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Coastal Protection Strategies for the Red River Delta

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ABSTRACT

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The coastal zone in the Red River Delta of Vietnam is under large threat due to fluvial flooding, coastal flooding, and coastal erosion. As an important input for ongoing studies that focus on finding an optimal coastal protection strategy for reducing the vulnerability of the coastal region, this paper aims to describe the current situation of the coastal region and assess its present protective measures. In the region, sea dikes have been used as the predominant countermeasure with two intended functions: (i) protecting low-lying areas from coastal flooding and (ii) reducing the risk to the hinterland caused by erosion. However, the sea dikes seem not to function well and are insufficient to withstand dike breaches at the low frequency they are designed for. To have better insight into the actual situation of the whole system, this paper first investigates the historical development of the coastlines in the delta based on available information. Second, hydrodynamic and morphological processes of the coastal and estuarine systems are reviewed and further analysed. An effectiveness assessment of the present protection strategies is subsequently presented. Finally, further research needed to improve the rehabilitation of coastlines and the safety of the region is discussed based on analysis results.

ADDITIONAL INDEX WORDS: *Coastal flood defences, sea dikes, longshore sediment transport, Nam Dinh coast, Typhoon Damrey.*

INTRODUCTION

Vietnam, situated in the tropical monsoon area of southeast Asia, is a typhoon-prone country. A large part of the population is mainly involved in agricultural and fishery sectors, which are situated in low-lying river flood plains, deltas, and coastal margins. In addition, important ports are located along the coast. These areas are the most important potential disaster areas due to flooding and land erosion (Wijdeven, 2002). Typhoons from the South China Sea bring torrential rainfall and high winds to the coast and further inland. On average, six typhoons attack the coast annually. The monsoon season coincides with the typhoon season, resulting in heavy damage, loss of life, and destruction of infrastructure facilities and services. The reason that flood disasters are so serious is that most of the population lives in areas susceptible to flooding originating either from the rivers or from the sea. The main population centres and intensively cultivated lands in the Red River and Mekong deltas, and the narrow connecting coastal strip of the country, are particularly vulnerable to flooding from monsoon rains and typhoon storms. In addition, due to the dynamic nature of coastal and river processes, land erosion is occurring seriously at many places. Thus fluvial and coastal flooding and associated land erosion are the most important potential disasters facing Vietnam (Pilarczyk and Nguyen, 2002).

In the past, because of limited budgets and inaccessability of technology (proper expertise and technical facilities), shore management and flood control were limited to simple and inexpensive approaches such as manual labour, training in dike inspection, procedures for evacuating the population during emergencies, strategic positioning of supplies for emergency repairs, providing relief after a disaster, and accepting land retreat.

Currently Vietnam is seeking to build a modern system of shoreline protection, dike management, and flood control based on new design methodologies and technologies, such as using more advanced design and construction methods (often adopted from foreign countries) in combination with state-of-the-art warning and forecasting systems to improve emergency preparedness and with the construction of storm-proof shelters for disaster impact reduction. These objectives are incorporated into the recently initiated Vietnam water defence development plan, where safety against flooding and sustainable land protection are recognized as fundamental requirements for all forms of development. Great emphasis is placed on strengthening and improving the entire system of sea dikes to prevent sea flood damages. The importance of dike safety has long been recognized as fundamental for the continued development of Vietnam.

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The Red River Delta, known as the most important region for all economic activities in the north of Vietnam, is where the majority of the region's population is concentrated and supports nearly half of the country's rice production; it is under threat due to fluvial and coastal flood and coastal erosion. In the delta there are six river mouths distributed over approximately 200 km along its coastlines, which results in a complex coastal estuarine system. Due to the impacts of natural processes from the sea (waves, storm surges, currents, sediment transport, and sea level rise), the coastlines have experienced dynamic changes and occasional destruction due to episodic events (typhoons). At present sea dikes are used as the predominant coastal protection measure for protecting low-lying areas from coastal flooding and reducing the risk to the hinterland caused by erosion. However, the sea dikes seem not to function well and fail more frequently than they are designed for. Consequently, the risk of damage and land loss is still high. Typhoon Damrey, which occurred on 27 September 2005, is considered the most vigorous typhoon in the last 50 years, causing sea dike breaches, seawater flooding, and serious loss of land. The need for finding a more proper coastal protection strategy to reduce the risk for the whole region is now being expressed by both local and national authorities in Vietnam.

This study focuses on analysis of coastline changes and the effectiveness of the present coastal protection works in the region. The outcome of this study could be used as an input for more comprehensive further studies on reducing the risk to the coastal region in the Red River Delta. Further research needed for improving the rehabilitation of coastlines and safety of the region is also discussed based on analysis results.

In order to have good insight into the actual situation of the whole coastal system in the Red River Delta, an investigation of the historical development of the coastlines in the delta is presented based on available historical information. Second, an overview of hydrodynamics of the complex coastal estuarine system in the Gulf of Tonkin will be presented by reviewing and analysing previous related studies. Subsequently, a study on coastal morphology and coastline changes is carried out using a two-dimensional advanced numerical model. The historical development of the coastlines is used to calibrate the models. Additionally, effectiveness of the present coastal protection in terms of safety for the protected region is presented. The paper ends with conclusions and recommendations.

DESCRIPTION OF THE STUDY AREA

The Red River Delta is characterized as low lying with an extensive network of river branches and with long stretches of dikes and sea defences (Figure 1). There are six active river mouths, namely Thai Binh, Ninh Co, Tra Ly, Ba Lat, Van Uc, and Day. The Ba Lat river is the main branch of the Red River, discharging its water into the Gulf of Tonkin in the South China Sea.

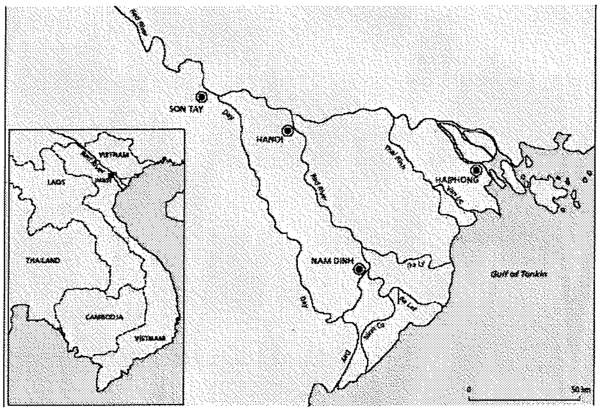

Figure 1. Position of the Red River Delta in Vietnam.

