COASTAL EROSION ON A DENSELY POPULATED DELTA COAST

the interactions between man and nature

a case study of Nam Dinh province, Red River delta, Vietnam

Master of Science thesis in Civil Engineering

Bas Wijdeven

October 2002

TU Delft

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Faculty of Civil Engineering and Geosciences
Section of Hydraulic Engineering

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Preface

This thesis work was done as a part of the MSc program of the Faculty of Civil Engineering, Delft University of Technology, the Netherlands and was carried out at WL| Delft Hydraulics from October 2001 to October 2002. The study included a two-month visit to Vietnam from October to December 2001, sponsored by Nedeco and the Lamminga Fund. The report is aimed at scientists, institutional managers, dike managers, engineers and other people that are interested in the background of coastal erosion in Nam Dinh province.

I would like to thank the Lamminga Fund for their financial support for travelling to Vietnam, Nedeco for supporting the working visit to Vietnam, WL | Delft Hydraulics for their support in the Netherlands and the graduation committee from TU Delft for their guidance and judgement.

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Delft, October 2002

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Summary

Introduction

This report is a result from a MSc thesis (Delft University of Technology, the Netherlands). In the framework of the VNICZM project (2000-2003), conducted by the ministry of Science and Technology of Vietnam and Nedeco (the Netherlands).
An aim of this project is the encouragement of the implementation of coastal zone management on a national and regional level. The coastal province Nam Dinh, located in the Red River delta in the north of Vietnam was chosen as study area, suffering from severe coastal erosion. Nam Dinh province had an overall-accreting coastline until the last century, fed with sediments from various river mouths from the Red River system, of which the Red River is the major supplier of sediments. However, the coast is partly eroding for more than 100 years. The coastal defences applied were developed to protect accreting beaches, reclaiming the accreted land. However, changes in the system (man- or natural made) have caused the accumulating beaches to be turned into eroding beaches. The dikes are therefore being eroded in places leading to failure and consequently, the loss of land. In these locations, the reclamation strategy switched into a retreat strategy. Because of the dense population (800-1700 inhabitants per square kilometre), the loss of land implies an increase in population pressure in the coastal areas and a decrease of the total area for agriculture, aquaculture and salt mining. In order to find the causes and proportions of the coastal erosion, an overview was created on the historical and future coastal development.
The wave climate, known as the most important marine parameter, influencing coastal processes, was modelled with WATRON (WL | Delft Hydraulics) and the UNIBEST CL package (WL | Delft Hydraulics) was used to simulate near future coastline behaviour. Mitigating measures were also proposed.

Delta development

Human intervention in the natural delta system, starting 1.000 years ago comprised the training of rivers and the reclamation of lands for cultivation of the delta. interventions have greatly influenced the development of the delta. The construction of river dikes confined the rivers, preventing the delta from flooding. The outside delta plain became more depressed over the course of time due to lifting of the riverbed and subsidence of the agricultural lands. Land reclamation caused the sea no longer faced by tidal flats combined with sparse beach ridges, but by human constructed sea dikes. The sediment output of the rivers was also confined to the river mouths leaving longshore transport as the only mechanism left to feed the coastline in between the river mouths. Deforestation in the Red River catchment areas and on the delta plain itself caused soil erosion and accelerated accretion near river mouths. In more recent times, flood control works and hydropower dams changed the discharge distribution of the Red River system and sediment was trapped in reservoirs, impacting the supply of sediments to the coast.

Nam Dinh coastal development from 1500

Because of yearly net southward-directed longshore currents, the developments of the beaches of Nam Dinh province are highly characterised by northward influences. Both the origin and morphological development of the present Red River mouth (forming the northern administrative border of Nam Dinh province) have therefore decisive influence on the development of the downdrift located eroding beaches. Probably after 1500, avulsion occurred, which caused abandoning of the So River (discharging at the northern boundary of Hai Hau district, in the middle of the province coastline) as former major river and thereafter, the developing of the present course of the Red River in a northern direction, creating a new river mouth. The developing mechanism of this mouth is characterised by a leapfrog displacement forward, enforced by temporal variability in monsoon discharge. The development of spits in longshore direction in front of the river mouth implied a cut-off for the longshore sediment. Projecting this morphological mechanism on the Red River mouth in the beginning of the century, it is clear that it created a large, sheltered sediment trap just south of it (ever recurring morphological mechanism of the Red River), cutting off the sediment supply to the beaches down drift of the So River. The diminishing supply from the So River in combination with the cut-off in sediment supply from the major supplier, the Red River caused accelerated erosion (which may have started already in the middle of the 19th century) in Hai Hau district, located south of the So River. This erosion was magnified in the period after 1955 when the So River was dammed. After 1965, when the river mouth seemed to have found stable equilibrium, having created a continuous coastline, the erosion diminished. Accelerated excessive accumulation due to deforestation and a major flood changing river mouth geometry in 1971 caused a new cycle in river mouth growth, cutting off again all sediment supply to downdrift beaches. Near the village of Van Ly, in the middle of Hai Hau district, the most severe erosion occurred in the last century. A comparison of French and Vietnamese maps proved the following historical erosion rates for Van Ly Village:

From	To	Lower boundary rate [m/year]	Upper boundary rate [m/year]
1912	1955	5.5	9.5
1955	1965	20	24
1965	1995	6	9

Erosion mainly occurs in winter, when alluvial sediment supply is very low and strong winds come from north and east directions, generating refracting waves approaching the coast at an angle of 45 degrees. Due to the extension of the Red River mouth, nearshore wave induced circulation patterns have changed, causing the Hai Hau beach tending to re-orientate from a convex into a concave form. The beaches just north of the So River mouth seem stable and there is little wave action due to the sheltering effect of the protruding Red River mouth. The longshore currents generating sediment transport have a net southward direction, induced by waves and tides. As the tide is asymmetric with periodically southward-directed ebb currents dominating the flood currents, it amplifies the southward-directed longshore transport of sediments.

Future development

In the present situation, the Red River shows an ongoing extension in seaward direction. As this river started to be confined between dikes in former times, it extended to deeper water. Had there been an absence of river dikes, confining the river, the river mouth would never have protruded into the Tonkin Gulf as it does in the present situation.
The erosion in Hai Hau may continue in the near future as long as the Red River mouth extends with its characteristic leapfrogging development at the same longitudinal location on the Red River delta coast. However, when extending more in a southward direction, possible future nourishing of the region southward and northward of the So River may be expected. Downstream of the So River, the coastline will continue in developing a concave geometry, adapting to the changing wave climate that is induced by the cyclic changing shape of the protruding Red River. However, decreases in sediment load of the Red River indicate decreasing supply of sediment to the coast, possibly increasing the duration of the river mouth cycle. If the Red River mouth partly looses its leapfrogging character, the beaches downstream will show a more steady development. Future nourishing of the eroding beaches by longshore sediment transport coming from southern directions in summer is regarded as insignificant because of observed river mouth siltation, indicating diminishing discharge and thus, sediment supply from the Ninh Co River mouth.
On basis of the WATRON wave climate computations and UNIBEST longshore transport computations, an estimate was made of the possible future trend of coastline evolution of Nam Dinh. Within the limitations of the model, the equilibrium angle north of Ninh Co River bank was estimated at about 29 degrees to north. The northern beaches of Nghia Hung district represent approximately this angle at present. However, as the wave action from northeast and eastern directions decreases when going to north, the orientation in these locations will more or less represent a direction increasing to 40 and 75 degrees orientation, being adjusted to the waves coming from southern directions. The coastline change from a more concave into a convex form may continue until an equilibrium situation will be reached. The northern part of Nam Dinh will be accreting, connecting in a smooth line with the southern spit of the Red River barrier system. As the Red River mouth seems to be relative stable the last 10 years, it is expected that the wave climate south of it will not change dramatically, influenced by the shape of the protruding river mouth. If the Red River mouth will break through its artificial created levees forming a new river course, it will drastically change the morphological system. This change may happen in arbitrary locations and at an arbitrary moment. If the river will change its course in northern direction as it did some 500 years ago, the erosion problems in Nam Dinh province will increase, whereas a change of course in a southern direction will reduce or even may stop the erosion problems south of its present river mouth.

Mitigation

Because of the uncertainty in the Red River development, dominating the coastal processes, costly defence measures on the Nam Dinh coast are not sustainable. Relocation of people according to a setback line theory in the areas being at risk, together with the relocation of people from the former So River bed (introducing an artificial change of the Red River course in favourite of rehabilitating sediment supply to the eroding beaches) could create opportunities for short term and long term solutions without the involvement of high costs. However, the social problem involved with these measures will initially be considerable, but on long term, this will change as attitude of people regarding this strategy may change.

2 Introduction

2.1 Reason for this study

In the period from 1994 to 1996, a project was conducted by consultants concerning the vulnerability of the Vietnamese coastal zone to the effects and impacts of accelerated sea level rise. In this vulnerability assessment (VA) study, three pilot studies were conducted in order to evaluate the physical, socio-economic and institutional issues faced in coastal zone management in Vietnam. Partners in this project were Marine Hydrometeorological Centre (Hydrometeorological Services, Hanoi, Vietnam), Polish Academy of Sciences (Gdansk, Poland) and a joint venture between Frederic Harris b.v. and WL| Delft Hydraulics (the Hague, the Netherlands).
A follow-up project is the Vietnam-Netherlands Integrated Coastal Zone Management Project. The Integrated Coastal Zone Management Project is a 3-year project (Sept. 2000-Aug. 2003) aimed at establishing a longer term Vietnam Integrated Coastal Zone Management Programme. It is focused on the goal of advising the Vietnamese Government in the planning and development of the Vietnamese coastal zone, its communities and its resources in a sustainable way (NEDECO, 2000). Partners in this project are the Ministry of Science and Technology (MOSTE, Vietnam) and Nedeco, a consortium of consultants from The Netherlands comprising Royal Haskoning, DHV Consultants and WL| Delft Hydraulics.
Within this follow-up project a MSc thesis research subject was formulated concerning coastal erosion and related coastal defence problems in Nam Dinh province, located in the Red River Delta, in the north of Vietnam. Nam Dinh province was the subject of one of the pilot studies conducted during the 1994-1996 VA study.

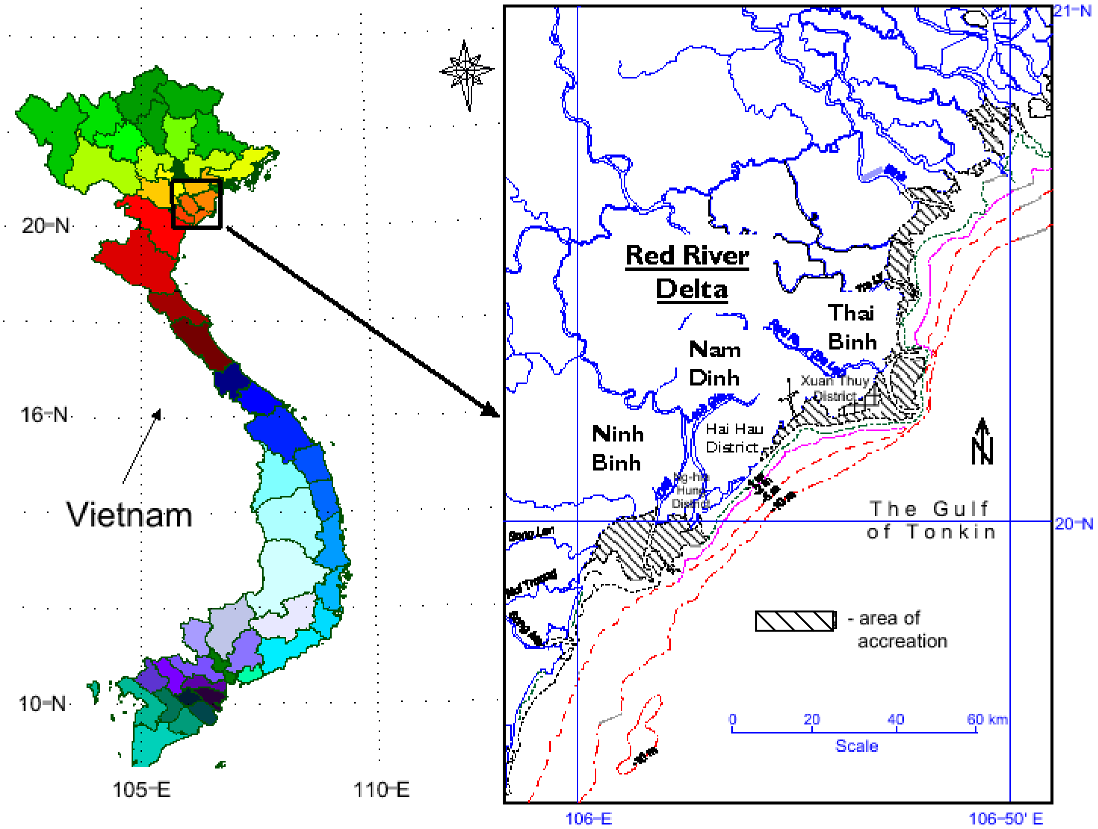


Fig 1.1. Study area (Pruszak et al, 2002).

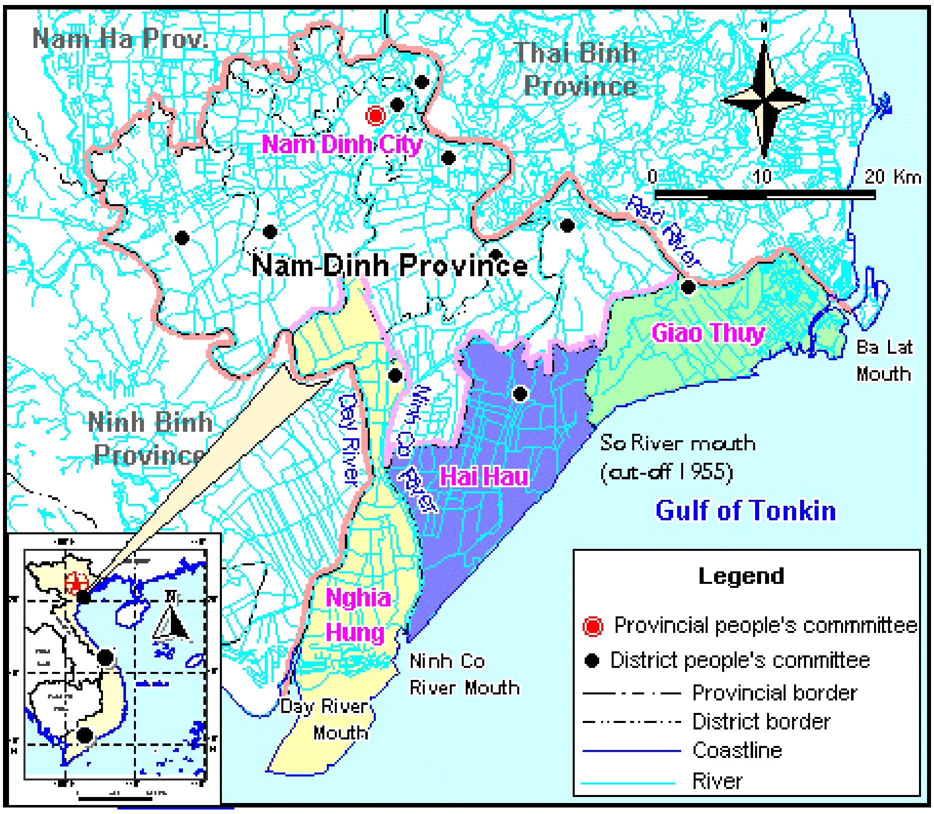


Fig 1.2. Map of Nam Dinh province (VNICZM project, Hanoi).

2.2 Study area description: Nam Dinh, Red River delta, Vietnam

The Red River delta (fig. 1.1) is located in the north of Vietnam and is the second largest delta in Vietnam. Its delta coastline measures 160 km in a straight line and is interrupted by 6 active and one in-active river mouths. From north to south, the Red River delta coastline forms the seaward border of five provinces: Quang Ninh, Hai Phong, Thai Binh, Nam Dinh (study area) and Ninh Binh.

Nam Dinh province (fig. 1.2) lies in between Thai Binh and Ninh Binh provinces and has three coastal districts, Giao Thuy, Hai Hau and Nghia Hung. The province is bordered northeast by the Red River, northwest by the Nam Dinh River, southwest by the Day River and southeast by the coastline. The border between Giao Thuy District and Hai Hau district is formed by the former So River, which was cut-off in 1955 by construction of a discharge sluice upstream. The total coastline measures 70 km, divided into three sections according to table 1.1 and fig. 1.2. Because of the fertility of the alluvial soil, Nam Dinh province is one of the densest populated areas of the Red River delta. The main sources of income are agriculture (rice), fisheries, aquaculture, salt mining and tourism. Human settlement is concentrated in communes, with population densities varying from 800 to 1700 inhabitants per square kilometre.

Table 1.1. Coastline sections (from north to south).

	Coastline length
Ba Lat estuary (Red River)	
Red River – So River	27 km
Ha Lan estuary (So River)	
So River – Ninh Co River	27 km
Lach Giang estuary (Ninh Co River)	
Ninh Co River- Day River	16 km
Total	70 km
The So River is considered as having a dead estuary so the distance from Ba Lat estuary to Lach Giang estuary is 54 km.	

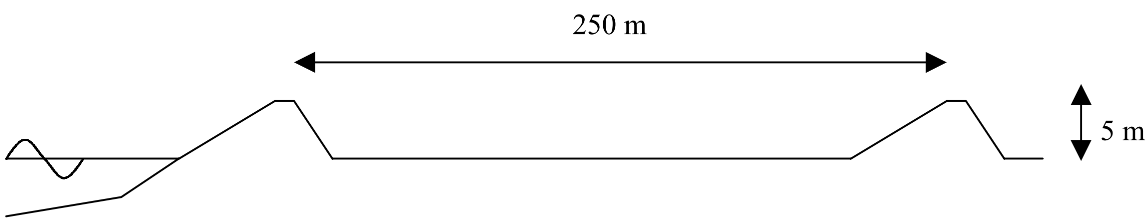


Fig. 1.3. Cross section of dike defences in Nam Dinh.

Fig. 1.4. Church of Hai Thrieu village, Hai Hau district, Nam Dinh province. The first dike was broken late 1999 and the land between the first dike and the second dike was abandoned.

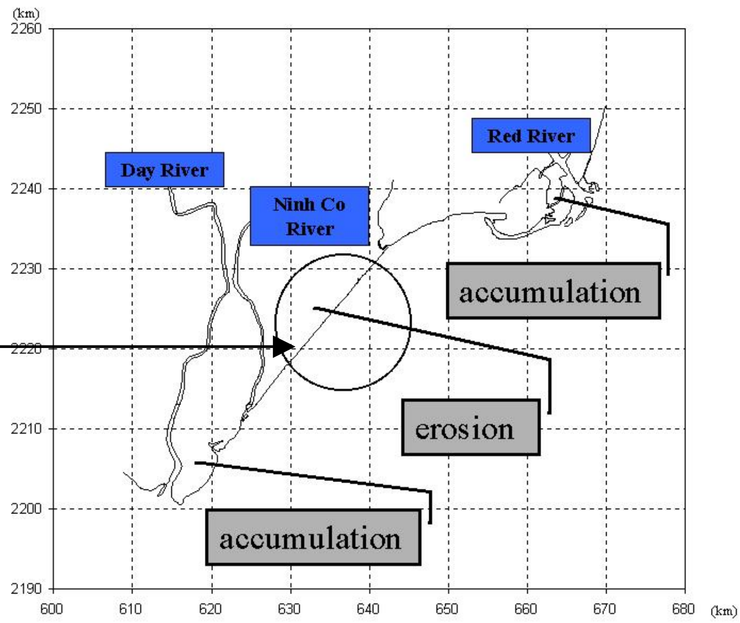


Fig. 1.5. Location of erosion and accumulation in Nam Dinh.

2.3 Problem analysis

2.3.1 Introduction

In general, the Red River delta coastlines show temporal dynamic behaviour. However, the coastline of Nam Dinh shows structural erosion in places. The dynamic coastal behaviour is characterised by the following phenomena: Near river mouths at the northern and southern provincial boundaries accretion takes place, creating tidal flats, beach ridges and spits. In between the river mouths, structural erosion takes place, which is reported to be continuing already for more than 100 years (fig. 1.5). Because of the dense population, the loss of land implies an increase in population pressure in the coastal communes and a decrease of the total area of land for agriculture, aquaculture and salt mining.

2.3.2 Coastal defence problems in Nam Dinh

In the present situation, the local authorities try to fixate the eroding coastline by means of dike defence. The coastal defence comprises two parallel dikes with a distance of 250 m in between (fig. 1.3). The idea behind this is to withstand attacks by heavy storms and typhoons. To prevent inundation, a second dike is build behind the first dike. During typhoon and storm attacks, which seldom last longer than six hours, the first dike is usually capable of withstanding the wave attack. However, after some hours of severe storm parts of the dike may fail which results in inundation of the area in between the two dikes. The land in between the dikes is considered as lost and a new dike will be built behind the former second dike.
The funds and knowledge needed for the construction of one single dike that is strong enough to withstand attacks from the sea was never sufficient. A five-year project (1995-2000) with a budget over 10.3 million USD, funded by the French government, upgraded dike sections in Nam Dinh province with a total length of 50 km (fig. 1.5). Some dike sections were upgraded, provided with a revetment. However, these upgraded sections have not been seriously attacked in the period from the end of construction up until now and thus there is no experience in the reliability of these dikes. Despite upgrading of the dikes in places, still some dike sections consist of poorly constructed dikes. A poignant example is the Hai Hau district, one of the three coastal districts of Nam Dinh province, with 700 households (3200 people) being at direct risk, living behind dikes that are very weak (Hien, L.D., 2001).

Fig. 1.6. Recently finished dike, project PAM 5325 (Project Alimentation Mondial).

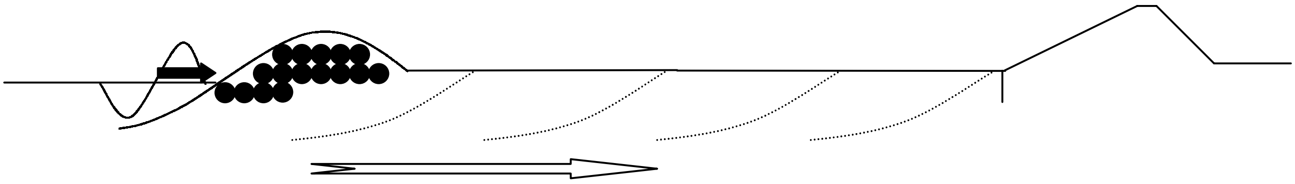


Fig. 1.7. Coastal retreat due to beach and sea dike erosion.

Fig. 1.8 Local interaction between a collapsed sea dike and the eroding beach: the former sea dikes acts like an offshore breakwater (picture dated late 2001, collapse of the sea dike late 1999).

2.3.3 Interaction between erosion problems and defence problems

Due to poor construction methods, Red River delta sea dikes are not able to survive extreme conditions, such as storms and typhoons. The newly constructed PAM dikes (Project Alimentation Mondial, completed in 1995) (fig. 1.6) have concrete and stone revetments that might be able to survive these conditions. However, these newly, safe looking dikes are still at risk. According to Pilarczyk et al, 1996, Vinh et al, 1997, Nedeco, 2001, Van Kessel, 2001 and personal observation, the main causes of dike collapse are not only the stability of the dike revetment, but also undermining and resulting settlement of the toe. The eroding beach fig. 1.7) may undermine the toe and as a result, the structure of the revetment will settle. This problem will cause secondary effects like failure of the revetment in case of extreme storm conditions with high waves and thus, failure of the dike. This may accordingly lead to inundation of the hinterland.

The historical rate of erosion is time and location dependent. Because of the interaction between the collapse of dikes in places and the resulting local flooding of land (fig. 1.8), a reasonable overall yearly rate of erosion is not straightforward to quantify. Local sources report a variety of rates, ranging between 3 to 50 meters per year, varying over the last 100 years.

Both natural and man-induced changes in the system of land and sea may have caused a transition between an overall accumulating coast and a partly accumulating, partly structural eroding coast. The history of the delta’s dike defence lies in the reclamation strategy that the ever-increasing population of the delta has applied. In periods when the coastline was extending due to alluvial deposits, man created new farmland by reclamation. Dikes were constructed to guarantee the safety of the land against flooding due to tide and waves. However, these dikes were constructed in order to protect accreting beaches and not to protect eroding beaches. These two situations require a different design approach.

2.3.4 Problem definition

The present coastal defence seems to be developed as a result of almost 1.000 years of land reclamation. Changes to the system (natural or man-made) have caused long-term accumulating coastal stretches to be turned into eroding coastal stretches. The dikes are therefore being eroded in places, leading to failure and consequently, the loss of land. In these locations, the reclamation strategy switched into a retreat strategy.

2.4 Objectives

2.4.1 Definition of objectives

As stated in the problem analysis, the design problems of Vietnamese sea dikes are considerable. However, the primary problem addressed in this study is the erosion problem, of which the cause and the proportions are subject of study.
The main objectives of this study are to create an overview of the 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, to predict possible future problems of dike erosion and to propose mitigating measures.

2.4.2 Study approach

The data needed for this study were acquired from the VA study, and from studies done by scientific institutes, such as the Haiphong Institute of Oceanology, The Institute of Mechanics, (Centre for Marine Environment, Survey, Research and Consultation), Vietnam Institute for Water Resources Research (Centre for Estuary and Coastal Engineering) and the Institute of Geography. Bas van Maren, PhD Student at Utrecht University is acknowledged for providing data from his study on the cyclic evolution of the Ba Lat delta (Red River mouth). On basis of historical maps, satellite images and collected literature, a hypothesis was formulated concerning the historical- and future development of the coastline of Nam Dinh.
A mathematical model study of specific hydronamic and morphological processes along the coastline of Nam Dinh was conducted, using the 1D wave-modelling package WATRON and the UNIBEST packages for longshore sediment transport modelling and coastline dynamics modelling (WL | Delft Hydraulics). These models have been verified on basis of the hypothesis before extrapolating to future developments. A proposal for mitigation measures, analysis of both qualitative and quantitative results and recommendations form the last part of the report.

2.5 Report structure

Chapter 1 gives an introduction into the coastal defence problems and the interaction between the coastal erosion and the coastal defences, the objectives and study approach. Site conditions such as geography, geology, climate and the hydronamic conditions are described in chapter 2. A short introduction on the theory of delta development is given before discussing the Red River delta development in chapter 3. On basis of satellite images, work of Vietnamese geologists and geographical maps, an overview of the development of the Nam Dinh coastal area from 1500 is given in chapter 4 and this chapter is concluded by the hypothesis of the cause and future development of erosion in Nam Dinh. This hypothesis was used as a reference for the judgement of modelling results of waves and coastline changes, discussed in chapter 5. The last part of the report is formed by the proposal of mitigating measures in chapter 6, followed by conclusions and recommendations in chapter 7 and 8.

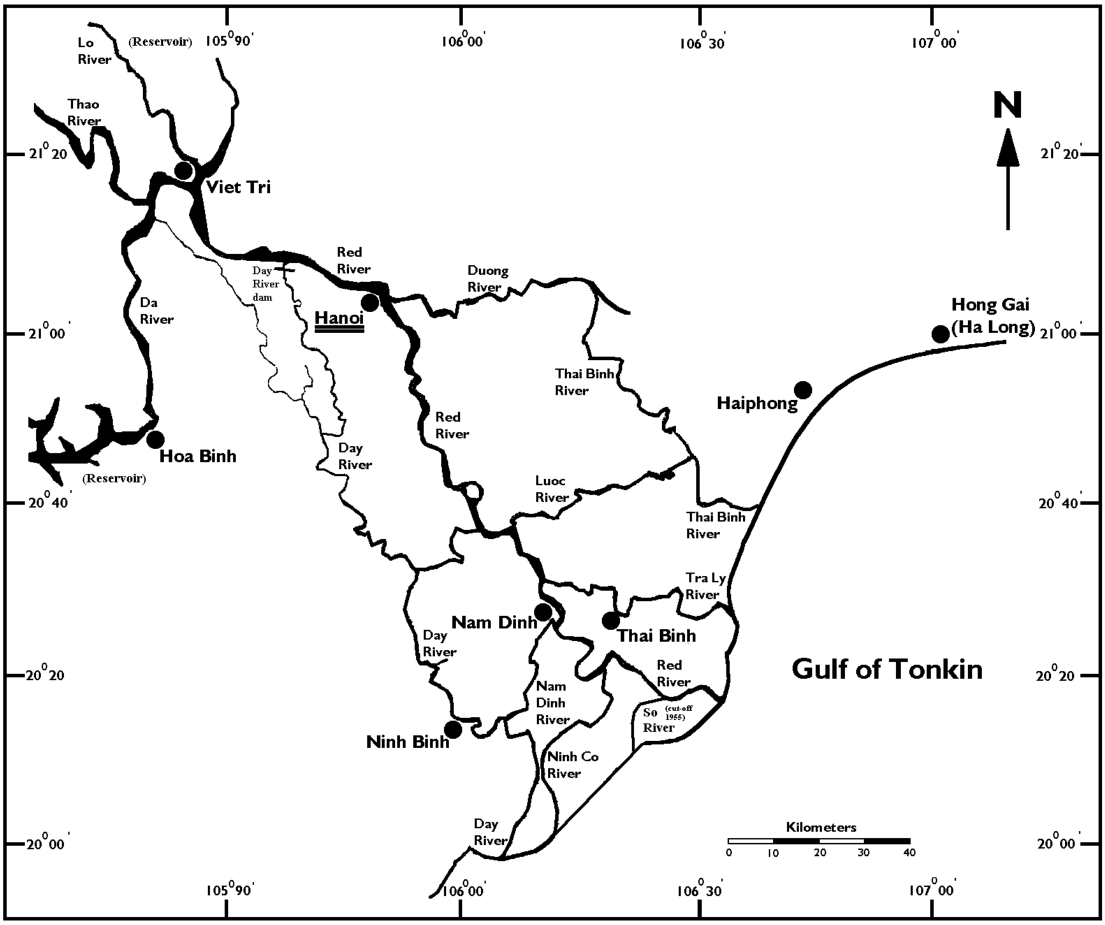


Fig. 2.1. Map of the river system of the southern part of the Red River delta.

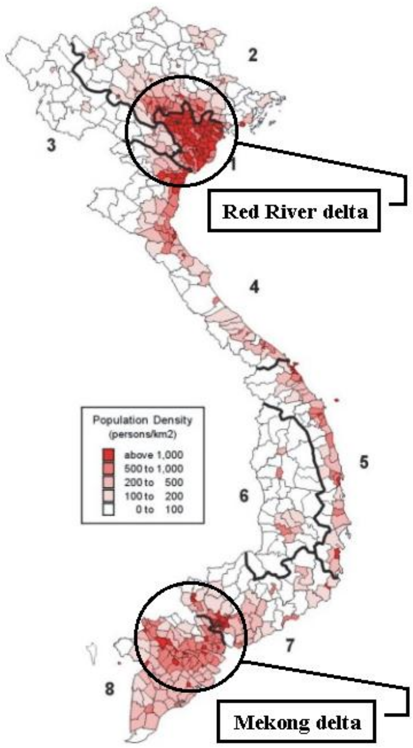


Fig. 2.2. Population density of Vietnam (1996).

3 Site conditions

3.1 Geography

The Red River delta (fig. 2.1) is located in the northern part of Vietnam in the lower plain of the Red River catchments. The Red River is the second largest river of Vietnam, after the Mekong. Named Thao River, it descends from Yunnan, a mountainous region in the south of China. It is known as the "six-head river" that enters Vietnam at Lao Cai, in the northwest of Vietnam. At Viet-Tri (north-western part of the Red River delta), the Thao River forms the Red River, together with the Lo River and the Da River. The total catchment of the Red River covers 169.000 km^2, of which 87.000, including the delta are in Vietnamese domain.
The delta is bordered landwards by mountains and seawards by the coastline, measuring 361 km. The delta of the Red River is a large, flat alluvial plain with more than 50% lower than 2 m + mean sea level. Dikes along the rivers and coastline protect the land from flooding.
The volume of flow in the Red River is approximately 122 billion m^3 per year and its sediment load is about 100-114 million tons.

3.2 Economy / demography

Nearly 90% of the delta's area has alluvial soil, suitable for cultivating various kinds of crops. Rice is the dominant crop, followed by maize, potatoes, soybeans and other vegetables. Rice accounts for 86% of the cultivated area, generating about 6.0 million tons/year.

The delta's population in 1996 was approximately 17 million, which accounts for 22% of the total population of Vietnam. With its population density (fig. 2.2) of more than 1.000 persons per km^2, the Red River delta is considered as one of the most densely populated areas in the world. By comparison, the Mekong delta has 400 persons per km^2 and the national average is 200 persons per km^2.
More than 75 % of the working population earn an income out of agriculture, which accounts for 70% of the land use. An employment / land-use distribution table (1996) is given in table 2.1.
The GDP per capita in 1993 was US$165, respectively US$400 in 2000.

Table 2.1. Employment & land use.

Employment sector	Percentage of employed	Land-use sector	Percentage of land use
Agriculture	75.4	Agriculture	70
Industry	9.5	Aquaculture	4
Trade and commerce	3.8	Forestry	4
Construction	2.5	Infrastructure	16
Education	2.4	Housing	6
Transport	2.1		
Others	4.3		

Fig. 2.3. Tropical storm Lingling on 11-11-2001, carrying winds of 110 kilometres per hour and gusts of up to 140 kilometres per hour, moving with a speed of 13 kilometres per hour towards the coast of Vietnam.

3.3 General climate

The climate of the Red River delta region is tropical with a pronounced maritime influence. The average annual rainfall is 1.600-1.800 mm, 85% of which occurs during the rainy season (April to October). The heaviest rainfall occurs in August and September, causing extensive flooding in the delta due to the overflow of riverbanks.
The winters are cool and dry, with mean monthly temperatures varying from 16.3 to 20.9 degrees Celsius. Fine drizzle is frequent in early spring, after which temperatures rise rapidly to a maximum of 40 degrees Celsius in May. The summers are warm and humid, with average temperatures varying from 27 degrees Celsius to 29 degrees Celsius. The prevailing winds are north and east in winter, and south and southeast in summer.

Typhoons and tropical storms (fig. 2.3) are frequent between July and October. During the period between 1911 and 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 of the pacific, through the Philippines or the Eastern Sea. Then they shoot into the coastal areas of south China and Vietnam. Among the typhoons that occurred between 1954 and 1990, strong winds with grade 12 were observed for 31 cases. The annual average number of typhoons is 4.7, but more than 10 were observed in 1964, 1973 and 1989. The latest typhoon hitting Nam Dinh province was typhoon Nikki in 1996, causing a surge of 3.11 m at the Hai Hau district coastal area.
Typhoons also bring about periods with heavy rains, (over 100 mm/day, possibly 300-400 mm/day) causing severe flooding. The rains, which affect areas in a radius of 200-300 km, may become terrible natural calamities. When such storms break over the mainland, a huge amount of water is released, damaging the sea dikes (rainfall erosion), and flooding the coastal areas.

Fig. 2.4. Red River delta plain, Terra Modis image, 16 November 2001.

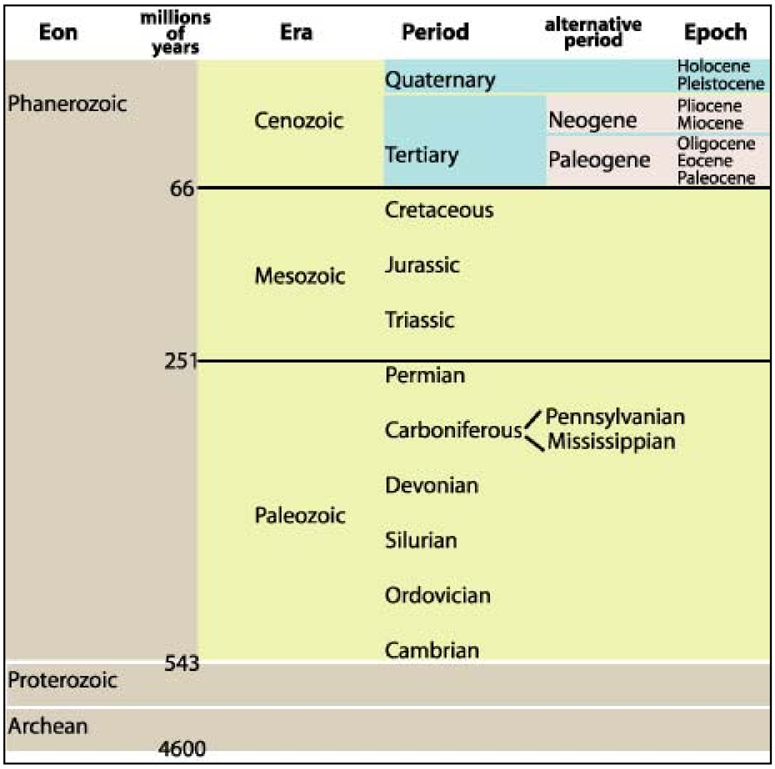


Fig. 2.5. Geological timescale (source: The Paleontological Research Institution, NY, USA).

3.4 Geology

3.4.1 Introduction

When describing ancient coastline development, it is difficult to establish where the earliest coastline was because much of the evidence has been moved by erosion or concealed by deposition. However, the picture becomes clearer in the most recent of the geological periods, the Quaternary (fig. 2.5) which comprises the Pleistocene (starting 1.81 million years ago), and the succeeding Holocene (the last 10.000 years). The Quaternary followed the Tertiary in which the Neocene was de latest epoch. It was one of the major global climate and sea level fluctuation periods, and Quaternary coastlines can be found above and below the present sea level (Bird, 2000). Coastlines have changed in response to coastal processes. Advance occurs when the deposition of sediment exceeds the rate of erosion, or where there is emergence due to uplift of the land or a fall in sea level. Retreat occurs as the result of erosion exceeding deposition, or where there is submergence due to land subsidence or sea level rise (Valentin, 1952).

3.4.2 Delta topography

According to Le, Ngoc, Le, 1997, the delta (fig. 2.4) has a flat topography, gradually sloping from northwest to southeast, from 10-15 m to mean sea level over a distance of about 150 km. During the mid- and late Holocene period, the mountainous bottom of the Tonkin Gulf filled up with alluvium. In the middle of the delta mountains and hills can still be found, linked to the geological formation under the alluvial sequences. The delta plain can be subdivided into three parts, the Rim Plain, the Central Plain 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 the underlying geological foundation. The area is elevated 3 m above mean sea level. The Central Plain is the area built with new alluvium 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 by the sea (Le, Ngoc, Le, 1997). The area elevates 1-3 m 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 1 m below mean sea level to 1 m above mean sea level, where beach ridges are present. The pro-delta zone (the most seaward portion of the subaqueous delta) has a depth of 20-30 m, covered with silt and silty clay of red colour (Hoi, Tuan, 1994).

