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Environmental Issues and Recent Infrastructure Development in the Mekong Delta: review, analysis and recommendations with particular reference to large-scale water control projects and the development of coastal areas

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1. INTRODUCTION

1.1 Background and aims

Deltas have played an important role in human existence since prehistoric times. It is no coincidence that many of the earliest agricultural and urban civilisations flourished on the fertile soils of great deltas such as those of the Nile, Yangtze, Tigris-Euphrates and Indus. It is also in these ancient civilisations that the first recorded accounts of the adverse environmental impacts arising from the human utilisation of deltaic environments originate. It is apparent that these impacts have not only affected the natural environment, but have at times threatened the very survival of the civilisations. In comparison with some of the other deltas of the world, large-scale human modification of the natural environment is a relatively recent phenomenon in the Mekong Delta, starting approximately 300 years ago with the arrival of the pioneer Vietnamese farmers. The greater part of the Mekong Delta today lies within the borders of Vietnam, and the delta is an important centre of economic activity, supporting 16 million inhabitants (22 % of the total population of Vietnam), contributing to over 27 % of the national GDP, and producing 50 % of the annual national rice production (Tin and Ghassemi, 1999). The concentration of human activity within a relatively limited area, compounded by the effects of warfare and rapid economic development in recent years, has placed heavy pressures on the natural environment of the Mekong Delta. In addition, the co-existence of diverse activities has frequently resulted in resource use conflicts, which have jeopardised the economic viability of the activities themselves.

Figure 1. The catchment of the Mekong River.

The main aim of this working paper is to identify significant environmental issues in the Mekong Delta with a particular emphasis on those related to recent infrastructure development. Initially, environmental issues which arise from natural conditions in the Mekong Delta, and which pose a constraint to human activities are examined. In particular, their mode of genesis, spatial and temporal extent, and severity are outlined. This is followed by an analysis of infrastructure development interventions in terms of their rationale and assumptions, and actual and potential environmental problems arising from them. The two examples examined to this end, namely large-scale water-control projects and the development of the coastal zone, contrast in their origin and scale; the former are nationally planned and implemented at a large spatial scale, whereas the latter comprises the cumulative effect of individual- to national-scale decisions implemented at various spatial scales. The two overlap to some extent, as some water-control projects extend into the coastal areas of the delta. The subsequent discussion establishes a conceptual basis for understanding the environmental problems arising from recent infrastructure development by viewing them as symptoms of disruptions to the functioning of a dynamic biophysical system. Scale issues pertaining to these environmental problems are identified, and the likely

implication of future environmental change explored. The paper concludes with recommendations for future infrastructure development interventions within the delta.

This paper limits most of its analysis to the Vietnamese part of the Mekong Delta. Hence, throughout the paper, the term "Mekong Delta" is employed to denote its Vietnamese part unless otherwise stated.

1.2 The natural setting

1.2.1 Mekong River and its catchment

The Mekong River is one of the major river systems of southeast Asia (Figure 1). Globally, it is ranked twelfth in length and sixth in mean annual discharge (Koopmanschap and Vullings, 1996). It is one of a series of drainage systems which have evolved through the collision of the Indian and Eurasian tectonic plates along the Himalayas. The headwaters of the Mekong proper originate high on the eastern Tibetan Plateau, from which it descends steeply through the deeply incised gorges of Yunnan Province in south-western China. The lower half of the Mekong, which traverses Laos, Thailand, Cambodia and Vietnam, is essentially a lowland river characterised by very low stream gradients and a wide channel system unconfined or partially confined by bedrock. However, numerous short and often steep tributaries draining the Annamese Cordillera join the trunk stream along its left bank as far downstream as Cambodia. The Mekong catchment has an extremely high length-to-width ratio as a result of regional tectonic control, such that it lacks tributaries of significant length and discharge. A notable exception is the Mun River which drains a large area of the Khorat Plateau in northeast Thailand. Right-bank tributaries in the Cambodian lowlands are affected by backwatering during the wet season; their flow is reversed as floodwaters from the trunk stream of the Mekong enter and travel upstream. Thus, floodplains and lakes (notably the Tonle Sap) along these tributaries act as important regulatory storages for floodwaves moving down the Mekong.