Most of the coastal regions of the Red River Delta have an elevation of less than 1 m above mean sea level. This makes the coastal area vulnerable to sea flooding and salt water intrusion. The deltaic coastal areas and low-lying coastal strips to a distance of about 20 km landwards are threatened because of the combined occurrence of storms, surges from the sea, and a high flow discharge from the rivers. Along the coastline, sea dikes are the most dominant coastal structures protecting the regions behind from sea flooding.

Sea dikes were built over the centuries mainly through local initiative. The sea dikes are generally poorly designed and poorly constructed. Due to the bad state of the dikes, a significant part of the yearly Vietnamese national budget has to be allocated to repairs and maintenance.

Generally, two main interrelated problems are distinguished in project areas: (i) serious erosion of the coastlines and (ii) heavy damage of the coastal flood defences. As stated in the "Annual reports on losses and damages of coastal regions" from 1976 to 2005 by the Department of Dike Management and Flood Control (DDMFC), more specific problems are as follows.

Severe structural longshore erosion and foreshore erosion take place along the unprotected coastlines and protected coastlines respectively. Structural erosion is due to a lack of fluvial sediment supply to the shore, which is necessary to compensate for the net natural longshore sediment transport occurring during the northeast monsoon, while foreshore erosion is due to longshore and cross-shore sediment transport, which takes place during storms. The structural erosion rate is about 10 to 20 m per year, while foreshore erosion leads to a deepening of the foreshore in front of the sea dikes, ranging from 0.3 to 0.6 m per year. This may lead to rapid retreat of the shoreline if appropriate countermeasures are not taken in time.

Beach erosion, dike breaching due to typhoons, storm surges, and wave action caused the retreat of up to 3000 m of the shoreline during the last 100 years. The total area of land loss is approximately 18,000 ha (nearly as large as the current area of the Hai Hau district).

Typhoons often attack coastal regions with wind strengths of 9 to 12 on the Beaufort scale, causing house collapse, loss of life, and huge property damage. In the last 30 years, from

Figure 2. Serious damage and breach of sea dikes in Hai Phong province, after typhoon Saola in 2005.

1976 to 2005, storms demolished about 7000 houses and 100 fishing ships, and 1000 people died.

Due to dike breaches, seawater has overflowed the hinterland, resulting in flooding of and salt intrusion in cultivated land. Statistics show that nearly 40,000 ha of cultivated land was contaminated by salt, and over 100,000 tons of food was lost. Salt mining fields and shrimp hatching ponds were also heavily damaged.

Storm surges often accompanied with high tides caused damage of Nam Dinh sea dikes almost every year. From 1976 to 2005, about 1,900,000 m^3 of earth and 1,000,000 m^3 of stone were taken away from the sea dikes. Therefore the expenditure on maintenance is very large (in the order of millions of euros).

Heavy damage and collapses of the defensive system, especially the dike system and revetments, have occurred. Many sections of dikes and revetments failed and were breached through a variety of modes of failure. This caused flooding in a wide area along the coastlines, and as a consequence, it led to loss of land, economic value, and even human life.

It appears that coastal erosion and damage of the defensive system have many effects on social and economic development in the area. In response the central and local authorities have undertaken some efforts in order to restrain adverse consequences. Also, some sections of new sea dikes have been built. However, due to budget constraints and a lack of a suitable design methodology, such efforts are still limited to reactive and temporary measures instead of implementing structural and long-term solutions.

Figure 2 shows the recent extent of sea dike failures at Hai Phong province due to Typhoon Saola. Figure 3 provides evidence of fast coastline retreat due to heavy erosion at Hai Trieu and Hai Ly communities, in Hai Hau district, Nam Dinh province, in the Red River Delta. As can be seen from Figure 3, normal village life was there in 1995; however, just 6 years later, the village was totally removed due to erosion.

Causes of Erosion

The most dynamic part of the coastal zone in the Red River Delta lies in the centre of the Nam Dinh province. The coastal zone of Nam Dinh is roughly 80,000 ha in size and has about 70 km of coastline. This coastline is naturally divided into three sections by four large estuaries: Ba Lat (Red River main reach), Ha Lan (So River, which was cut off some 10 years ago), Lach Giang (Ninh Co River), and Day (Day River). From north to south, these sections are as follows: Giao Thuy section, from Ba Lat estuary to So estuary, belonging to Giao Thuy district (about 2 km); Hai Hau section, from So estuary to Ninh Co estuary, belonging to Hai Hau district (27 km); and Nghia Hung section, from Ninh Co estuary to Day estuary, belonging to Nghia Hung district (16 km long; see Figure 4).

In Figure 4 we observe two accretion areas, one north and one south of the eroded area of Hai Hau district. It should be noted that accreted areas usually are stabilized by local people reducing the natural distribution of sediment along the coast. This could have accelerated the erosion rate in the eroded areas of Hai Hau. In eroded areas the beach is rather narrow—approximately 100–200 m at low tides. According to the records of the Provincial Dike Department (PDD) of Nam

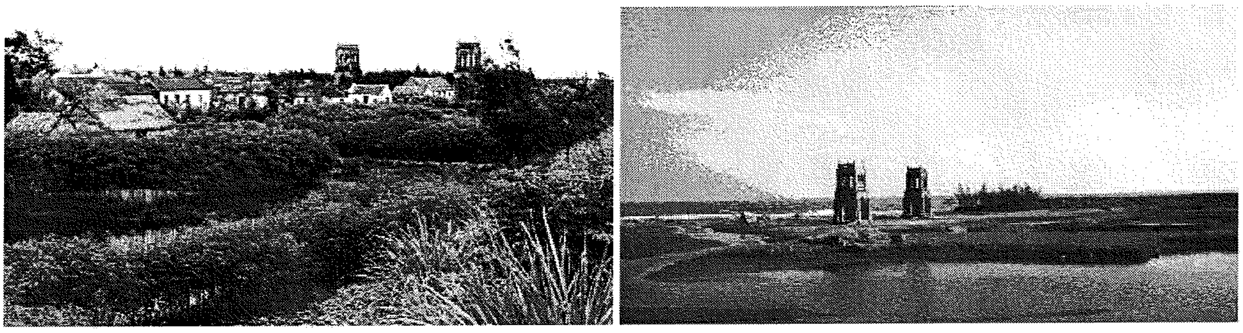

Figure 3. Hai Trieu Village in 1995; by 2001, it had disappeared.

Dinh province, the total average retreat distance during the last 60 years (from 1952) at the Hai Hau coasts is estimated at 1100 m.