Upstream, in the mountainous area surrounding the delta plain, the Red River is confined to a straight narrow northwest-southeast aligned valley (fig. 2.4), 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).

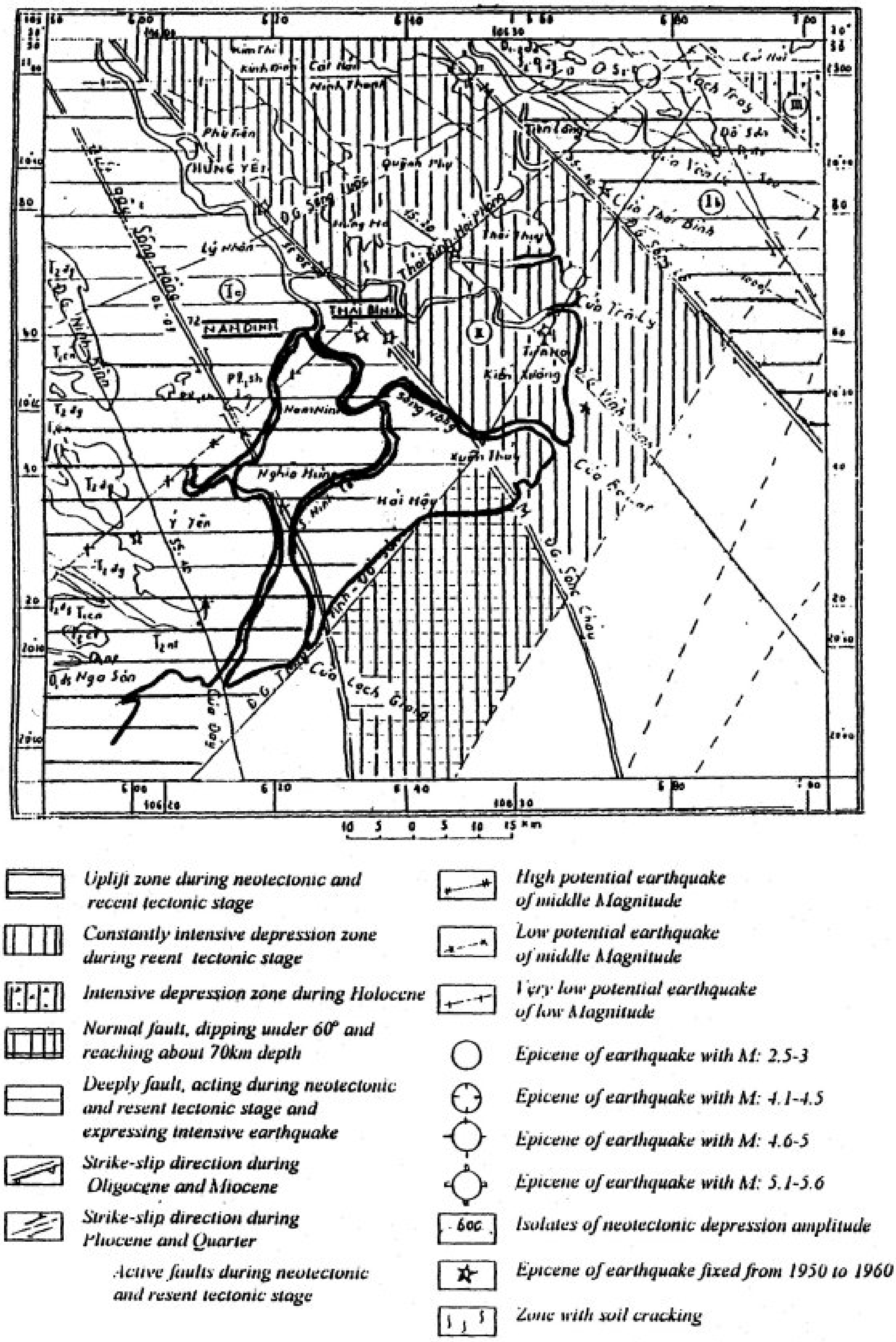


Fig. 2.6. Neotectonics and recent tectonics of the Red River delta (source unknown).

3.4.3 Quaternary sequence (adopted from Mathers and Zalasiewicz, 1999)

The quaternary sediments of the marginal parts of the delta plain enclose numerous low hills: inliers of Triassic and older rocks. The delta plain is surrounded by mountainous areas of which the structure is dominated by northwest-southeast aligned faulting (Workman, 1977). The quaternary sequence within the delta plain is about 100 m thick beneath Hanoi and thickens eastwards to attain about 200 m beneath parts of the coastline. The shallow water depths in the Gulf of Tonkin (<50m) suggest that much of the sequence is preserved offshore.

Low sea level stand sediments (Pleistocene)

These deposits are believed to have accumulated during global cold phases when sea level stood significantly lower than present. This sequence is thin at the basin margins but attains a thickness of about 50 m beneath Hanoi and more than 100 m beneath the central parts of the coastline. Generally, these deposits constitute 60-75 % of the thickness of the entire quaternary sequence. Boreholes indicate that an alluvial regime was dominant.
Deposits from the high sea level stands during the Pleistocene are likely to have been similar to those of the Holocene: of predominantly fine-grained character and unlikely to survive erosion during the succeeding cold (low sea-level) stage.

High sea level stand sediments – the Modern Delta (Holocene)

At the end of the last major global expansion of ice-sheets (ca. 15.000 years BC) sea level is believed to have stood at about 100 m lower than at present. The Vietnamese shoreline would have been far out in the South Chinese Sea with the entire Gulf of Tonkin emergent.
Between 7.000 and 4.000 years BC the deglaciation of large areas let to the rapid rise in sea level to perhaps 1-3 m above present levels, called the “Dong Da” regression.
Since then, the sea level has been relatively stable. This has led to progradation of the delta, resulting in accumulation of the Hai Hung formation (7.000-4.000 BC) and the Thai Binh formation (3.000 BC – present).

3.4.4 Neo-tectonics and recent tectonics

The Red River Graben is 30 to 50 km wide and has an accumulation of about 3 km of neogene sediments. This Graben is thought to have subsided about 6 km over the last 50 million years. This yields an average subsidence rate over this period of 0,12 mm/year. Next to the subsidence in the central Graben, active subsidence is present along the normal fault, in between the Red River mouth and Ninh Co river mouth (fig. 2.6). Areas of uplift relative to sea level may be represented by basin margin terraces of Pleistocene.

Fig. 2.7.hydro-power dam, creating Hoa Binh reservoir.

3.5 Urban and Rural development

According to historians, the settlement of the delta began 4.000 years ago. The Vietnamese agriculture began in the middle region of the Red River delta, in the early bronze period, 2nd millennium BC. The lower delta was exploited later, during the Dong Son period, one millennium BC (Tuan et al, 2001).

3.5.1 Interventions in the river system: flood control and hydro-power

Infrastructure for flood protection and for irrigated agriculture has been evolving for at least 1.000 years. There are 30 individual irrigation and drainage schemes, irrigating more than 750.000 hectare and draining more than 990.000 hectare.
The multipurpose Hoa Binh reservoir (fig. 2.1) is artificial created, by building a dam (fig. 2.7) on the Da River. The dam is provided with a hydropower station. Yearly 60 million m^3 of sediment is trapped in the reservoir, which is expected to be filled up in 150 years time (Red River Master plan, Binnie et al, 1994). The second reservoir is much smaller, located at Thac Ba on a tributary of the Lo River (Fig. 2.1). These recently built dams play a role in regulating the flow in all seasons. The Hoa Binh dam is expected to reduce the peak flood level at Hanoi with 1.5 m. A new reservoir near Son La, 190 km upstream Hoa Binh on the Da River, is planned to be completed by 2007. It is expected to produce 3.600 MW of power. The impacts of these interventions on the natural system will be discussed in chapter 3.

3.5.2 Land reclamation in coastal areas

Land reclamation characterises the expanding of the delta. Wherever newly formed tidal flats could be reclaimed, people built dikes to protect the land from the sea. A river dike system was built, dividing the delta in separate portions. The alluvium discharged by delta tributaries is now no longer being levelling the land but discharges into the sea, being confined between river dikes. The land reclamation process is already ongoing for more than 1.000 years. From the 2nd century BC tot the 10th century BC, the Red River plain was dominated by Chinese dynasties and was the most densely populated area of the south of China. After gaining independence in the 10th century BC, the land reclamation process became more extensively. The area became the richest centre in Vietnam. In 1266, the Trân dynasty allowed aristocrats to recruit poor people to reclaim land along the seashore to form domains. Plantations were set up and controlled by the government. Peasants were also encouraged to reclaim land to form new villages. An example showing the proportions of the reclamation process is Phát Diêm church, in Ninh Binh province (fig. 2.1), built in the late 19th century near the seashore and now being located 25 km inland.
During the French colonial period (1884-1945), the space of the rural areas reduced, due to the growth of urban areas, such as Hanoi, Haiphong and Nam Dinh. In addition to the traditional plantations, French capitalists set up private plantations. Both of these changes increased the need for more land and thus the scope of the reclamation process.

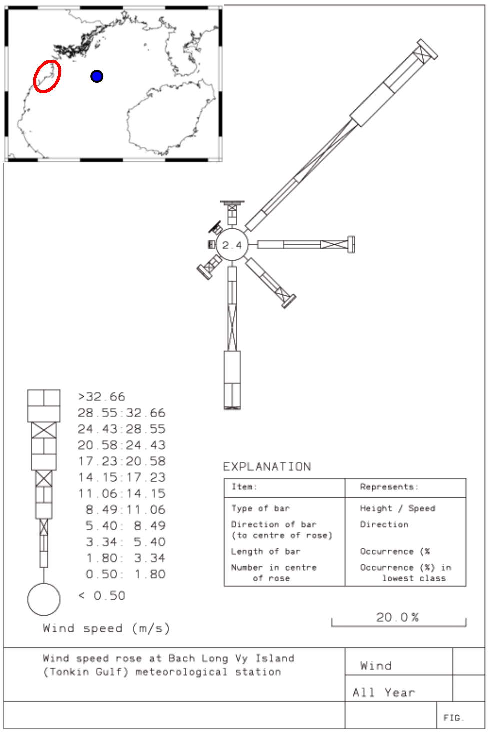


Fig. 2.8. All year wind rose.

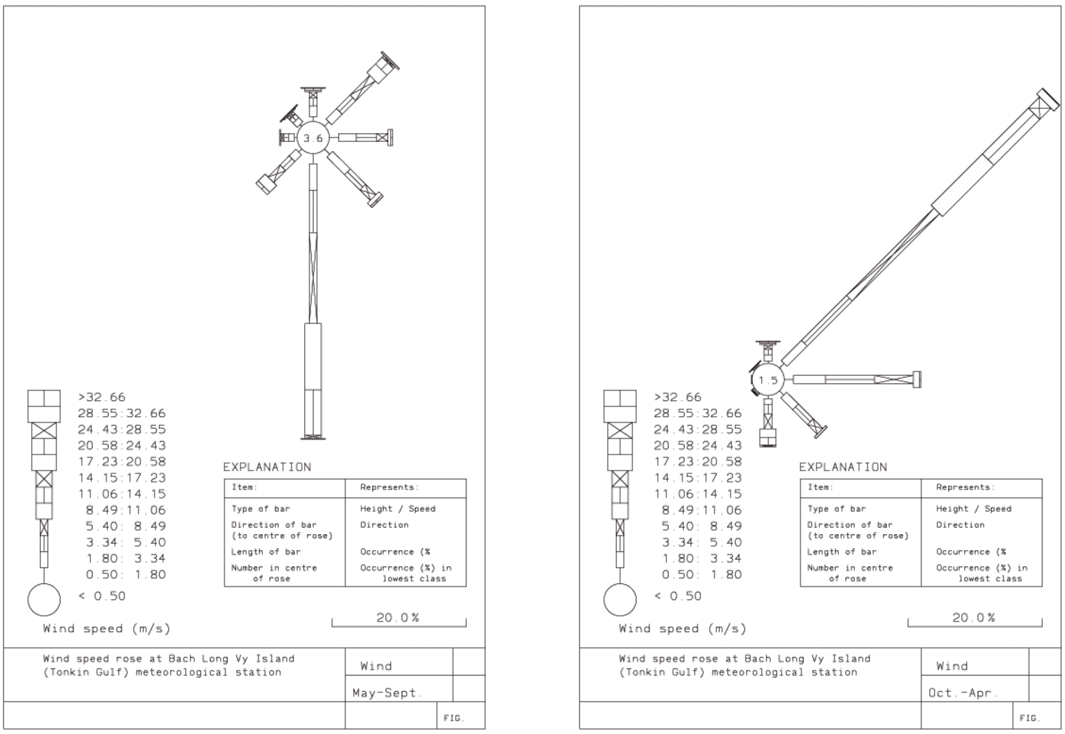


Fig. 2.9. Summer and winter monsoon wind roses.

3.6 Waves

Hung, 2001, calculated an offshore wave climate with the Svedrup, Munk & Brettschneider wave growth model (SMB method) basis of a 20-year offshore wind record. The nearshore wave transformation at a depth of 17 meters has been carried out with a 2D random wave transformation model based in the mild slope equation. The results for the coast of Nam Dinh (Hai Hau district) are presented in table 2.2. Presented are H_{mo}(average wave height), T (average wave period) and N (number of waves) for 9 direction sectors (Hung, 2001).
In chapter 5, the computation of nearshore wave climates along the coast of Nam Dinh will be discussed in more detail.

Table 2.2. Average wave height, average wave period and number of waves for 9 direction sections at 17 m depth offshore Hai Hau district (Hung, 2001).

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	Calm
H_{mo} [m]	1.22	1.60	2.05	1.47	1.35	1.15	1.54	1.99	1.73	-
T [s]	5.0	6.0	7.0	6.0	6.0	6.0	6.0	8.0	7.0	-
N[-]	1604	3211	7962	1466	3054	972	1850	1415	4922	2028

3.7 Winds

Analysis of the offshore wind climate has bean done according to measurements, done at the rocky island Bach Long Vy, situated in the middle of the Gulf of Tonkin (fig. 2.8, inset). A meteorological observation post is situated at a level 72 meters above sea level. 20-year time series data of wind observations (every six hours) in the period 1976 to 1995 have been classified in wind speed and direction classes. The results are presented by wind rose, which represent the percentage of time, that wind occurs in each wind speed (Beaufort classes) and direction class (Fig. 2.8).
Two wind climates can be identified, summer monsoon and winter monsoon (fig. 2.9). May and September are considered to be transition months between the two seasons. The following parameters represent the yearly averaged wind climate at 72-m. height at Bach Long Vy Island: 70% of the time the wind speed is lower or equal to Beaufort 4, 85 % of the time it is lower or equal to Beaufort 5 and 95% of the time it is lower or equal to Beaufort 6. Average wind speed is equal to Beaufort 3.5. These figures are almost the same for summer monsoon and winter monsoon. The prevailing wind direction varies per season. In winter (October to April), the wind blows most frequently from sections between NE (60% of the time) and E (20% of time). In summer (May to September), the wind blows most frequently form sections between SE (10% of the time), S (40 % of the time) and SW (10% of the time). The prevailing summer monsoon winds vary from sections between SE and S in May to sections between S and SW in August. There is also a seasonal variation in strength of the wind. In winter, the highest winds with speed Beaufort 9 are coming from sections between N and NE. In summer, the highest winds with speed Beaufort 8 are coming from sections between NW, N and NE, whereas winds with speed Beaufort 9 are coming from section S. The strongest winds with speed Beaufort 12 (typhoon conditions) have occurred in the period 1976-1995 in June, August and October.

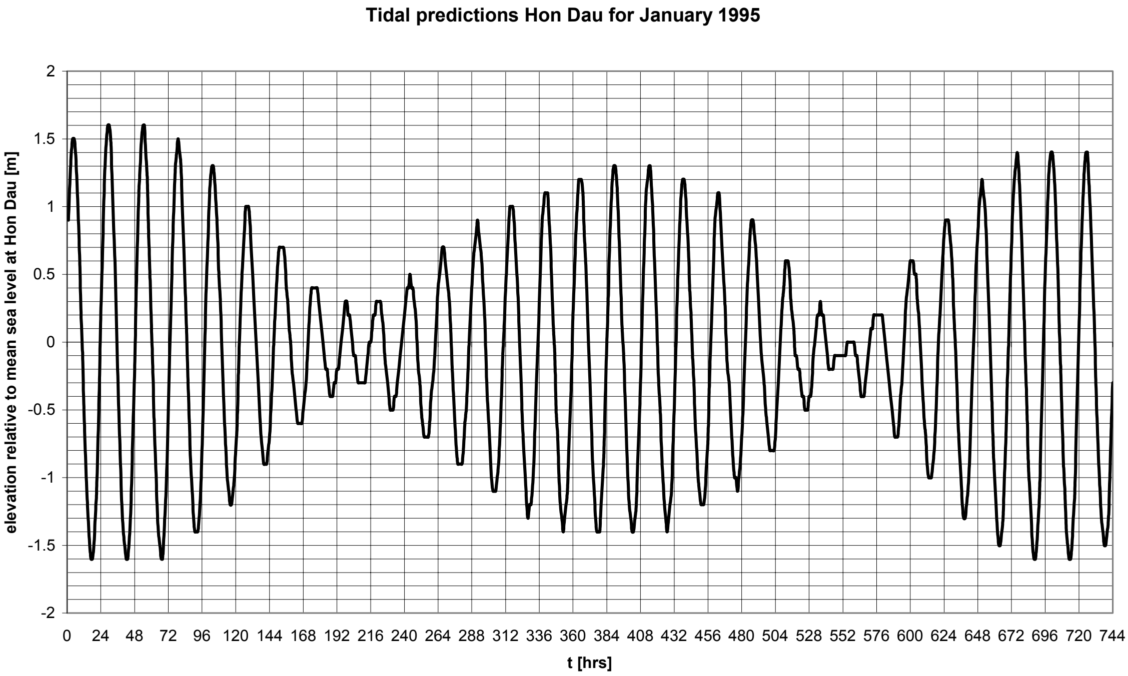


Fig. 2.10. Tidal predictions for Hon Dau station, just south of Haiphong (Fig. 2.1).

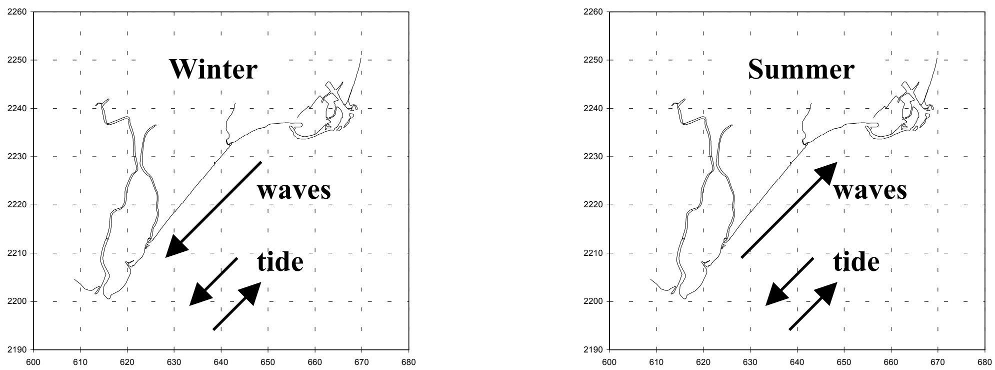


Fig. 2.11. Longshore currents along the coastline of Nam Dinh according to origin and season.

3.8 Tide and currents

3.8.1 Tidal current velocity and tidal amplitude

The tides along the shoreline of the Red River delta are diurnal with a neap tide - spring tide cycle of 14 days. The tidal wave propagates from south to north with mean velocities between 20-30 cm/s. The maximum ebb-tidal current is 60 cm/s and the maximum flood- tidal current is 50 cm/s (Thanh et al, 1997). According to the Department of Agriculture and Rural Development (DARD) in Nam Dinh, the local tidal amplitude varies between 1.9 to 2.6 m depending on astronomical tide period. Low water level was reported in between – 0.4 m to – 0.8 m and high water level in between + 1.5 m to + 1.8 m).

The maximum amplitude at spring tide is 2.7 m and the minimum amplitude at neap tide is 0.02 – 0.05 m. At the Red River mouth, the average tidal amplitude in the 1972-1990 period was 1.92 m, with the maximum of 3.64 m on 23-12-1987 and 01-07-1988 (Ninh et al, 2001). Figure 2.9 gives an example of tidal predictions for Hon Dau station, near Haiphong (fig. 2.1, annex 4).

3.8.2 Tidal asymmetry

According to Thanh et al (1997), in the northeast margin of the Red River delta, the duration of the ebb tide is slightly longer than the flood tide duration. However, in the southwest margin of the Red River delta, the ebb tide duration exceeds the flood tide duration (Thanh et al, 1997).

Results from the tidal generator WXTide32 program (WXTide32 is a public domain program for displaying tides and currents for about 9.000 locations around the world) (Annex 4) show the differences in tidal propagation at locations in the Tonkin Gulf (reference level: Hon Dau level). Estimates for 19 September 2002 show that for that particular day, in the northern part of the Tonkin Gulf at Kao Thao islands, the flood tide is dominant, lasting more than four hours longer than the ebb tide. Near Hon Dau, the flood dominance turns into ebb dominance, lasting nearly 1 hour longer than the flood tide. Near Ba Lat estuary (Red River mouth), the duration difference between both tides increases to about 3 hours whereas near Hon Mé Island in Thanh Hoa province, the ebb tide duration is nearly 5 hours longer than the flood tide duration (see annex 4 for locations and WXTide32 results).

According to Van Maren, 2002, measured velocities in front of the Red River mouth were asymmetrical and diurnal during spring tides, with a short period of strong southward flow and a longer period of weak northward flow. Nearly symmetrical semi-diurnal currents characterise the flow pattern during neap tide. This difference in flow conditions is attributed to interaction of O1, K1 and M2 tidal constituents, which are able to induce a tidal asymmetry with a distinct periodicity (Van Maren, 2002).

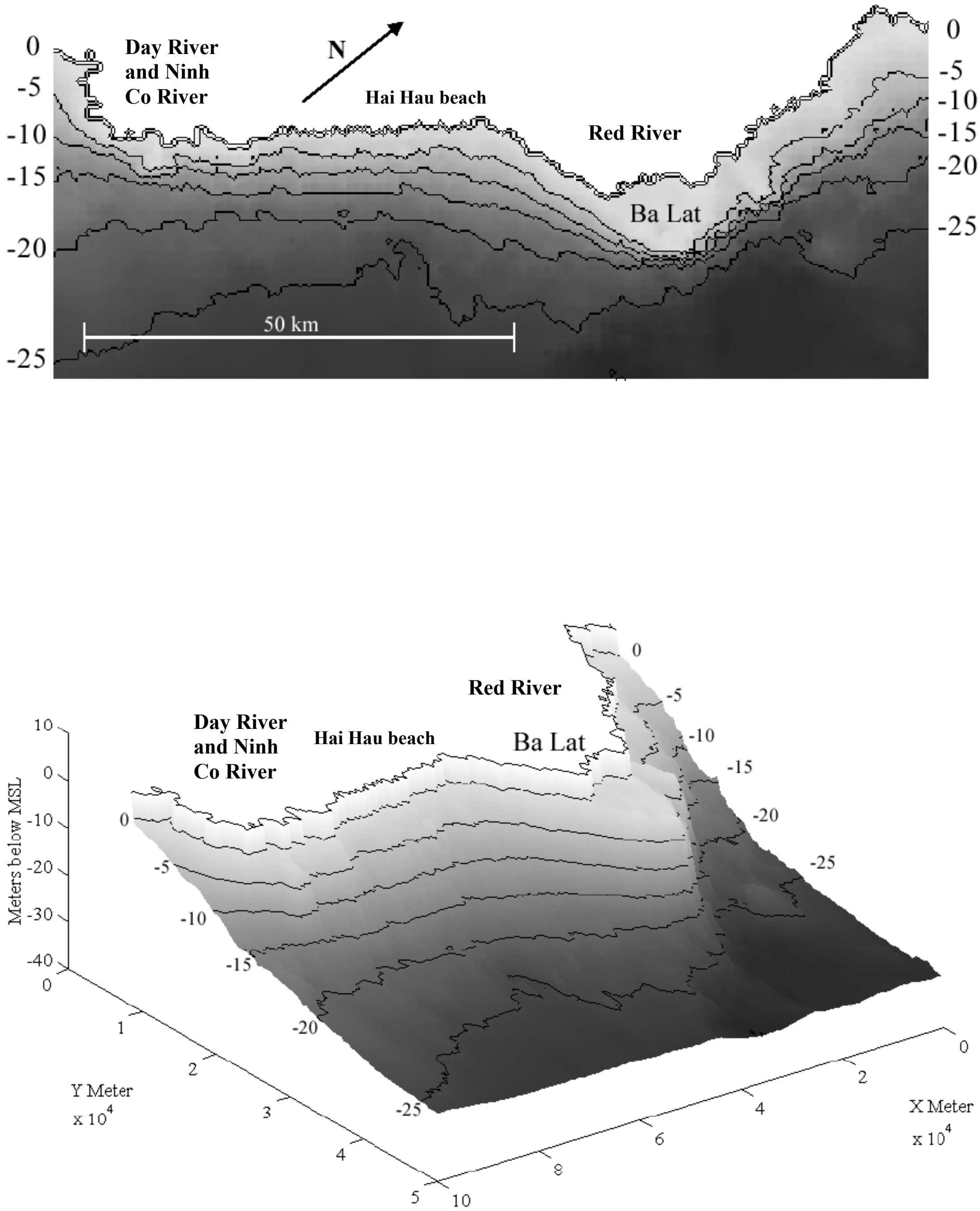


Fig. 2.12. 2D and 3D bathymetry of Nam Dinh nearshore area (Häglund & Svensson, 2002).

According to field observations done by Hung, Ninh 2001, wave-induced long shore currents have an averaged value of 0.2 – 0.4 m/s and a maximum of 0.7 – 1.0 m/s at a depth of 2.5 m. These figures include the tidal current velocity (Hung, Ninh 2001). Longshore wave-driven currents are southwestwards in winter and northeastwards in summer. In winter, the total longshore current is magnified during ebb tide and decreased during flood tide. In summer, the total longshore current is magnified during flood tide and decreased during ebb tide (fig. 2.11).

3.9 Reference levels

The Vietnam datum level is Hon Dau level (water level measuring station, on the rocky coast just north of Haiphong), 0.14 m above mean sea level.

3.10 Bathymetry

The nearshore region of Nam Dinh province (fig. 2.13) shows a very gentle slope, creating a relatively wide zone for wave transformation and energy dissipation (Pruszak, 2002). The beach slope in Hai Hau district, related to the depth at an offshore distance of 17 km is about 0.0015. Offshore the Day River and Ninh Co River, the slope is 0.0009.
The Red River mouth has steep slopes, creating losses of alluvial sediments to offshore locations. Near the Red River mouth, the sea floor has a slope of 0.004.

Cross shore profiles, measured in 1991 (fig. 2.14) show a concave sea floor profile just south of the Red River main channel. The eroding beaches in Hai Hau district have a more convex sea floor profile.

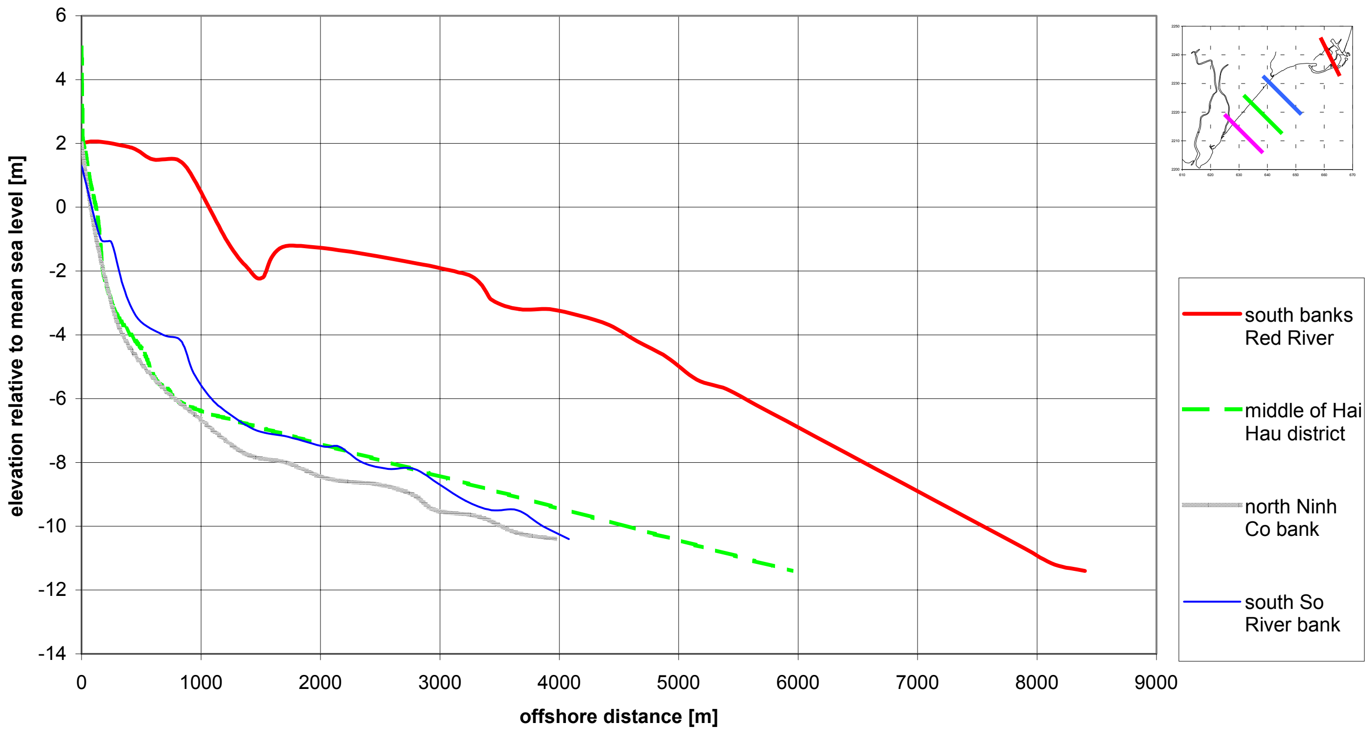


Fig. 2.13. Cross-shore profiles (Center for Estuary and Coastal Engineering, N.K. Nghia, 1991).

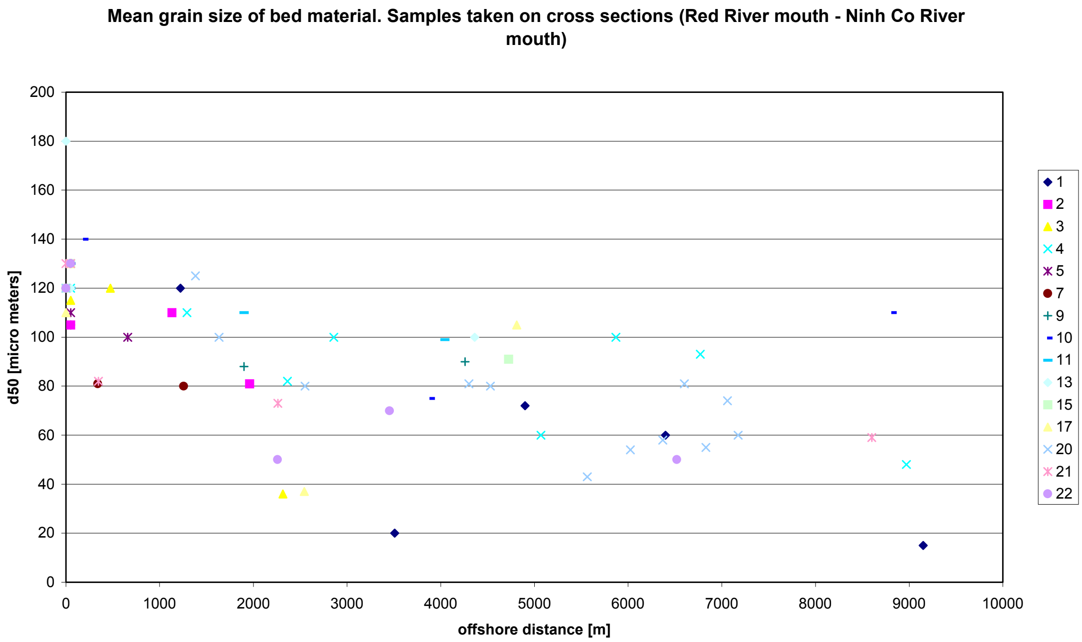


Fig. 2.14. Sediment sizes along the coast of Nam Dinh (Center for Estuary and Coastal Engineering, N.K. Nghia, 1991).

3.11 Sediments

From north to south, five Red River distributaries (table 2.3) drain the delta plain, discharging into the Tonkin Gulf.

Table 2.3. Sediment discharge at river mouths in the southwestern part of the Red River delta (Vinh et al, 1996).

Province	River	Estimated sediment output [million tons/year]
Thai Binh	Thai Binh River	15-20
	Tra Ly River	12-15
Nam Dinh	Red River	23
	Ninh Co River	18
	Day River	12
	Total:	80-88

The total yearly sediment load of the Red River system is estimated at 100 million ton/year (Vinh et al. 1996) to 114 million ton/year (Pho, N.V. 1984).

Figure 2.14 gives sediment sizes measured in 22 cross-sections (source: Center for Estuary and Coastal Engineering, Hanoi) along the coast of Nam Dinh. Section 1 is located near the Red River mouth in the north; section 22 is located at the northern bank of the Ninh Co River.

Figure 2.15 gives a characteristic sieve curve based on soil tests, done by “Sea Dike Engineering Services” (source: Institute of Mechanics, Hanoi). It appears from the tests that the sieve curves for different locations along the Nam Dinh coast have a similar sediment size distribution.

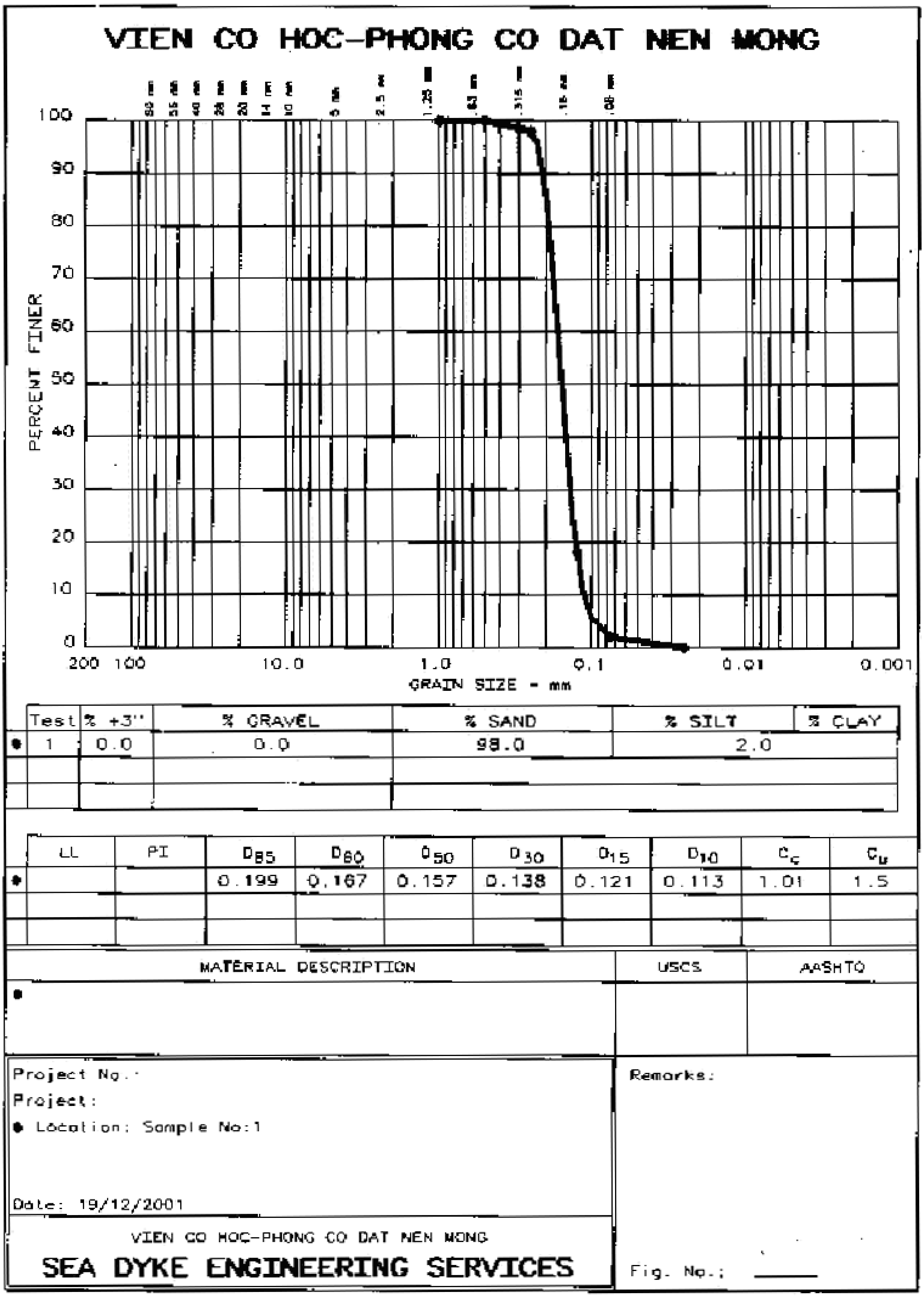


Fig. 2.15. Characteristic sieve curve for the beaches of Nam Dinh.

4 Delta development

4.1 Theory of delta development

4.1.1 Introduction

Nam Dinh province is part of a deltaic landform. The behaviour of the coastline of Nam Dinh is influenced by several processes, of which the deltaic processes of the Red River delta dominate. Before elaborating on the processes in the Red River delta, an introduction is given to provide some basic knowledge about delta formation and delta evolution in general.

