35	163.00	2.94	8.35	163.02	2.94	8.35	163.02	0.153%	0.56
3.29	8.35	159.91	3.34	8.35	159.63	3.34	8.35	159.63	0.010%	0.04
3.99	10.71	158.51	4.11	10.71	158.38	4.11	10.71	158.38	0.005%	0.02
0.40	3.08	212.78	0.40	3.08	212.72	0.40	3.08	212.72	0.480%	1.75
0.68	3.48	213.40	0.68	3.48	213.49	0.68	3.48	211.80	1.652%	6.03
1.01	4.47	209.49	1.01	4.47	209.42	1.01	4.47	209.42	1.054%	3.85
1.38	5.07	206.04	1.38	5.07	205.81	1.38	5.07	205.81	0.247%	0.90
1.55	5.74	201.56	1.55	5.74	201.71	1.55	5.74	201.71	0.054%	0.20
1.93	5.74	199.55	1.94	5.74	199.70	1.94	5.74	199.70	0.010%	0.04
2.29	6.50	197.66	2.32	6.50	197.96	2.32	6.50	197.96	0.020%	0.07
3.50	8.35	188.02	3.48	8.35	187.60	3.51	8.35	187.99	0.005%	0.02

Annex 3
UNIBEST CL+

A3.1 INTRODUCTION

The UNIBEST software suite is an acronym of Uniform Beach Sediment Transport. It has been developed by WL| Delft Hydraulics in order to yield an integrated package with diagnostic capabilities in the study and simulation of longshore and cross-shore processes and related morphodynamics of beach profiles and beach plan form shapes (coastline evolution).

The UNIBEST software suite consists of two separate modules:

- **UNIBEST-TC**: Designed for the computation cross-shore transport and resulting beach changes induced by waves, tidal currents and wind.

UNIBEST-CL+: Designed for the simulation of coastline changes due to longshore sediment transport gradients. The longshore transports are induced by tide and wave driven longshore currents.

UNIBEST-CL+ consists of two integrated sub-modules:

- The Longshore Transport module (LT-module)
- The CoastLine module (CL-module)

The required longshore sediment transports are computed with the LT-module. These transports are used by the CL-module to perform coastline evolution simulations in which effects of structures such as groins, offshore breakwaters and revetments can be incorporated.

A3.2 LONGSHORE TRANSPORT (LT) MODULE

The LT-module is designed to compute tide- and wave-induced longshore currents and sediment transports on an alongshore-uniform beach with an arbitrary profile.

The surf zone dynamics are derived from a built-in random wave propagation and decay model, which transforms offshore wave data to the coast taking the principal processes of linear refraction and non-linear dissipation by wave breaking and bottom friction into account. The longshore sediment transports and cross-shore distribution are evaluated according to various transport formulas, which enables a sensitivity analysis for local conditions.

The computational procedure may take any pre-defined wave climate and tidal regime into account in order to enable an assessment of gross and yearly transports, seasonal variation and even storm events.