The main reason for the heavy erosion along the Hai Hau coastline is changes in the distribution of the natural fluvial sediment discharge to the whole system. At the end of the 19th century, the Ngo Dung River (presently named So River) lost its importance as a major branch of the Red River. This could have been a result of either a natural development or man-made river training works, which changed the Red River flow direction. The Ngo Dung River was dammed in 1955 because of the low flow discharge in this branch. These influenced the total loss of sediment transport to the beaches of Hai Hau section.

Another reason is thought to be the construction of the Hoa Binh hydropower dam upstream of the main input branch (Da River) of the Red River Delta (1979–1994). The main objective of the project is electricity generation; the dam currently contributes nearly 30% of the electricity of Vietnam. The dam project thereby regulates about 70% flow discharge in the Red River system (increased downstream river discharge in the dry season and decreased risk of flooding downstream in the rainy season). However, this has reduced about 50% of the total natural suspended sediment concentration of the downstream river system, as shown in Figure 5. This led to a reduction of half the sediment supply to the coastal areas. In summary, the construction of the Hoa Binh Dam could have been an accelerating factor for coastline erosion along the Red River Delta's coastal areas.

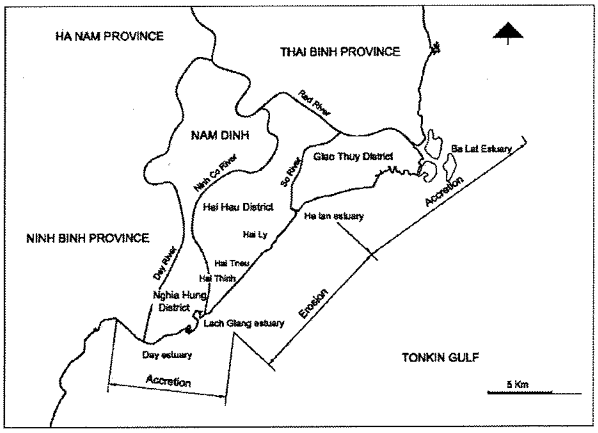

Figure 4. Nam Dinh coastlines and its current situation (Source: PDD Nam Dinh, 2003).

Historical Information on Coastline Changes

On a smaller scale, historical information on coastline changes and coastal protection in Nam Dinh is available from

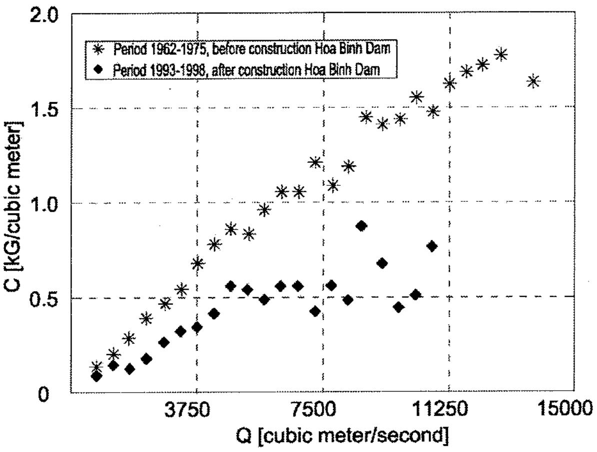

Figure 5. Annual sediment concentration measured at Son Tay gauging station before and after construction of Hoa Binh Dam on Da River, a main upstream branch of the Red River. Son Tay station is located about 100 km downstream of Hoa Binh Dam; it measures water levels, river discharges, and suspended sediment concentration of the Red River.

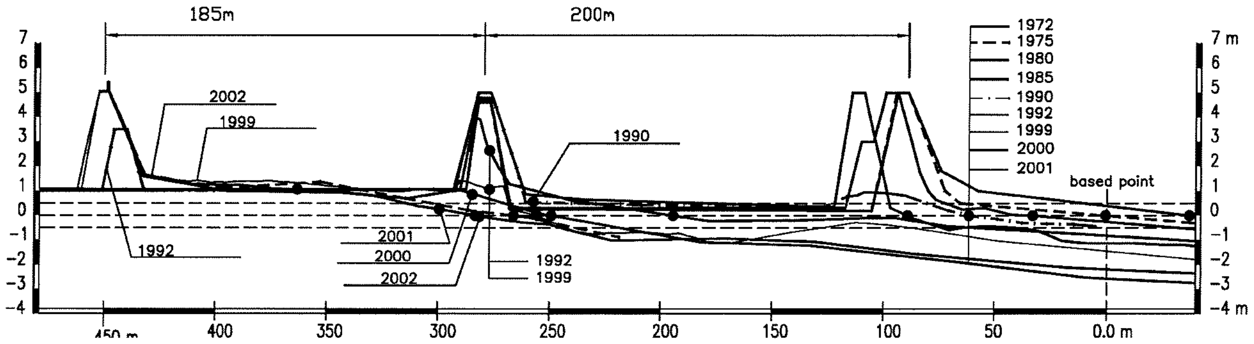

Figure 6. Overlapping cross-shore profiles from 1972 to 2003 at the Hai Ly/Hai Trieu section.

1890 on. For obvious reasons, for the period from 1890 to 1972 there exist no observations and measured records; however, there are several reports, which include the major events of coastline retreat due to erosion and dike breaches. More extensive information has been available since 1972. Observations of cross-shore profiles of Nam Dinh dikes were made at several locations, enabling an analysis of the situation in more detail. Since 1972 beach profile measurements have taken place once every 1 to 4 years.

During the period from 1890 to 1971, dikes often breached after severe typhoons due to erosion and erosion-induced dike weakening. As a consequence the coastline shifted inland about 850 m. Six occurrences of dike breach and associated coastline retreat are reported during those 80 years.

During the 31–year period from 1972 to 2003, event-related coastline retreats were approximately 400 m on average. Six dike breaches occurred and three reconstructions of the dikes were undertaken. These can be observed clearly from the overlapping cross-shore profiles in Figure 6.

Average retreat rate of the coastline during the 31–year period is shown in Figure 7. The retreats of foreland based levels of −0.50, 0.0, and +0.50m (+MSL) are indicated. The base point is the position of the foreland at level 0.0 in the year 1972. Based on the average trend from this analysis, and if no proper measures for erosion mitigation are undertaken, the situation would continue to be similar to the trend of the last period. This means that after every 10 years, coastline retreat would be around 150 m inland. According to the current trend, every 10 years the location of the dikes will have to shift 200 m landward.