A delta is a subaqueous accumulation of riverine sediments at the mouth of a river. The receiving basin may be an ocean, sea or lake. Once this basin is reached, deposition results from the loss of momentum and the ability of the river to carry sediment.
The term “delta” was first applied (circa 450 BC) by the Greek historian Herodotus to the triangular alluvial deposits at the mouth of the Nile River. Deltas form wherever sediment at a river mouth is being supplied faster than it can be removed by marine processes. Most deltas do not exhibit the classic deltoid form but have a wide range of morphologies and features that reflect the environment of the receiving basin. Numerous variables, such as the hydrographic regime (domination of tide / waves / river) of the receiving basin, influence delta formation. As a result, the morphology of deltas is extremely variable (Hanson, 2002).
River-dominated deltas are found where rivers carry so much sediment to the coast that the deposition rate overwhelms the rate of reworking and removal due to marine forces. The morphology of wave-dominated deltas reflects the balance between sediment supply and the rate of reworking and redistribution. In tide-dominated deltas, for parts of the year, tidal currents may be responsible for a greater fraction of the sediment transporting energy than the river. As a result, sediment transport is bi-directional over a tidal cycle. Furthermore, the zone of marine-riverine interactions is greatly extended.
Historically, deltas have been important for civilisation as regions for agriculture, habitation, navigation, and fishing. More recently, deltas have been exploited for oil, gas, and fresh water.
Deltas experience rapid local relative sea level rise because of the natural compaction of deltaic sediments from ground water extraction and consolidation due to superficial drainage. They are extremely vulnerable to floods coming from the landward side and storms coming from the seaward side, because the subaerial surfaces are flat and only slightly above the local mean sea level. Only a slight rise in sea level can extend the zone subject to storm surges and waves further inland (Anonymous, 2001).

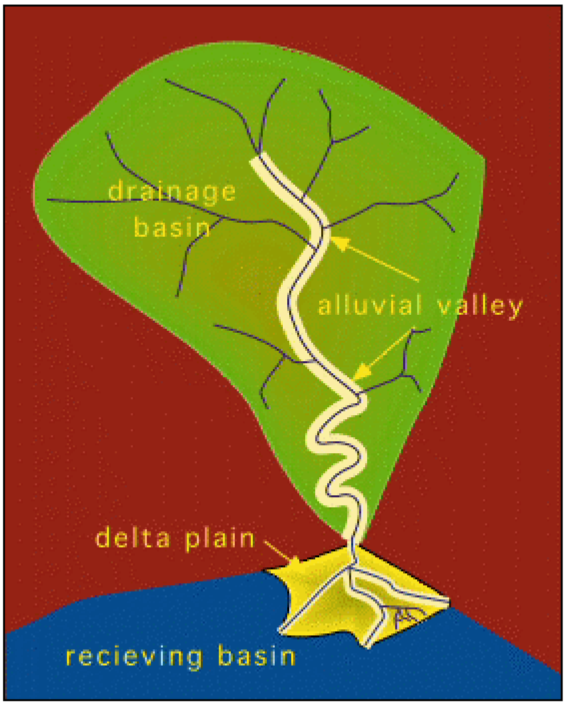


Fig. 3.1. Components of the fluvial system of a delta.

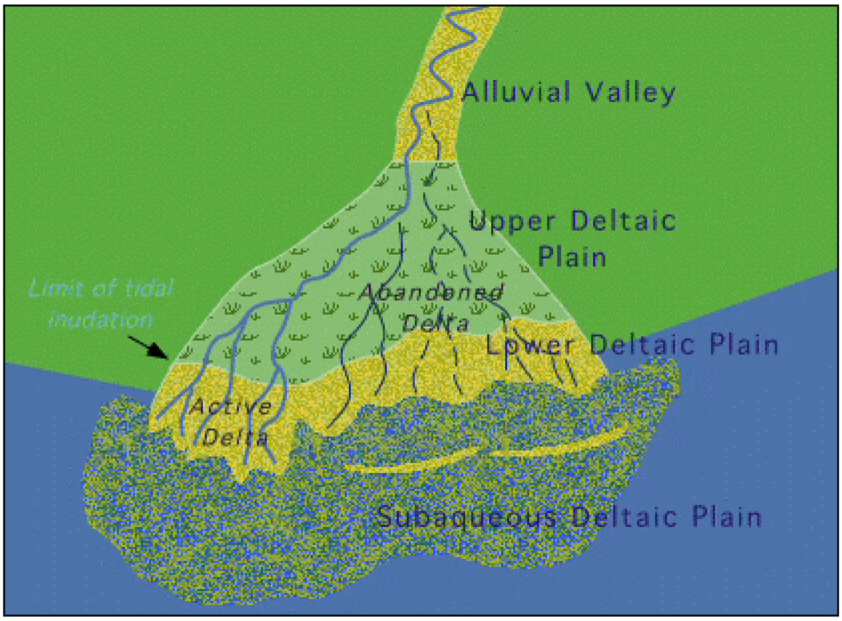


Fig. 3.2. Physiographic zones of the marine delta plain.

4.1.2 Components of the fluvial system

The fluvial system consists of four components (fig. 3.1) of which each of them will have some effect on the delta system.

Drainage basin:	The region drained by a river and its tributaries. The tributaries form a collection system that transfers sediment and water to higher order streams. Sediment- and river discharge are a function of the size, relief, tectonics, climate and geology of the drainage basin.
Alluvial valley:	The principle region of sediment transport through the drainage basin. Damming and diversion of discharge within the alluvial valley is greatly altering the sediment and water discharge to the delta.
Delta:	The region of sediment dispersal and sedimentation. Shape of the delta plain is governed by the energy of the receiving basin and fluvial output.
Receiving basin:	Base level for the fluvial system. Slope, orientation, and hydrodynamics of the receiving basin all influence delta morphology.

4.1.3 Physiographic zones of the marine delta plain

The delta can be subdivided in the subarial plain and the subaqueous plain (fig. 3.2).

Subaerial delta plain:	region above low tide limit; built on top of subaqueous delta plain;
Upper delta plain:	above the influence of marine processes;
Lower delta plain:	between low tide and high tide limits; dominated by marine and fluvial processes; width of the lower delta plane is governed by tidal range.
Subaqueous deltaic plain:	
Prodelta:	seaward-most portion of the subaqueous delta, typically composed of clay and silt;
Delta front:	landward portion, typically composed of silt and sand;
Active delta plain:	occupied by active distributaries; the area of active building dominated by fluvial and marine processes;
Abandoned delta plain:	not longer receives sediment from distributaries; dominated by marine processes and subsidence; erosion and redistribution of sediment occurs in areas of high wave and/or tidal energy; through erosion and subsidence, the region may return to open marine conditions.

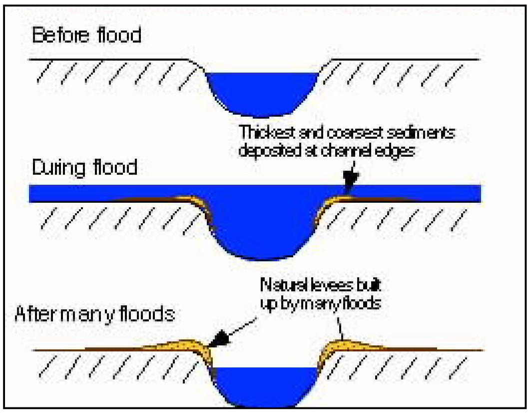


Fig. 3.3. Formation of natural levees by river floods.

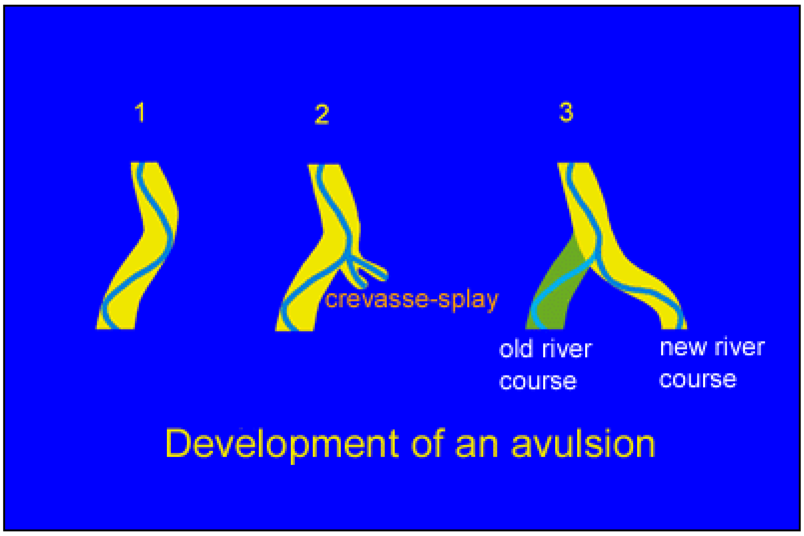


Fig. 3.4. Changing of river course by breaching through the natural levees.

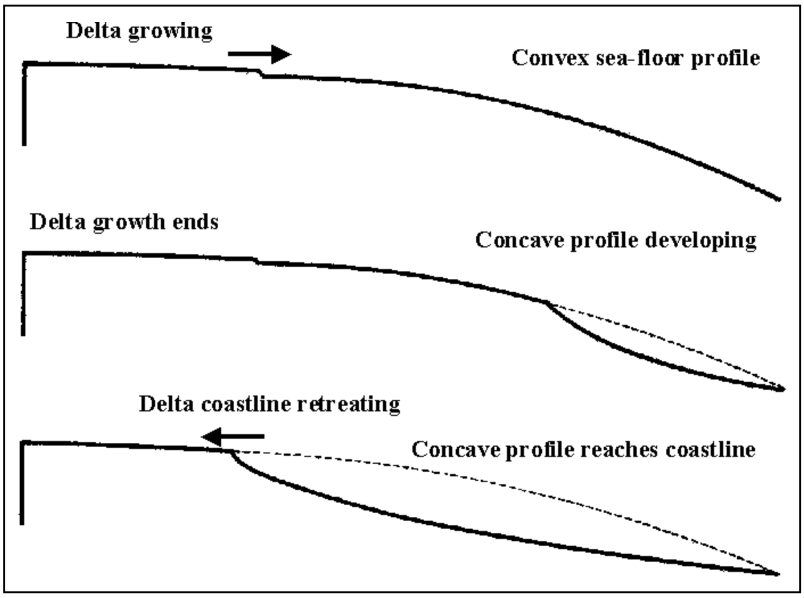


Fig. 3.5. Change of sea floor profile due to delta evolution.

4.1.4 Deltaic processes

According to Bird, 2000, in the fluvial system of deltas, distributaries may form as the result of breaching of natural levees (fig. 3.3, 3.4) during floods, in particular after deposition of sediment on the floor of a river channel has lifted the river, so that it spills out over its banks and finds a new outlet. Alternatively, a river mouth may be split up into two or more channels by the formation of shoals that grow up as islands. Some distributaries may become major river channels while others silt up. The tidal range influences the penetration of the tide upstream, reversing the river discharge and causing overbank flow. As deposition of sediment at river mouths proceeds, natural levees bordering the river channel are prolonged seaward and the various bars and shoals move forward in front of them. Where wave energy increases, these river mouth deposits are reshaped into smooth actuate shore parallel swash bars that are driven shoreward and eventually incorporated in beaches on the delta coast.
On deltas where the main river branches into distributaries, progradation is by means of sedimentation at and around the mouths of these channels, in particular during river floods. Waves and currents can spread the sediments alongshore, sorting them into sandy beaches and spits and separating finer sediment to settle in backing lagoons and swamps or to be dispersed seaward (Bird, 2000).

4.1.5 Delta evolution

Stages in the evolution of deltas may be traced from the time when the sea attained its present level relative to the land, and sedimentation began to fill a valley-mouth inlet through the complete filling of that inlet and the formation of a depositional landform protruding into the sea. The outlines of such a delta change as the result of deposition and erosion along its coasts. Deltas continue to prograde as long as the supply of sediment, mainly from the river, exceeds its removal by wave and current action.
Delta progradation can be accelerated by increased sediment yield due to deforestation, overgrazing, or unwise cultivation leading to rapid soil erosion, or mining activities in the river catchment. Erosion of deltaic coastlines may follow diminished sediment yield from the river. Upstream dam construction may reduce the fluvial sediment yield. Another reason for a change between a prograding delta coast and a erosive delta coast is the natural diversion of a river mouth, followed by erosion of the former delta and the building of a new one.
If the fluvial sediment supply to a delta is reduced or cut-off, and erosion of the delta coastline follows, there is usually an interval between the halting of the fluvial sediment supply and the onset of erosion (Bird, 2000). The change from a convex aggrading sea floor profile to a concave, eroding sea floor profile begins offshore and is transmitted landward (fig. 3.5). As the concave profile intersects the deltaic coastline, erosion begins, or is accelerated (Bird, 2000).

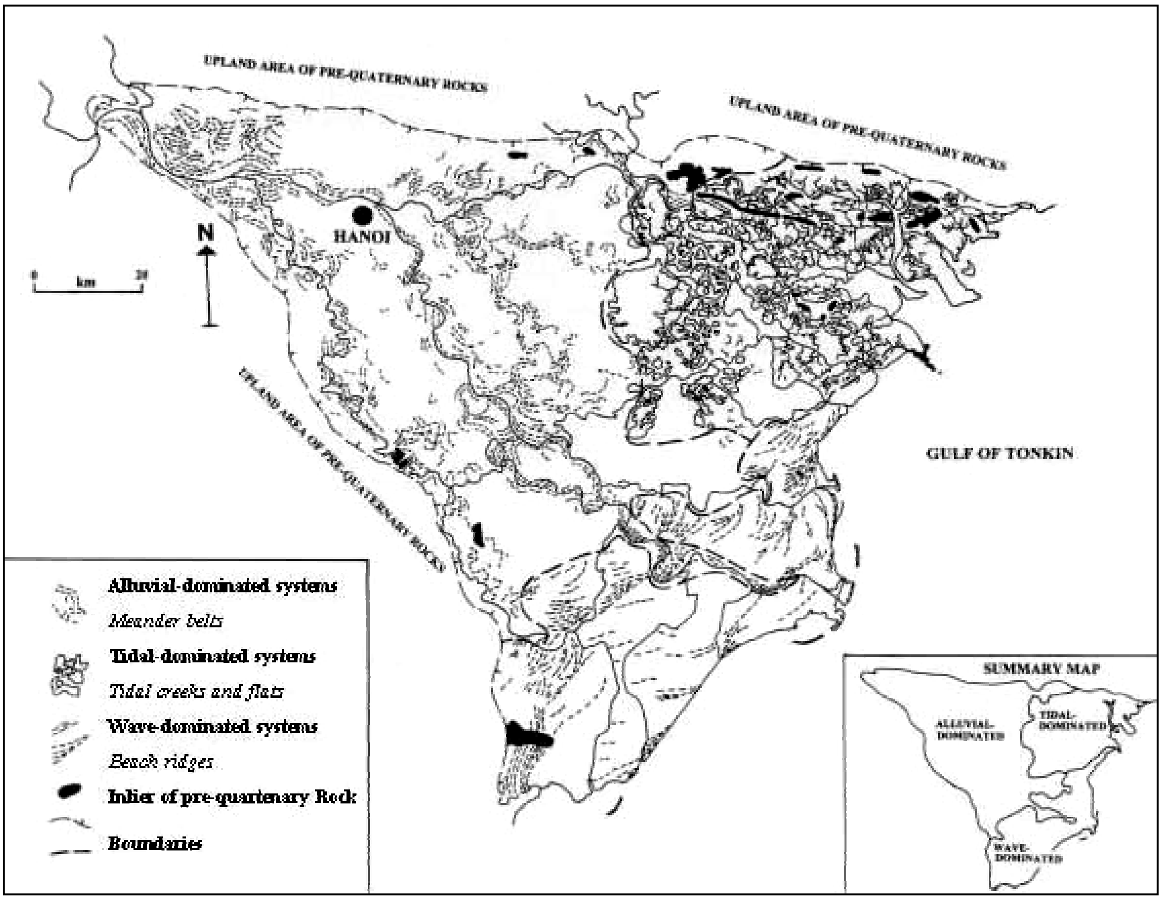


Fig. 3.6. Morphological classification (Mathers, Zalasiewicz, 1999).

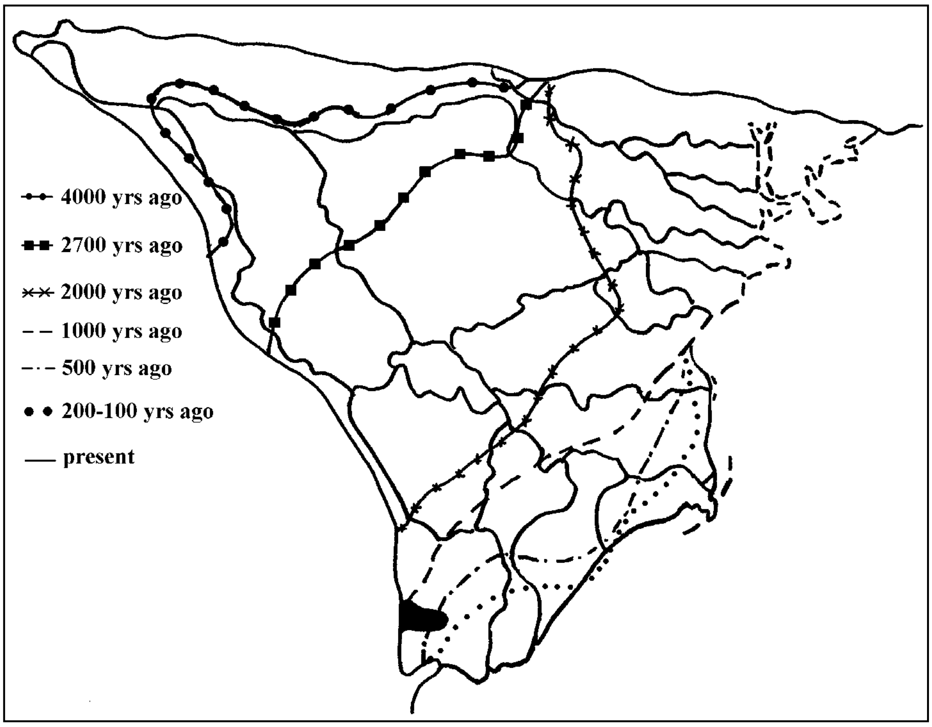


Fig. 3.7. Red River delta plain development from 4.000 years ago until present (modified from Lê et al, 1997).

4.2 Red River delta development

4.2.1 Introduction

Before finding the cause of the widespread erosion problems in Nam Dinh, an overview must be created on historical delta development and the various mechanisms that control the morphological system of the Red River delta coastal system. The impacts of morphological mechanisms, relative sea level rise and human interventions on the natural system will be discussed.

The Red River delta plain took various shapes during its development the last 4.000 years (fig. 3.7). After 4.000 to 2.700 years ago, a gradual shift in southeast direction was followed by an extension of the southern and middle part into east-southeast direction, whereas the northern part of the delta seemed to be abandoned, generally retaining its position. In the period from 2.000 to 1.000 years ago, the opposite occurred: the southern part seems to be abandoned, extending in southeast direction but with a much lower rate than the extension in the northern part of the delta. The high density of succeeding beach ridges and their small mutual distance may give evidence for a long-term stable- to slowly accreting area. The last 1.000 years, the northern part of the delta retained its position, changing from delta into estuary (Thanh et al, 1997), being abandoned by the major Red River branches. The southern part developed into the active part of the delta, forming a curved coastline that is concave between river mouths and convex near river mouths. Major beach ridges (fig. 3.9) have a large mutual distance, indicating an increase in progradation speed of the delta during the most recent developments.

4.2.2 Morphological classification

Interpretation of satellite images by Mathers, Zalasiewicz, 1999 revealed the position of river meander belts, tidal creeks and beach ridges. On basis of this analysis a morphological classification of the different alluvial, tidal and wave-dominated systems was made.
The northern part of the delta is characterised by tidal influences (fig. 3.6) being protected from wave action by the Hainan Island, whereas the southern part, mainly belonging to Thai Binh and Nam Dinh provinces, is highly wave-dominated.

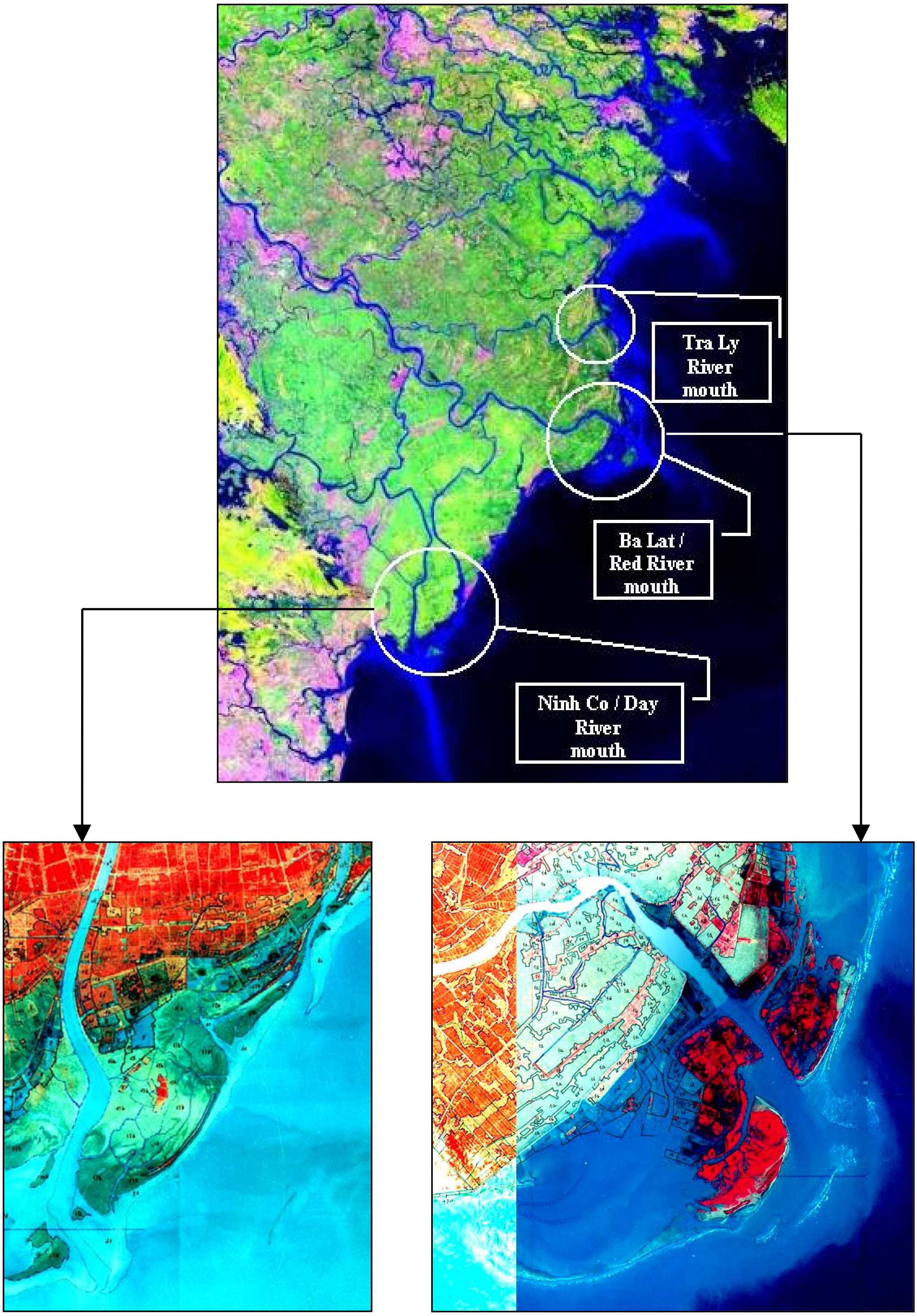


Fig. 3.8. River mouths in the southern part of the Red River delta (upper image: landsat 21-09-2001, lower images: SPOT 1995).

4.2.3 Morphological mechanisms

The wave-dominated part of the Red River delta shows a seaward development characterised by alternation of beach ridges and muddy tidal lagoon deposits.
Both the Tra Ly River and the Red River (fig. 3.8) end in a barrier beach, which projects some 10 km in front of the general coastline, while mud is accumulating in the intervening, sheltered lagoon. During the summer monsoon, in a period of excessive flooding and fluvial input, the river mouths deposit a mass of sediment that is reworked by longshore drift in winter, when river discharge is low and wave action is strong due to strong northeast winds and long fetches. The river mouth is leapfrogging in a seaward direction (Mathers, Zalasiewicz, 1999). The river mouths show 30-40 year cyclic behaviour, with regard to their orientation. After a major flood, offshore bars and levees are broken, creating new channels and possibly new river mouth orientation.
In the south, 70 km from the Red River mouth, between the Ninh Co River and the Day River (distance in between the river mouths being approximately 10 km) accumulation occurs (fig. 3.8).
However, the accumulation mechanism is different from both the Tra Ly and the Red River mouths. Although small barriers have formed 10 km in front of the coastline, they have not created a sheltered lagoon similar to those in the northern river mouths.
However, an immense tidal flat is present. Wave action therefore is depth limited and will smoothen out towards the coast.

4.2.4 Impact of relative sea level rise

According to Nicholls and Leatherman, 1994, the physical effects of sea level rise can be summarised into 5 categories. These are inundation of low-lying areas, erosion of beaches, salt intrusion into aquifers and surface waters, higher water tables, and increased flooding and storm damage. Relative sea level rise is defined as the summation of the absolute sea level rise and the absolute subsidence of the land. Its effect on coastal retreat is passive submergence of coastal lands. The area lost varies greatly from one portion of the coast to another, depending on the degree of slope of the terrain.

The longest and most reliable record on sea level rise in Vietnam is measured on a rock at Hon Dau, in the northeast of the Red River delta. A sea level rise of 0.19 cm per year has been observed at this station for the period between 1955 and 1990. The Hydrometeorological Service of Vietnam has done the measurements.
According to Thuy, N.N et al, 1994, the sea level rise at Hon Dau is 0.244 cm per year.
Neotectonic subsidence is 0.04-0.15 mm/year and during the quaternary 0.04-0.10 mm/year (Can, N. 1989). According to Thang, Bach, 1992, The Red River Graben is thought to have subsided about 6 km over the last 50 million years, leading to an average subsidence rate of 0.12 mm/year (Thang, Bach, 1992).
According to these various figures, relative sea level rise has a lower boundary of 0.194 cm/year and an upper boundary of 0.259 cm /year, without taking into account the effects of accelerated sea level rise, which seems to be a global trend.

Appliance of the " Bruun rule" (Bruun, Schwartz, 1985) gives a first rough estimate of the effect of sea level rise on beach changes.
The basic assumption for this simple model is that the profile, whatever its form, maintains its shape during a period of sea level rise. If the sea level rises "a" meters and the width of the bottom influenced by sea level rise is "B" meters extending to depth "D" meters, the shoreline recession "r" is determined by: r * D = B * a (r = (cot (slope) * a)).

Table 3.1. gives an indication of the sensitivity of the coast of Nam Dinh for maximum relative sea level rise. Hypothetic situations of an acceleration of the relative sea level rise with a factor 2 and 3 are also taken into account. As many different slopes are present along the coast of Nam Dinh, just three of them, 1:100 (beaches of Hai Hau district), 1:500 (Red river mouth beaches) and 1:1.000 (Ninh Co and Day River mouth beaches) have been evaluated.

Table 3.1. Coastal retreat as a result of relative sea level rise.

Relative sea level rise (cm)	**Resulting coastal retreat in 100 year (m) for slope 1:100**	**Resulting coastal retreat in 100 year (m) for slope 1:500**	**Resulting coastal retreat in 100 year (m) for slope 1:1000**
0.259	26	130	259
2 * 0.259	52	259	518
3 * 0.259	78	389	777

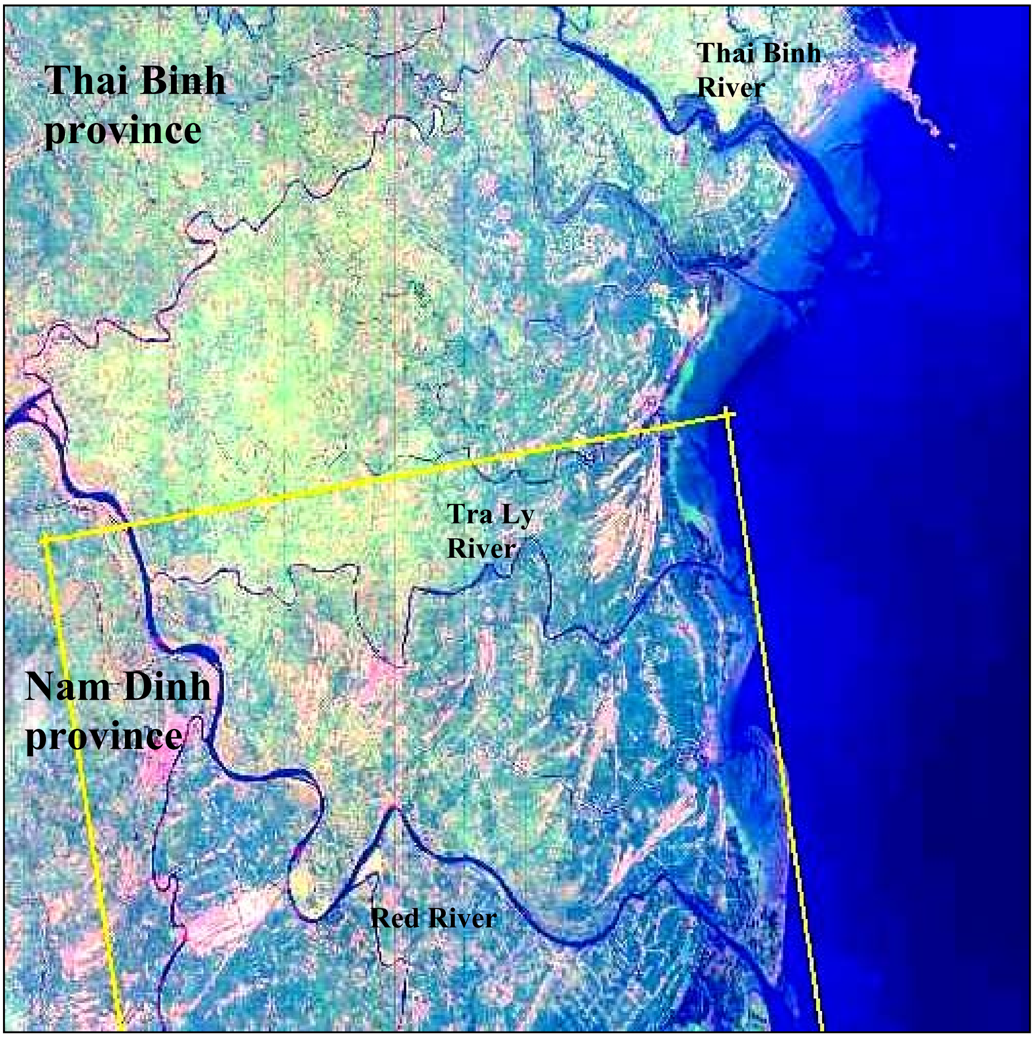


Fig. 3.9. SPOT image (27-03-2000) of mainly the Thai Binh province coastline. Beach ridges are clearly visible and the image therefore gives a good indication of the morphological mechanisms and relating human settlement and reclamation strategy.

4.2.5 Impact of human activities

Introduction

Man started to settle on the alluvial deposits of the Red River 4.000 years ago, developing an area that in present times is known as one of the largest rice production areas in the world. The cultivation of the delta area brought about a though struggle against natural hazards such as storms, typhoons and floods, impacting the low-lying delta. Inventiveness of man resulted in measures such as river training works, land reclamation, and flood control to cope with these natural hazards. At the same time, these measures have impacted the development of the alluvial delta. An overview of the impacts of cultivation and protection of the delta is given in this section.

River training works versus elevation of the delta plain

A natural developed delta plain is criss-crossed by natural levee-bordered river channels. When during the summer monsoon the river rises, the banks overflow and the delta plain is flooded. Coarser particles settle along the riverbanks and finer particles spread out over the delta plain, accumulating in calm water. Distributaries may form which results from the breaching of natural levees during floods, particularly when the riverbed has been lifted by deposition of sediment.
Man has constructed dikes to confine the river, preventing it from overflowing its banks and protecting the delta plain from flooding. Man-made irrigation systems control the supply and discharge of water. Because of its confined position, the river tends to raise its riverbed and consequently the outside plain becomes more depressed over the course of time, and is no longer supplied with alluvial sediments.

Land reclamation versus natural coastal defences

In an undisturbed delta system, the tributaries discharge an abundance of sediment during the wet, summer season. As the delta plain is flooded, sediment is deposited over the delta lobes. In winter, both longshore and cross-shore transport rework the sediment deposits, creating offshore beach ridges. The intervening area is protected from wave action and is filled up with alluvial sediment. In the case of severe flooding, the river mouth will discharge an abundance of sediment, creating a new offshore bar. The process of spit forming and filling up of the intervening area will start again.
In a situation of human intervention, starting more than 1.000 years ago, man decided to settle on former beach ridges (fig. 3.9), and to prepare the highly fertile alluvial land for rice growing. Because of the population pressure, human settlements extended to the first sea facing beach ridges. Sea dikes were built, reclaiming the tidal flats between the beach ridges and the main land. Even directly exposed tidal flats without barrier protection were being reclaimed. The sea was no longer faced by tidal flats combined with sparse beach ridges, but by human constructed sea dikes combined with natural developed coastal protection.

As the delta plain is not being flooded anymore by river and tides, the sediment output is concentrated in the river mouths. Longshore transport is the only mechanism left to feed the coastline between the river mouths, whereas in former times both longshore sediment transport and fluvial input fed these coastlines.

Groundwater extraction and superficial drainage versus subsidence

Superficial drainage and groundwater extraction are a major cause for soil settlement in unconsolidated Holocene sedimentary environments such as dense populated deltas (e.g. city of Bangkok, located in the Chao Praya delta, Thailand).
Hanoi faces serious land subsidence (25-30 cm in the period 1988-1993) with pumping rates of about 3.00.000 m^3/day in 1988 and 4.00.000 m^3/day in 1991. This rate is estimated to be increasing to about 9.00.000 m^3/day in 2010. However, Hanoi is located 95 km from the Nam Dinh coastal areas and no influence is to be expected at the coast. However, the subsidence in Hanoi may cause subsidence of the riverbed of the Red River, passing Hanoi. It may induce the trapping of sediment.
In Nam Dinh province, little is known about quantities of groundwater extraction and about the possible adverse effects of groundwater extraction. Probable extraction sources are its main industries, from which the textile industry is the most likely one and an urban water supply plant. Nam Dinh City (the only major city in Nam Dinh province) has a population of 228.053 people and a density of 4.920 people/km^2 (2001) and is equipped with a plant supplying water for 71% of the city population. In the rural area of the province, there are 17 works supplying water and approximately 80.000 drilled wells. The city of Nam Dinh is regarded as the most probable area where groundwater extraction on larger scale might be applied. Still, as the distance between Nam Dinh City and the coastline is about 40 km, little influence is to be expected regarding groundwater extraction related subsidence in the coastal areas.
Superficial drainage of the agricultural lands will also induce subsidence. As this is widespread practice in the coastal areas, it may have a significant influence. However, since no measurements of subsidence are available, the influence cannot be quantified.

Flood control and hydro-power versus decreased fluvial sediment yield

Floods are the worst of all hazards facing Vietnam. The people in the Red River delta have been largely successful in coping with the floods, by constructing flood control works.
Among the flood control works, the upstream damming of rivers has been applied, creating reservoirs. The advantages of these river dams are twofold: First, a significant reduction in flood levels can be achieved downstream in case of floods. Second, the dam can host power generators for the production of electricity. However, dams may have significant side effects.
The most important side effect, relevant for the Red River delta coast is a possible reduction in sediment supply to the coast as a result of the trapping of suspended sediments in the reservoir.

The Day River was dammed in 1937 (fig. 2.1). A water gate was built at the beginning of the river (bifurcation of Red River) in order to protect the Day River basin from floods of the Red River and to reduce the water level of the Day River for gravity drainage for fields along the Day River. The water gate will be opened to divert floods from the Red River when water levels at Hanoi exceed 13.6 m.

Thac Ba reservoir is located on the Chay River (parallel to and east of the upper Red River), with a storage capacity of 1.2 * 10^9 m^3, long 80 km and wide 8 km. This reservoir has a catchment that accounts for 4.3% of the total Red River basin area, so its flood mitigation effect is limited. During the dry season, a flow is released of about 160 m^3/s. The Thac Ba power plant has a capacity of 108 MW.

Hoa Binh reservoir on the Da River (fig. 2.1) has an area of 208 km^2 and had an initial storage capacity of 9.45 * 10^9 m^3. Construction works commenced in 1979 and finished in 1983. The Hoa Binh power plant has a capacity of 1920 MW and its average yearly energy production is 7-8 billion kWh. The dam (fig. 2.7) was built near the town of Hoa Binh, approximately 250 km upstream of the Red River mouth.
During high floods (1945, 1969, 1996), the Da River flow had a proportion of 53% -57 % of the total Red River discharge at Son Tay (location where all the inflow by highland catchment tributaries is redistributed to the delta tributaries). During the dry season, a flow is released of about 240 m^3/s. Suspended sediments settle in the reservoir, limiting the storage capacity and therefore shortening the life span (expected life time: 150 years). Average annual siltation has reached 60 million m^3 (100 million tons) in the period 1990-1995, but in 1990 and 1991, the figures were 90 million m^3. The total sediment load of the Red River system is estimated at 114 million tons per year.
Positive effects of the Hoa Binh dam are the availability of cheap electricity, accounting for 40% of the yearly national electricity production. Hence, the dam is of great importance for the economic development of the country. Next to that, the flood levels at Hanoi are to be reduced with about 1.5 m. Negative effects are water shortage and saline intrusion in the coastal areas during the dry season and social-economic problems because of the resettlement of people living in the reservoir area. The riverbed downstream of the dam is believed to be impacted in a range of 30-40 km, having scouring depths of about 10 m (An, 2000, Nghia, 2000).