1.2.2 Mekong Delta

1.2.2.1 General characteristics

The Mekong Delta covers an area of approximately 55,000 km^2 which represents 7 % of the total catchment area. The greater part of the delta (39,000 km^2) falls within Vietnam (Figure 2). The upstream limit of the delta is generally regarded as being located near Kompong Cham in Cambodia, where it grades into the alluvial plains extending further upstream. At Phnom Penh, the channel of the Mekong divides into two major

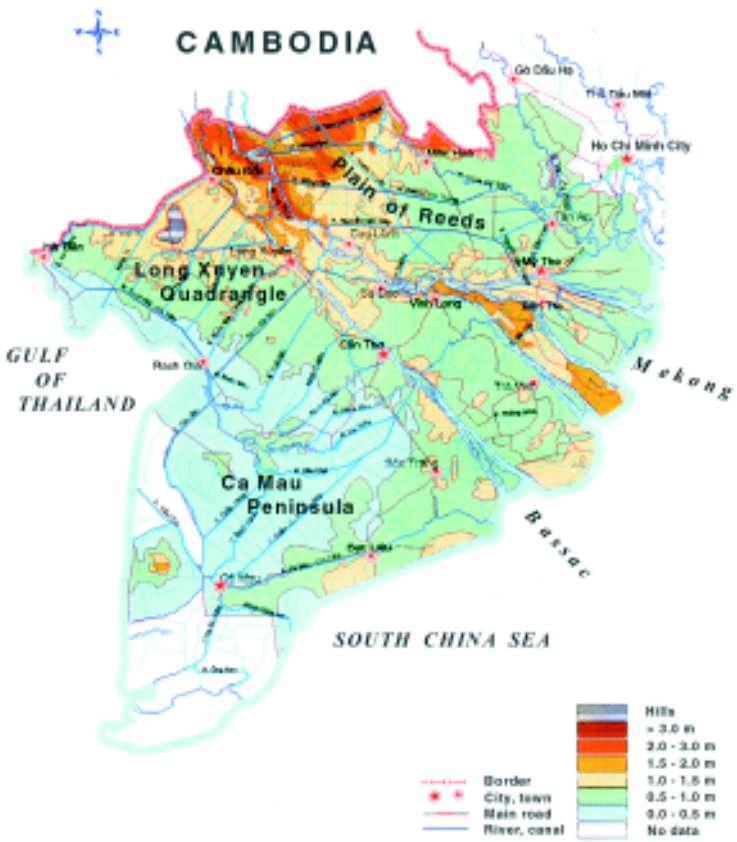


Figure 2. Physiography of the Mekong Delta in Vietnam (Source: SIWRPM).

distributaries: the Mekong (Tien Giang) and the Bassac (Hau Giang). These distributaries trend roughly parallel to each other for most of their journey to the South China Sea, deflecting from a southerly to a southeasterly course in the vicinity of Chau Doc and Tan Chau near the Vietnam-Cambodia border and following a linear course thereafter to the coast. There is a noticeable difference in the channel network morphology of the Mekong and the Bassac branches; the former divides into a number of smaller distributaries before discharging into the sea, whereas the Bassac more or less maintains a single straight course to the sea. This reflects tectonic control (see Section 1.2.2.6). There are innumerable smaller local drainage channels (such as the *rach*[1]) which traverse the delta plain, and which have formed the basis for a large part of the dense canal network covering the delta today. The roughly triangular Ca Mau Peninsula extends to the southwest of the mouth of the Bassac and forms the divide between South China Sea and the Gulf of Thailand. The Ca Mau Peninsula and the Gulf of Thailand coast are generally swampy and lack large channel systems. The Plain of Reeds is another extensive area of swamps, albeit landlocked, which occupies the area to the north of the Mekong branch. These areas were formerly largely isolated from the drainage network of the main distributaries until the construction of canals.