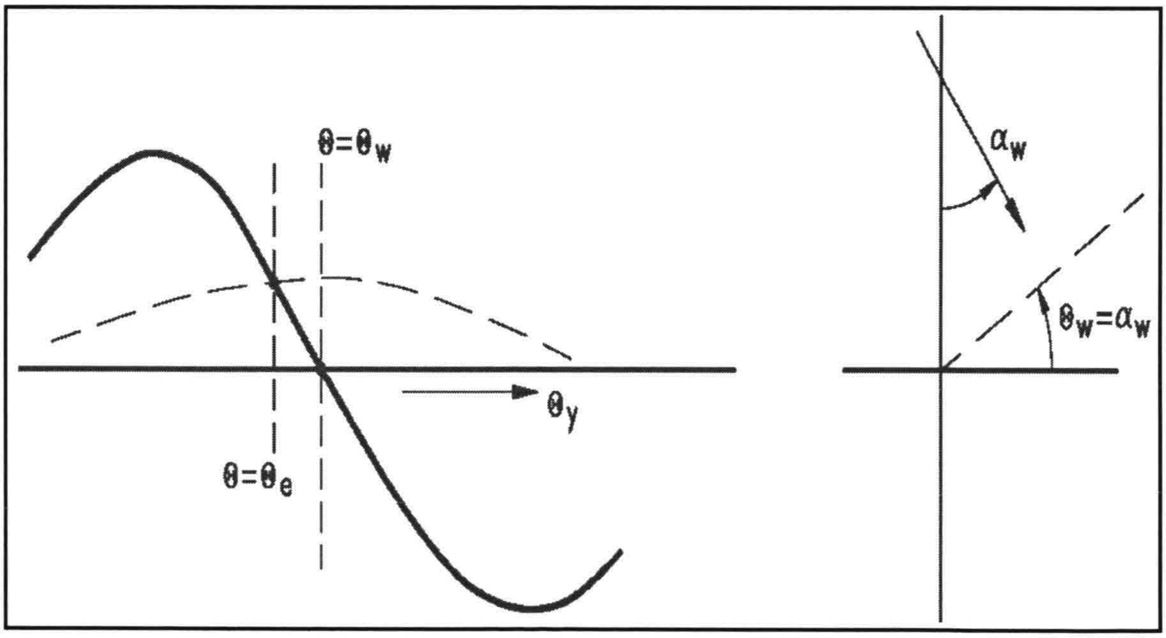


Fig. A3.1: Equilibrium angle (θ_e) is approximated by: $\theta_w + c^2_i/c^1_i$.

The input for an LT-run calculation step is:

- A wave-and-current scenario (definition wave angles with respect to the north);
- The coastal orientation angle (with respect to world co-ordinates);
- A cross section (perpendicular to coastal angle);
- A selected transport formula and the required coefficients;
- Coefficients for the energy decay calculation.

A LT-calculation runs as follows:

Making an estimate of the equilibrium angle (the rotation of the coast, where the total sediment transport $Q_s = 0$), based on a simplified method;

For a number of angles around the equilibrium angle (–60 degrees, +60 degrees) the calculation of the total transport Q_s for all wave/current combinations of the wave-and-current scenario;

By using the least-square method the function becomes (Figure A3.1):

$$Q_s(\theta)= c_1.\theta_r.\exp\{-(c_2.\theta_r)^2\}$$

Where $\theta_r = \theta - \theta_e$, with θ = the actual coast orientation and θ_e = the equilibrium angle, the coast angle for which $Q_s = 0$.

The simplified method, which is used for the estimation of the balanced angle (and of the effect of the current), is used as follows:

For each combination of wave-and-current a 'one-wave' approximation:

$$Q_s = c_{1i}\frac{90}{\pi\sin\theta_n} + c_{2i}\sqrt{\cos\theta_n}$$

is made, where:

$$\theta_n = \theta - \theta_w$$

and θ_w is the wave angle with respect to the coastal normal.

A3.3 COASTLINE (CL) MODULE

The CL-module is designed to simulate coastline changes due to longshore sediment transport gradients of an alongshore nearly uniform coast, on the basis of the single line theory. Various initial and boundary conditions may be introduced as to represent a variety of coastal situations. Along the modelled coastline sediment sources and sinks may be defined at any location, to cater for river sediment yield, subsidence, offshore sediment losses, beach mining, etc.

Furthermore, it is capable of modelling the morphologic effects of various coastal engineering measures, such as headlands, permeable and non-permeable groins, coastal revetments and seawalls, breakwaters, harbour moles, river mouth training works, artificial sand by-pass systems and beach nourishments. The effect of wave shielding (diffraction, directional wave spreading) behind coastal structures can also be incorporated in the model. The model can be used for the conceptual design (location, dimensions and spacing) of coastal structures and the impact assessment on adjacent coastal stretches.

The actual longshore transports at along the considered coastline are computed with the LT-module. This allows for a very flexible model set-up in which occurring coastal structures or natural phenomena can easily be incorporated.