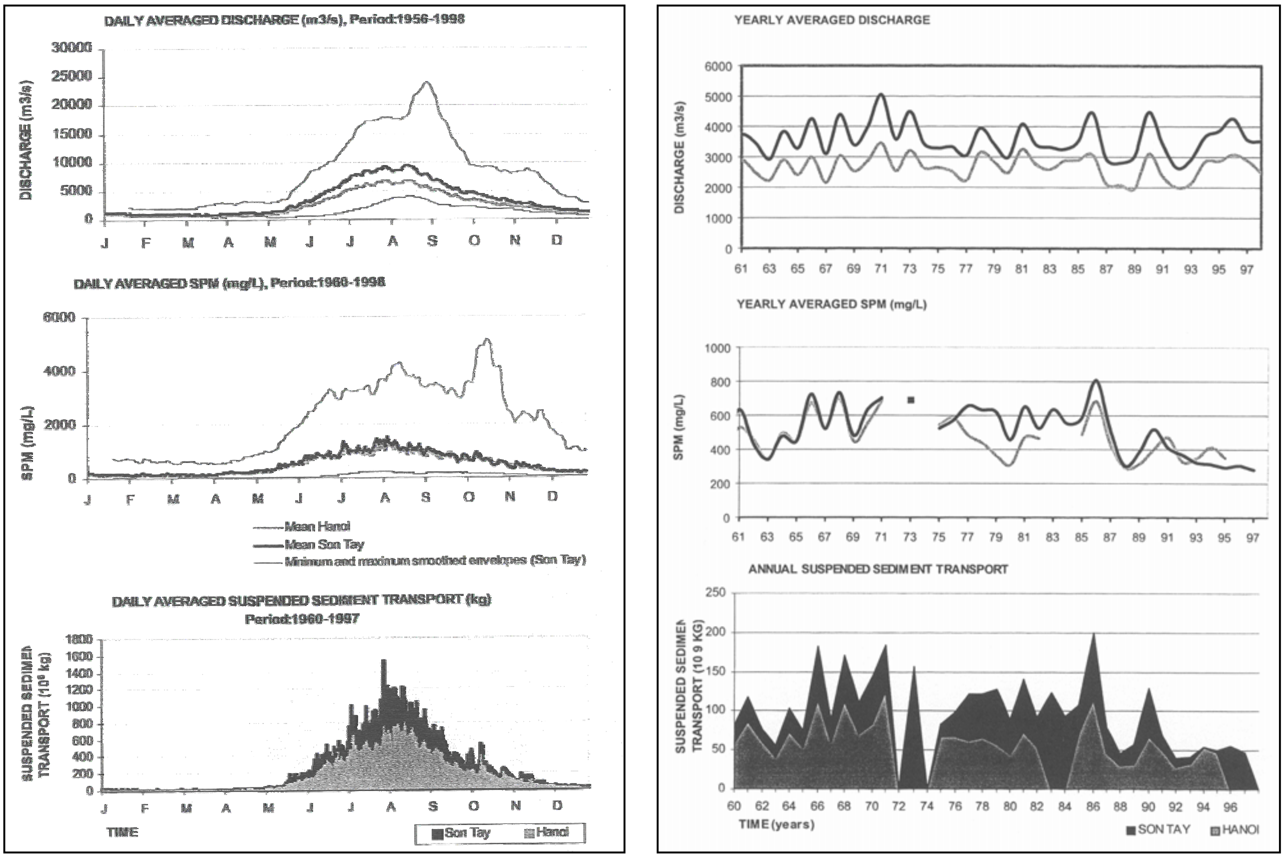


Fig. 3.10. Seasonal variation and yearly averages in discharge, SPM and suspended sediment transport at measuring stations Son Tay and Hanoi (Van Houwelingen, 2000).

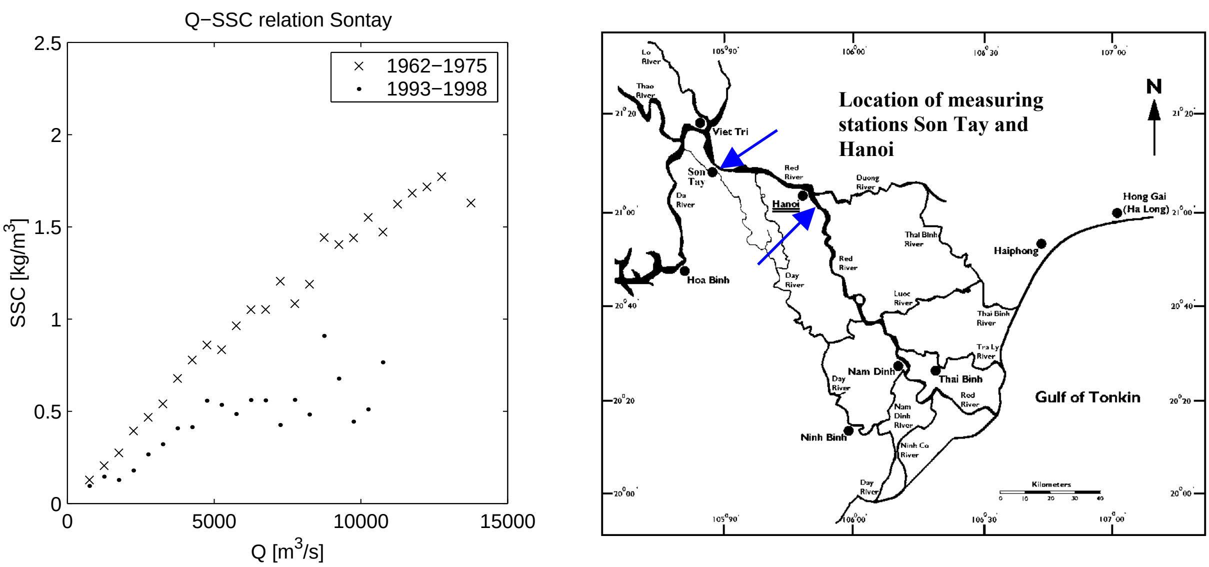


Fig. 3.11. Correlation diagram of discharge at Son Tay and SPM for periods before and after construction of the Hoa Binh dam (Van Maren, 2002) (locations of measuring stations on the right).

A 1990 internal survey of World Bank concerning hydroelectric dam projects showed that 58% were planned and built without any consideration of downstream impacts. Downstream of the Hoover dam in the US, the riverbed downstream of the dam had lowered more than 4 meters in 9 years after construction. Since the building of the Aswan dam in Egypt, located more than 900 meters upstream of Cairo, the sediment supply to the coast reduced with 98%, leading to severe erosion, with rates exceeding 100 m/year. The sediments are trapped in the reservoir and on the delta itself, because of the reduced flow in the delta channels.

Since the construction of the Hoa Binh dam, erosion is reported in the Red River mouth (Ba Lat estuary). Van Houwelingen, 2000, has studied the temporal and spatial variability of the Red River and the impact of the construction of the Hoa Binh dam. The used data set comprised daily water levels, discharge, suspended particle matter (SPM) and suspended sediment flux for the period 1960-1998, measured at the stations of Son Tay and Hanoi.
After 1987 a decrease in SPM and suspended sediment transport is observed, the discharge however, does not seems to change (fig. 3.10), except a shift of the peak discharge.
The correlation diagram of discharge and SPM for the periods before and after the construction of the dam (Van Maren, 2002)(fig. 3.11) showed since 1993 lower SPM values for a certain discharge, indicating that less sediment is transported in the period after construction of the dam.

Other plausible causes for the decrease in SPM values may be decreasing erosion in the catchments of the Red River. As this is a recent governmental policy, raised in the mid 90's, it does not give a plausible explanation for the rapid decrease in SPM values after 1987.
Compared to the total load of the Red River system, being estimated 100-114 million tons per year, the yearly trapping of approximately 60 million m^3 (100 million tons) is enormous. The accuracy of the approximations may be subject to debate. Nevertheless, these figures indicate in any case a major impact of the dam on the sediment supply to the coastal areas.

In case that there would be soil tests available for various locations along the longitudinal profile of the Red River, downstream of the dam, a more reliable hypothesis of the influence of the dam could be posed. In places where downstream of the dam erosion occurs, the sediment sizes should be coarser than where there is no erosion of the riverbed. In this way, the total river length, impacted by the dam can be quantified.

Deforestation versus soil erosion and excessive accumulation near river mouths

One of the reasons for the accelerated excessive accumulation in the direct vicinity of the Red River mouths is soil erosion in the catchment areas of the Red River and in the delta plain itself. Degradation of the natural rainforests in Vietnam is the most important reason for soil erosion. In this section, an overview is given on the extent of the forest loss, the causes and the time and spatial scale on which the clearance has occurred.

Extensive forest loss has taken place in Vietnam since the 1940's. Until that time, clearance was largely restricted to the Red River delta, the drier parts of the Mekong delta, the coastline, lowland riverine areas and some upland areas. During the colonial times, large areas of natural forests were cleaned for the cultivation of rubber and coffee trees and other tropical cash crops. Despite the fact that some 43% of forest cover still remained, the process of forest clearing for profits continued.

> Geographer E. Willard Miller wrote in 1947:
> "The Forestry Service of Indochina has indicated that 16 percent of the forests were being destroyed by ray cultivation (that is the traditional `slash and burn' method employed by the wandering tribes), 17 percent were impoverished by deforestation, 33 percent were intact but largely in the inaccessible interior areas of Laos and Cambodia, and 34 percent were accessible and were being exploited."

Continuous warfare during the period to the mid-1970's caused considerable forest destruction. However, it must be noted that erosion was already a problem on the steep hillsides with thin jungle soils long before the wars, which devastated the country (Tully, 1993). The massive spraying of defoliant herbicides (e.g. Agent Orange) by the US administration in the 1960's caused massive vegetation losses. However, these defoliants were not used in the northern part of Vietnam (Arison, 1995).
In the Red River delta, deforestation was most intensive in the 1960's and 1970's. At that time, the US administration ordered the bombing of Hanoi, Haiphong and strategic communication centres in the north of Vietnam. Due to these war-related events, several of the provinces surrounding the delta had to host large numbers of migrants.
Reconstruction after the war resulted in intense lumbering operations to provide materials for rebuilding homes, schools, hospitals and industry (Collins, N. M, Sayer, J. A., and Whitmore, T.C., 1991, Tuong, 1997, De Koninck, 1999).
Then came a period of population explosion, with a size of population of only 35 million people in 1945 coming up to 72.5 million people in 1994, thus making the practice of forest clearing for food production become widespread over the whole of Vietnam.

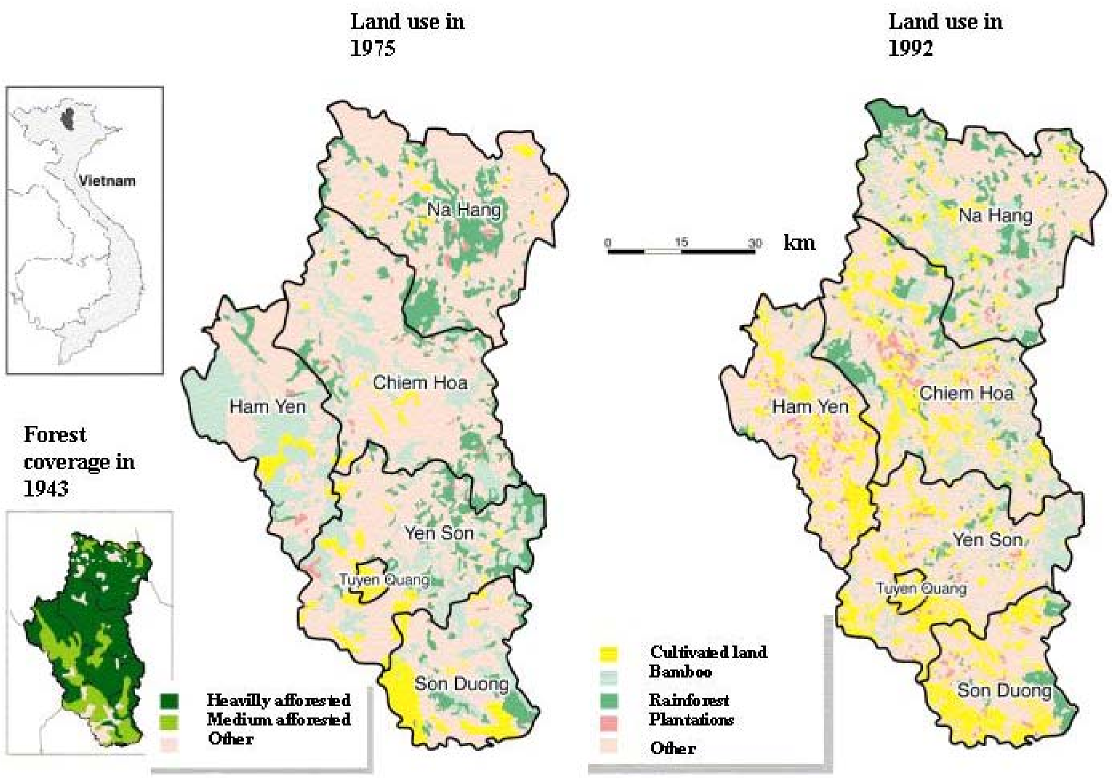


Fig. 3.12. Forest coverage in Tuyen Quang province in 1943 (Maurand, 1943) and land use in 1975 and 1992 (Forest Inventory and Planning Institute, Hanoi, 1994).

Next to the refugee migration to the northern highlands during the American war, governmental regulated migration projects were carried out, reducing the population of the Red River delta by sending people to the northern highlands. The previous mentioned secondary effect was increased deforestation in the highlands. In colonial times, administrators did initiate some population transfers, but they remained very limited. In the period between 1961 and 1966, the Vietnamese administration sent one million migrants to the mountainous provinces surrounding the Red River delta, creating "New Economic Zones" as a solution for the overpopulation of the delta. Due to this massive out-migration of the delta the provinces belonging to the foothills and mountains surrounding the delta have nearly doubled their relative demographic weight, from 9% to 17 % in the period from 1926 to 1991 (De Koninck, 2000).

According to De Koninck, 1999, the fundamental present causes of deforestation in Vietnam are demographic growth; economic growth; an increasing demand for food and export crops; and an increasing demand for forest products - primarily wood for the pulp and paper industry, for construction, and for fuel. Agricultural expansion, achieved at the expense of the forest domain, is a result of the already mentioned demographic growth and the national aim for economic growth, encouraging export-orientated commercial agriculture. It is clearly a major cause of deforestation in the Red River delta.
Table 3.2 gives an overview for 1999 of the forest coverage for different areas in Vietnam.

De Koninck, 1999 gives for the Tuyen Quang province, located just northwest of Hanoi at the foothills of the northern highlands, a comparison between the forest coverage of 1943 (study conducted by French forestry engineers), 1975 and 1992 (fig. 3.12). The study reveals a declination in forestry coverage from 90% in 1943 to nearly 12% in 1975.

Table 3.2. Forest coverage in Vietnam, 1999.

Region	Percentage
nation-wide	28%
north west	**14%**
paper raw material area (in the north)	**24%**
northeast	**20%**
Red River delta	**4%**
north central Vietnam	35%
coastal south central Vietnam	35%
western high plateaux	56%
east south Vietnam	21%
Mekong delta	5%

4.3 Hypothesis of historical and future development of the Red River delta

The southern part of the Red River delta, of which Nam Dinh province forms a part, is the present active part of the delta. The northern part seems to be abandoned 1.000 years ago.

The mechanism of river mouth development is temporal variability in monsoon river discharge, causing a leapfrog displacement forward. River training works confine both the river flow and the sediment supply to river mouths, causing the raising of the riverbed and a decrease in riverbed slope. Both river training works and settlement of the subsoil due to superficial drainage in the agricultural lands (which accounts for 70% of the land use) cause an increasing difference between riverbed elevation and surrounding coastal plain elevation.

The Red River mouth has a cycle of 30-40 years with regard to its orientation. However, the last time that it drastically changed its course was 500 years ago. Due to the increased resistance of flow in the river mouth, the river sooner or later may break through its levees in case of a major river flood and it will find a shortcut to the Tonkin Gulf. As the coastal plain is depressed relative to the riverbed, it will be subjected to flooding and a new river course may form in the coastal plain.

A breach in the dike system near the So River is not unlikely, resulting in a restoration of the former river into a major river branch. However, the location of a possible breach in the dike system may also occur on the north river bank, resulting in a diversion of the Red River to the Thai Binh province, located north of Nam Dinh province.

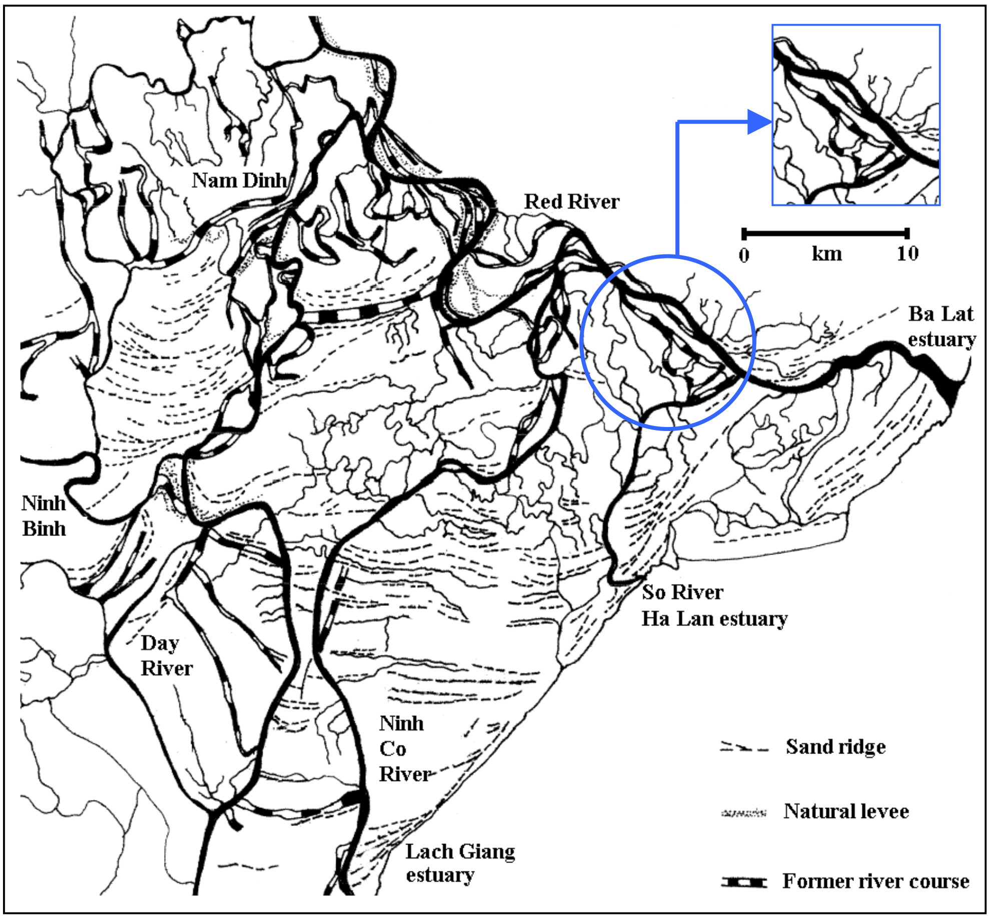


Fig. 4.1. Morphological changes in Nam Dinh (source unknown).

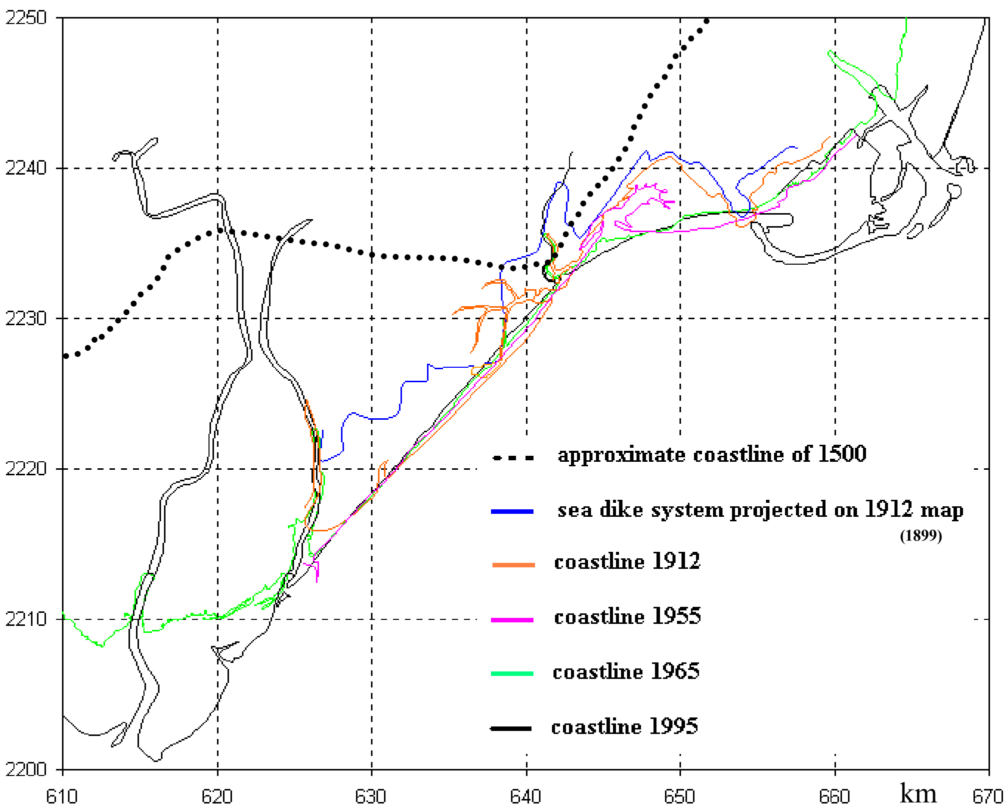


Fig. 4.2. Coastline changes Nam Dinh between 1500 and present.

5 Nam Dinh coastal development from 1500

5.1 Introduction

In this section, the coastal development from the Red River delta from 4.000 years ago until now (fig. 3.7), will be linked to the development of the part of the delta belonging to Nam Dinh province, from 1500 up until present (fig. 4.1).
For studying the development of the delta, use was made of the work of Vietnamese geologists, an image taken by SPOT satellite in 1995 and for recent time development, geographical maps.
The oldest available map of the Nam Dinh coastal districts (1912), based on present-day earth projections was made by “Service Geographique de l'Indochine". SGI (Indochina Geographic Service) was founded in 1899 by the French administration in Vietnam. SGI was responsible for every undertaking in surveying and mapping in Indochina (Vo, 2001). Comparison of maps with various projections, published in 1912, 1955, 1965 and 1995 provides an estimate of coastline changes during the last century. For comparisons of the different coastlines, the maps have all been transformed to a Gauss projection, fitting the 1995 SPOT satellite image, using inland landmarks as a reference. The accuracy of the mapping of the 1912 map on the 1995-satellite image is estimated at approximately 100-150 meters. Maps published since the 1960’s show a much higher accuracy. In this study, more accurate methods of coastline mapping than the method described above could not be applied because in the past, accurate frequent coastline mappings were not applied in Vietnam.

5.2 General coastal development

At around 1500, the coastline of Nam Dinh was characterised by a convex shaped coastline near the So River mouth. This convex shape turned into a concave form in both northern and southern directions (fig. 4.2, fig 3.7).
After 1500, the So River mouth showed little accretion and the region just located north of it developed as the major accretion area. In the south of Nam Dinh province, both Ninh Co and Day rivers started the expansion of their estuaries rapidly. A reason to assume that before 1500, the So River might have been the major branch of the Red River is that the former course of the Red River was more southward located and was directed southward, connecting to the present So River (inset in fig. 4.1). Likewise, the coastline orientation of 1500 (fig. 4.2) with the protruding So River mouth gives a similar indication. There might have been an avulsion, which caused abandoning of the So River and thereafter, the developing of the present course of the Red River, in a northern direction (fig. 4.3). This avulsion seems to be combined with lateral channel migration. The resulting morphological phenomenon shows the development of a convex-shaped river mouth similar to the former So River mouth.

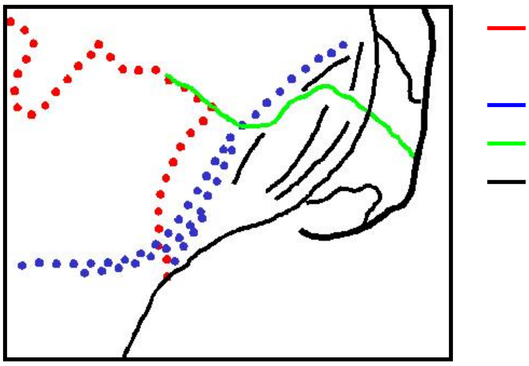


Fig. 4.3. Shift of Red River in northern direction and resulting river mouth development

The region located between the So River and the Ninh Co River (fig. 4.1, 4.2) (coastline of Hai Hau district) used to reflect an orientation of 100 degrees to the north. In the first stage of land extension after 1500, the land tended to retain its 100 degrees orientation. In later stages, the coastline tended to reflect a 45 degrees orientation, similar to the orientation of the former 1500 coastline northeast of the So River mouth. The most recent land extension near the Ninh Co River mouth extended not as a rectangular area, offsetting in southward direction, but as a 50 to 60 degree orientated curved extension. The overall present coastline orientation was reshaped into a 45 degrees orientation. In fact, when comparing the shape of the coastline of 1500 and the present one without taking into account the intermediate coastline stages, it can be concluded that present coastline is not that different from the shape in 1500 (fig. 4.2), it just shifted in northeast direction.

The sea dike system (fig. 4.2), projected on the 1912 map (sea dike construction date approximately 1899) indicates the coastline position in the middle of the 19th century and is a result of a large reclamation project, carried out between 1828 and 1830 by Nguyen Cong Tru, an administrative servant of King Minh Mang and King Thieu Tri. The reclamation project comprised coastal lands in Nam Dinh and Ninh Binh.
Going to the north, the position of this sea dike near the Red River mouth indicates a late 19th century coastline position.

From the last century up until now, the middle part of the Nam Dinh province coastline is known as eroding. The rate of erosion is subject to discussion and will be discussed in section 4.4.

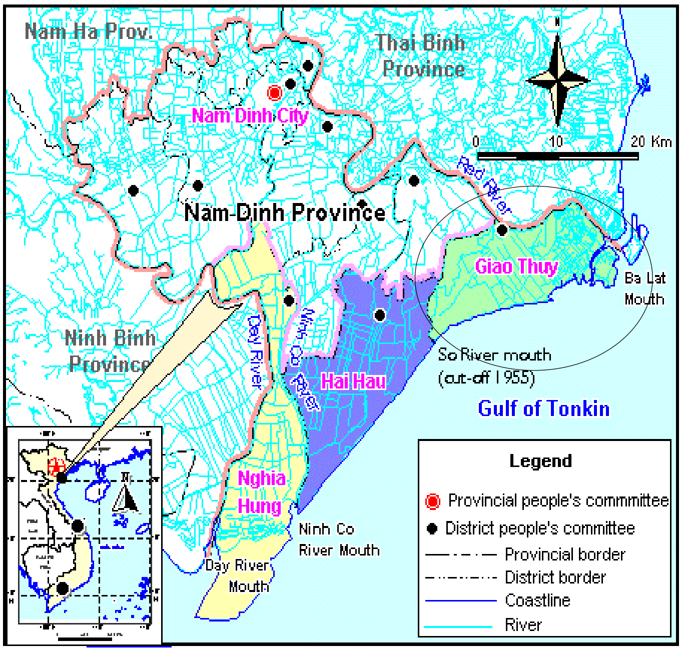


Fig. 4.4. Map of Nam Dinh province, Giao Thuy district encircled.

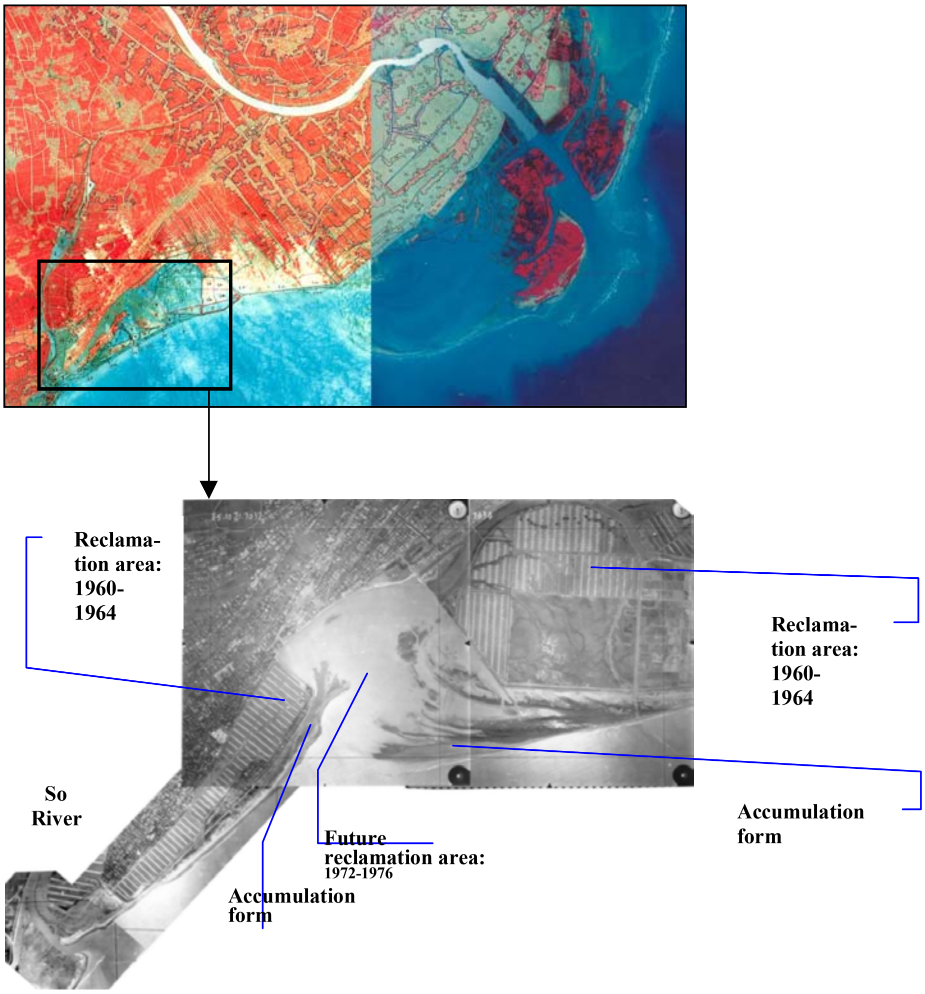


Fig. 4.5. Upper image: SPOT image Giao Thuy district, 1995. Lower image: Arial picture of Bach Long saltpan reclamation area dated probably late 1960's (source: Hung, N.M., IM Hanoi).

5.3 Giao Thuy district coastal development

Giao Thuy district (fig. 4.4) started it development in the early 19th century by accumulation of Red River sediments (estimated sediment output of the Red River is 23 million tons/year (Vinh et al, 1996)). The land reclamation by Nguyen Cong Tru (fig. 4.6, 4.7) in the period 1828-1830 just eastwards of the upper course of the So River is an example of the first land reclamation project for agricultural development in Giao Thuy, to be followed by many successive reclamation projects until 1976. The latest reclamation activities south of the present river mouth took place in the period 1960-1976 and were aimed at development of areas for sea salt panning (fig. 4.5). In order to let seawater, being the supplier of salt, into the area, it was levelled below mean sea level. The reclamation area is coloured blue-green in figure 4.5, indicating the tidal influence.

According to the Ramsar convention, the present river mouth estuary is a preserve for migratory birds. However, widespread reclamation is still being applied, not for agricultural reasons but for the recent boosting development of aquaculture basins, for the lucrative breeding of shrimps. The Vop River, a small tributary penetrating into the southward-located lagoon was dammed in 1985, to be re-opened at present.

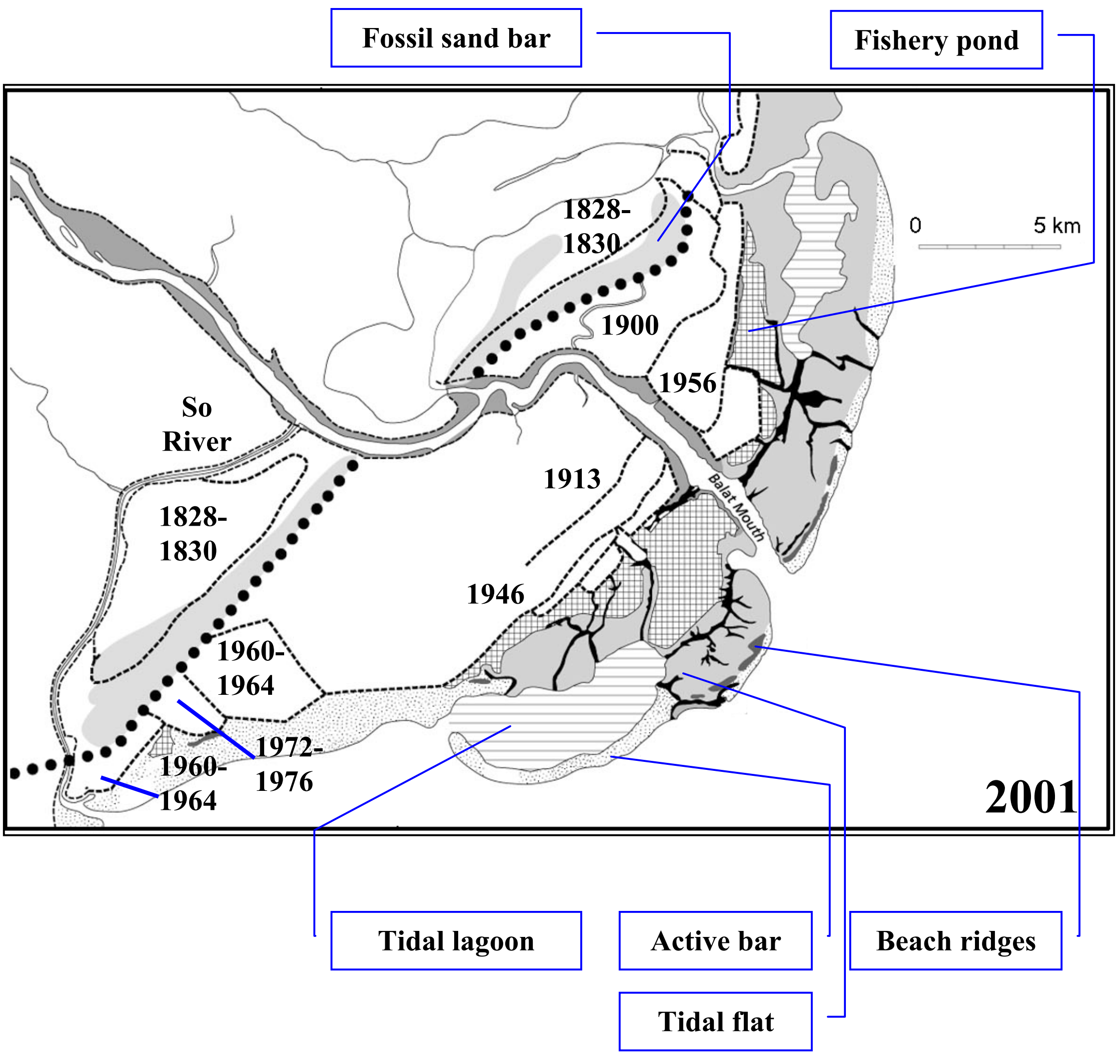


Fig. 4.6. Classification of the Red River mouth, Ba Lat estuary (modified from Van Maren, Utrecht University, the Netherlands).

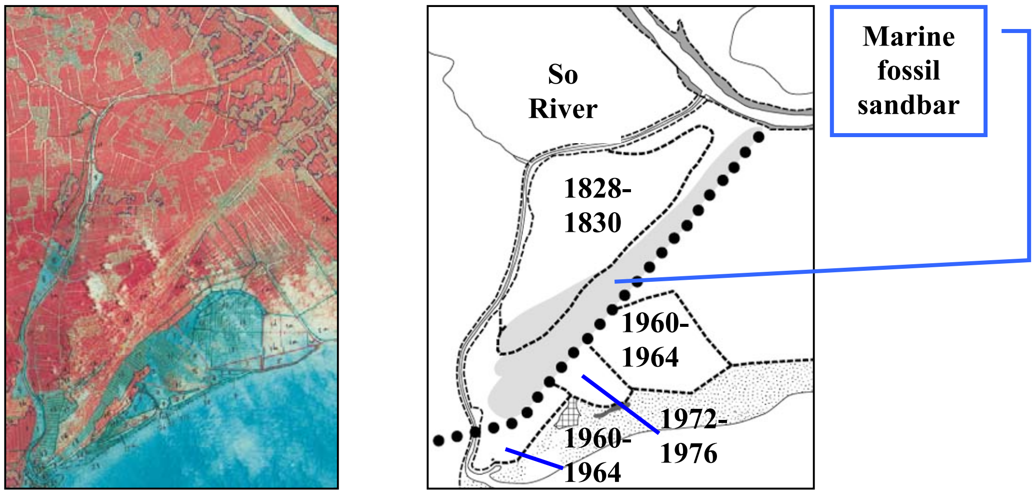


Fig. 4.7 Nguyen Cong Tru reclamation located in between the present So River and a marine sand bar.

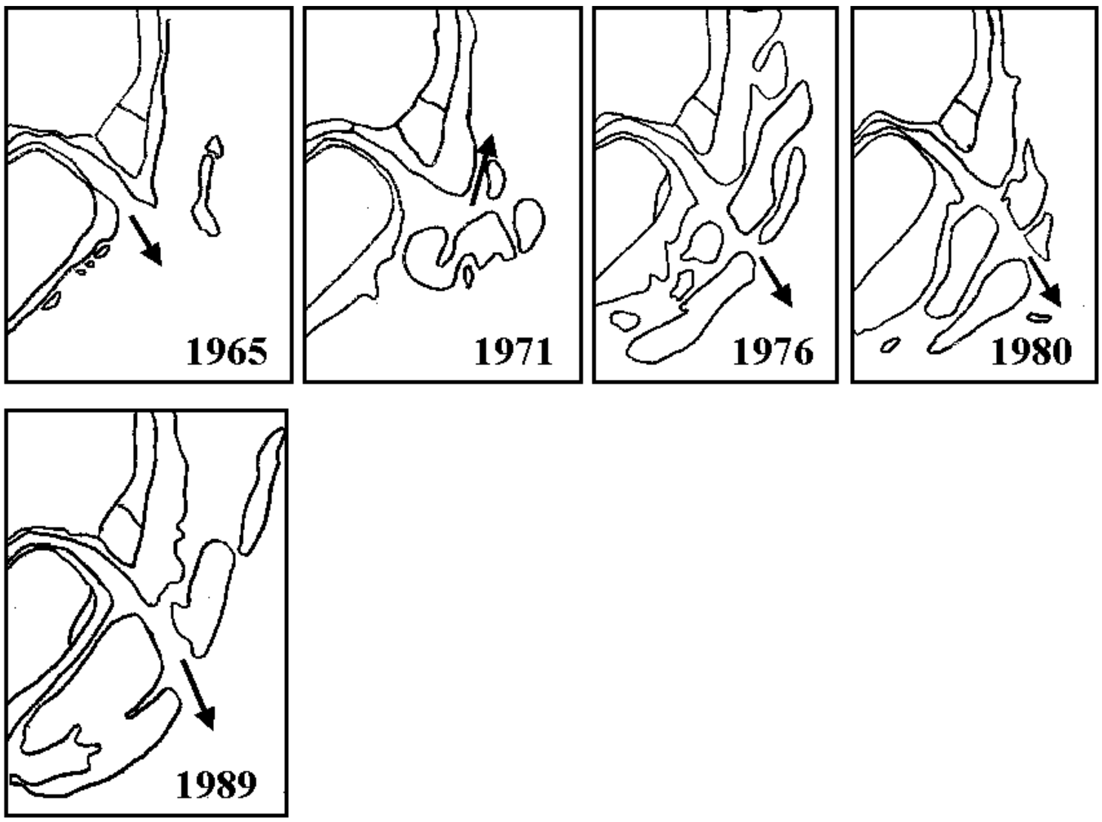


Fig. 4.8. Red River mouth orientation from 1965 to 1989. The arrows indicate the altering main discharge gullies (modified from Cu, N.V., 1989, Geography Institute Hanoi).