1.2.2.2 Climate

The Mekong Delta lies within the humid tropics, characterised by consistently high mean monthly temperatures (25 –29 ^{o}C) and high but seasonal rainfall (1200 – 2300 mm). Seasonal climatic variations are predominantly controlled by the Asian monsoons: during the wet season from May to November, the dominant winds are from the southwest, bringing over 90 % of the annual total rainfall; during the dry season from December to April, characterised by long hours of sunshine and higher temperatures, winds are chiefly from the northeast. Tropical depressions which develop over the South China Sea seldom reach the Mekong Delta, but the delta is episodically affected by heavy rain, wind and high ocean waves which are associated with such storms situated offshore or in central Vietnam during the wet season. The rare storms which cross the coast of the Mekong Delta have catastrophic impacts on both the natural and human environments, *e.g.* Typhoon Linda in 1997. Some spatial variability in climatic conditions is apparent within the delta. For example, mean annual rainfall is higher in the western coastal areas (2000 – 2300 mm) than in the central inland areas (1200 – 1500 mm), and the rainfall peak during the wet season is attained earlier in the west (August) than in the central and eastern areas (October or November).

1.2.2.3 River discharge regime

Discharge of the Mekong River exhibits strong seasonal variation in response to rainfall. The flood season (June to November) coincides with wet-season rainfall in the catchment associated with the southwest monsoon and tropical depressions from South China Sea entering central Vietnam. The low flow season (December to May) occurs during the dry season and the earliest stages of the wet season. Over 85 % of the total annual discharge occurs during the flood season. Peak flood flow usually occurs sometime between August and early October, while the lowest flow is recorded in March and April (Tin and Ghassemi, 1999). The lake basin of Tonle Sap in Cambodia plays an important role in regulating the flood discharge travelling downstream to the delta; the backwatering of water from the Mekong into Tonle Sap until the attainment of annual discharge peak has the effect of attenuating the flood peak, moderating the effects of flooding in the delta, while the slow back-release of stored floodwater from the lake to the Mekong increases the discharge, and hence water availability in the delta, during the dry season.

1.2.2.4 Ocean tide and wave regime

The Mekong Delta is affected by the contrasting tidal regimes of the South China Sea and the Gulf of Thailand. The tide in the former is irregular semi-diurnal, with two high tides in one day (NEDECO, 1991a; Tin and Ghassemi, 1999). Tidal range is large (over 3.5 m; Koopmanschap and Vullings,1996; Tin and

Ghassemi, 1999) and is characterised by a high variability in low-water levels (by up to 3.0 m at Vung Tau) which results in prolonged high water (Tin and Ghassemi, 1999). Superimposed on the daily tidal fluctuations are a spring/neap tide cycle of approximately two week duration, and monsoon-driven variations in mean water level, which is highest in December and January and lowest in June and July (NEDECO 1991a; Tin and Ghassemi, 1999). Tides in the Gulf of Thailand are dominantly diurnal, with a high variability in high-water levels. Consequently, the period of low water is more prolonged than that of the high water (Tin and Ghassemi,1999). Tide range is less than 1.0 m. Mean and high-tide water levels are higher in the latter half of the year than in the first (SIWRPM, 1997).

The wave regime of the seas surrounding the Mekong Delta is driven by the monsoons. Incident wave energy is generally highest at the end of the wet season and during the dry season. During November and December, typhoons generate periods of high waves in the South China Sea. From December onward, strong northeast winds associated with the winter monsoon results in relatively persistent wave action from the same direction (Interim Committee for Co-ordination of Investigations of the Lower Mekong Basin, 1987; Miyagi, 1995). Seas frequently exceed 1 m and the swells in the open sea commonly are over 2 m during this season. During the wet season, the wave direction matches that of the southwest monsoon, but conditions are far less energetic than during the winter months. The seasonal wave regime sets up a reversing coastal circulation regime along the South China Sea coast of the Mekong Delta: during the southwest monsoon, sediment discharged by the high river flow is transported to the northeast of the river mouths and deposited; during the typhoon season and the northeast monsoon, coinciding with a period of low river discharge and sediment supply, sediment along the delta coast is reworked by waves and transported by strong southwesterly currents, eventually being deposited in southern Ca Mau Peninsula (Interim Committee for Co-ordination of Investigations of the Lower Mekong Basin, 1987; Miyagi, 1995).

1.2.2.5 Hydrological regime within the delta

The hydrological regime within the Mekong Delta is a product of interaction between river discharge, tides, and the landform and configuration of the delta. In recent years, it has become increasingly complex due to the human modification of the natural environment, such as flood-mitigation works and canal construction.