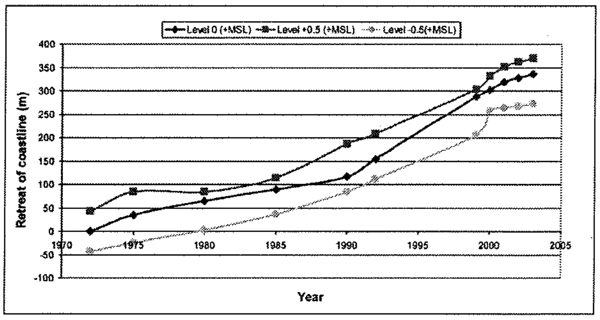

Figure 7. Average coastline retreat distance of the Hai Hau coast based on observations by the PDD of Nam Dinh province from 1972 to 2003.

The Year 2005: Typhoons and Their Consequences

The year 2005, which brought hurricane Katrina to New Orleans, was also a historical year because of the disastrous impact of typhoons on sea defences in Vietnam. Eight typhoons hit the Vietnamese coast that year, resulting in human casualties and large economic damage. Typhoons 2 and 7 were of exceptional strength and are among the heaviest typhoons of the last 3 decades.

Typhoon 2, named Saola, made landfall on 31 July 2005, with wind force near the storm eye at Beaufort scale 9 (75–88 km per h). It hit mainly the coastal areas of Quang Ninh and Hai Phong provinces, resulting in several kilometres of sea dike damages, especially on the island Cat Hai, where 8-km dikes were heavily damaged and needed complete rehabilitation.

Typhoon 7, named Damrey, is considered the most vigorous of the last 50 years. With wind force in the storm eye at Beaufort scale 12 (118–133 km per h) and the wind gusting above Beaufort scale 12, the typhoon attacked all coastal provinces of the Red River Delta. The typhoon was forecasted to be very dangerous, particularly to the sea dike system, which protected hundreds of thousands of people, rice fields, and aquaculture production areas along the coasts. By 0500 local time on 27 September 2005, the wind force rose from Beaufort scale 7 to scale 12 (133 km per h), hitting provinces in the area as the typhoon moved in a west-to-northwest direction. The typhoon caused high storm surges, which coincided with high tide.

The wave run up was as high as 3–4 m. High storm surge in combination with high tide led to extensive overtopping of sea water at sea dikes in almost all affected provinces. It broke certain sea dike sections in Hai Hau district in Nam Dinh province and Hau Loc district in Thanh Hoa province. Total damage was enormous, and 25 km of sea dikes were

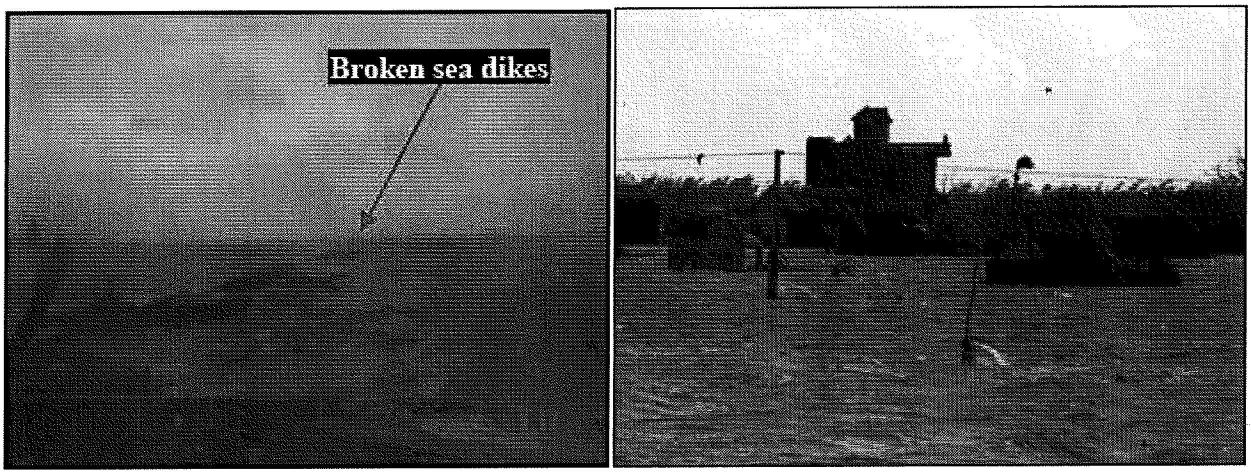

Figure 8. Consequences of the Damrey typhoon in September 2005. The picture on the left shows a sea dike breach at Hai Hau district, while the right picture illustrates sea flooding of the protected regions behind the dikes.

seriously broken. In Nam Dinh an 800-m stretch of sea dikes was completely washed out (Figure 8).

The seawater penetrated inland by 3–4 km in coastal provinces, and the following flash floods in upland areas destroyed at least 1194 houses and damaged another 11,576. More than 130,000 ha of rice fields have been submerged and damaged, most of which could not been harvested before the typhoon. Severe damage occurred to transport and electricity infrastructure and particularly to irrigation systems. According to the rapid assessment of the Disaster Management Working Group, the direct damage estimate as of 28 September 2005 is estimated at US$430 million (UNDP, 2005).

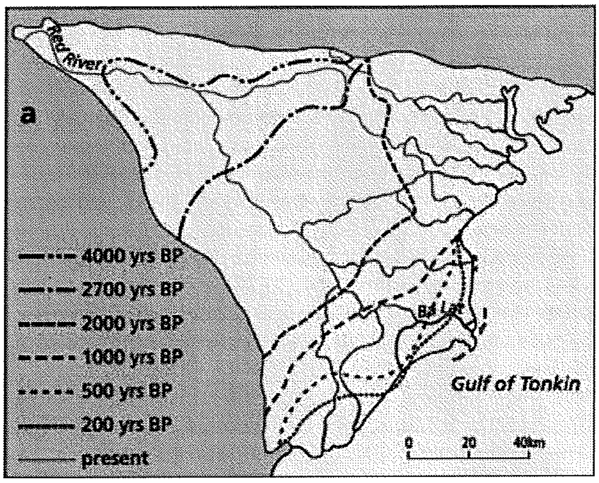

Figure 9. Historic evolution of the Red River Delta, based on Van Maren, 2004.

DELTA FORMATION AND CLASSIFICATION OF THE ESTUARINE SYSTEM

The Red River Delta is a combination of the Day–Ninh Co Delta and the Van Uc–Thai Binh delta. The water discharge from the Red River is distributed relatively evenly between these two river groups (Van Maren, 2004). These river deltas result from the interaction between fluvial sediment supply and subsequent remodelling and dispersion of sediment by waves and tides. The type of delta can be determined by using a morphological classification diagram of river deltas by Galloway (1975), based on the relative importance of waves, tides, and sediment input. Based on this method, the Red River Delta estuaries are in between "fluvial and wave domination."