Both the Nguyen Cong Tru reclamation in the former riverbed of the So River (fig. 4.7) and the river avulsion in earlier times give evidence for diminishing discharge trough the So River in the past. However, it lasted even until 1955 before the upper course of the river was dammed for drainage of the agricultural lands, surrounding the river course. The upstream parts of the So River silted up, the downstream part retained its navigational function.

To illustrate the cyclic behaviour of Red River mouth, an overview is given of the various shapes that it took in the period from 1965 to 1989 (fig. 4.8). The cycle of the mouth orientation is about 30-40 years, enforced by the occurrence of major river floods, which occurred in this century. The last century three devastating river floods occurred in 1945, 1971 and 1996.

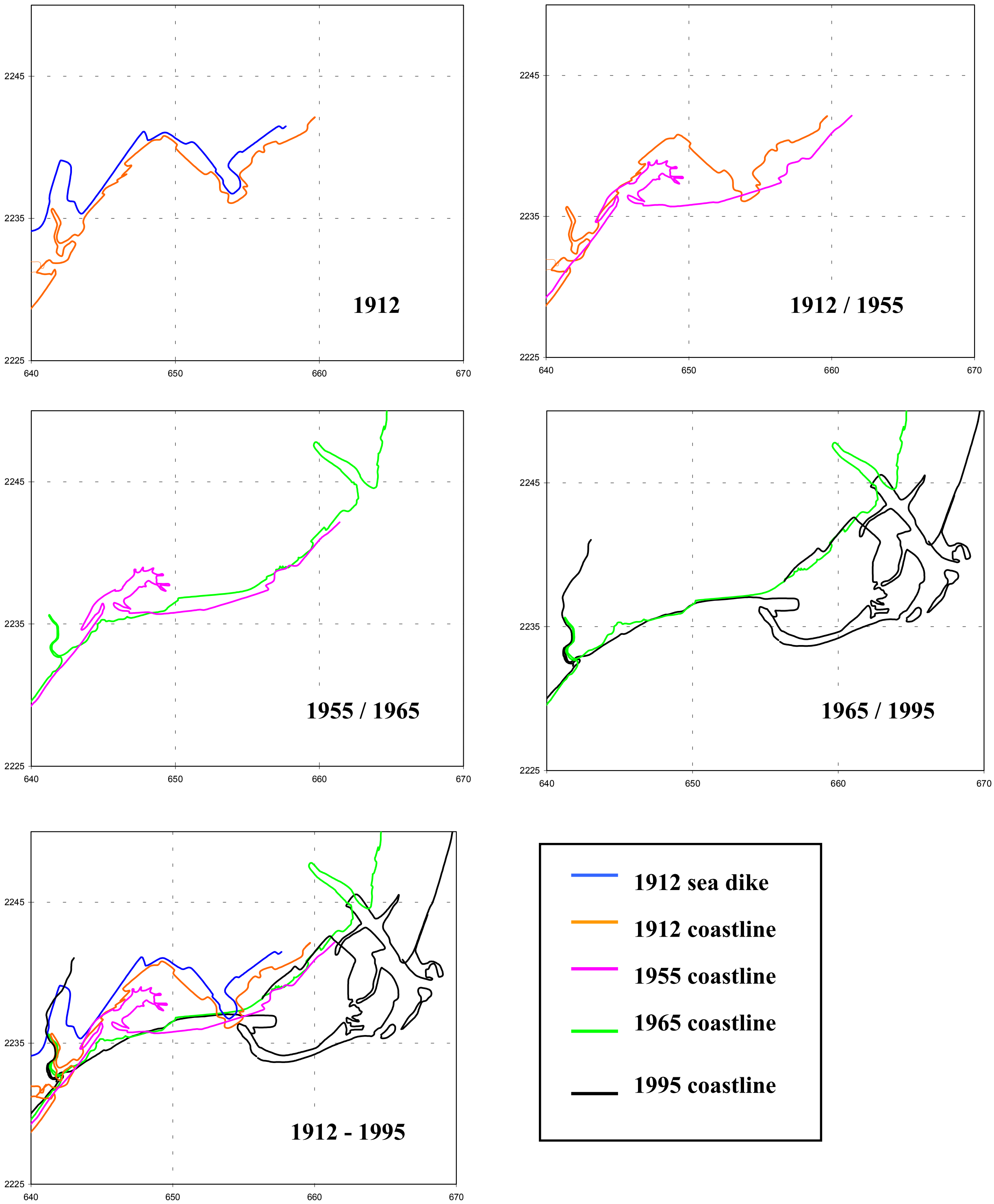
About 90% of the sediment discharge of the Red River occurs during the summer monsoon in a relatively short period from July to August, when the flow can reach up to 23.000 m^3/s. During the winter monsoon period in the months from January to May, the flow can decrease to about 700 m^3/s. Longshore transport, both in north-east and south-west direction, (dependent on the monsoon season) redistributes the sand fraction of the Red River sediment yield along the coast, nourishing (and thus elongating) the two spits on both sides of the river mouth.

It is not surprising that the shape of this mouth influences both transports in northward and southward direction. In fact, the development of spits in longshore direction implies a cut-off of the sediment supply as long as the spit is growing in longshore direction. Sediment supply to southward and northward-located coastal sections will not continue before the spit will be reconnected to the mainland.

Because of the loss of the So River, as secondary supplier of sediments on the northern part of Nam Dinh, the beaches located southwards of both the So River and Red River mouths are now fully dependent on the sediments supplied by the Red River mouth, transported by southward directed longshore transport currents. Northeast directed longshore currents may supply sediments from both Day River and Ninh Co River mouths during summer monsoon periods. But as the net transport is southwestwards directed, the influence of the Red River mouth is dominant. Moreover, it can be concluded that during the historical development of the Red River mouth, the alternating development of spits has greatly influenced the nourishment of the southern located beaches by longshore transport. Despite the fact that little details are known about development of this river mouth before 1965, it is clear that after the 1960's the beaches southward located of the river mouth have been greatly lacking any supply of sediments, transported by southwestward longshore currents.

In figure 4.5, both the upper image and the lower image show the development of accumulation forms, cutting off the sediment supply to downdrift located beaches.

A detailed overview of coastline changes in the last century is given by means of a comparison between maps from 1912, 1955, 1965 and 1995, all transformed to a Gauss projection, shown in figures 4.9 and 4.10.



1912: No. 72, edition march 1912, projection: Clarke ellipsoid / Bonne, source: Service Géographique de l'Indochine Institute Géographique National, Paris, France
1955: No. 72, edition 6-sgif, projection: UTM, source: Service Géographique de l'Indochine, France
1965: No 6249 II, projection: UTM, source: Cartographic Distribution Centre, Hanoi
1995: SPOT satellite image, projection: Gauss, source: Remote Sensing Institute, Hanoi

Fig. 4.9. Comparison of Giao Thuy district coastlines between 1912 and 1995, all fitted onto a Gauss projection (distances in km).

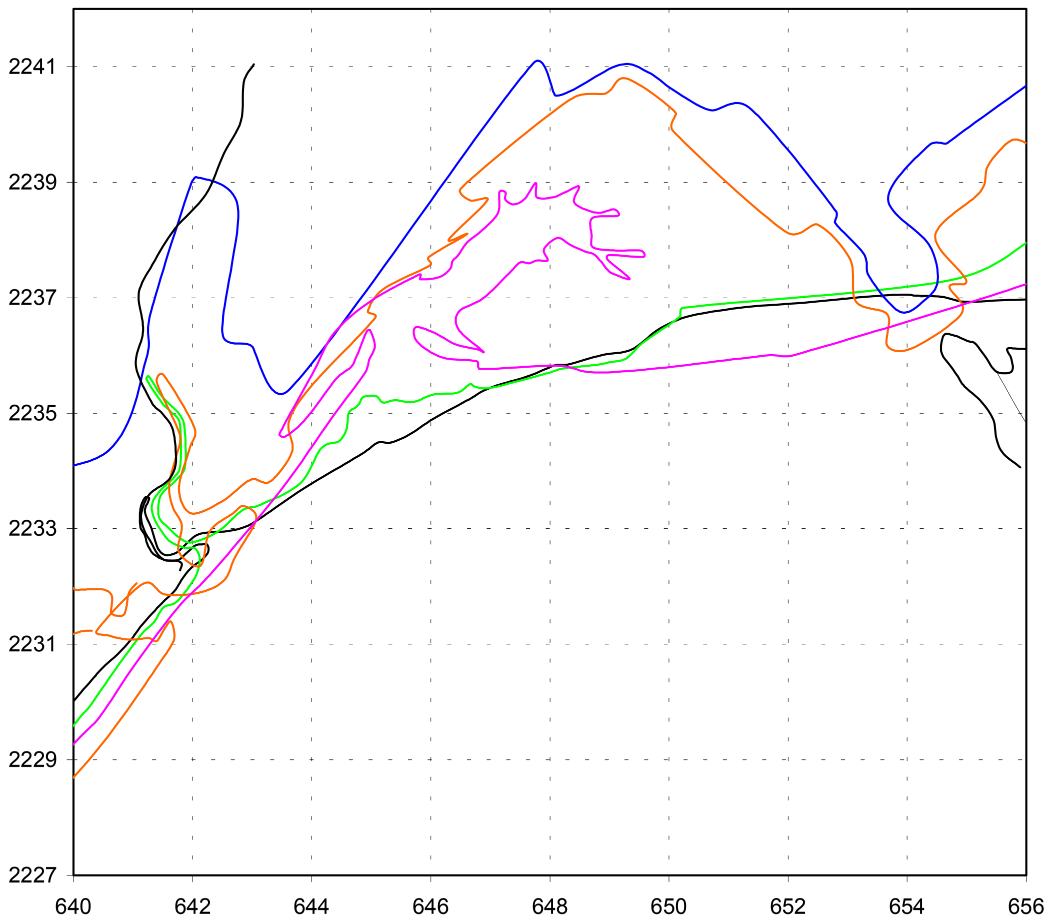


Fig. 4.10. Enlargement of the area just north of the So River mouth, being a major sediment sink until the 1960's (distances in km).

The 1912 coastline is characterised by a hooked landform, creating a bay just south of the Red River mouth. The ongoing land reclamation process in Giao Thuy district may have caused the unnatural shape of this landform. However, when comparing the 1912 coastline with the 1955 coastline, in 1955 some of the protruding “hooked” landform was already eroded and the bay was almost closed with sediment, reshaping the “hook” and the bay into a curved landform. Evidence that the bay, present in 1912, acted like a major sediment trap is given by the presence and shape of accumulation forms (1912/1955 image and fig. 4.5). Due to the cut-off in southward direction, the beaches located just south of the So River mouth already started to erode, generated by increasing longshore currents. The gradients in longshore transport form the mechanism for erosion.
Net longshore drift refers to the difference between volume of material moving in one direction along the coast and that moving in opposite direction. However, net drift averaged over the years or decades may conceal the fact that significant amounts of material also flow in the opposite direction, due to for example storms or local current circulation patterns (Anonymous, CERC, 1992). This seems the case just north of the So River mouth. Between 1912 and 1955, a spit growing in a northern direction (fig. 4.5) was formed just north of the So River mouth (fig. 4.5 upper image) In general, the direction of spits indicates the net longshore drift direction, which is in this situation southward. However, in this particular location, the northward spit growth is the result of local drift reversal, probably due to the refraction of waves around the protruding Red River mouth. The shape and direction of the So River mouth on the 1912 map (fig. 4.10) gives the same indication.

In 1965, the actuate landform was reshaped into a curved form, convex in the north, going to the south turning into a concave form just above the So River mouth. There was some erosion just eastwards of the small bay that was still present in 1955. After 1965, the bay was closed, forming a continuous coastline. Also the first shoals appeared in front of the Red River mouth (not visible on the coastline mapping images, see fig. 4.8), indicating a new cycle in river mouth development.

In 1995, the Red River mouth had formed sandbars projected some 10 km distance of the river mouth coastline in 1965. Fig. 4.8 shows the stages that this river mouth process characterises. After 1965, shoals started to develop in front of the river mouth but the main flow retained its southeastwards direction. During an enormous flood in 1971, the river broke through the main shoal and formed a new main channel in northeast direction. Between 1971 and 1976, the river mouth showed massive accretion accompanied with the formation of tributaries in both longshore directions. One single, closed longshore bar was formed, forcing the river mouth to distribute the flow in both longshore directions. At the end of the period 1971 – 1976, the closed bar was penetrated, forming a new mouth in offshore direction. The 1980 image shows that three south-westward located shoals were formed that eventually were connected into one massive shoal, hosting a tidal lagoon. This is showed in the 1989 image. The latest river mouth shape did not change dramatically during the last 10 years, which may give evidence for temporal relative river mouth stability like in the 1950’s and 1960’s. In future, the adjacent coastlines probably will be reshaped from discontinuous ones into continuous ones, a process similar to the process that has been observed in the region just above the So River mouth, in the first half of this century.

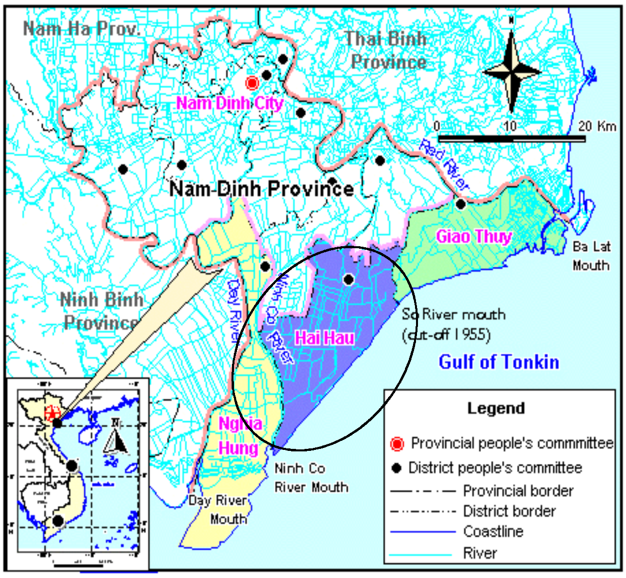


Fig. 4.11. Map of Nam Dinh province, Hai Hau district encircled.

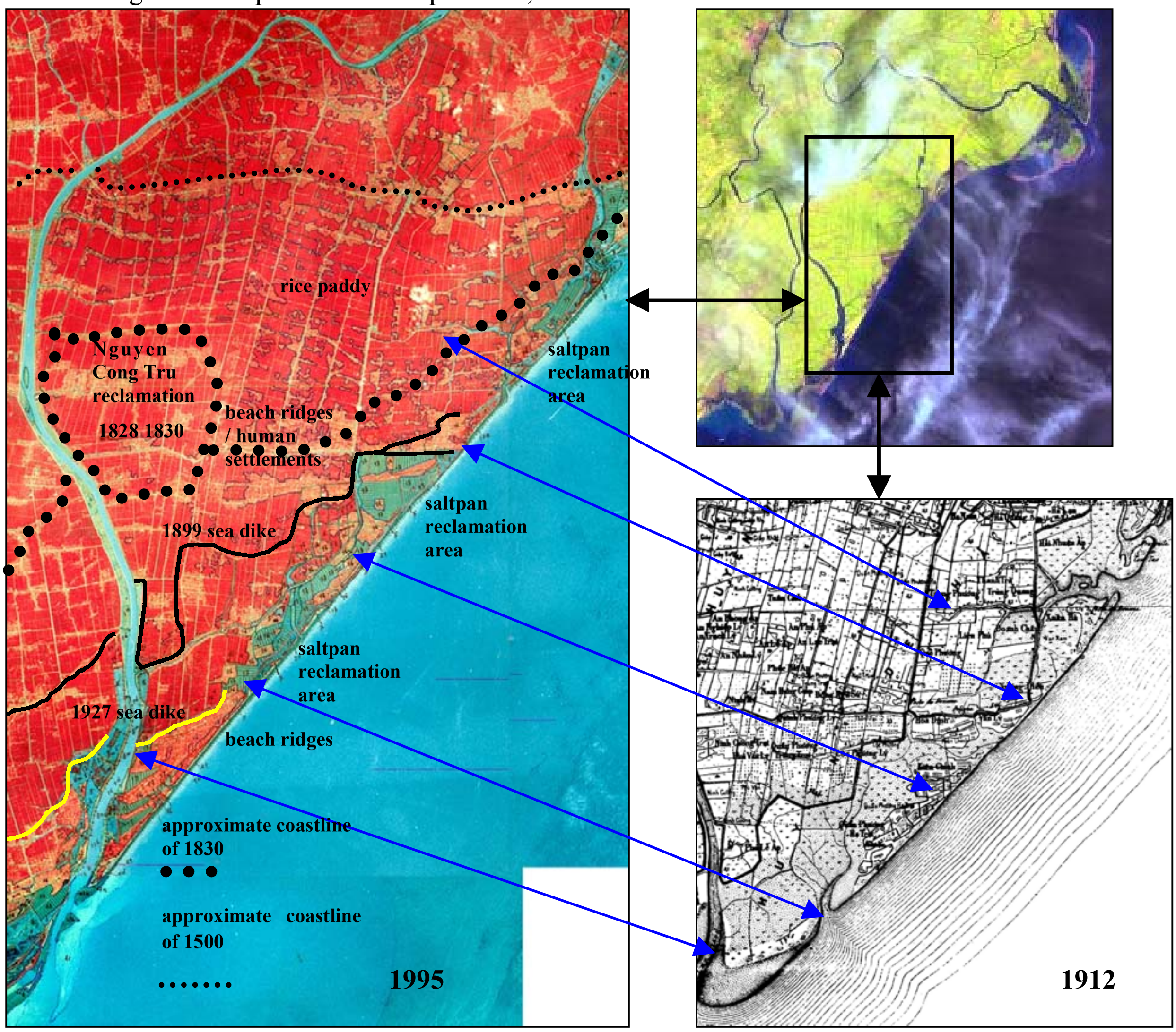


Fig. 4.12 Upper right image: Landsat image (05-05-2001). Dark coloured coastal areas indicate that tidal influence is present. Left image: SPOT image (1995) indicating land use and coastal development (Nguyen Cong Tru reclamation 1828-1830). Lower right image: 1912 map (SGI Paris, France). The blue lines connect locations on both 1912 and 1995 maps.

5.4 Hai Hau district coastal development

The coastal development of Hai Hau district was characterised by the extension of land in a southerly direction. The orientation of district spatial planning indicates the former natural coastal advance (fig. 4.12, left), marked by succeeding reclamation projects and beach formations, indicating human settlements with accompanying infrastructure. Initial human settlement started on beach ridges but extended on man-made mounds as soon as low-lying land was reclaimed. As already mentioned in section 4.2, the coastline turned from a 100 degrees reflection into a 60 to 45 degrees reflection.
The dotted line in figure 4.12 represents the approximate coastline of 1500. However, little is known about the development in time between 1500 and present. The coastline of 1830 can be estimated according to the location of a reclamation project carried out by Nguyen Cong Tru between 1828 and 1830. The most recent reclamation projects have been carried out for salt panning.

> Hai Hau district has 500 hectares of saltpans. Most of them are located directly behind the sea dikes. The land, consisting of compacted clay is covered with one centimetre of sand, used for the extraction of salt from seawater. Saltpan workers are allowed to renew the sand on their land once per year. Sand mining from the beach is officially allowed, from a seaward-directed boundary located 100 m from the sea dikes. The maximum allowed excavation depth is 30 cm. Because of salt production methods (the daily repeatedly re-use of beach sands for salt extraction), the sand looses gradually its porosity, causing decreasing profits. Illegal sand mining for yielding the highest profits is not very unlikely, considering the very low living standard of the salt pan workers (USD 1.5 per family per day). According to the official allowed sand refresh rate, 50.000 m^3 of sand each year is mined from beaches near the saltpan reclamation areas. The beaches bordered by the saltpan reclamation areas are at the same time the most eroding locations of the district. Based on the probably (illegal) higher refresh rate, the quantities of mined sand from the beaches of Hai Hau may be doubled. The mining of sand from eroding beaches may even increase the existing erosion on these beaches.

Figure 4.12 (upper right) shows a Landsat image on which the green colours represent agricultural land use; the dark areas near the coastline indicate influence of the tide. The areas under influence of the tide are known as saltpan reclamation areas. As these reclamation areas (fig. 4.13) (areas in between dotted and continuous line) were carried out in the beginning this century, they mark the difference between the present landform and the landform of the late former century (see also the location of the sea dike in 1912, fig. 4.12). These low-lying former tidal flats (relatively low to the rest of the delta) are extremely vulnerable for flooding in case of dike failures.

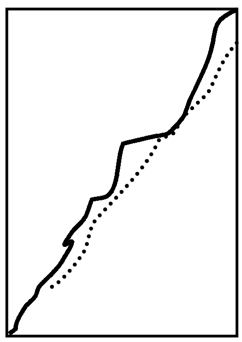


Fig. 4.13. —— Coastline late 19th century
…….. Present coastline

These former tidal flats have probably deliberately been reclaimed in a premature stadium of their development, to be able to make use of the tidal difference for salt mining activities.
A detailed overview of coastline changes in the last century is given by means of a comparison between maps from 1912, 1955, 1965 and 1995, all transformed to a Gauss projection, shown in figures 5.14 and 5.15.

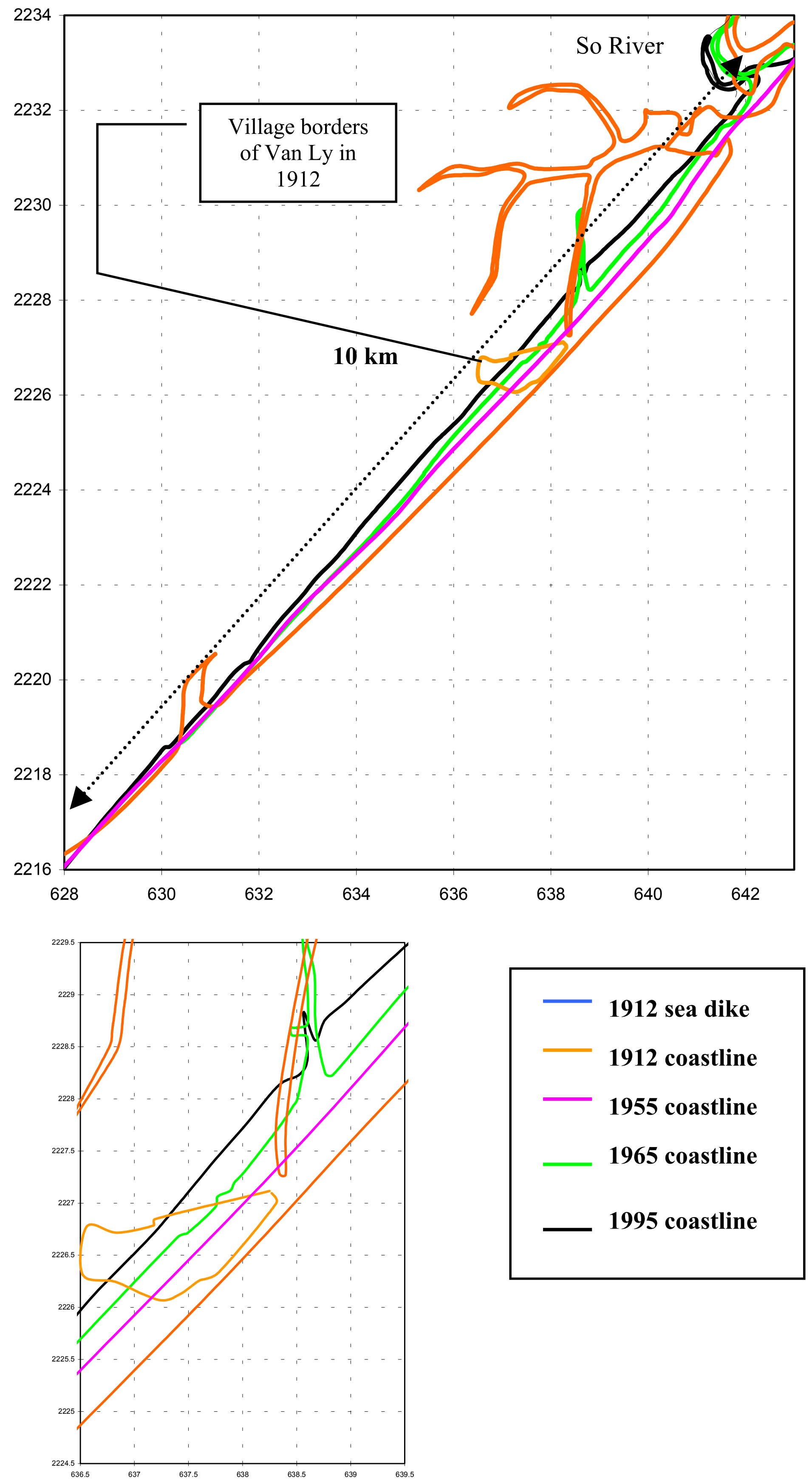


Fig. 4.14. Comparison of Hai Hau district coastlines between 1912 and 1995, near Van Ly village (orange circle representing village borders in 1912).

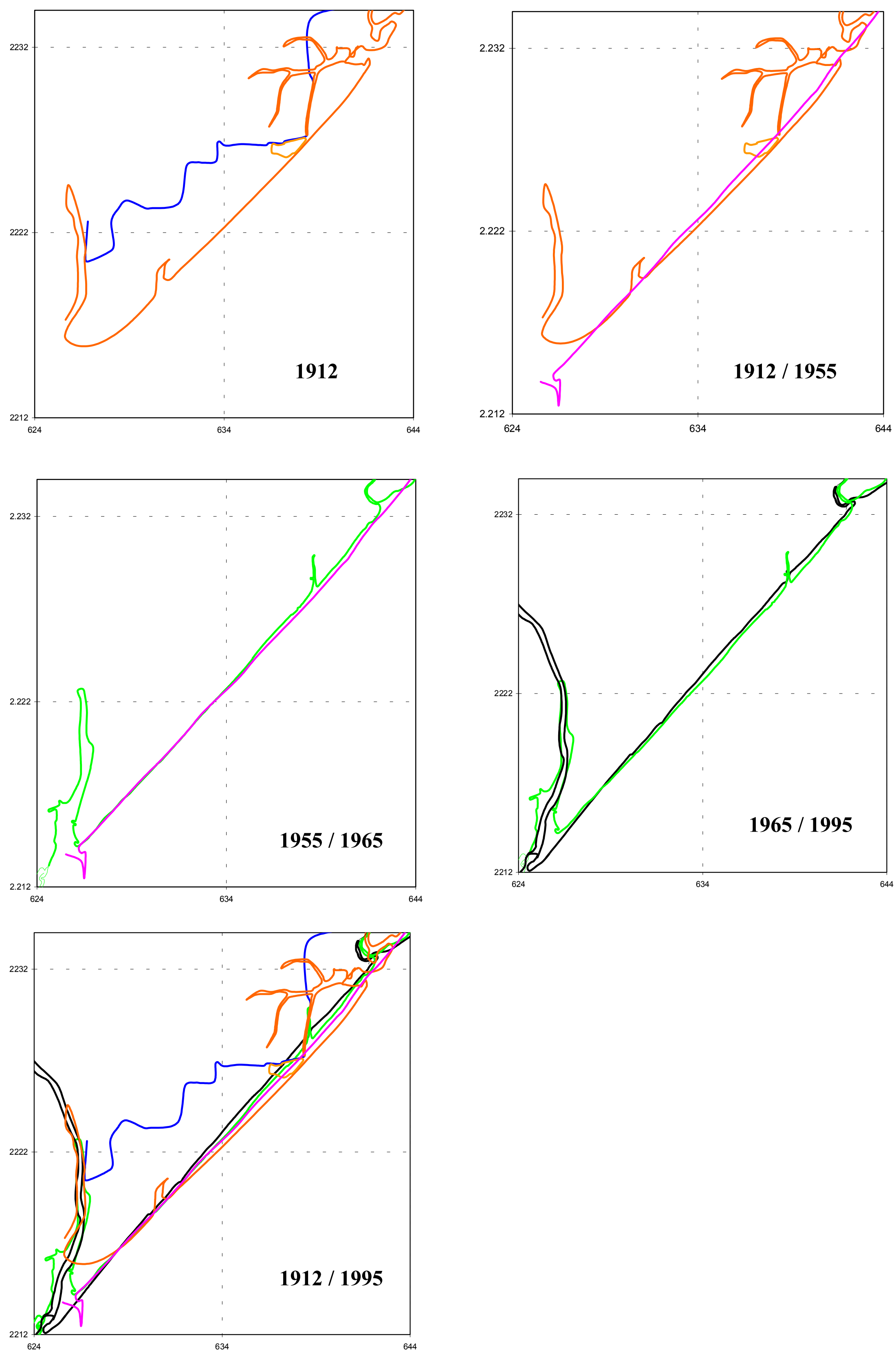
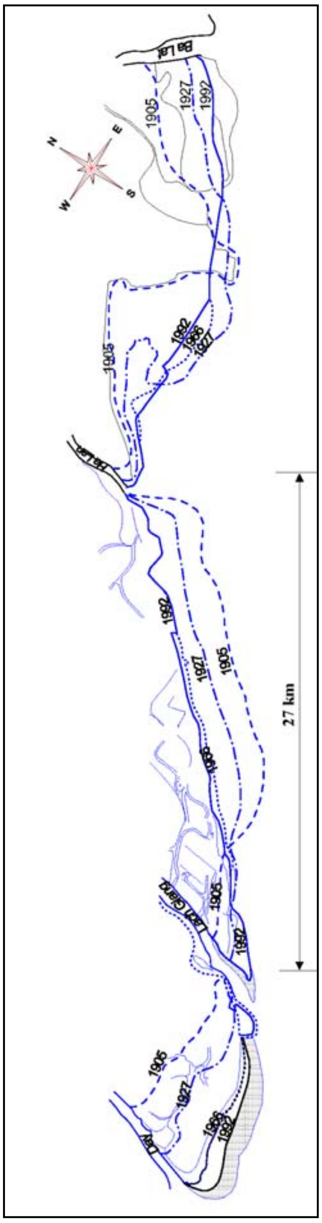


Fig. 4.15. Comparison of Hai Hau district coastlines between 1912 and 1995, all fitted onto Gauss projection (distances in km).



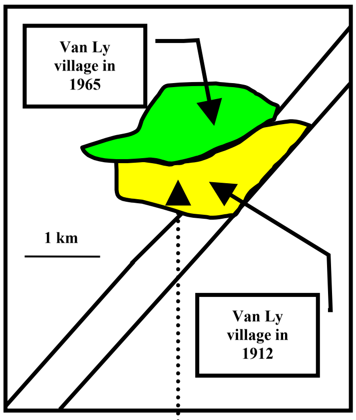


Fig. 4.17. Relocation of Van Ly village in the period from 1912 to 1965

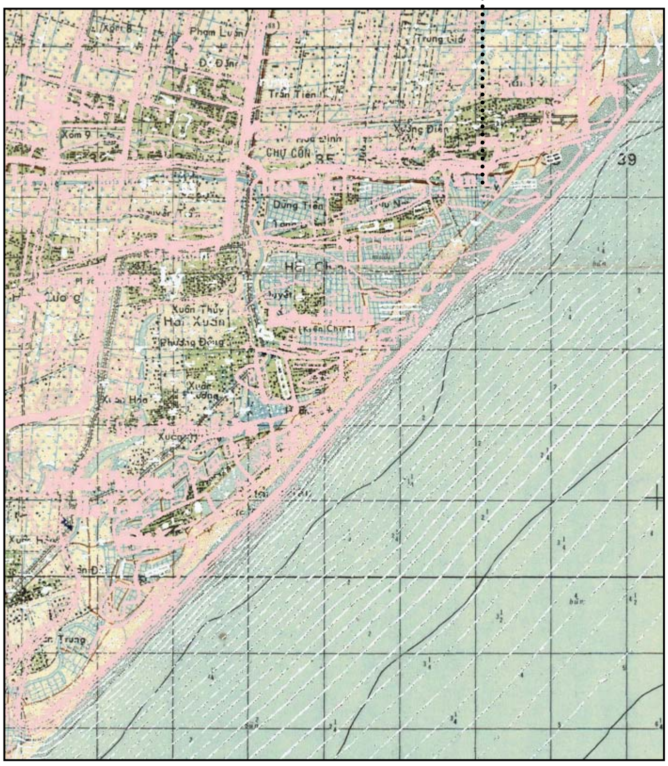


Fig. 4.16. Coastline changes according to Pruszak, 2002, based on a 1992 local coastline map.

Fig. 4.18. Fitting of the 1912 (pink) and the 1965 map. The accuracy is in the range of 100-150 m.

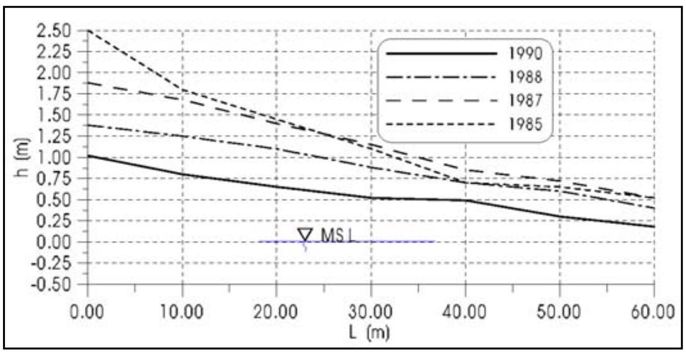


Fig. 4.19 Beach level changes, measured in the middle of the erosive part of Hai-Hau district (Pruszak, 2001).

Comparison of the various maps of the last century (fig. 4.14, 4.15) shows an erosion trend, turning the coastline from a convex form into a concave form. It is not exactly known when the erosion started. However, it is clear that until the beginning of this century, man has reclaimed land, being confident about the stability of the coast. It must be noted that the land expansions were essential, in coping with the increasing population pressure in the delta.
In the 19^{th} and 20^{th} century, the lands were reclaimed, the rivers were confined by dykes and the small rivers in the district were cut-off with sluices, being part of the reclamation of the coastal areas. The already diminishing sediment supply from the So River and the cut-off of small rivers crossing the district caused a major decrease in alluvial sediment supply to the low-lying lands. As shown in figure 3.5, there is an interval between the time of abandoning of a delta coast and the onset of the erosion. Probably, at the time of the land reclamation projects in the middle of the 19^{th} century, the delta front was already eroding, leaving a stable coastline. However, the convex sea floor profile started to change in a concave retreating profile. When intersecting the coastline, probably late 19^{th} century, the erosion accelerated.
The coastline could not adapt itself in all the locations along the coast, because of local fixation by sea dikes. This caused lowering of the beach in places (fig. 4.19).

The rate of erosion is subject to debate. DARD Nam Dinh reports the following varying erosion rates:

Table 4.1. Erosion rates according to DARD Nam Dinh.

From	To	Lower boundary rate	Upper boundary rate
1950	1954	35	50
1954	1973	15	25
1973	1990	8	10
1990	2000	15	20

These rates however may seem to be related to beach retreat due to the collapse of dike sections, not indicating the rate of retreat of a natural beach.
A local map, modified from a local source by Pruszak, 2002 (fig. 4.16) shows coastlines that deviate from figures 4.14 and 4.15. According to the local map, the coastal retreat would be equal divided along the coast of Hai Hau. Pruszak, 2001, estimates the erosion rates according to the local map as follows:

Table 4.2. Erosion rates according to Puszak, 2002.

From	To	Rate
1905	1927	34.7
1927	1966	18.7
1966	1992	3.6

The coastline change analysis presented in this report however is regarded as the most reliable, because of proved accuracy of mapping techniques used by the “Service Geographique de l'Indochine". Fig. 4.18 gives an indication of the accuracy of the used mapping techniques, showing a comparison between a 1912 map and a 1965 map.

Table 4.3 gives the maximum erosion rates (near Van Ly village, fig. 4.14) derived from figure 4.14 and figure 4.15. The erosion in Hai Hau district started nearby the So River. It extended into southwestward direction and decreased to a point were all former coastlines intersect, 10 km downstream of the So River mouth. In the period from 1912 to 1955, the erosion was rather constant along the coast. At that time, the hooked-formed bay just north of the So River filled up with sediments. The down drift located beaches were fully dependent on the supply of sediments from the So River that already had lost its importance at that time. The maximum erosion rate in this period was about 5.5 to 9.5 m/year. However, in the period from 1955 to 1965, the erosion rate was higher in some places, but the coastline length subject to erosion was much shorter than in the preceding period. The So River was dammed and the bay north of the So River was still accreting. Both these events must have caused the much higher erosion rate over this period. The maximum erosion occurring just north of Van Ly Village amounted to 20 to 24 m/year.
In the period from 1965 to 1995, the erosion just south of the So River mouth was diminishing. This diminishing erosion can be explained by the restoration of a continuous coastline just north of the So River, giving way to southward-directed influx of sediment.
However, there was still erosion further down drift, with a rate of about 6 to 9 m/year.
When mapping old geographical maps, the history of retreat and relocation strategies becomes clear. It goes back to the beginning of this century. Figure 4.17 shows the relocation of Van Ly village in the period from 1912 to 1965.

The southern part of Hau Hai district is stable to accreting near the Ninh Co River mouth, being supplied by sediments from the Ninh Co River.

It must be noted that the erosion rates from about 1940 to present, mentioned earlier are not equal to the erosion rates of a natural beach. As since the 1940's the entire coastline of Hai Hau district was protected with hard structures, the temporal collapse of these structures caused accelerated erosion on the local undefended coastline. The erosion rate is therefore lower than that it should be without hard defending structures.

Table 4.3. Maximum erosion rates according to figure 4.14 and 4.15
(including the error due to mapping accuracy between 1912, 1955 and 1965).

From	To	Lower boundary rate	Upper boundary rate
1912	1955	5.5	9.5
1955	1965	20	24
1965	1995	6	9

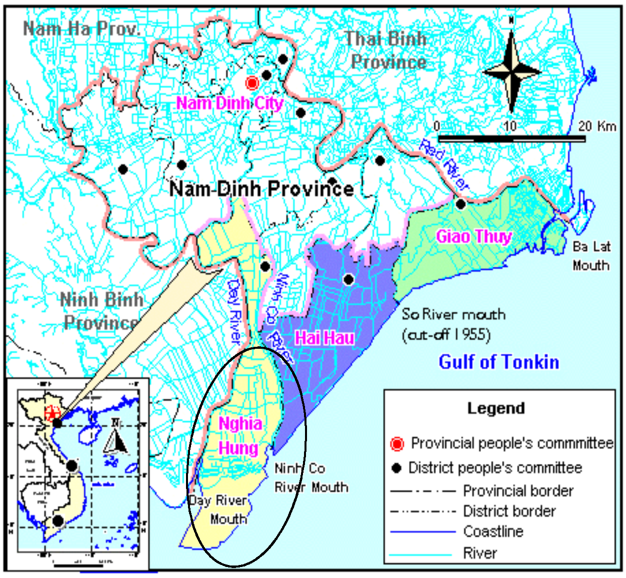


Fig. 4.20. Map of Nam Dinh province, Nghia Hung district encircled.