At Phnom Penh near the head of the delta, the mean monthly discharge ranges from approximately 2000 $m^3 s^{-1}$ in April/May to a high of over 30000 $m^3 s^{-1}$ in October (NEDECO, 1991a;Wolanski *et al.*, 1998). Although the total discharge in the dry season remains relatively constant downstream of here (*e.g.* mean monthly discharge at Tan Chau on the Mekong branch and at Chau Doc on the Bassac add to 2340 $m^3 s^{-1}$ in April (Mekong Committee, 1986, cited in Tin and Ghassemi, 1999), a significant proportion of the wet-season discharge is rerouted from the channel through overbank flooding, causing complex downstream variations in channel discharge. Highest monthly discharge at Tan Chau and Chau Doc amounts to 20340 $m^3 s^{-1}$ and 5480 $m^3 s^{-1}$ respectively and occurs in October (Mekong Committee, 1986, in Tin and Ghassemi, 1999). There is a distinct lag between the onset of the seasonal rains and the rise in river water levels, which normally commences in July. Water levels rise rapidly in the early part of the flood season due to the confinement of flow to channels, typically exceeding 3.5 m at Tan Chau and 3.0 m at Chau Doc by late August (Tin and Ghassemi, 1999).

During the peak and the latter part of the flood season, approximately 19000 km^2 of the Vietnamese Mekong Delta is affected by overbank flooding, of which 10000 km^2 experiences inundation exceeding 1.0 m in depth (Tin and Ghassemi, 1999; Figure 3). The most serious flooding is experienced in the upper delta, where the mean inundation depth and duration may reach 4.0 m and 6 months respectively (Tin and Ghassemi, 1999). Flooding is especially prolonged in low-lying backswamps distal to the main distributaries, such as the Plain of Reeds (Integrated Land and Water Development and Management Group Training Vietnam, 1997). Shallower and shorter inundation is experienced nearer to the main chan-

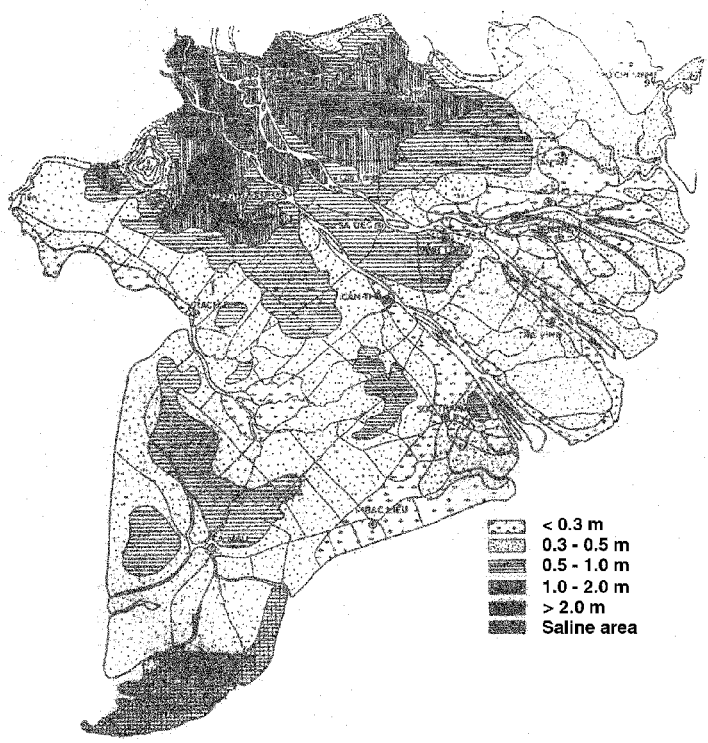


Figure 3. Mean depth of annual overbank flooding in the Mekong Delta (Source: SIWRPM).

nels, due to the higher elevation, but floods here may be extremely destructive as a result of high flow velocities. Flood depth and duration generally decrease in a downstream direction, and many coastal areas do not experience regular annual inundation. In recent years, flood-protection / irrigation schemes have shortened the period of inundation in many areas of the upper delta. For example, the onset of inundation is delayed until after mid-August in many areas, and in some cases, such as the North Vam Nao Project area located between the Bassac, Mekong and Vam Nao Rivers, natural overtopping of the river banks has been eliminated totally.