The Red River Delta has a triangular shape of a distinct type. This shape is typically created when a river meets a shallow sea, where the wave attack is perpendicular to the shore. Due to small longshore currents and the existence of several channels, the sediment is not spread parallel but mainly transported directly into the sea (Häglund and Svensson, 2002). Annual sand transport from the river to the sea is around 100 million tons (Sjödahl and Kalantari, 2005), of which nearly 80% is transported in the rainy season, from June to October.

Due to heavy erosion along certain coastal zones of the delta (exceeding 2 km during the last few decades), several villages have been lost to the sea (see Figure 3). In contrast, the coastline accretion around estuarine areas has been estimated to be up to 5 km.

The Red River Delta can be divided into a northern and southern region. The northern region is sheltered by mainland China and Hai Nan Island and therefore protected against wave motions. This makes it a tide-dominated delta. The further south along the delta, the more wave-dominated the delta becomes.

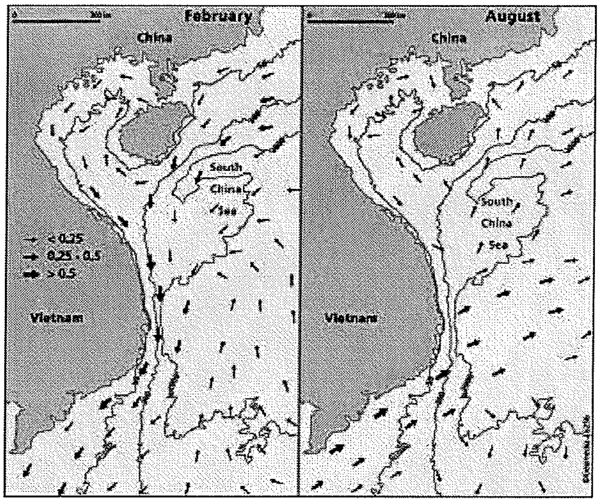

Figure 10. Residual flow in the Gulf of Tonkin, based on the National Atlas of Vietnam, 1996.

From a historical map it can be observed that the 23 km of the present-day Red River Delta plain that is furthest downstream was formed in the last 500 years (Figure 9). This implies an average seaward delta growth of about 5 km per century. However, this rapid seaward growth was episodic. Van Maren (2004) stated that large shoals that appeared seaward of the Ba Lat mouth (1965–85) were reworked into a barrier-spit system in 1995, and this spit system had already formed in the late 1980s. Since then the spit system has not changed much, and the coastlines appeared stable again on a delta scale.

HYDRODYNAMICS IN THE GULF OF TONKIN

The Gulf of Tonkin is connected to the South China Sea in the Pacific Ocean. It experiences a tropical climate with monsoon winds. It is a semienclosed sea with an average water depth of 50 m. During the winter monsoon, the wind blows from the northeast, generating a southward flow, while during the summer monsoon the wind blows from a southern direction, creating a northward flow. The circulation pattern in the Gulf of Tonkin depends on the seasonal monsoon (winter and summer monsoons, respectively). During the dry season the southward flow dominates and is characterised by an anticlockwise rotating cell. During the wet season there are two circulation cells which diverge near the coastline of the Red River Delta (see Figure 10).

Residual flow in the Gulf of Tonkin during the dry season (February) and the wet season (August) is shown in Figure 10, based on the National Atlas Of Vietnam (1996). The 50-, 200-, and 2000-m depth contours are presented for reference.

Mean wind velocity during the dry season is higher than that during the wet season. The significant wave height (H_s) is up to 3 m 10% of the time in the dry season and up to 2 m during the wet season. In August and September the north of Vietnam is often struck by typhoons, and this result in a significant wave height up to 6 m (Sundström and Södervall, 2004). There exist records 30 years long (1949–88) of wave observations at Hon Dau (nearshore) station and 25 years of wind measurement data at Bach Long Vi Island, which is located 200 km offshore of the Nam Dinh coast. SWAN (Booij *et al.*, 2000), a nearshore wave hindcasting model developed at Delft University of Technology, is used for simulating the nearshore waves based on these data. The estimated average offshore wave heights are in the range of 1.2–1.4 m in the summer and about 2.0 m in the winter. The maximum wave height decreases from 6.0–8.0 m in the offshore zone to 3.0–5.0 m in the nearshore zone. Mean wave periods are in the range of 8–12 seconds. These yearly averages for wave height and period are valid at depths of about 17 m near the Hai Hau beach. The simulated waves generated by SWAN are used as input wave conditions for later morphological analysis.

Tidal currents can also be significant in coastal areas, though typically in deeper water. In weak winds with small waves, however, the tide may exceed the wave contribution, and the direction of the current can be opposite to the wind. The coastline of the Red River Delta runs approximately northeast-southwest and is exposed to the tides and monsoon-induced waves. Field observations show that astronomical tides are the diurnal type, with tidal ranges of 2.0–2.5 m. At the Ba Lat mouth, the average tidal range in the period of 1972–90 was 1.92 m, with a maximum tidal range of 3.64 m on 12 December 1987 and 1 July 1988, according to Ninh, Quynh, and Lien (2001) and Hung *et al.* (2001). The predominant diurnal tidal flow has a velocity of 25–40 cm/s, and its predominant direction in the coastal area is northeast during flood tide and southwest during ebb tide. The maximum tidal velocity reaches 60–80 cm/s. The tidal currents play a considerable role in formation of tidal flats and tidal channels in the coastal low-lying wetland areas. At the Hai Hau coast, the tidal wave is propagating from south to north, resulting from a northeasterly directed flood current and southwesterly directed ebb current.

Most of the sediment supply to the Gulf of Tonkin occurs during the summer monsoon (rainy season) with low wave energy at sea. This indicates that the sediment particles probably settle from the suspension in a relatively quiet environment during the wet season. In the dry season with the winter monsoon, the waves prevent sediment deposition, and wave-induced redistribution of the sediment occurs (Sjödahl and Kalantari, 2005).

MODELLING OF LONGSHORE SEDIMENT TRANSPORT AND COASTLINE CHANGES

Simulation of longshore sediment transport and coastline changes along the Nam Dinh coastal zone in this study was performed by using advanced two-dimensional numerical models deployed in UNIBEST, the Uniform Beach Sediment Transport model (WL|Delft Hydraulics, 1992). The models were set up and calibrated based on collected available data and historical maps. The model output allowed predicting the trend and rate of coastline changes in the region.