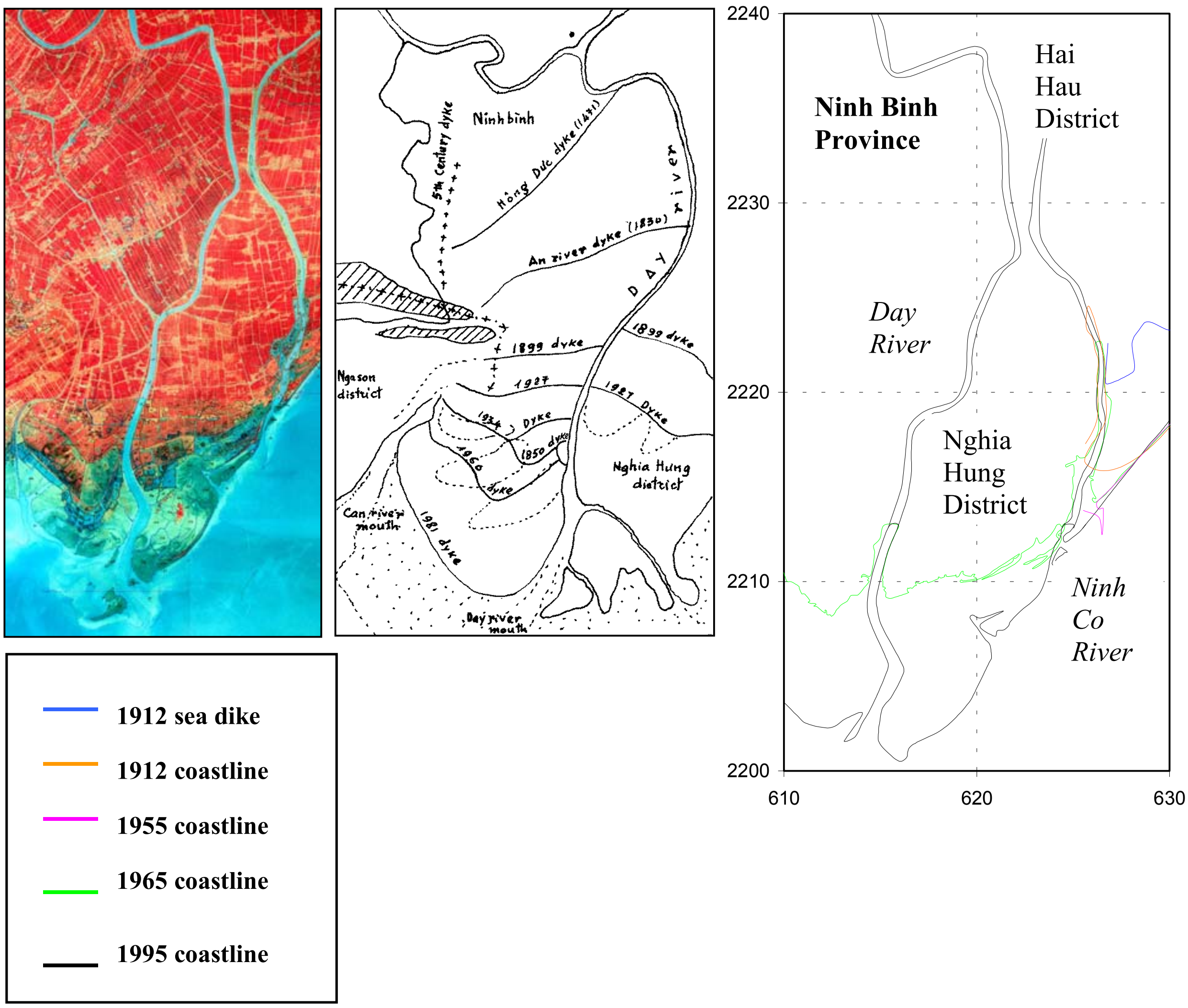


Fig. 4.21. Development of Nghia Hung district (Left image: SPOT (1995), middle image: dike construction from the 5th century (Tanh, et al 2002, modified from Gourou, 1936), right image: coastline development between 1965 and 1995 (distances in km).

5.5 Nghia Hung district coastal development

Nghia Hung district (fig. 4.20) is considered to be outside the boundary of the study area. For the overview of the total provincial development, the coastal development of this area is shortly introduced (fig. 4.21).

Both Day and Ninh Co rivers deliver an abundance of sediment during the summer monsoon period. Their sediment output is estimated at 12 and 18 million tons per year (Vinh et al, 1996). There are some indications that the distribution of discharge over the two rivers is changing, in favourite of the Day River. First, the present shape of both river mouths gives notion of a changing distribution of flow. Second the Day River mouth is much wider than the Ninh Co River. Moreover, the Ninh Co River has a narrow estuary. The formation of a sandbar in front of the river mouth and complaints of fishermen, that the river mouth is difficult to navigate, imply a siltation of the Ninh Co River mouth. This siltation process may be induced by diminishing flow of the Ninh Co River.

5.6 Hypothesis of the cause and future development of erosion in Hai Hau district

Because of yearly net southward-directed longshore currents, the development of the beaches of Nam Dinh is highly characterised by northward influences. Both the origin and morphological development of the present Red River mouth (Ba Lat estuary) have therefore decisive influence on the development of the downdrift located eroding Hai Hau beach.

Probably after 1500, avulsion occurred, which caused abandoning of the So River (discharging at the north boundary of Hai Hau district) as former major river and thereafter, the developing of the present course of the Red River, in a northern direction, creating a new river mouth. In the mean time, as a result of human interference comprising coastal reclamation activity, cultivation of lands and river training, the delta plain was not being flooded anymore by river and tides. The sediment output was concentrated in the river mouths, which were confined by river dikes. Longshore transport was the only mechanism left to feed the coastline between the river mouths. The former So River steadily lost its importance and the new river mouth developed in seaward direction just north of it.

The Red River mouth developing mechanism is characterised by a leapfrog displacement forward, enforced by temporal variability in monsoon discharge. This mechanism causes 30-40 year cyclic spit formation in front of the river mouth, causing a variable sediment supply to down drift located beaches. The development of spits in longshore direction in front of the river mouth implies a cut-off for the longshore sediment supply as long as the spit is growing in longshore direction. Sediment supply to southward and northward-located coastal sections will not continue before the spit will be reconnected to the mainland. Projecting this morphological mechanism on the Red River mouth in the beginning of the century, it is clear that it created a large, sheltered sediment trap just south of it (ever recurring morphological mechanism of the Red River), cutting off the sediment supply to the beaches down drift of the So River. The diminishing supply from the So River in combination with the cut-off in sediment supply from the major supplier, the Red River caused accelerated erosion (which may have started already in the middle of the 19th century). This erosion was magnified in the period after 1955 when the So River was dammed. After 1965, when the river mouth seemed to have found stable equilibrium, having created a continuous coastline, the erosion diminished.

Accelerated excessive accumulation and a major flood changing river mouth geometry in 1971 caused a new cycle in river mouth growth, cutting off again all sediment supply to downdrift beaches. A reason for the accelerated accumulation is soil erosion due to deforestation in the catchment areas of the Red River and in the delta plain itself. Deforestation was caused by cultivation during and after colonial times, war-related events in the 1960's and 1970's and resettlements of people to the delta's surrounding hills in order to reduce the increasing population density in the delta. The result of the newly developed river mouth geometry is ongoing erosion on southward-located beaches.

Erosion mainly occurs in winter, when alluvial sediment supply is very low and strong winds come from north and east directions, generating refracting waves approaching the coast at an angle of 45 degrees. Due to the extension of the Red River mouth, nearshore wave induced circulation patterns have changed, causing the Hai Hau beach tending to re-orientate from a convex into a concave form. The beaches just north of the So River mouth seem stable and there is little wave action due to the sheltering effect of the protruding Red River mouth. The longshore currents generating sediment transport have a net southward direction, induced by waves and tides. As the tide is asymmetric with periodically southward-directed ebb currents dominating the flood currents, it amplifies the southward-directed longshore transport of sediments.

It seems not to be a coincidence that Hai Hau beach is located on a tectonic active normal fault, whereas the area north of the Red River mouth is known as a neo-tectonic depression zone. The region of Day and Ninh Co River estuaries is characterised by coastal uplift. However, because of the large ratio between time and spatial scales of both tectonics and the massive sediment supply from rivers, being dominant to the tectonic subsidence. The tectonic effects are regarded as having insignificant effect on the accelerated erosion of the last century.
Relative sea level rise, generating the passive submergence of the coastal lands, also influences the erosion of Hai Hau beach. This effect may have been accounting up to 1 meter coastal retreat per year up until now. Considering possible future accelerated sea level rise, this passive coastal retreat may even increase.

In the present situation, the Red River shows an ongoing extension in seaward direction. As this river started to be confined between dikes in former times, it extended in one direction, to deeper water creating steep underwater slopes. This leads to lifting and reducing the slope of the riverbed, subaquous sliding and loss of sediments to deep water. Had there been an absence of river dikes, confining the river, the river mouth would never have protruded into the sea as it does in the present situation. It would have already breached through its natural levees to find a shorter and easier way to discharge its flow. However, as the river courses remained stable in the recent past, their regimes were not. Natural change and man induced changes because of damming, irrigation, river training and dredging, caused the distribution of the Red River sediment discharge to change. Since the damming of the Da River, (responsible for 53 percent of the total discharge of the Red River system) 250 km upstream of the Red River mouth between 1979 and 1983, erosion has been observed in the Red River mouth, that seems again to have found a stable equilibrium, creating a continuous coastline.
Measured lower values of suspended particle matter since the construction of the dam give evidence of a lower sediment supply to the coast. This seems to be related to the damming of the Da River.

The erosion in Hai Hau will continue in the near future as long as the Red River mouth extends with its characteristic leapfrogging development at the same longitudinal location on the Red River delta coast.
However, when extending more in a southward direction, possible future nourishing of the region southward and northward of the So River may be expected. Downstream of the So River, the coastline will continue in developing a concave geometry, adapting to the changing wave climate that is induced by the cyclic changing shape of the protruding Red River. Decreases in sediment load of the Red River indicate decreasing supply of sediment to the coast, possibly increasing the duration of the river mouth cycle. This decreasing sediment supply has impacts that are twofold. First the supply of sediments to the coast will decrease but second, the coast will remain stable in a longer period because of the increase in cycle duration. If the Red River mouth partly looses its leapfrogging character, the beaches down stream will show a more steady development.

Nourishing of the eroding beaches by longshore sediment transport coming from southern directions in summer seemed to be effective on a distance of about 5 kilometres northward from the southern united estuaries from both Ninh Co and Day River. However, the future nourishing effect is regarded as insignificant because of the observed river mouth siltation, indicating diminishing discharge and thus, sediment supply from the Ninh Co River mouth.

If the Red River mouth will break through its artificial created levees forming a new river course, it will drastically change the morphological system. This change may happen in arbitrary locations and at an arbitrary moment. If the river will change its course in northern direction as it did some 500 years ago, the erosion problems in Nam Dinh province will increase, whereas a change of course in a southern direction will reduce or even may stop the erosion problems south of its present river mouth.

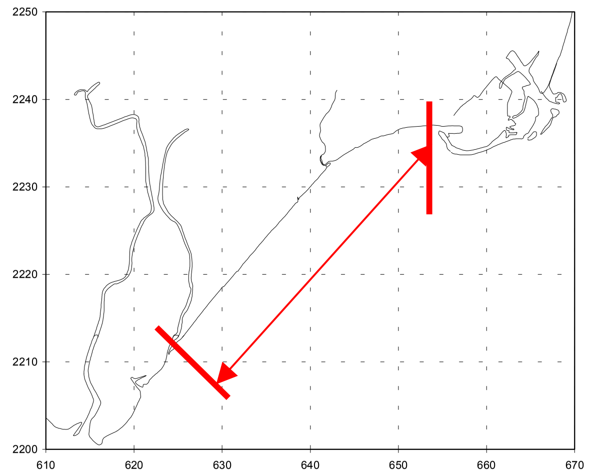


Fig. 5.1. Model area with its boundaries at the north bank of the Ninh Co River and just south of the offshore spit near to the Red River mouth.

6 Modelling of waves and sediment transport

It is desirable to predict the future development of coastline changes in Nam Dinh, considering the possible future coastline changes along inhabited areas and the resulting future planning of these areas. The longshore transport model UNIBEST LT in combination with UNIBEST CL (annex 2) has been proven to be successful in similar studies and will therefore be used to determine the coastline changes. First, the sediment transport capacity in various locations along the coast of Nam Dinh were calculated. These locations are marked by a change in wave climate or a change in coastline angle. The calculated S-φ curves (yearly sediment capacity as function of the coastline angle) for the various locations are used within UNIBEST CL and according to the single line theory, the coastline evolution can be determined. The first step in the modelling procedure is the computation of a nearshore wave climate in various locations along the coast. As the coastline of Nam Dinh has a curved orientation, different wave climates were to be expected in characteristic locations. These various wave climates were included in the sediment transport capacity calculations.

6.1 Modelling objectives

6.1.1 Definition of modelling objectives

Simulate representative nearshore wave climates with the 1D wave model WATRON. Thereafter, to include the nearshore wave modelling results in a simulation of transport capacities along the Nam Dinh coast and accordingly, a determination of coastline changes with UNIBEST CL. After testing of the coastline behaviour hypothesis, extrapolate the model for future developments by using UNIBEST CL.

6.1.2 Modelling methods

First, time series of offshore wave data were computed, verified and calibrated. Thereafter, nearshore transformation of the offshore wave date was applied in order to compute input nearshore wave climates for the UNIBEST longshore transport calculations with the LT module. The model area was subdivided into littoral cells from which the individual influx and out flux of sediment perpendicular to and parallel to the coast must be balanced. The basis for the formulation of the littoral cells is formed by the yearly sediment losses and sediment gains in each cell, basically derived from analysis of the coastline changes in the last century and longshore transport calculations at each cell boundary by UNIBEST LT. The total yearly in- and out flux of longshore sediment fluxes at the model boundaries has to balance the yearly on- and offshore sediment fluxes over a year (fig. 5.1).
This is a strict requirement to be fulfilled before going into detailed modelling in UNIBEST CL. The model boundaries were imposed just south of the Red River mouth were longshore transport is regarded as having been cut-off and the northern Ninh Co River bank in the south where the coastline is interrupted by a river mouth and large tidal flats in front of it.

6.2 Offshore wave modelling

6.2.1 Introduction

When modelling wave induced long shore 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. Because of the tabulated form, making the data unsuitable for further calculations, an alternative method had to be applied.

First, time series of offshore winds were calculated on basis of a 20-year time series of wind speed and wind direction. The calculated offshore climate were 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 numerical model WATRON (WL | Delft Hydraulics) was used to compute the offshore and nearshore wave climate. The numerical package SCATTER (WL | Delft Hydraulics) was be used for the graphical and tabular presentation of the results.

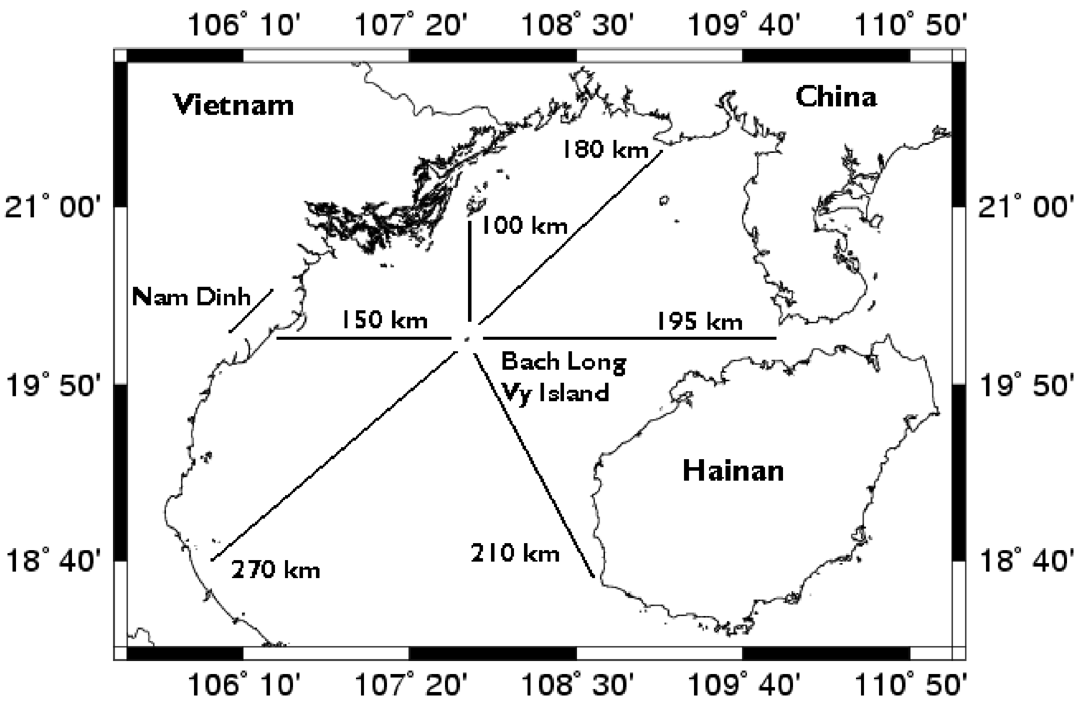


Fig. 5.2. Wave hindcast location Bach Long Vy Island.

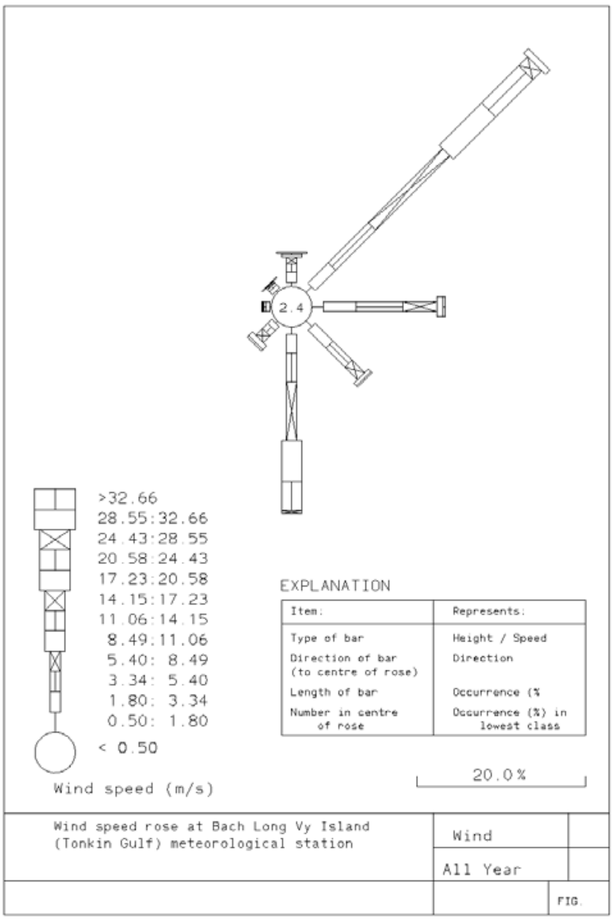


Fig. 5.3. Wind Rose at Bach Long Vy Island.

6.2.2 Offshore wave validation and calibration

An introduction into the background of the WATRON package and the used wave growth model is included in annex 1.

Inputs for the offshore wave computations are time series of wind data, fetch lengths and a assumption for the distribution of storm duration and wind speed.
Figure 5.2 shows the Tonkin Gulf bordered in the west by the Red River delta coastline, in the north by the Chinese mainland, the peninsula and the in the east by the Hainan Island. Fetches vary between 80 km to a maximum of 500 km. The Bach Long Vy Island, where the winds were measured (fig. 5.3) is located 150 km offshore the coastline of Nam Dinh.

The wind data record interval of 6 hours is considered to be too large for detailed estimation of storm duration, which is therefore assumed to follow a distribution as represented in figure 5.4. Furthermore, the wind speeds have to be corrected for elevation (fig. 5.5). The Coastal Engineering Manual (Sept 2001) gives three graphs for elevation correction for the difference in seawater and air temperature of + 3 degrees, -3 degrees and zero degrees. As the sea water is between 0.3 and 1.4 degrees warmer than the air temperature, varying over the year, the difference was neglected and the correction factors U/U_{10} were interpolated from the graph corresponding to the sea-air temperature difference of 0 degrees. Fetch lengths were calculated from British Admiralty Chart 2661A, London, published 1964 with latest corrections 1986. Directional spreading was accounted for with a COS^4 multiplication in the directional energy calculation.

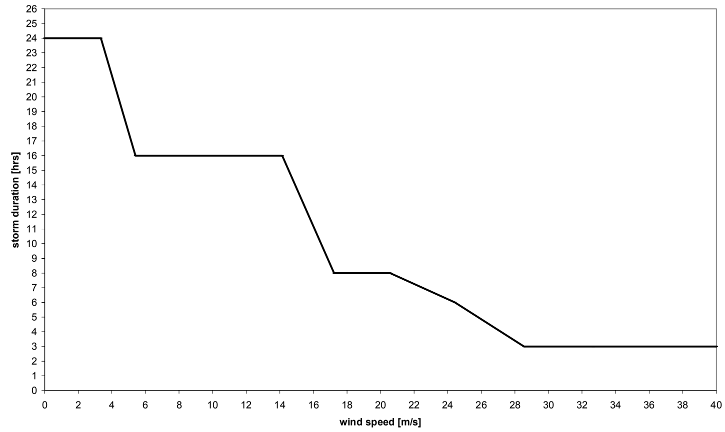


Fig. 5.4. Storm duration as function of wind speed.

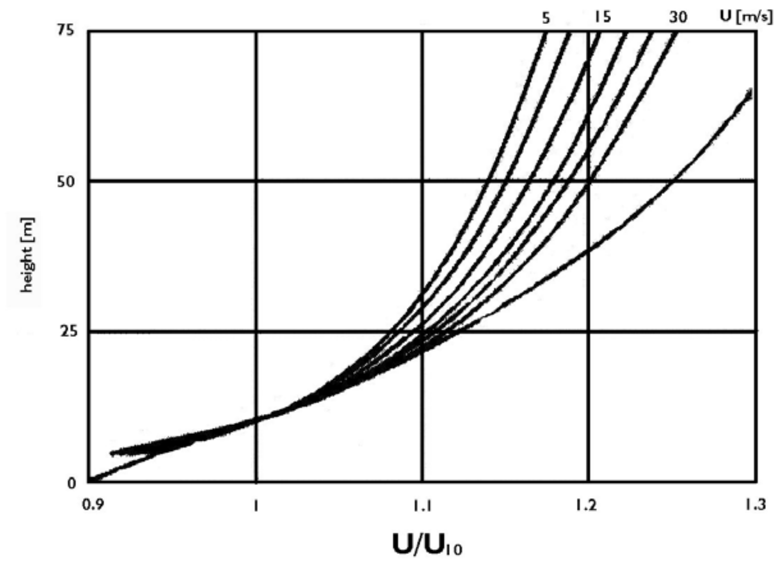


Fig. 5.5. Ratio of wind speed at any height to the wind speed at the 10-m height as a function of measurement height at a selected value for air-sea temperature difference and wind speed.

Fig. 5.6. Offshore wave calculation at Bach Long Vy station.

Comparative analysis of the computed wave climate with the observed wave climate (fig. 5.6) showed that the number of waves in the lower wave height sectors was too high compared with the observed wave data (about 30% appeared to be in the lowest class, which seems not realistic). The wave climate therefore was scaled to fit best the exceedence frequency curve of the observed wave heights. These observations were taken as the most accurate reference. The input parameters (for example variations in fetches, wind speed-storm duration distribution) were varied in order to test the assumptions that were done. However, testing did not have significant effects on the results in a way that both the exceedence frequency curves coincided. Eventually, the transformation factors that WATRON generates for computing wind speeds into wave heights were adjusted to fit both curves best. The results of this offshore wave hindcast were analysed and classified with the program SCATTER and are presented in annex 2.

6.3 UNIBEST modelling

6.3.1 Introduction

For the background of the UNIBEST model, the reader is referred to annex 2.
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. This hypothesis is also supported by Hung (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).
The dominant direction of the wave climate determines the coastline angle, enforced to reflect a direction perpendicular to the dominant wave direction. In this particular situation, the wave climate was modelled with a 1D model under certain assumptions, introducing a considerable uncertainty in the input parameters for UNIBEST. The uncertainties in the wave modelling may had their effect on the results of the longshore transport calculations.
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 linearly extrapolated from this reference point. In this particular situation with a rather wide dynamic zone (more than 1 km offshore, bounded at 6 m depth) this yielded unrealistic tidal velocities, and thus a domination of tide to waves.
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.
Furthermore, the effects of variable grain sizes and fall velocities on the resulting sediment transport were tested. A sediment balance based upon the coastline volume changes derived from historical maps and additional sedimentation / erosion maps (source: Department of Land Administration, Hanoi) functioned as a reference for the testing of the longshore transport calculations. On basis of consistency requirements of the sediment balance, the decision was made for a following stage in the modelling procedures: coastline change modelling with the UNIBEST CL module.

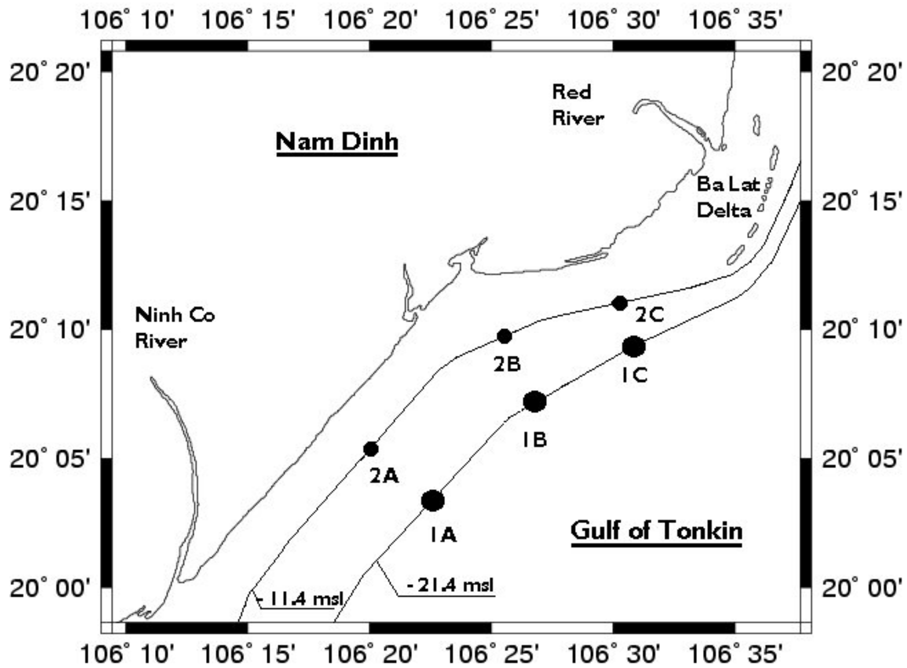


Fig. 5.7. Characteristic locations at the 21.4 depth contour and the 11.4 depth contour.

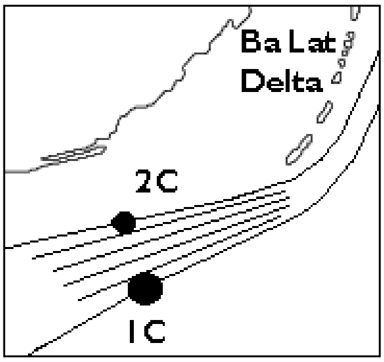


Fig. 5.8. Refraction – shoaling computations from location 1C to location 2C.

6.3.2 Response of UNIBEST on different approaches of nearshore wave modelling

In this section, the influence of the modelled wave climate on the results of the longshore transport calculations will be tested. Annex 2 gives an overview of the input parameters.

Approach: Offshore wind speeds in combination with nearshore measured fetches

Introduction

The steps to be followed to quantify the nearshore wave climates were as follows.

- Prediction of deep water wave climate at 21.4 m depth contour offshore Van Ly (on the centre line of the 70-km coastline of Nam Dinh with the wave growth model;
- Appliance of wave refraction and shoaling to estimate the transition of wave height and wave direction from the 21.4 m depth contour to the 11.4-meter depth contour. This had to be done at various locations near shore where depth contours show a change in orientation;
- Verification if the nearshore wave climate at various locations corresponded to the expected local nearshore wave climate, based on offshore wind climate, Tonkin Gulf topography, local bottom topography and local coastline geometry.

Wave climate at 21.4-m depth contour

At the 21.4-m depth contour in location 1A (fig. 5.7) offshore the village Van Ly (where erosion occurs most severely) the wave climate was calculated with WATRON.
Fetch length were measured on British Admiralty Chart 2661A and the 1976-1995 wind data set from Bach Long Vy Island was used as representative wind climate as input for the wave growth model. Depth relative to mean sea level was taken 21.4 m, as the sum of water depth at the navigational chart (relative to lowest low water level) plus half the mean tidal range.
The climate calculated at location 1A is considered as representative for location 1B and location 1C, as fetch lengths projected on the main wind directions vary little for the three different locations (fig. 5.7).
WATRON gives as output 24 * 13 combinations of significant wave height relative to wind speed, 24 * 13 combinations of input wind direction and wave direction and 24 *13 combinations of spectral peak period wave period relative to wind speed. These coefficients are used by the program SCATTER to transform the offshore wind climate to a near shore wave climate based on the probability distribution of offshore wind conditions and the nearshore fetch restrictions.

Wave climate 11.4-m depth contour

According to Battjes, 1999, waves propagating to the coast will change due to refraction, diffraction and shoaling, bottom dissipation and other physical phenomena. These phenomena strongly depend on bathymetry, which varies along the coast because of strong curvatures of the coastline.
Refraction is a phenomenon described by a change of wave propagation direction and wave height as a result of variations in phase speed along wave crests, induced by non-uniformity of the water depth. As a result of the change in propagation direction, the wave energy will be re-distributed. The movement of waves is considered as quasi – uniform (Battjes, 1999).
Shoaling is the phenomenon described by a change in wave height as a result of conservation of energy when waves approach the coast without breaking (d' Angremond, 1998).

The near shore wave climate therefore needs to be calculated for characteristic points representing a stretch of coastline with characteristic orientation and a characteristic orientation of the depth contours. The locations 2A, 2B and 2C (fig. 5.7) are located on the 11.4-m depth contour and represent a characteristic orientation.
A refraction/shoaling calculation was applied to transform the 21.4-m wave climate of wave period, wave height and wave direction to a 11.4-m depth climate for the specific location and accompanying contour orientation.

The two-dimensional refraction-shoaling calculation is based on energy conservation and the assumption that the sea bottom has parallel depth contours. For locations 2A and 2B this approach seems valid. For location 2C a different approach is required because of non-parallel depth contours south of Ba Lat estuary. Locations 2A and 2B need one single refraction-shoaling transformation whereas for location 2C multiple refraction-shoaling transformation will be needed.
Considering multiple depth contour lines for every meter depth difference between the 20-m contour and the 10-m contour, the difference in orientation is infinitesimal small and therefore the refraction – shoaling transformation based on parallel depth contours is assumed to be valid.
For location 2C (fig 8.2), five transformations were applied, from 21.4-m to 19.4-m, from 19.4-m to 18.4-m, from 18.4-m to 17.4-m, from 17.4-m to 15.4-m and from 15.4-m to 11.4-m.

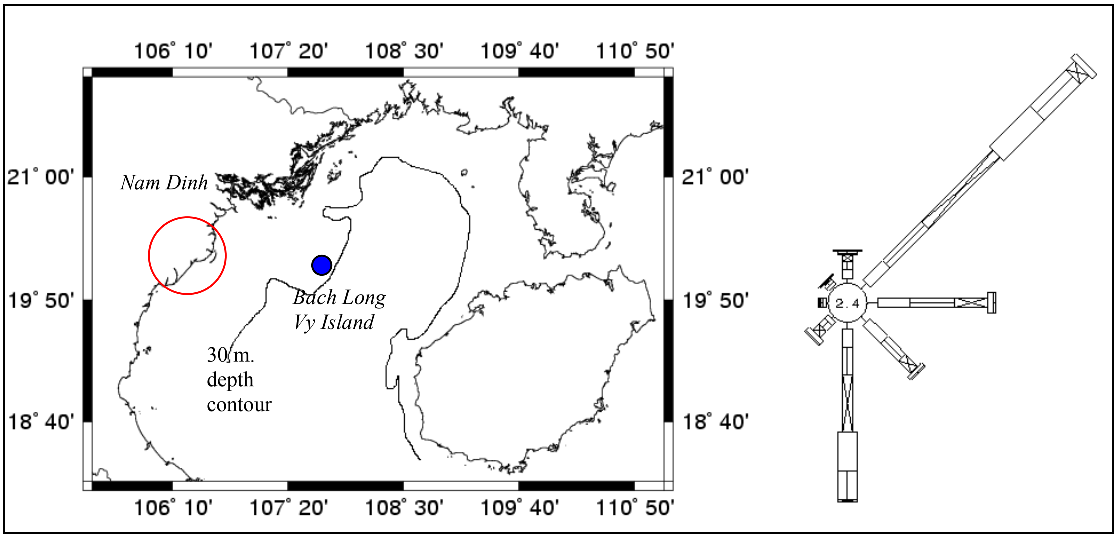


Fig. 5.9. 30 m. bottom contour in the Gulf of Tonkin (wind rose included for Bach Long Vy Island, study area encircled).

UNIBEST results

First, an estimate of the eroded and accumulated sediments was made in order to set up a sediment balance for the study area. For the eroding beaches, a closure depth of 6 meters is assumed. The filling of the area just north of the So River is assumed to grow with half a meter per year. Comparisons of different coastlines yielded the following estimates for the yearly losses of sediments for the study area (table 8.1).

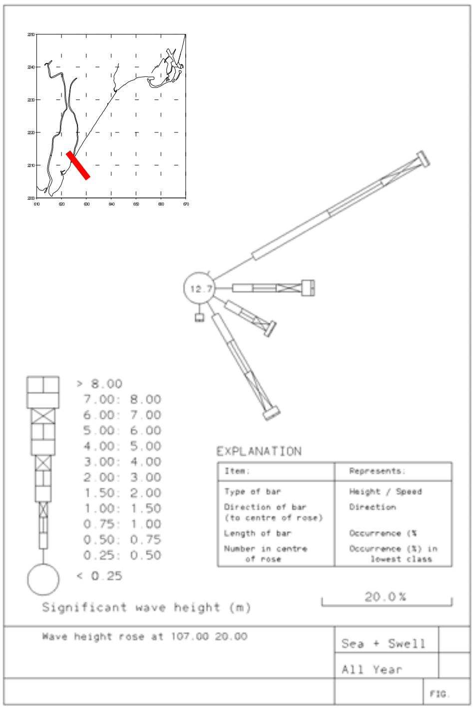
Table 5.1. Sediment losses according to various sources.

From	To	Area	Lower boundary (^10^3 m^3/year	Upper boundary (^10^3 m^3/year
1912	1965	Total area	650	837
1985	1995	Total area	262	709
1971	1986	Hai Hau district	289	479

However, the resulting sediment transports (Bijker approach) calculated by applying the three wave climates could not balance the yearly losses of sediment presented in table 5.1.
In location 2A (Hai Hau district, fig. 5.7), northward going sediment transports were calculated. As was already know by observation of the coastal processes and from Hung, 2001 and Pruszak, 2002, the resultant net transport should be southward going, increasing from north to south.

A cause for the wrong direction of the sediment transport was found in the 1D wave modelling approach. The very important section of waves coming from 45 degrees to north was filtered out by the refraction calculations, causing the wave climate to be dominated by waves coming from southern and eastern directions. The depth where waves start to refract can be calculated by a simple rule of the thumb: depth $< ½$ wavelength on deep water. Waves with a period of 4 seconds already start to refract at a depth of 12 m. For 6 and 8 seconds this is 30 and 50 meters. As the deepest points in the Gulf of Tonkin are at about 30 to 45 meters it may be reasonable that the on deeper water generated waves already start to refract before they even approach the shallows along the coast. Figure 5.9 shows the orientation of the 30 m. depth contour.
Clear is that the nearshore wave climate at Hai Hau beach (coastline orientation 42 degrees TN) should include a strong portion of waves coming from northeastern directions in order to represent the longshore transport capacity in a way that the yearly sediment fluxes in longshore and offshore direction are balanced.

Also a variation in fetch lengths for locations 1A, 1B and 1C was applied, rejecting the assumption that the differences in fetch lengths for the various locations would have an insignificant effect on the nearshore wave climate calculations. However, these variations did not influence the nearshore wave climate in a way that the sediment balance requirement could be fulfilled.



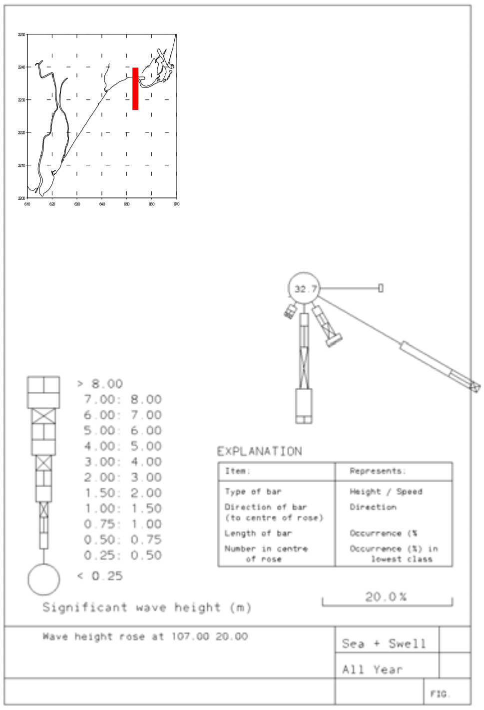
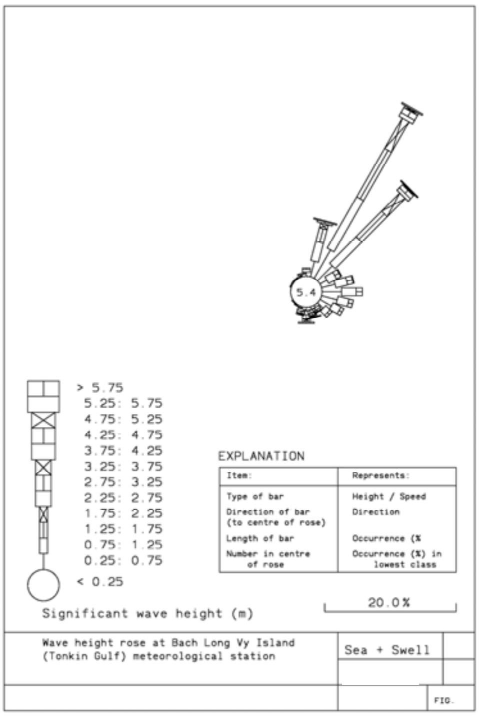


Fig. 5.10. Nearshore all year wave climates represented in 12 sectors of 30 degrees.
Left: based on refraction on a coastline directed 20 degrees to north (actual angle 42 degrees)
Right: based on refraction to a coastline directed 75 degrees to north (actual angle 85 degrees)



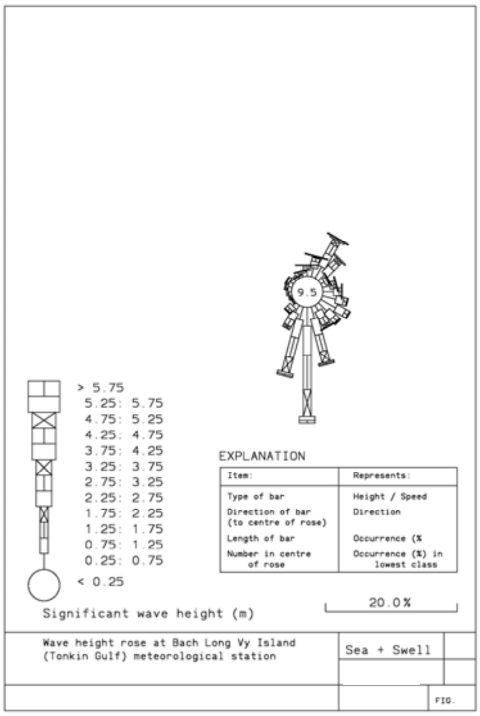


Fig. 5.11. Offshore seasonal wave height roses (Bach Long Vy station), represented in 24 sectors of 15 degrees.
Left: Northeast monsoon (month 10/11/12/1/2/3/4)
Right: Southwest monsoon (month 5,6,7,8,9)

6.3.3 Approach: Refraction computations of offshore waves

A second method was applied in order to manipulate the nearshore climates in such a way that it corresponded with the hypothesis that in the north, the wave climate is mild due to the sheltering effect of the Red River mouth, increasing in strength going to the south. There, it should include a strong portion of north-east of waves.
This approach is based on a nearshore transformation of offshore waves. The offshore waves were transformed by means of refraction directly from 30 meters to 10 meters, choosing an arbitrary orientation of the coast in such a way that a reasonable climate (according to the wave climate hypothesis) was computed. For the region just south of the Red River mouth and for the region just north of the Ninh Co river mouth the results were reasonable. However, the wave climate on the strongly curved coastline just north of the So River mouth could not be modelled in a way that the sediment fluxes were balanced.

On basis of the Bijker formula (input parameters are given in annex 2), the computations yielded the following sediment fluxes (fig. 5.12, 5.13).
The calculation of the sediment flux showed in figure 5.12 was based on a coastline angle of 75 degrees. The input wave climate is showed in figure 5.10, on the right, based on a fictive coastline (and corresponding depth contour) angle of 85 degrees. The calculation of the sediment flux showed in figure 5.13 was based on a coastline angle of 42 degrees. The input wave climate is showed in figure 5.10, on the left, based on a fictive coastline (and corresponding depth contour) angle of 20 degrees.

Both influx longshore influx and out flux of sediment yields a total amount of sediment yearly lost of about 5.00.000 cubic meters. This matches the estimated losses of sediments according to the ranges in table 5.1. Also comparison with other calculations based on the CERC formula by Hung (2001) (figure 5.15), shows correspondence although these calculations yield maximum transport rates that are in the range of 300.000 to 400.000 m^3/year. According to Pruszak (2002), the net longshore transport capacity on the Hai Hau coastline is approximately 900.000 m^3/year.

However, detailed wave climate modelling along the curved coastline (especially in the area just north of the So River mouth) with a 1D model did not give reliable results and therefore, a detailed sediment balance could not be formulated. Before going into future coastline modelling procedures with the UNIBEST CL module, a 2D nearshore wave climate should be applied in order to be sure to take into account of al 2D effects in the Gulf of Tonkin and the nearshore region. The UNIBEST coastline model for calculating coastline changes was therefore not applied in this study. The longshore transport calculations and the hypothesis made in chapter four were used to predict the future trends in coastline evolution.

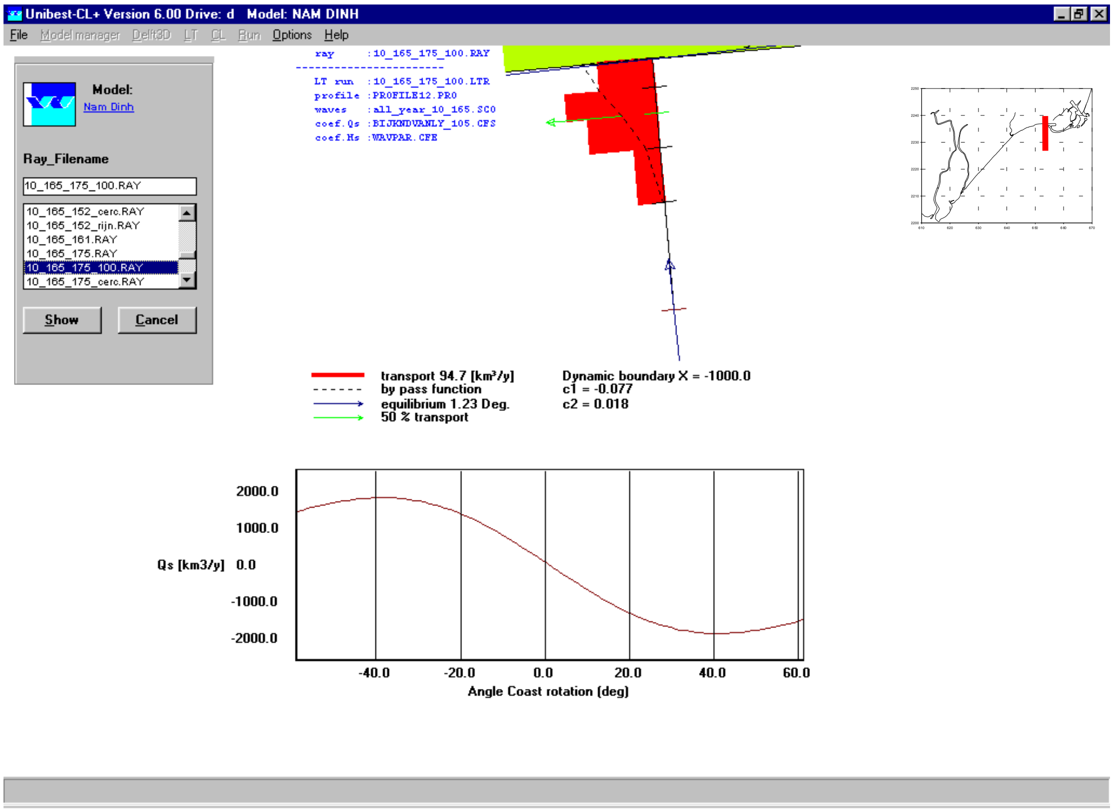


Fig. 5.12. North boundary flux.

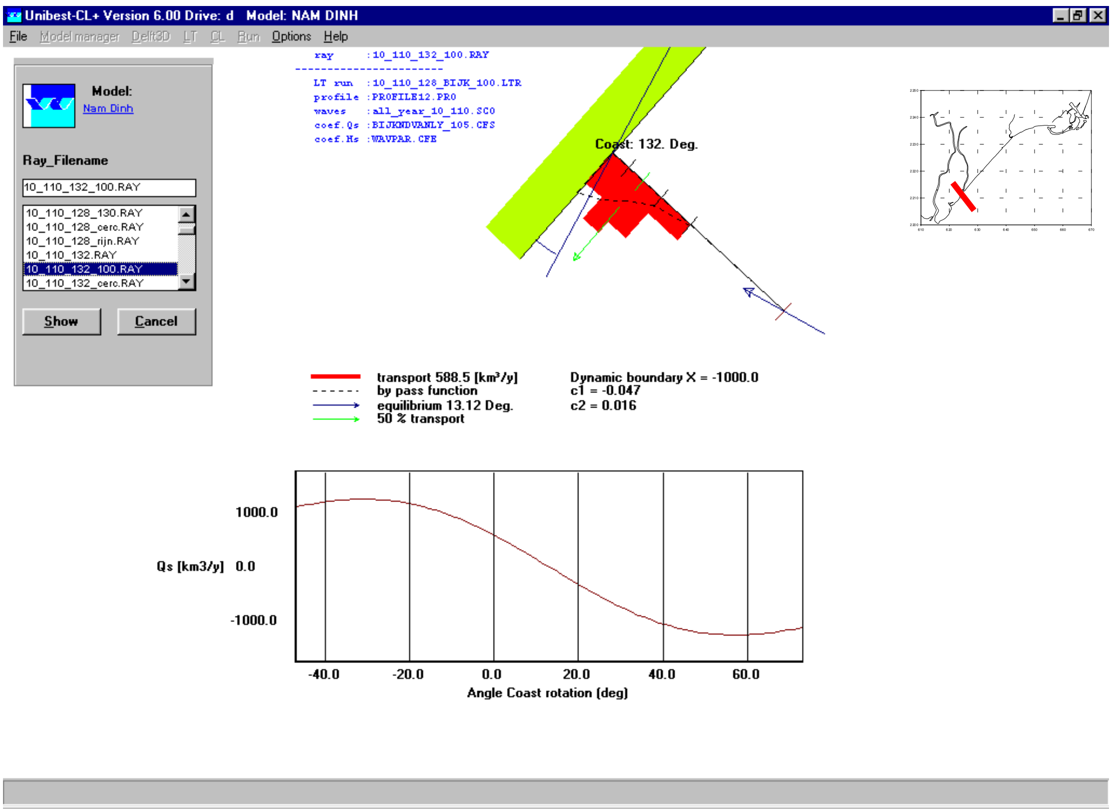


Fig. 5.13. South boundary flux.

6.4 Future coastline changes

On basis of the wave climate calculations, the work from Hung (2001) (fig. 5.14) and UNIBEST calculations, an estimate was made of the possible future trend of coastline evolution of Nam Dinh. Within the limitations of the model, the equilibrium angle north of Ninh Co River bank was estimated at about 29 degrees to north. The northern beaches of Nghia Hung district represent approximately this angle at present. However, as the wave action from northeast and eastern directions decreases when going to north, the orientation in these locations will more or less represent a direction increasing to 40 and 75 degrees orientation, being adjusted to the waves coming from southern directions (fig. 5.15).

What is clear, also from the historical coastline changes in chapter 4, is that the coastline changes from a more concave into a convex form. This change may continue until an equilibrium situation will be reached. The northern part of Nam Dinh will be accreting, connecting in a smooth line with the southern spit of the Red River barrier system. As the Red River mouth seems to be relative stable the last 10 years, it is expected that the wave climate south of it will not change dramatically, influenced by the shape of the protruding river mouth. The two inflection points that can be observed in figure 4.2, may therefore retain their positions.

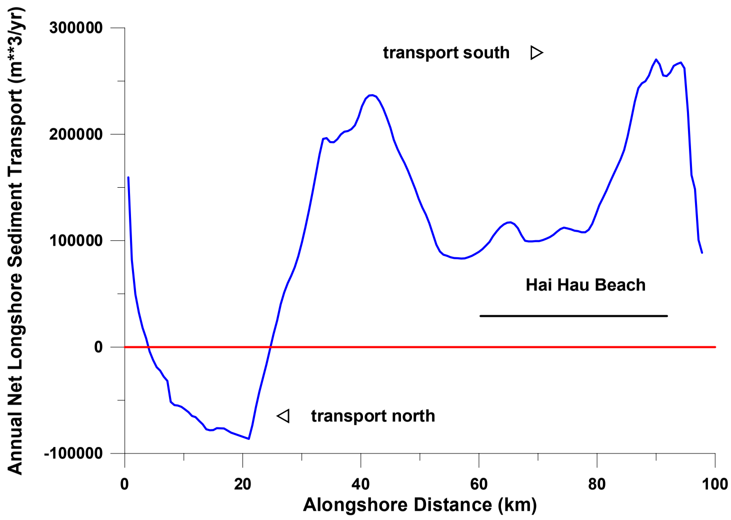


Fig. 5.14. (Hung, 2001) Mean annual net longshore sediment transport along the RRD shoreline determined based on wave properties from a 2D wave transformation model and the CERC formula.

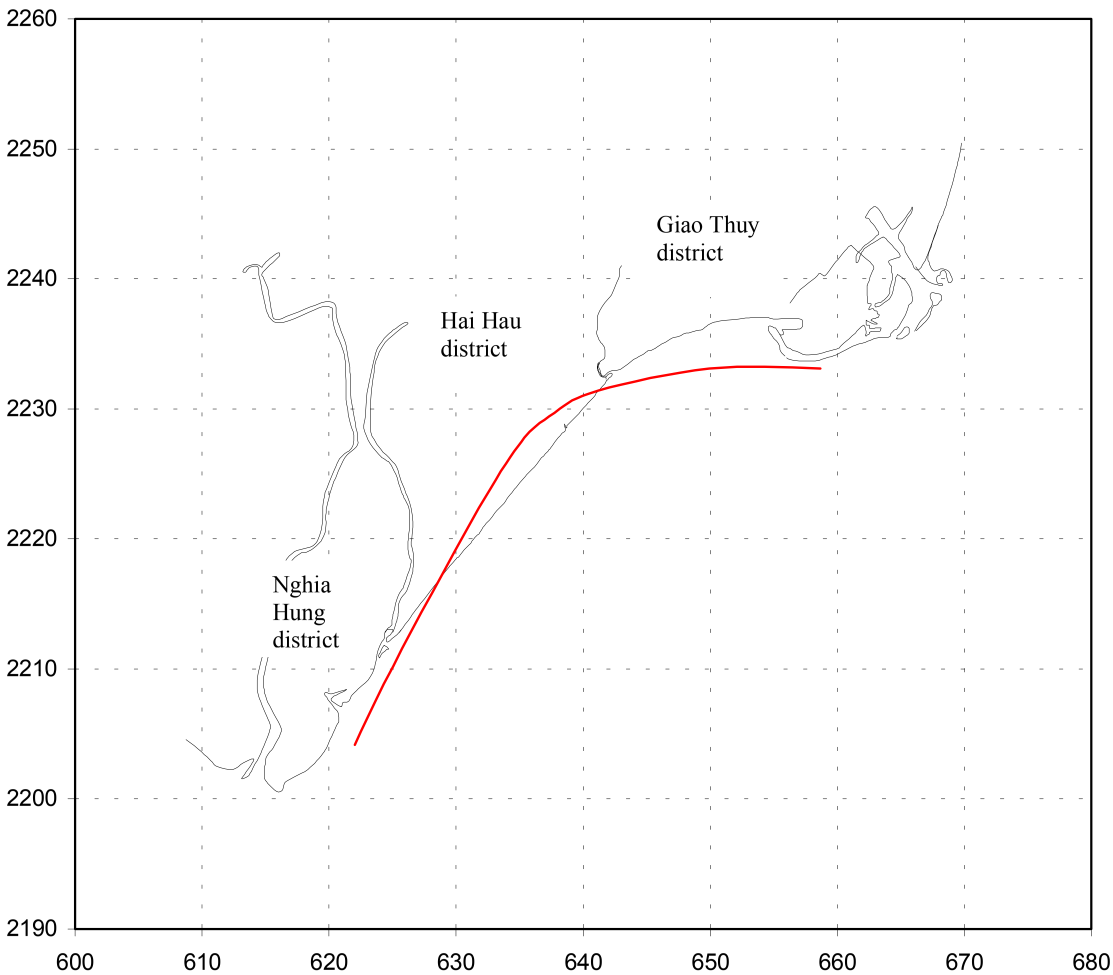


Fig. 5.15. Possible future trends (red line) in development of the Nam Dinh coastline (the line does not present the exact equilibrium position, it just indicates the trend).

7 Mitigation

In this chapter, some mitigating measures will be given for possible measures to cope with the erosion problems. Both short-term, medium-term and long-term options will be presented.

7.1 Long term measures

Future predictions from modelling results however have some limitations. In the modelling procedures, a major assumption was done. The modelling results are simply and solely valid in a situation where the Red River mouth maintains its present position. A change in the river discharge system will completely change the morphological situation. If the river will break through its river dikes during a future major flood, a new river branch may be formed and the old one ending in Ba Lat estuary will then be slowly losing its importance. The forming of a new river branch is to be expected in future as the river mouth will not endlessly move on in seaward direction. The river may find a shorter way to the sea and in a situation of extreme river discharge. River training works such as dikes may not prevent this event.

If the Red River (in case of a future avulsion) will recommence discharging near Hai Hau district as it did some 500 years ago, the problems of erosion will be resolved and sediment supply to the eroding beaches will be resumed.

Rehabilitation of the So River as major river branch is therefore a reasonable long-term solution for the erosion problems in Hai Hau district.

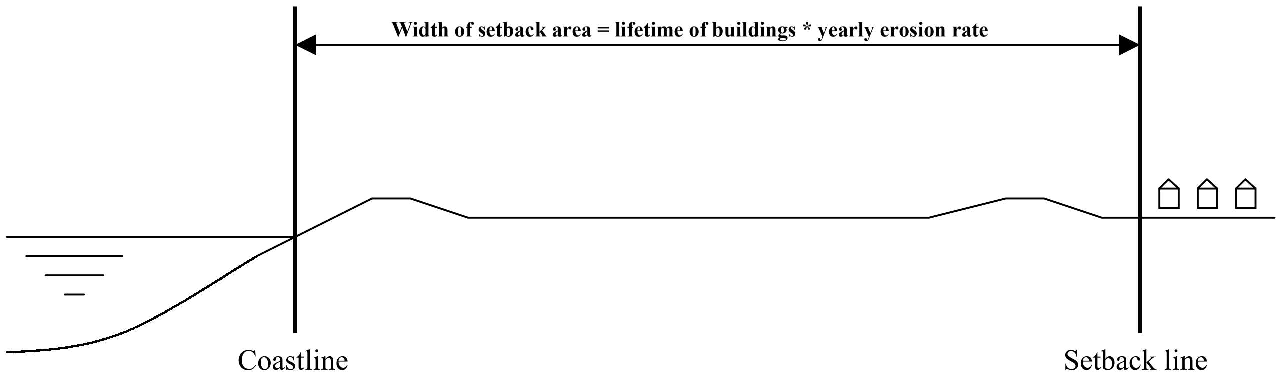


Fig. 6.1. Definition of setback lines.

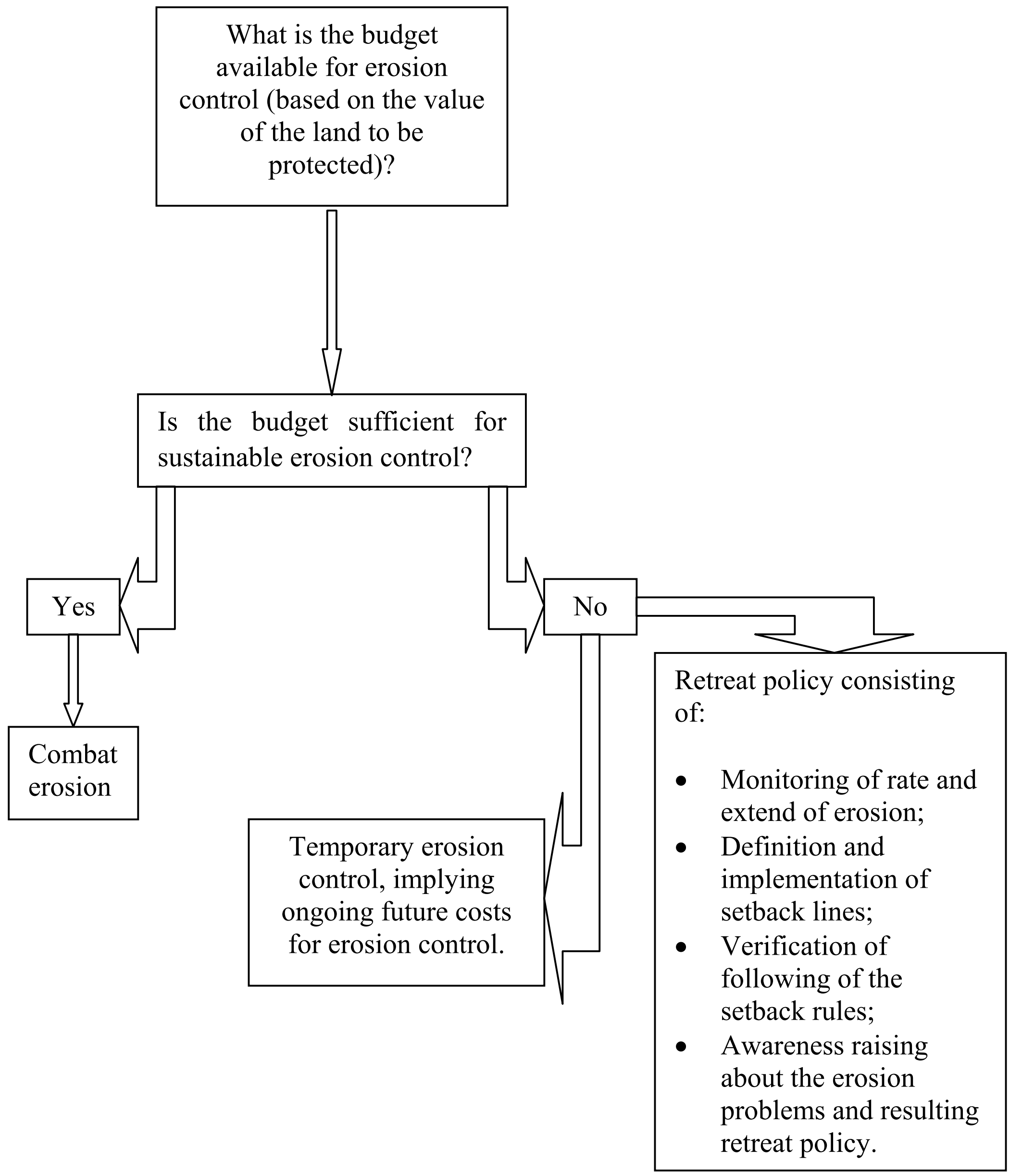


Fig. 6.2 framework for decision process on erosion control, modified from Verhagen, 1999.

7.2 Short term and medium term measures

The short-term or medium-term management of the eroding coastline of Hai Hau district can be approach in several ways. It must be noted that there is no optimum solution. It is up to politicians to decide what option is the most suitable one to apply.

The problem may be approached by:

1. Retreat: the coastline is allowed to erode, provision has to be made to mitigate the effects of erosion;
2. Selective preservation: the coastline is allowed to retreat, except in those places where major interest in the coastal zone may be lost;
3. Preservation: the entire coastline will be maintained at a given location.

Option 1, retreat:

Relocation of people within or outside the delta will reduce the problem in the coastal areas. However, relocation of people from their native soil will also cause adaptation problems.
Accreting areas could possibly be used for relocation of people. However, reclaiming these natural tidal flats will again cause impacts on the natural system. Furthermore, the future coastal development in these areas cannot be foreseen. But from the economic point of view, this option is most effective.

Relocation of activities out of the area being at risk can be done by the definition of setback lines (Verhagen, 1999). Between the setback line and the coastline, no activities are allowed (fig. 6.1). The coastline should have a clearly defined position. The setback area could have a width that is related to the lifetime of the buildings in the coastal zone. For example, if the lifetime of a commune is 100 years, the width of the setback area is 100 times the yearly-expected erosion rate. The location of the setback line is subject to change as the erosion rate is not a given constant. Moreover, the setback line will move inland with the time.
Applying this policy in Nam Dinh, it would imply that in the present situation, the initial action is large-scale relocation of people. However, future relocation of people due to the ongoing coastal retreat and the accompanied inland moving of the setback line could be planned an implemented on a much lower scale, having less drastic social impacts than the initial phase of the setback line strategy.
According to Verhagen, 1999, questions (and resulting actions) should be raised when discussing the need for erosion control according to figure 6.2.

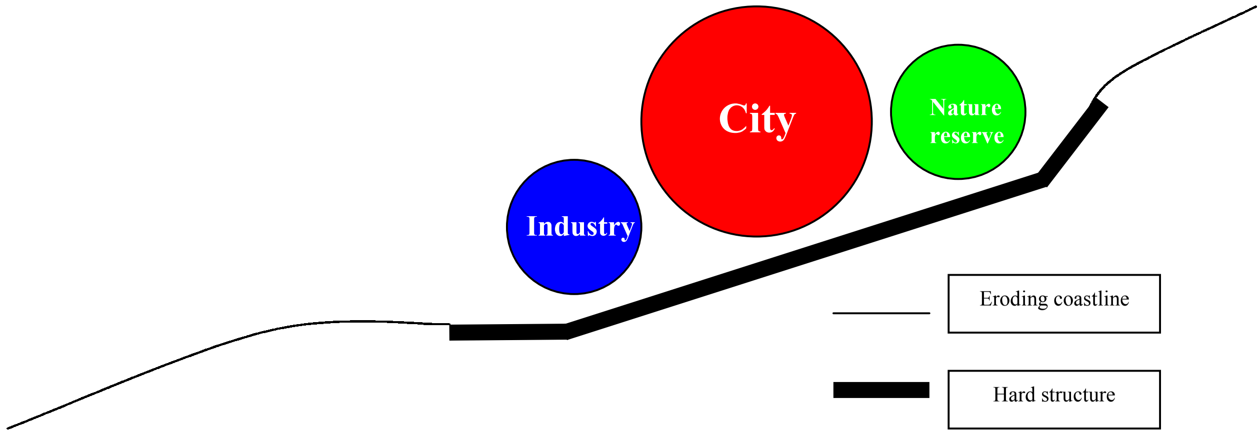


Fig. 6.3. Selective preservation.

Fig. 6.4. Groins along the Dutch coast.

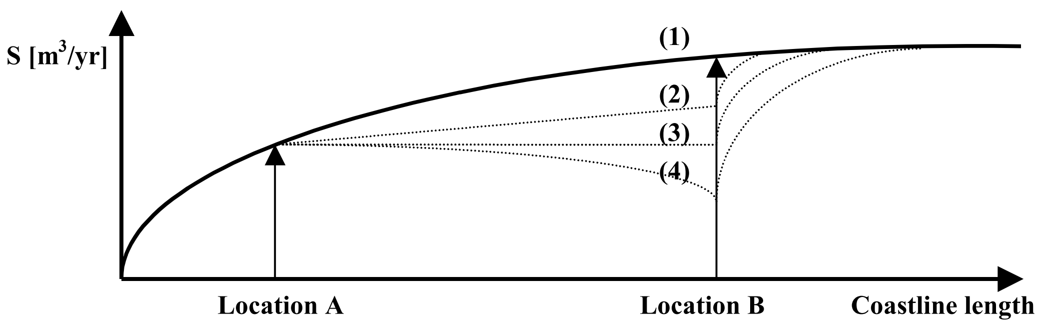


Fig. 6.5. Impact of groin systems on structural coastal erosion (modified from TAW, 1995).

Option 2, selective preservation:

In areas where the eroding zone hosts important functions, action will be taken in order to protect the coast. The erosion will be controlled in a selective way. The remaining beaches will continue to erode, leaving the protected parts of the coast as fixed headlands, difficult to defend. Which areas will have to be protected is a political choice (Verhagen, 1999).

Option 3, preservation:

The full coastline will be maintained by hard or soft measures. An example of hard structures is a groin system. Soft measures are for example artificial beach nourishment schemes.
Full coastline protection will involve high initial and maintenance costs. For example in the Netherlands, because the costs must relate to the benefits, these measures are only applied if lands with high social-economic values have to be protected against erosion.

In a situation with longshore transport gradients, groin systems (fig. 6.4) can be applied in order to manipulate the longshore currents.
Groins are structures that extend perpendicularly from the shore. Usually constructed in groups called groin fields, their primary purpose is to trap and retain sand, nourishing the beach compartments between them. Groins initially interrupt the longshore transport of littoral drift. They are most effective where longshore transport is predominantly in one direction, and where their action will not cause unacceptable erosion of the downdrift shore. When a well-designed groin field fills to capacity with sand, longshore transport continues at about the same rate as before the groins were built, and a stable beach is maintained. The beach fed by the sand trapped between the groins acts as a buffer between the incoming waves and the backshore and inland areas: the waves break on the beach and expend most of their energy there (USACE, 2002). In the Netherlands, most groin types are made up of gravel, covered with stones. However, sheet piles of treated timber, steel, or aluminium can also be used to build effective and long-lasting groins in situations where they can be driven to adequate depth. (USACE, 2002).

However, groins have also adverse effects. Downdrift of groin systems, in most of the situations, the beach tends to erode (TAW, 1995).
Figure 6.5. will illustrate this. From location A to location B, the longshore transport capacity increases (situation (1)), resulting in beach erosion. The construction of coastal protection works such as groins on the coastal stretch between location A and location B could adjust the longshore sediment capacity distribution to situation (3), reducing the transport capacity to the upstream capacity, resulting in a stable beach. Situation (2) means only partly reduction whereas situation (4) gives accretion of the shore. Which one of the three situations occurs is dependent on the geometry of the groin field. However, it must be noted that due to situation (2), (3) and (4), there is a difference between longshore capacity just downdrift of location B where the protection works end and the further downstream longshore transport capacity. This results in erosion on beaches downdrift located of B. In fact, the erosion has not stopped but it has moved to downdrift located beaches (TAW, 1995).

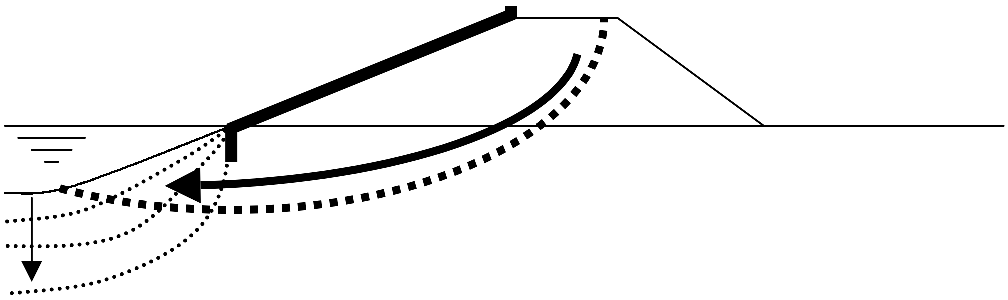


Fig. 6.7. Beach erosion and resulting sliding of a sea dike revetment

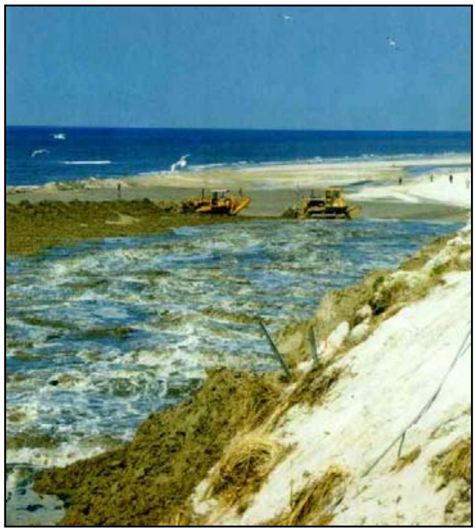


Fig. 6.8. Supply of a water-sand mixture to pumpedthe beach via a pipeline, connected with a sea bottom pipeline to the pump of a trailing suction hopper dredger, fully loaded with sand, anchored on deeper water.

Fig. 6.9. Redistribution of onshore mixture of sand and water, with help of bulldozers

Beach walls and sea dike revetments (fig. 6.7) may be effective for protection against wave attack and storm surges. However, they will not stop beach erosion if the mechanism is a gradient in longshore transport. The only effect is that erosion is not projected on the beach but in front of the beach wall or revetment, under the waterline, not visible for inspection.
The foreshore will increase in depth and in slope and eventually, the beach wall will tumble down into the sea and a revetment will fail because of the subsidence of the toe and the resulting sliding of the revetment (fig. 6.7). Both situations will bring on accelerated erosion after collapse due to adaptation of the artificial created beach slope to a gentler, natural slope.

Artificial beach nourishment (fig. 6.8, fig. 6.9), regularly applied on the Dutch coast is based on the idea that sand is brought towards the coastline from other locations (for example dredged from deeper water with a trailing suction hopper dredger), with the intention that it may erode. In this way the nourished sand protects the original coastline. After nourishment, the beach will not maintain its artificial created profile but it will adapt its profile to a more natural one. These nourishments have to be repeated after some years, its interval is depending on number of storms. In the Netherlands, the price per cubic meter nourished sand is approximately 2 to 4 USD, depending on the supply method.

Without going into a detailed cost-benefit study, it already can be concluded that costly defence measures on the Nam Dinh coast are not sustainable. Because of the uncertainty in the Red River development, little can be said about the functional and technical lifetime of these constructions. If for example, coastal defence measures will be applied, associated with enormous investments and if subsequently the Red River will cause a dike breach, rehabilitating the former So River into a major river branch, the need and functioning of these constructions will be superseded.
Relocation of people according to the setback line theory in the areas being at risk, together with the relocation of people from the former So River bed (introducing an artificial change of the Red River course in favourite of rehabilitating sediment supply to the eroding beaches) could create opportunities for short-term and long term solution without enormous cost involvement. However, the social problem involved with these measures will initially be considerable, but on long term, this will change as attitude of people regarding this strategy may change.

8 Conclusions

The coastal erosion in Nam Dinh province is a problem.

- The reclamation of the flat, low lying intertidal 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 now directly behind sea dikes that protected 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.

The main causes for the erosion are found in the changing geometry of the Red River system and the morphological mechanisms that characterises river mouth development.

- The abandoning of the So River, the former major river mouth in the southern part of the Red River delta after 1500 and next to it the development of the new, present Red River mouth is a result of the first mentioned cause.
- The development of the Red River mouth to its present shape is the second cause of the erosion.

The cyclic mechanisms of the Red River mouth cause cyclic alternation of supply and non-supply of sediments of the river mouth to downdrift located beaches. During the historical development of the Red River mouth, the alternating development of spits has greatly influenced the nourishment of the southern located beaches by longshore transport. The shape and growth in seaward direction created an obstacle that caused a change in wave climate along the downdrift located beaches.

- The shape of the present mouth is a result of the mouth developing mechanism that is characterised by a leapfrog displacement forward enforced by temporal variability in monsoon discharge.
- The reason for the accelerated accumulation near river mouths during the last century is the limitation of alluvial sediment supply only to the river mouths. Coastal reclamation projects and river training works prevented that alluvial sediments could be equally spread out over the delta.
- An other reason for the accelerated accumulation near river mouths is the is soil erosion and resulting deposition of sediments near river mouths, due to deforestation in the catchment areas of the Red River and in the delta plain itself during and after colonial times and in the 1960's and 1970's.

The diminishing supply from the So River in combination with the cut-off in sediment supply from the major supplier, the Red River caused accelerated erosion (which may have started already in the middle of the 19th century) in Hai Hau district, located south of the So River. This erosion was magnified in the period after 1955 when the So River was dammed. After 1965, when the river mouth seemed to have found stable equilibrium, having created a continuous coastline, the erosion diminished. Accelerated excessive accumulation due to deforestation and a major flood changing river mouth geometry in 1971 caused a new cycle in river mouth growth, cutting off again all sediment supply to downdrift beaches. Near the village of Van Ly, in the middle of Hai Hau district, the most severe erosion occurred in the last century. A comparison of French and Vietnamese maps proved the following historical erosion rates for Van Ly Village:

From	To	Lower boundary rate [m/year]	Upper boundary rate [m/year]
1912	1955	5.5	9.5
1955	1965	20	24
1965	1995	6	9

The development of Ba Lat now seems to stabilise, possibly leading to a restoration of the sediment supply to downdrift located beaches.

- Decreasing values of suspended particle matter and resulting decrease in sediment supply to the coast has impacts that are twofold. First the absolute supply of sediments to the coast will decrease but second, the coastline will remain stable in a longer period because of the increase in cycle duration of the Ba Lat. If the Red River mouth partly looses its leapfrogging character, the beaches down stream will show a more steady development, despite the decrease of supply of sediments.
- The damming of the Da River, responsible for 53 % of the total discharge of the Red River systems, is the most plausible cause for the decrease in sediment supply to the coast.

If the Red River mouth will break through its artificial created levees forming a new river course, it will drastically change the morphological system. This change may happen in arbitrary locations and at an arbitrary moment. If the river will change its course in northern direction as it did some 500 years ago, the erosion problems in Nam Dinh province will increase, whereas a change of course in a southern direction will reduce or even may stop the erosion problems south of its present river mouth.

- Due to the increased resistance of flow in the river mouth, the river sooner or later may break through its levees in case of a major river flood.
- As the coastal plain is depressed relative to the riverbed, it will be subjected to flooding and a new river course may form in the coastal plain.

Despite the fact that the nearshore region in front of Hai Hau beach has parallel bottom contours, required for reliable 1D wave model results, this 1D approach is not applicable in this particular situation because of offshore refraction and complex nearshore refraction.

- The shallow depths of the Tonkin Gulf cause a strong portion of the waves refracting already some 150 km offshore, where water depth is about 30 m, increasing to maximum depths of about 40-45 meters in the middle of the Tonkin Gulf
- The complex offshore seafloor orientation is caused by offshore depositions of Red River sediments. As approximately 45 % of the waves on deeper water come from 15 to 75 degrees sections, they must have significant influence on the resulting sediment transport capacity patterns along the coast. However, because of the 1D approach of wave propagation and refraction, this portion is generally discarded in the nearshore wave calculations for the coast of Nam Dinh, that generally reflects a 42 degrees orientation.

In the nearshore region of Nam Dinh, the protruding Red River mouth causes refraction and diffraction over curved complex bottom contours.

- A mild wave climate occurs just south of it along the strongly curved coastline north of the former So River mouth. Going further to the south, the portion of north and northeasterly waves increases.
- Because of the complex curved topography of bottom contours, a 1D model cannot represent the wave climate in these locations.