The basic model covered the Nam Dinh coastlines from Ha

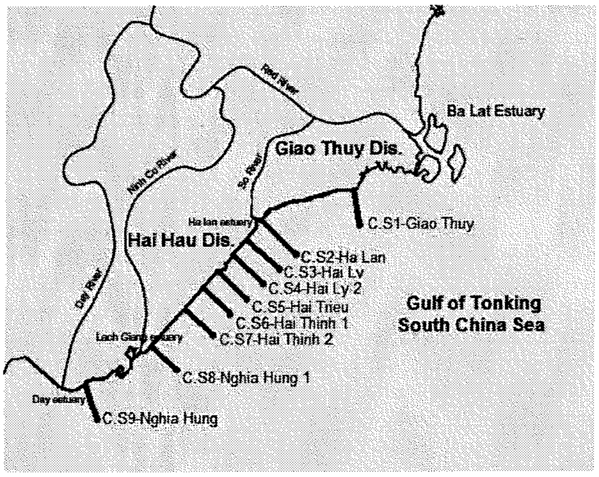

Figure 11. Schematisation of Nam Dinh coastlines for setting up the basic morphological model.

Lan estuary (So River) in the north to Lach Giang estuary (Ninh Co River) in the south of the project area. The coastline was divided into eight subsections which are marked by nine cross sections (see Figure 11). Longshore sediment transport rates were calculated at these cross sections.

In this stage, different transport formulas were used, *i.e.*, Bijker formula, Van Rijn formula, and Coastal Engineering Research Council (CERC) formula (WL|Delft Hydraulics, 1992), to estimate the net longshore sediment transport rates. In the model, a positive sign is defined as the direction of the sand transporting from north to south. Distribution of sediment transport capacity along the coastlines by applying different formulas is shown in Figure 12. Model results show that the Bijker and Van Rijn formulas give quite close results, while the CERC formula provides smaller net transport rates along the coastlines. Although there are some differences, all applied formulas show that the direction of the annual net sediment transport is from north to south along the project area. As a first interpretation from the model results, the greatest potential erosion of coastlines occurs between Ha Lan (C.S2) and Hai Thinh (C.S7), while the accretion occurs in the northern part of Ha Lan and the southern part of Hai Thinh. This is in good agreement with visual observations as stated in previous sections.

Coastline evolution was simulated by using the UNIBEST-CL module deployed in the UNIBEST package. The coastline evolution model was set up for the coasts with the highest potential erosion from C.S2 to C.S7, which belong to the Hai Hau district. The results of 30 years of simulation of coastline retreat rates are presented in Figure 13.

Calibration of the coastline evolution model was carried out by comparing the model simulation results with the available collected erosion rates per location (see Figure 13), which were deduced from the historical erosion map for 1972–96. In general the model results and observed data are quite similar in trend and rates. However, at some points, the model results are somewhat underestimated. For instance, the maximum coastline retreat rate is at Hai Ly (C.S4), approximately 22.5 m per year (based on the Van Rijn formula) and 21.5 m per year (based on the Bijker formula), while calculating from a historical map it is around 30 m per year. The reason for this could be due to not including cross-shore sediment transport in the model. Nevertheless, the model results give useful insight into the trend of coastline changes.

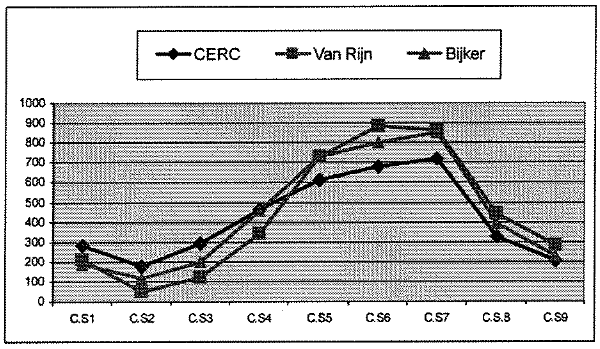

Figure 12. Longshore sediment transport capacity along the Nam Dinh coastlines.

Obviously, the whole section of the Hai Hau coastline is subject to erosion. The retreat rates have a downward trend in the southward direction.

ACTUAL SAFETY OF COASTAL PROTECTIONS

The sea defence strategy in the Red River Delta is based on a sea dike system with multiple defensive lines (often two defensive lines). The dike system is typically positioned as shown in Figure 14 with two defensive lines, and it is separated section by section by subcrossing dikes. The reason be-

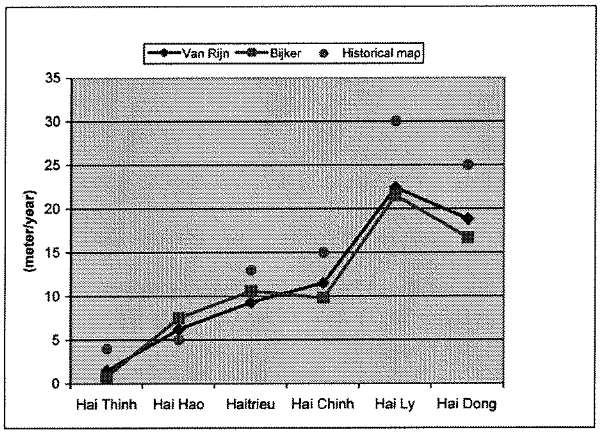

Figure 13. Simulated erosion rates by UNIBEST (lines) and the rates estimated from the historical map (diamonds) at various locations along the Nam Dinh coast.

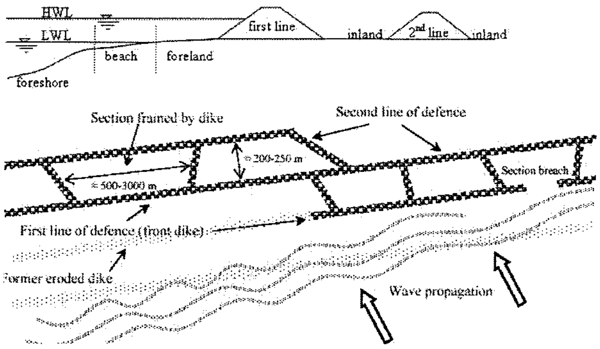

Figure 14. Schematised cross section and plan view of the coastal flood defence system in the Red River Delta.

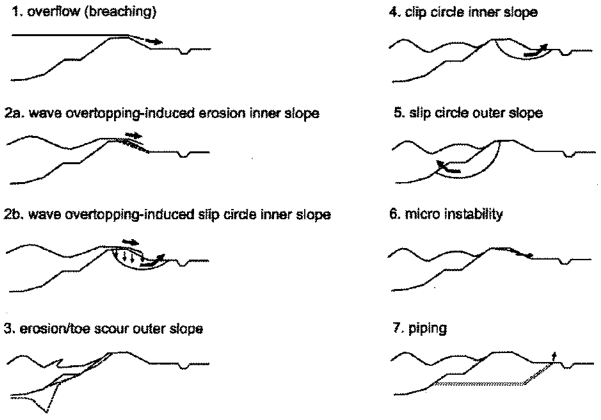

Figure 15. Possible failure mechanisms of sea dikes in Vietnam.

hind using such system is that when a breach takes place at the main dikes (first lines), the subcrossing and secondary dikes can limit flooding and become a new first line of defence. The design distance between two defensive lines is about 200 m.

In the region, sea dikes and revetments have been the prevalent coastal protection system, protecting coastal areas from erosion, seawater floods, and wave attack. This system has been constructed and developed continuously. Existing sea dikes in the region are designed with 20-year return periods of sea loads (1/20 per year design frequency). Dikes are relatively low (1.5 m of crest-free board) with poor protection of the dike crest and inner side. The outer slopes are protected by concrete block revetments of 35-cm thickness.

The sea dikes and revetments were designed with two intended functions: (i) sea flood defence and (ii) prevention of coastline erosion. However, it seems that the system does not fulfil its second function at all, since the dikes themselves can only provide flood prevention, and the revetments can only protect the dike body/land surface behind from wave- and current-induced erosion. These structures are not able to prevent erosion of the front beach and foreshore. Moreover, a dike's toe may be threatened by erosion, unless sufficiently deep toe protection is provided.

In addition, due to budget constraints, lack of information about the sea boundary conditions, and a proper design methodology, as well as good strategic and long-term solutions, the dike system was usually designed and constructed for low design conditions with low quality. As a consequence, the system has a high probability of failure, even up to once every 10 years, as learnt from practical experience. Therefore, the costs of dike maintenance and/or rehabilitation are very high. Statistically, costs for maintenance of sea dikes in the Red River Delta system represent nearly 95% of the total budget for the coastal flood defence of Vietnam.

As a result of relatively high design frequencies (1/20 per year), the sea dike system can fail in various ways. The most frequent failure mechanisms relevant to the sea dike system in the Red River Delta are illustrated in Figure 15 (see Mai [2004] for more detail on inventory and description of failure mechanisms). Some of these mechanisms are interrelated; one can induce the other in consecutive failures.

Previous studies of sea dike failures in Vietnam (for example, Vinh *et al.* [1996] and Mai, Van Gelder, and Vrijling [2007]) indicated that the current design frequency resulted in low dikes with a high occurrence of heavy wave overtopping. Wave overtopping–induced dike failure is therefore a major problem. Apart from this, dike collapse due to deepening of foreshores or loss of dike toes are frequent mechanisms. Loss of a dike toe occurs mostly during a storm surge, while disappearance of a foreshore is caused by a transport deficit in the longshore direction under normal sea conditions. A deeper foreshore can accommodate more severe wave conditions, and thus more overtopping will occur at the dikes. As a result, in situations where foreshores are retreating, the probability of total failure will considerably increase.

In this study, an extensive assessment of the safety and reliability of the coastal flood defence system was carried out (for methods and detailed analysis, see Mai, Van Gelder, and Vrijling [2006]). Various failure mechanisms likely to occur with the sea dike system in the region, as shown in Figure 15, were considered. The safety assessment was done for both the old sea dike system, which was constructed in the early 1990s, and the current one, which was recently constructed. According to the results, the probability that the defence system will fail due to the given failure mechanisms is very high. The overall failure probability of the old dikes is estimated at 96% per year (Mai and Pilarczyk, 2005). This implies that the old dike system could fail on average 1/0.96 (year), more often than once a year. Although the actual dikes were designed for a 20-year return period, the probability of dike failure is much higher, about $p_f = 0.14$ (year^{-1}). This is equivalent to a failure occurrence of about once in every 7 years, instead of 20 years as the expected return period.

Of all the possible failure mechanisms indicated above, overtopping contributes the most to overall sea dike failure, at about 45%. Foreshore erosion-induced dike failure and instability of the amour layer constitute as high as 28% and 22% of the overall failure probability, respectively (see also

Mai *et al.* [2007] for more detail on the sensitivity analysis). Geotechnical failures of the dikes, *viz.* micro- and macro-instability of dike slopes and dike body, and piping are likely to occur with low frequency.

DISCUSSION

The main problems in the coastal zone of the Red River Delta are severe erosion and serious damage of the coastal defence system. These can be considered representative of coastal problems in Vietnam. In general, since coastal erosion and failure of coastal flood defences occur, they result in serious social and economic consequences for the region.

Flood prevention and erosion control are the most necessary and urgent requirements for a coastal protection strategy in the Red River Delta. However, a clear distinction must be made between the erosion control problem and the flood prevention problem, since they are the results of different physical processes and different phenomena. Sea dikes could be used as a good solution for flood prevention; however, they cannot be used for erosion mitigation. To solve the latter problem, several measures can be considered, for example, shore-connected groynes, submerged breakwaters, sand beach nourishment, sand bypassing systems, and combined measures, among others. Selection of the best solution should be based on studying a long-term coastal protection strategy for the whole region.

Along the coastlines of the Red River Delta, sea dikes have been built for a long time, being indispensable to protect the hinterlands from sea flooding. However, existing dikes are designed for relatively high frequencies (1/20 per year), resulting in low dikes with a high frequency of heavy overtopping. The overtopping is the main problem of the dike systems in this region. If the dikes will not be heightened, extra attention should be paid to the resistance of the crest and inner slope to overtopping. On the other hand, the question should be asked if the applied safety standard of 1/20 per year is safe enough for the region in terms of flood risk.

The applied design frequency of the present sea dikes in the Red River Delta is estimated at 1/20 years; however, according to the results from the safety assessment, the dike system may fail at 1/7 years. This calls into question the suitability of the applied design methods/design guidelines and quality control of design phases and construction phases of the sea dikes. Therefore, components in design guidelines and design standards for sea dikes should be reviewed carefully and updated with actual knowledge of dike performance. Besides this, the approval process for design documents must be done carefully in order to ensure that the design fully complies with all design requirements and safety regulations before construction. In addition, attention should be seriously paid to quality control and quality insurance of all construction phases.

Alternative mitigating measures should be used in combination with upgrading works and maintenance of the existing dike system, in order to stabilise the shorelines and rehabilitate the dikes. At some places, where the sea dikes were breached and heavily damaged due to typhoons in 2005 (*e.g.*, sea dikes in Hai Hau and Hau Loc), an urgent short-term solution must be provided in time. Strengthening of all weakest points of the sea flood defence system must be carried out carefully before the next typhoon season. All the short-term improvement works should be in conjunction with the long-term plan for the whole region.