The shape and development of the Red River mouth cause complex nearshore circulation patterns. The longshore currents in winter, mainly responsible for the erosion of Hai Hau beach are composed by the asymmetrical tide, dominant in southwest direction and the wave and wind induced currents, both south-westward directed. The UNIBEST LT module is not able to simulate the nearshore currents in this particular situation, as basis for its longshore sediment transport capacity calculations.
For the Hai Hau district, the best estimate of the longshore transport capacity was 6.00.000 m^3/year. The equilibrium coast angle of the Hai Hau beaches was estimated at 29 degrees to north, implying a future reorientation of the coast at the expensive of the present coastline of the northern part of the Hai Hau district. Historical coastline changes show that the coastline alters from a more concave into a convex form. This change will continue in future until an equilibrium situation will be reached. The northern part of Nam Dinh will be accreting, connecting in a smooth line with the southern spit of the Red River barrier system. As the Red River mouth seems to be relative stable the last 10 years, it is expected that the wave climate south of it will not change dramatically in then near future, influenced by the shape of the protruding river mouth. The two inflection points on the coastline may therefore retain their positions. However, it must be noted that this possible reorientation is determined by the present course of the Red River and is therefore dependent on the future behaviour and future location of the Red River mouth.

Because of the uncertainty in the Red River development, dominating the coastal processes, costly defence measures on the Nam Dinh coast are not sustainable. Relocation of people according to the setback line theory in the areas being at risk, together with the relocation of people from the former So River bed (introducing an artificial change of the Red River course in favourite of rehabilitating sediment supply to the eroding beaches) could create opportunities for short-term and long term solutions without the involvement of high costs. However, the social problem involved with these measures will initially be considerable, but on long term, this will change as attitude of people regarding this strategy may change.

9 Recommendations

Direct action

- Action should be taken in order to restore the So River, rehabilitating the supply of sediment to the coast;
- Immediate relocation of people in areas at risk should be applied according to setback line theory.

Future studies

- This specific coastal problem was studied within the administrative boundaries of Nam Dinh province, because of the limitation of local data collection to this area. However, the problem requires an approach that should not be determined by the administrative boundaries but by physical boundaries that enclose the area influencing the specific problem. Therefore, a river basin approach for studying the specific problems along this coast should be applied in future studies;
- When predicting long term coastal development, the results of nearshore coastal modelling studies derive their validity on the course of the Red River and its river mouth location and river mouth shape. As the Red River may dramatically change its features in future, modelling results based on the present shape will lose their validity. Therefore, at present, more detailed modelling of nearshore coastal processes in order to predict future changes is not recommended;.

Suggestions

- Historical and future variability in temporal and spatial discharge distribution of the flow and sediment transport in the Red River system;
- Possibilities for sustainable settlement of people on the accreting areas in the north and the south of Nam Dinh district;
- Morphological impacts on the river system and the coastal system, if the Red River will have a future avulsion, discharging at both the present river mouth and one southward of it. Implementation of spatial planning in such a case;
- Impact of storms on flooding of the coastal lands in Hai Hau district in case that according to a setback line, people will be relocated and the dikes will be lost;
  Economical favourable measures for the defending the land from flooding;
- Impacts of superficial drainage and groundwater extraction on the settlement of the subsoil in the lower Red River delta;
  The vulnerability of the population for flooding in case of sea storms and river floods due to both of these impacts;
- Impacts of the Hoa Binh dam on the trapping of sediments in the reservoir and the erosion on downstream river branches and coastal areas.

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Annexes

1 WATRON model

1.1 Wave growth modelling (adopted from Holthuijsen, 2000)

The waves observed at sea, which cause the rocking of a ship and break along the coasts of continents, are composed of two types of waves. The first are sea waves, which are the waves in the wind-generating area and short period waves with unsymmetrical slopes and steep crests. The other variety is swell, which is a long and relatively symmetrical wave resulting from the wind waves after they leave the generating area. Swell generally has periods between 10 and 30 seconds.

It is very difficult to describe the surface wave motion if one considers that over the ocean there are always several weather systems generating waves and regarding the travel distances, interaction gives very complicated patterns. A good first estimate of wave conditions (sea waves) can be obtained by a wave growth model based on the assumption that a constant wind (constant in space and time) blows perpendicularly off a straight and long coastline over deep water or water with a constant depth. The wind field is idealised by reducing the actual wind field to a constant wind, which is limited in space and time by an upwind spatial boundary and an initial condition. The initial condition is a flat sea surface at time $t=0$ when the wind starts to blow with a constant speed and direction. In such an idealised case, the wave conditions are fully described as a function of wind speed, fetch and duration.

The wind is a three-dimensional vector, which varies randomly in three space dimensions and time. For the purpose of wave prediction the wind description is reduced to only one characteristic wind velocity at a fixed elevation. The only parameters that are assumed to affect the waves are fetch (F), time (t), wind speed at 10 m elevation (U10) and gravitational acceleration (g). Other parameters such as viscosity in the water and turbulence of the airflow are ignored. The duration of the wind can be expressed in terms of an equivalent fetch. The duration is the time during which the wind has had the opportunity to transfer energy from the atmosphere to the waves.

Wave growth can therefore be duration limited (equivalent fetch smaller than actual fetch) or fetch limited (actual fetch smaller than equivalent fetch). For very long fetches the wave height and wave period is limited, assuming that the wave growth will stop as soon as the group speed of the waves approach the wind speed. In shallow water at short fetches, the water depth has no effect on the waves. The waves at short fetches have relatively short wave lengths. As the waves move along a fetch, the wavelengths become larger and the depth becomes more important.

The Shore Protection Manual edition 1984 presents different equations for H_s and T_m for three cases; deep water developing seas, deep water fully developed seas and shallow water.
Hurdle and Stive (1989) adapted this model to remove some inconsistencies in the formulation and to provide a continuous transition between the results in shallow and deep water. The three sets of equations have been replaced by one single set of equations representing all cases.

$$\widetilde{H} = 0.25\tanh(0.6\widetilde{d}^{\,0.75})\tanh^{0.5}\left[\frac{4.3\times 10^{-5}\widetilde{F}}{\tanh^{2}(0.6\widetilde{d}^{\,0.75}}\right]$$

(non-dimensionalised significant wave height H_s)

$$\widetilde{T} = 8.3\tanh(0.76\widetilde{d}^{\,0.375})\tanh^{1/3}\left[\frac{4.1\times 10^{-5}\widetilde{F}}{\tanh^{3}(0.76\widetilde{d}^{\,0.375}}\right]$$

(non-dimensionalised spectral peak period T_m)

Distance, height and depth are non-dimensionalised (denoted by ~) by multiplying with a factor:

$$\frac{g}{U_A^2}$$

Time is non-dimensionalised (denoted by ~) by multiplying with a factor:

$$\frac{g}{U_A}$$

U_A is the wind stress factor (adjusted wind speed) calculated from wind speed over open water, adjusted for air/water temperature difference.

$$U_A = 0.71(U)^{1.23}$$

U is the mean hourly wind speed 10 m above sea level adjusted to air-sea temperature difference.

In case of duration limited wave growth, an equivalent fetch length is suggested formulated by:

$$\widetilde{F}_{equivalent} = \left(\frac{\widetilde{t}}{65.9}\right)^{3/2}$$

1.2 WATRON wave generation and wave propagation

By appliance of the wave growth model WATRON (WL | Delft Hydraulics), a wave climate can be computed. WATRON predicts the significant wave height, wave period, main wave direction and directional spreading at a single output point. The model accounts for directional spreading by considering wave growth to be directionally decoupled and by taking an empirical directional energy distribution for growth in an ideal situation. Directionally decoupled growth is based on the assumption that the two-dimensional energy density in direction θ develops independently from the energy densities in other directions. It does depend on the energy density at other frequencies in the same direction (Seymour, 1977).
The modelling procedure is as follows: a sector consisting of 90^o degrees on either side of the wind direction is divided into segments of a small angle. The available fetch length for each segment is computed and projected onto the wave direction. Furthermore, the wave height and period for each segment are computed corresponding to the projected fetch of each segment according to the Hurdle and Stive (1989) wave growth model. The energy in the segment is computed according to a theoretical directional distribution given by:

$$E(\theta) = k \cos^m(\theta - \theta_0) H_s^2(\theta)$$

in which E is the energy density, θ_0 the wind direction and k and m are constants. The coefficient m represents the width of the directional spreading.

Hence the wave height is:

$$H_s = \sqrt{E_{tot}} = \sqrt{\sum_{\theta} E(\theta)}$$

The wave period is computed by:

$$\overline{T} = \frac{\sum_{\theta} \left[E(\theta) T(\theta) \right]}{E_{tot}}$$

Fig. 1.1 shows the sensitivity of the directional spreading distribution to the coefficient m.
Plotted is COS to the power m for various m.

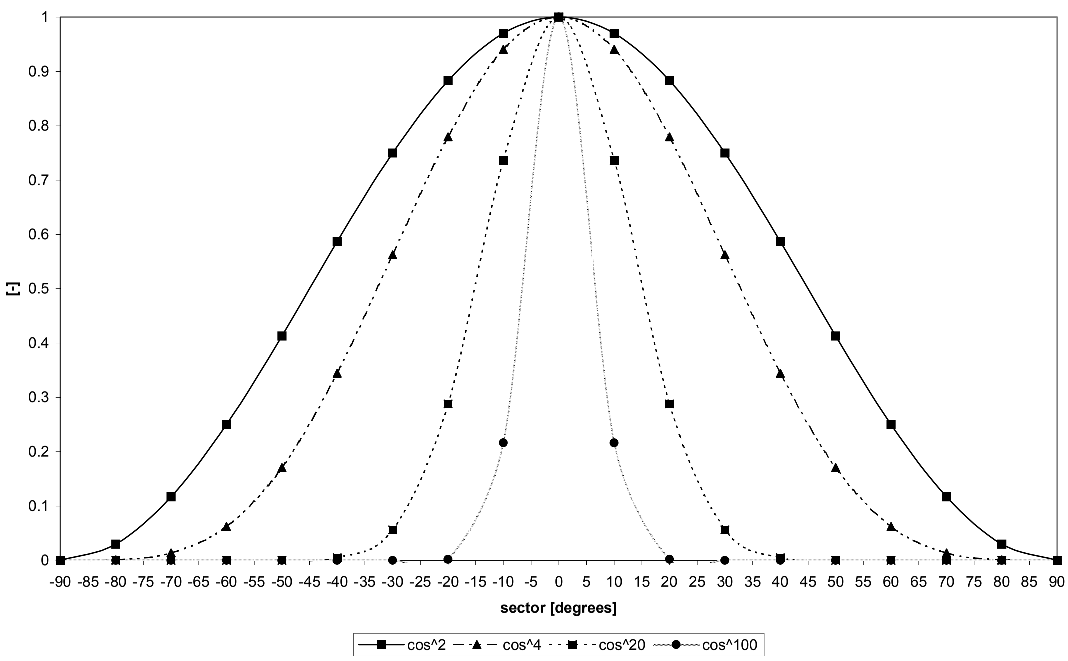


Fig. 1.1. COS^m for the range [-90 deg. to +90 deg.].

2 UNIBEST CL+

2.1 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:

1. The Longshore Transport module (LT-module)
2. 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.

2.2 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.

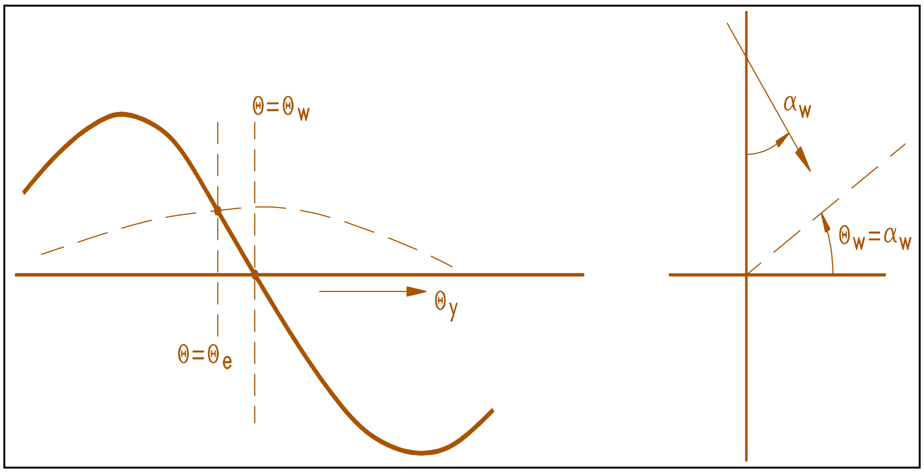


Fig. 2.1. Equilibrium angle (θ_e) is approximated by: $\theta_w + c^2{}_i/c^1{}_i$.

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 2.1):

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

  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.

2.3 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.

2.4 Input parameters for the UNIBEST model

Wind climate at 11.4 m. depth at north bank of the Ninh Co riverbank, calculated by assuming that the waves refract to a coastline reflecting a 20 degrees to north orientation.

Hsig [m]	Tp [s]	Wave angle with respect to north [degrees]	Duration [days]	Frequency [%]
0,4	3,9	60	26,2435	7,19
0,6	4,8	60	48,8735	13,39
0,9	5,8	60	34,2735	9,39
1,3	6,0	60	25,258	6,92
1,8	7,7	60	2,5915	0,71
2,5	8,0	60	0,7665	0,21
0,4	3,4	90	9,8915	2,71
0,6	4,0	90	11,315	3,1
0,9	4,7	90	13,2495	3,63
1,3	5,9	90	14,235	3,9
1,8	7,2	90	5,11	1,4
2,5	8,1	90	1,825	0,5
3,5	8,0	90	0,073	0,02
0,4	3,4	120	8,5775	2,35
0,6	4,0	120	9,417	2,58
0,9	4,4	120	8,614	2,36
1,3	5,7	120	9,0155	2,47
1,8	6,3	120	2,2995	0,63
2,5	7,4	120	0,584	0,16
3,5	8,0	120	0,1095	0,03
0,4	3,9	150	8,614	2,36
0,6	4,8	150	17,2645	4,73
0,9	5,5	150	19,6735	5,39
1,3	6,1	150	24,1265	6,61
1,8	7,4	150	3,6865	1,01
2,5	8,0	150	0,9125	0,25
3,5	8,0	150	0,0365	0,01
0,4	3,8	180	5,767	1,58
0,6	4,2	180	3,212	0,88
0,9	4,5	180	0,803	0,22
1,3	6,0	180	0,0365	0,01

Wind climate at 11.4 m. depth at the end point of the spit formed just south of the Red River mouth, calculated by assuming that the waves refract to a coastline reflecting a75 degrees to north orientation.

Hsig [m]	Tp [s]	Wave angle with respect to north [degrees]	Duration [days]	Frequency [%]
0,4	5,1	90	33,3245	9,13
0,6	4,0	90	1,971	0,54
0,9	4,0	90	0,073	0,02
0,4	5,2	120	54,4215	14,91
0,6	5,1	120	31,536	8,64
0,9	5,2	120	13,505	3,7
1,3	6,1	120	4,7085	1,29
1,8	6,8	120	0,292	0,08
2,5	8,0	120	0,0365	0,01
0,4	3,6	150	3,7595	1,03
0,6	4,0	150	4,745	1,3
0,9	4,8	150	6,132	1,68
1,3	5,8	150	8,4315	2,31
1,8	6,2	150	2,774	0,76
2,5	7,9	150	0,7665	0,21
3,5	8,0	150	0,1095	0,03
0,4	3,4	180	5,402	1,48
0,6	4,0	180	7,2635	1,99
0,9	4,7	180	11,534	3,16
1,3	5,8	180	23,433	6,42
1,8	6,1	180	15,3665	4,21
2,5	7,9	180	3,7595	1,03
3,5	8,0	180	0,292	0,08
4,5	8,0	180	0,0365	0,01
0,4	3,9	210	2,993	0,82
0,6	4,4	210	2,847	0,78
0,9	4,5	210	2,19	0,6
1,3	5,7	210	1,7885	0,49
1,8	6,0	210	0,4015	0,11
0,4	4,2	240	1,4965	0,41
0,6	4,0	240	0,1095	0,03

Tide parameters

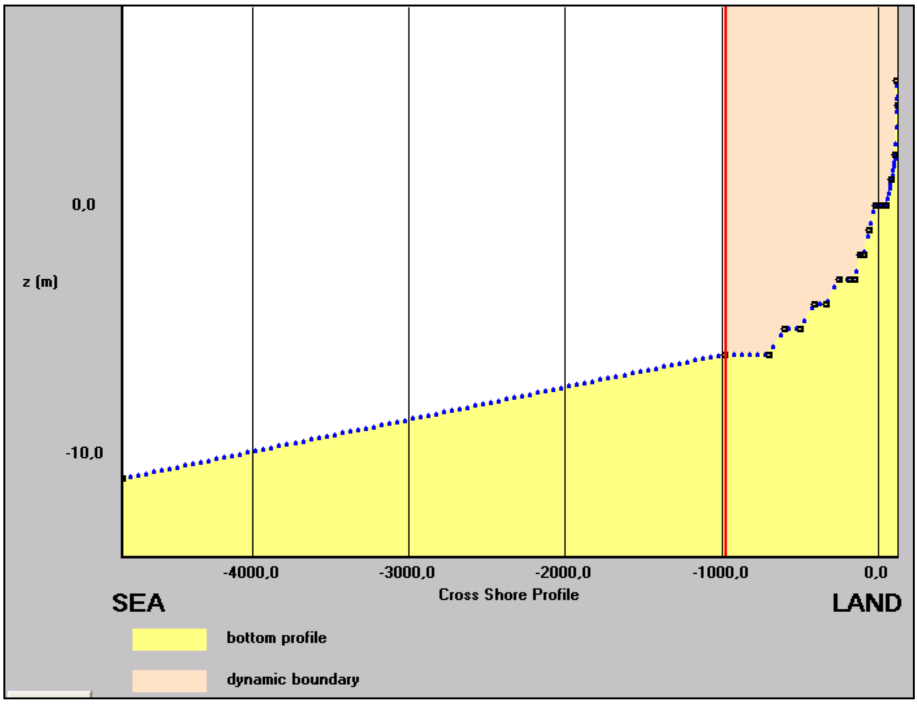
Tidal height [m] relative to mean sea level	Frequency [%]
0,25	9
0,75	17
1,25	22
-0,25	12
-0,75	11
-1,25	29

Wave parameters

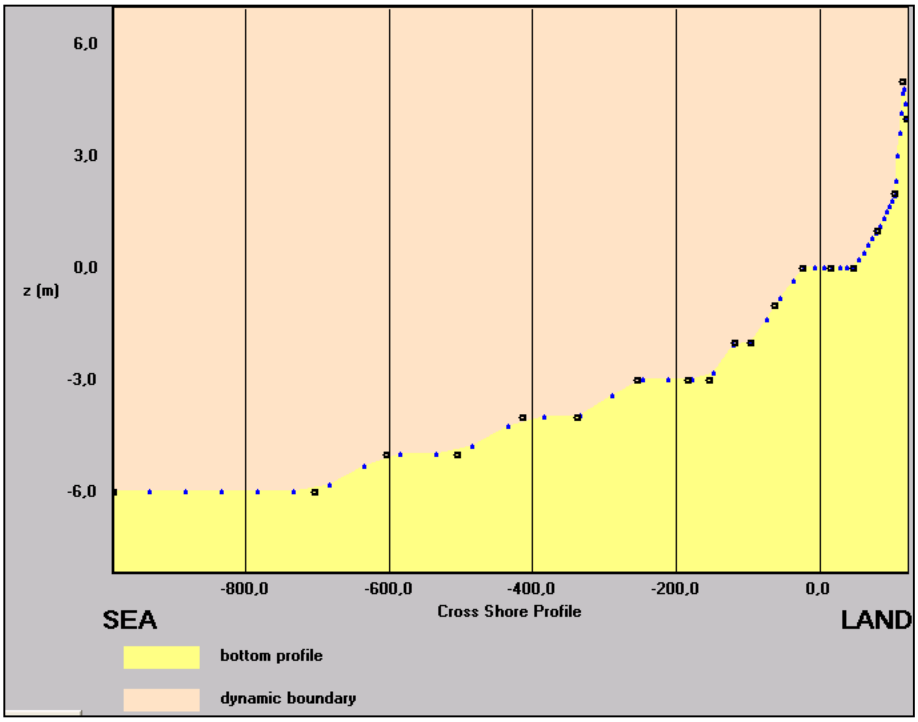
Wave parameters	
Coefficient for wave breaking (gamma) [-]	0.8
Coefficient for wave breaking (alpha) [-]	1
Coefficient for bottom friction (fw) [-]	0
Value of the bottom roughness (kb) [m]	0.1

Sediment transport coefficients

Sediment transport coefficients for application of the transport formula according to Bijker (1967,1971)	
D50, median (50%) grain diameter [μm]	100
D90, 90% grain diameter [μm]	200
Bottom roughness [m]	0.01
Sediment's fall velocity [m/s]	0.007
Deepwater criterion Hsig/h	0.07
Coefficient b on deep water	2
Criterion shallow water, Hsig/h	0.6
Coefficient b shallow water	5



Cross-shore profile (red line indicates the end of the dynamic zone)



Detailed cross shore profile of dynamic area

3 Offshore wave tables

3.1 All year offshore wave climate

Significant Wave Height (m)	Wave Direction (deg.N) -15.: 15.	15.: 45.	45.: 75.	75.: 105.	105.: 135.	135.: 165.	165.: 195.	195.: 225.	225.: 255.	255.: 285.	285.: 315.	315.: 345.	Total
< 0.25	2.51	0.97	0.25	1.00	0.92	0.20	0.58	0.26	0.04	0.12	0.18	0.06	7.08
0.25: 0.50	0.75	2.87	0.87	2.25	2.13	0.52	1.26	0.55	0.08	0.25	0.36	0.15	12.04
0.50: 0.75	0.69	4.48	1.35	2.54	2.40	0.73	1.73	0.66	0.08	0.23	0.31	0.14	15.33
0.75: 1.00	0.54	5.69	1.67	2.17	1.86	0.82	2.07	0.64	0.06	0.16	0.22	0.10	16.00
1.00: 1.25	0.28	5.50	1.27	1.11	0.96	0.71	2.39	0.55	0.04	0.07	0.10	0.05	13.01
1.25: 1.50	0.24	5.48	1.16	0.84	0.71	0.67	2.52	0.51	0.03	0.06	0.08	0.03	12.33
1.50: 1.75	0.13	4.02	0.84	0.47	0.42	0.52	2.34	0.46	0.02	0.02	0.04	0.02	9.29
1.75: 2.00	0.07	3.83	0.70	0.14	0.16	0.36	1.98	0.23	0.01	0.01	0.01	0.01	7.52
2.00: 2.25	0.01	1.29	0.24	0.04	0.05	0.19	1.51	0.20	0.00	0.01	.	.	3.55
2.25: 2.50	0.01	0.08	0.02	0.01	0.01	0.06	0.42	0.04	.	.	.	.	0.65
2.50: 2.75	0.01	0.54	0.07	0.00	0.00	0.01	0.02	0.00	.	0.00	0.00	.	0.68
2.75: 3.00	0.01	0.58	0.08	0.01	0.01	0.06	0.24	0.02	.	0.00	.	.	1.03
3.00: 3.25	0.01	0.24	0.03	0.01	0.01	0.04	0.20	0.02	.	.	.	.	0.56
3.25: 3.50	0.01	0.21	0.02	.	.	0.01	0.01	.	.	.	.	.	0.27
3.50: 3.75	0.01	0.21	0.02	.	.	0.01	0.01	.	.	.	.	.	0.28
3.75: 4.00	0.02	0.15	0.01	.	.	0.01	0.02	.	.	.	.	.	0.22
4.00: 4.50	0.02	0.07	0.00	.	0.00	0.00	0.03	0.01	.	.	0.00	.	0.15
4.50: 5.00	.	.	.	.	.	.	0.00	.	.	.	.	.	0.01
5.00: 6.00	.	.	.	.	.	.	0.01	.	.	.	.	.	0.01
6.00: 7.00	.	.	.	.	.	.	.	.	.	.	.	.	.
7.00: 8.00	.	.	.	.	.	.	.	.	.	.	.	.	.
> 8.00	.	.	.	.	.	.	.	.	.	.	.	.	.
Total	5.33	36.21	8.63	10.60	9.65	4.90	17.34	4.15	0.36	0.95	1.32	0.58	100.00

Season . . . . . : All Year

Period . . . . . : 1976 to 1995

Area . . . . . : 107.43 to 107.43 deg. East
20.08 to 20.08 deg. North

No. observations : 28484

Probability that highest of sea and swell occur in the given height and direction class at Bach Long Vy Island (Tonkin Gulf) meteorological station

3.2 Winter monsoon offshore wave climate

Significant Wave Height (m)	Wave Direction (deg.N) -15.: 15.	15.: 45.	45.: 75.	75.: 105.	105.: 135.	135.: 165.	165.: 195.	195.: 225.	225.: 255.	255.: 285.	285.: 315.	315.: 345.	Total
< 0.25	1.60	1.07	0.24	1.08	0.78	0.12	0.24	0.06	0.01	0.02	0.09	0.05	5.36
0.25: 0.50	0.58	3.63	1.07	2.70	1.87	0.31	0.47	0.11	0.01	0.05	0.14	0.10	11.03
0.50: 0.75	0.60	6.14	1.78	3.24	2.16	0.42	0.56	0.12	0.01	0.04	0.09	0.08	15.24
0.75: 1.00	0.51	8.15	2.32	2.88	1.83	0.48	0.62	0.11	0.01	0.02	0.04	0.04	17.01
1.00: 1.25	0.27	8.18	1.85	1.50	0.91	0.38	0.63	0.08	.	0.01	0.01	0.01	13.83
1.25: 1.50	0.23	8.17	1.72	1.15	0.66	0.34	0.64	0.06	.	0.01	0.01	0.01	12.99
1.50: 1.75	0.12	6.13	1.25	0.62	0.36	0.26	0.60	0.05	.	.	0.01	.	9.42
1.75: 2.00	0.06	5.91	1.04	0.15	0.10	0.18	0.53	0.02	.	.	.	.	7.99
2.00: 2.25	0.01	1.99	0.34	0.04	0.03	0.11	0.43	0.01	.	.	.	.	2.96
2.25: 2.50	0.01	0.12	0.02	0.01	.	0.04	0.16	.	.	.	.	.	0.37
2.50: 2.75	0.01	0.83	0.10	.	.	0.01	0.01	.	.	.	.	.	0.97
2.75: 3.00	0.01	0.90	0.12	0.01	.	0.04	0.09	.	.	.	.	.	1.18
3.00: 3.25	0.01	0.36	0.04	.	.	0.03	0.08	.	.	.	.	.	0.53
3.25: 3.50	0.01	0.31	0.03	.	.	.	0.01	.	.	.	.	.	0.37
3.50: 3.75	0.01	0.31	0.03	.	.	.	0.01	.	.	.	.	.	0.37
3.75: 4.00	0.01	0.21	0.02	.	.	.	0.01	.	.	.	.	.	0.26
4.00: 4.50	0.02	0.08	0.01	.	.	.	0.01	.	.	.	.	.	0.12
4.50: 5.00	.	.	.	.	.	.	.	.	.	.	.	.	0.01
5.00: 6.00	.	.	.	.	.	.	.	.	.	.	.	.	0.01
6.00: 7.00	.	.	.	.	.	.	.	.	.	.	.	.	.
7.00: 8.00	.	.	.	.	.	.	.	.	.	.	.	.	.
> 8.00	.	.	.	.	.	.	.	.	.	.	.	.	.
Total	4.08	52.50	11.98	13.39	8.70	2.73	5.10	0.62	0.05	0.15	0.39	0.29	100.00

Season . . . . . : NE monsoon (October, November, December, January, February, March, April)

Period . . . . . : 1976 to 1995

Area . . . . . : 107.43 to 107.43 deg. East
20.08 to 20.08 deg. North

No. observations : 16612

Probability that highest of sea and swell occur in the given height and direction class at Bach Long Vy Island (Tonkin Gulf) meteorological station

3.3 Summer monsoon offshore wave climate

Significant Wave Height (m)	Wave Direction (deg.N) -15.: 15.	15.: 45.	45.: 75.	75.: 105.	105.: 135.	135.: 165.	165.: 195.	195.: 225.	225.: 255.	255.: 285.	285.: 315.	315.: 345.	Total
< 0.25	3.79	0.83	0.25	0.88	1.11	0.30	1.07	0.54	0.07	0.26	0.31	0.08	9.49
0.25: 0.50	0.99	1.81	0.60	1.62	2.51	0.81	2.37	1.16	0.16	0.53	0.66	0.23	13.45
0.50: 0.75	0.81	2.16	0.74	1.56	2.73	1.16	3.35	1.41	0.17	0.50	0.62	0.23	15.45
0.75: 1.00	0.57	2.24	0.76	1.18	1.91	1.30	4.09	1.38	0.15	0.36	0.47	0.17	14.59
1.00: 1.25	0.29	1.76	0.46	0.56	1.02	1.17	4.84	1.21	0.08	0.16	0.22	0.09	11.87
1.25: 1.50	0.25	1.72	0.39	0.41	0.78	1.12	5.15	1.13	0.07	0.14	0.18	0.07	11.40
1.50: 1.75	0.14	1.05	0.27	0.25	0.49	0.87	4.78	1.03	0.04	0.05	0.08	0.04	9.11
1.75: 2.00	0.08	0.92	0.23	0.13	0.26	0.61	4.00	0.54	0.02	0.03	0.03	0.01	6.86
2.00: 2.25	0.01	0.31	0.10	0.05	0.09	0.31	3.02	0.47	0.01	0.01	.	.	4.38
2.25: 2.50	0.01	0.02	0.02	0.01	0.02	0.08	0.78	0.08	.	.	0.01	.	1.04
2.50: 2.75	0.02	0.13	0.03	0.01	0.01	0.01	0.05	0.01	.	0.01	0.01	.	0.27
2.75: 3.00	0.02	0.14	0.04	0.01	0.02	0.08	0.45	0.04	.	0.01	0.01	.	0.82
3.00: 3.25	0.01	0.08	0.01	0.01	0.02	0.05	0.37	0.04	.	.	.	0.01	0.60
3.25: 3.50	0.01	0.07	0.01	.	0.01	0.01	0.02	.	.	.	.	0.01	0.14
3.50: 3.75	0.01	0.07	0.01	.	0.01	0.01	0.02	.	.	.	.	0.01	0.15
3.75: 4.00	0.02	0.06	.	0.01	0.01	0.01	0.02	0.01	.	.	0.01	.	0.15
4.00: 4.50	0.03	0.04	.	.	0.01	0.01	0.06	0.03	.	.	0.01	0.01	0.19
4.50: 5.00	.	.	.	.	.	.	0.01	.	.	.	.	.	0.02
5.00: 6.00	.	.	.	.	.	.	0.01	.	.	.	.	.	0.02
6.00: 7.00	.	.	.	.	.	.	.	.	.	.	.	.	.
7.00: 8.00	.	.	.	.	.	.	.	.	.	.	.	.	.
> 8.00	.	.	.	.	.	.	.	.	.	.	.	.	.
Total	7.07	13.41	3.93	6.69	10.99	7.92	34.47	9.08	0.79	2.06	2.61	0.97	100.00

Season . . . . . : SW monsoon (May, June, August, September)

Period . . . . . : 1976 to 1995

Area . . . . . : 107.43 to 107.43 deg. East
20.08 to 20.08 deg. North

No. observations : 11872

Probability that highest of sea and swell occur in the given height and direction class at Bach Long Vy Island (Tonkin Gulf) meteorological station

4 Tides along the Red River delta

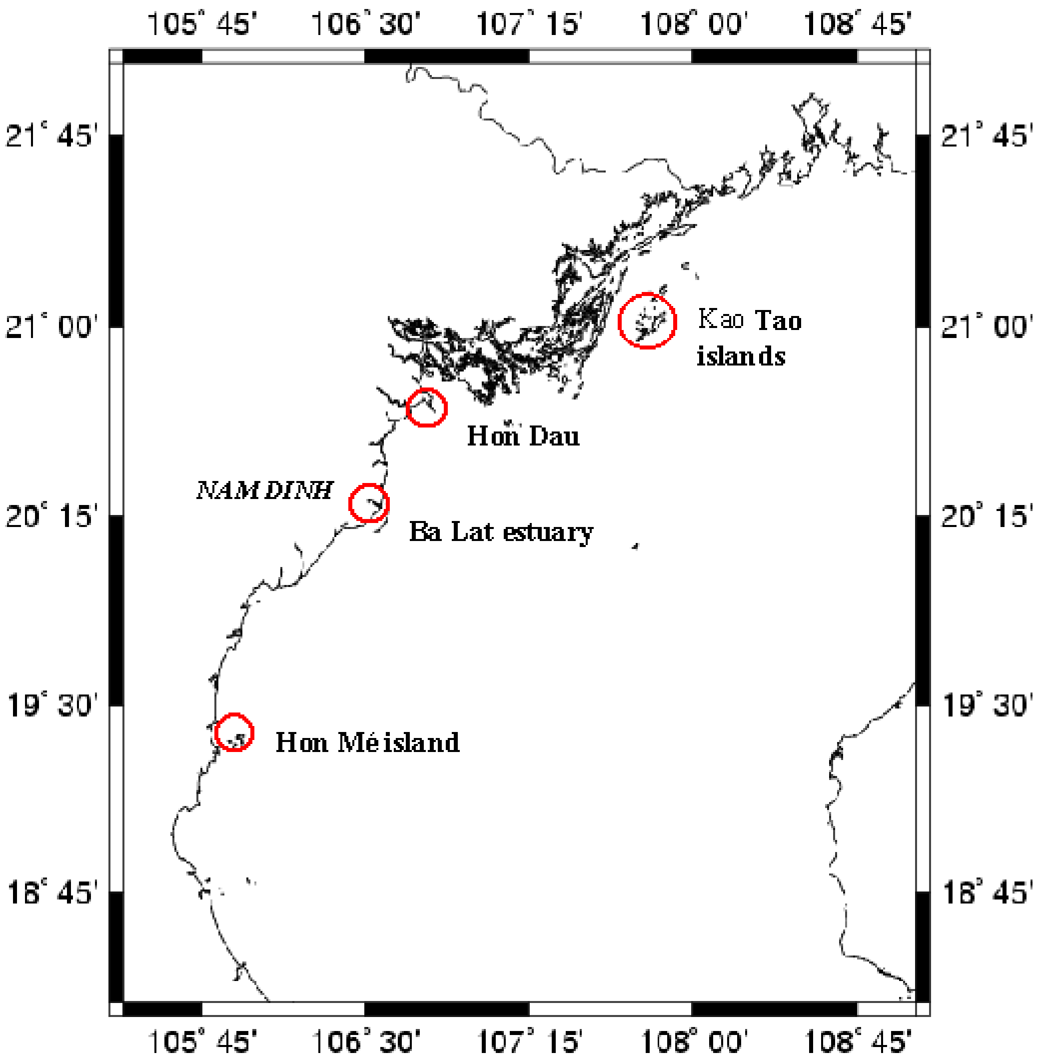


Fig. 4.1 Locations of water level measuring stations

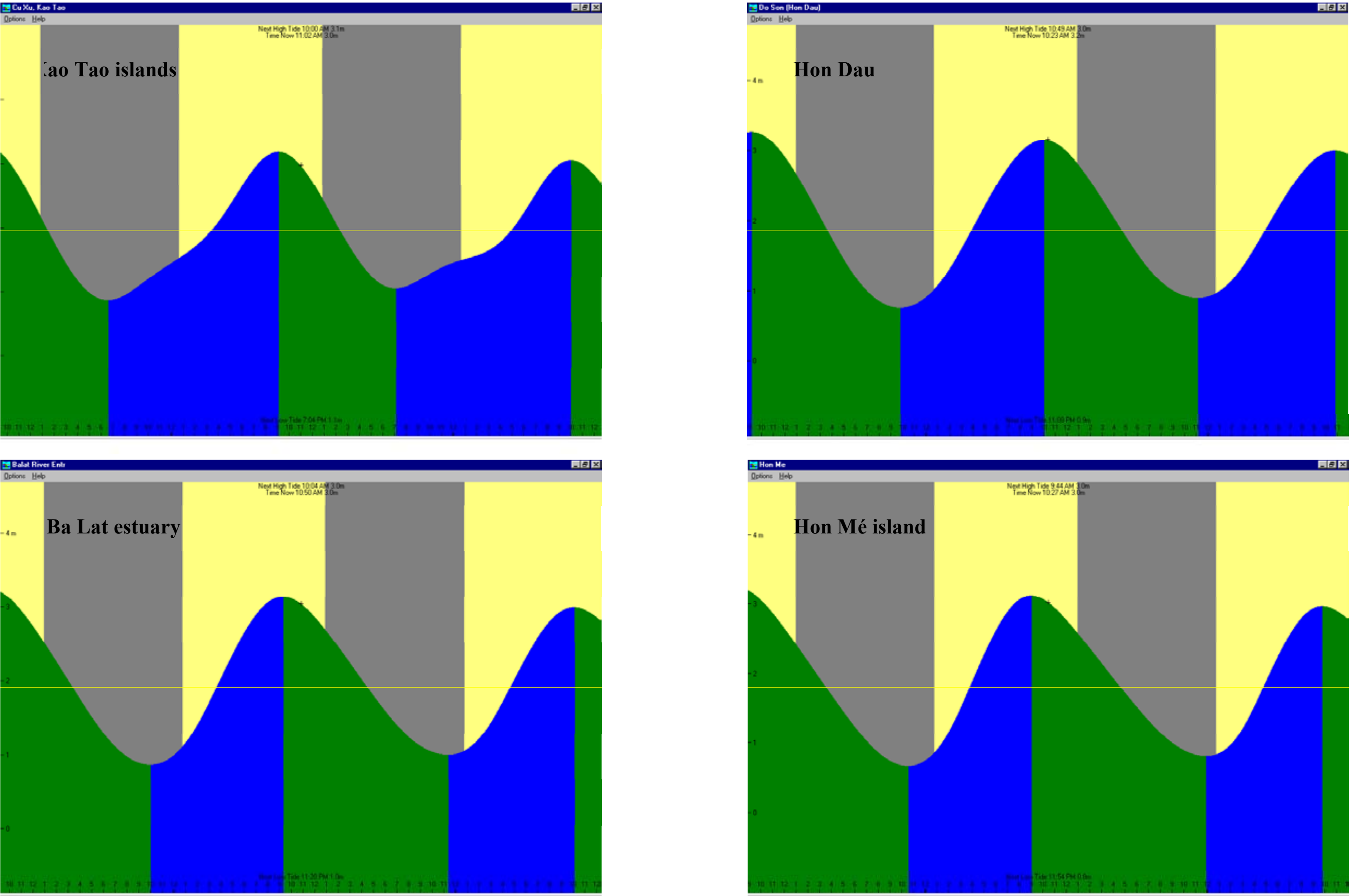


Fig. 4.2. Tide, generated by WXTide32, version 2.6, representing 19-09-2000