For building up a long-term coastal protection strategy for the whole coastal region in the Red River Delta, the following functional requirements should be taken into account:

- Providing flood prevention for low-lying areas along the coastlines
- Protecting the hinterland from erosion due to longshore and cross-shore sediment transport
- Creating foreshore beaches in front of the sea dikes in order to avoid dike toe erosion
- Creating beaches for recreational touristic development
- Avoiding downdrift effects (a must for the whole delta scale)
- Avoiding environmental impacts as much as possible

The first function requires reliable coastal flood defences. Optimum and robust design of the sea flood defence system for the region given Vietnamese conditions needs to be carried out. A probabilistic reliability analysis and risk-based optimal design of the whole system and system components could be applicable for this purpose.

The latter aspects can be considered by large-scale, long-term studies of the whole region, such as studies of coastal hydrodynamic processes, studies of long- and short-term morphological processes, and analysis of all possible alternative mitigation measures and their effectiveness to the coastal system and environment. Selection of a suitable countermeasure should be based on a multicriteria analysis, taking into account also cost-benefit considerations for the Vietnamese conditions. A pilot project should be implemented first on a small scale to see its effectiveness before applying the proposed strategy to the whole region.

The typhoon year 2005 caused serious losses and consequences for the whole coastal region in the Red River Delta. However, it is likely that the year 2005 will be a turning point in the national approach to sea defences in Vietnam, similar to the year 1953, which was a turning point for the Netherlands in formulating the new policy and safety standards for protecting the country against flooding. The rehabilitation of Vietnam's damaged and broken dikes will take a number of years and will be implemented under the guidance of the DDMFC. It is evident that the old dikes were too weak and that most of them were designed based on outdated design criteria, including rather poor hydraulic boundary conditions (for waves, storm surges, and design water levels). To overcome the existing problems of the old dike design and to come up with more proper alternatives, it is necessary to establish relationships and/or models for hydraulic, coastal hydro-morphodynamic boundary conditions in front of the sea dike system as input for the design. The following issues, which relate to sea boundary conditions, need to be examined:

- Extreme sea level analysis to find the best-fitted frequency distributions. This can be done based on data from the existing monitoring stations. However, the number of stations is too limited to cover the whole coast. Nowadays, new statistical estimation methods and prediction techniques are in development in which it is possible to use data from neighbouring stations to extend the length of data sets, and thus to include more data in analysis and prediction of the extreme values. These results can be used also for verification of results obtained through other methods (typhoon simulation and storm surge estimation in combination with astronomic tide).

- Simulation of historical typhoons up to the end of 2005 using existing data-driven process-based simulation models. Such simulations can be extended for other possible wind fields in order to simulate conditions exceeding historical storms; in this way some sensitivity information can be obtained when extrapolating the frequency curves beyond the observed range. Similar studies were performed by Van Gelder, Vrijling, and Van Haaren (2004) for the Dutch coastline.
- Frequency analysis of storm surges corrected for measured water levels and typhoon simulations for various locations along the Vietnamese coast, and estimation of the representative annual tidal high waters (average of astronomic high water spring). Combination of the storm surges and tidal high water levels provides the water levels per location. For locations with existing measurement stations, the estimated water levels can be compared with the water levels from direct observations.
- Deep water wave prediction and comparison of standard prediction methods with waves induced by typhoons. Recommendations should be prepared concerning the method which should be used, as well as, perhaps, diagrams for wave prediction.
- Analysis of the erosive tendency of the foreshore. Transformation of waves from deep water to shallow water, up to the toe of the structures, is a very crucial component in design, because it defines the wave height (H) and period (T) to be used in the design of structural elements of the dikes. The wave height depends on the water depth in front of the structure.

Therefore, the eventual erosive tendency of the foreshore should be taken into account (the wave height may increase over time). For a shallow foreshore the depth-limited wave height H can be applied: $H = a \times h$, where h is the local depth and a is a coefficient, which should be determined from local measurements (usually between 0.40 and 0.60).

- Prediction of morphological development of erosion areas. Such development may influence the wave prediction. Nam Dinh is especially known as a seriously eroded coast. The foreshore is gradually eroded, and high waves can approach the dikes, often leading to their destruction. In addition, prediction of morphological developments over the design lifetime of the sea dikes is needed to incorporate this in the dike design process, in order to avoid failure of the dikes due to foreshore erosion. Thus, the morphological maps and cross-shore profiles should be analysed in combination with morphological models to establish the tendency and speed of erosion. Yearly monitoring and surveying at critical eroded sections, especially after typhoons, should be incorporated in standard management activities.

CONCLUSIONS

The Red River Delta, a low-lying area, lies between the fluvial and wave-dominated river mouths and is connected to the South China Sea. These features make the delta a complex coastal-river system. Due to the interaction of complex hydrodynamic-morphological processes from sea and estuarine boundaries, the coastal zones of the whole region suffer seriously from unexpected accretion and erosion. The accretion often occurs at the river mouth areas (at Ba Lat, Day, and Lach Giang estuaries), which produces many negative effects for the waterway navigation system. Heavy erosion takes place along coastlines from south Giao Thuy to the end of the Hai Hau section (about 35 km long), which causes many losses for the coastal regions. The average erosion rate is significant and varies per location from 5 to 25 m per year. According to the results of a two-dimensional morphological model, UNIBEST, the net sediment transport is directed from north to south along the coastline. The maximum erosion occurs at Hai Ly and is about 22.4 m per year (Van Rijn formula) and 21.5 m per year (according to the Bijker formula). The erosion rate has a downward trend towards the south. This agrees well with historical maps and observation data.

Coastal protection within the Red River Delta consists mainly of sea dikes and revetments. However, the safety level of the current system is rather low compared to the design safety level. Failure of the sea dikes and revetments occurs frequently, almost every year, especially along the Nam Dinh coast. Although the return period of design loads is estimated at 20 years, failure of the system may occur on average once in 7 years (failure probability about $p_f = 0.14$ per year), according to the results from safety probability assessments. Practical situations in the last 30 years support this.

A disclaimer for this study, as well as previous studies, is the lack of coastal data and reliable sources of information. It is strongly recommended that a long-term monitoring program be implemented not only for the Nam Dinh coast but for the whole coastal area of Vietnam.

As already discussed in the previous section, in order to have a more comprehensive solution, further studies on long-term sea boundary conditions, long-term morphological changes, effectiveness of countermeasures, cost-benefit analyses, and a full-scale risk analysis of the whole system need to be carried out. The proposed mitigation measures should be included in the overall framework of an integrated coastal zone management program at both provincial and national levels.

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