Several mechanisms are responsible for flooding in the Mekong Delta. In the upper delta, overflow from the Mekong and the Bassac accounts for 85 to 90 % of the overbank discharge, while the remainder is derived from the influx of floodwater from Cambodia over the delta plain on both sides of the main distributaries, as overland flow and via tributaries and canals.

Floodwaters from Cambodia are predominantly responsible for the flooding in the Plain of Reeds on the left bank of the Mekong (Tin and Ghassemi, 1999), which sequesters up to 10 % of the total discharge entering the Vietnamese Mekong Delta. Direct overflow from the Mekong accounts for a maximum of 25 % of the floodwaters entering the Plain (Tin and Ghassemi, 1999). Floodwater tends to stagnate in the Plain of Reeds due to the occluded, landlocked situation and the ill-defined floodwater pathway through the area; most of the floodwater drains back into the Mekong, and the remainder to the South China Sea through the West Vaico River (NEDECO, 1991a; Truong, 1996 in Tin and Ghassemi, 1999; Integrated Land and Water Development and Management Group Training Vietnam, 1997).

On the right bank of the Bassac, in the Long Xuyen Quadrangle, direct overflow from the channel (in this case the Bassac) is more significant than in the Plain of Reeds, supplying up to 40 % of the floodwater here. Most of the floodwater drains away from this area to the Gulf of Thailand through the numerous canals and tidal creeks, accounting for 5 % of the total discharge entering the Vietnamese part of the Delta (NEDECO, 1991a).

In the lower delta and the coastal areas, interactions between incoming tides and river discharge and local runoff are usually more important than overflow from the main distributaries. Storm conditions in the South China Sea may also result in the temporary superelevation of the sea surface and high waves, which may lead to the inundation of low-lying coastal areas by seawater, especially if these conditions coincide with particularly high tides and high water levels within the local drainage network.

A hydrologic peculiarity of the Mekong Delta is the pronounced inequality in the discharges of the Mekong and the Bassac branches in the upstream areas. At the point of bifurcation of the two branches at Phnom Penh, as little as 15 % of the total discharge is directed into the Bassac branch (NEDECO, 1991a). The high mean water-surface elevation of the Mekong relative to the Bassac results in a tendency for water to flow from the former to the latter through interconnecting waterways, such that the difference in discharge decreases in a downstream direction. Thus, in the vicinity of Tan Chau and Chau Doc, the discharge of the Bassac is normally 15 – 30 % of that of the Mekong (the difference is smallest during the flood season), and the mean water level of the Mekong is commonly up to 0.3 m higher than in the Bassac (Tin and Ghassemi, 1999). At Tan Chau, the tendency for water to be transferred from the Mekong to the Bassac is accentuated by the sharp turn in the course of the former, which causes water to bank up along the southern side of the river (Truong Dang Quang, pers. comm.). The Vam Nao River downstream serves as a major diversion for water from the Mekong into the Bassac; during the dry season, approximately one-third of the discharge of the Mekong is transferred in this manner (Tin and Ghassemi, 1999). Downstream of the Vam Nao, the two branches carry comparable proportions of the total discharge and the difference in mean water level is reduced to 0.02 m or less (NEDECO, 1991a; Tin and Ghassemi, 1999).

The extent of tidal influence in the waterways of the delta is controlled by the seasonal variation in river discharge. During the dry season, tidal influence extends throughout most of the delta, causing water-level fluctuations into the Cambodian part. At Phnom Penh, tidal range during the dry season is approximately 0.3 m (NEDECO, 1991a). Seawater enters the distributary mouths and causes saline conditions in excess of 50 km upstream (Wolanski *et al.*, 1998; Tin and Ghassemi, 1999). Salinity structure within the main distributaries, such as the Bassac, alternate between well-mixed[2] conditions during peak tidal flow and stratified[3] conditions at lower current velocities (Wolanski *et al.*, 1998; Figure 4b). Under the latter conditions, a baroclinic flow becomes established, whereby the surface and bottom waters flow in opposing directions along the channel (Wolanski *et al.*, 1998). Another characteristic of tidal flow in the Mekong Delta is tidal asymmetry; due to friction exerted on the incoming tide by the shallow bottom, tides rise more rapidly than fall, causing the flood-tide currents to be faster than the ebb tides (Wolanski *et al.*, 1998). This has implications for sediment transport (see Section 1.2.2.8).

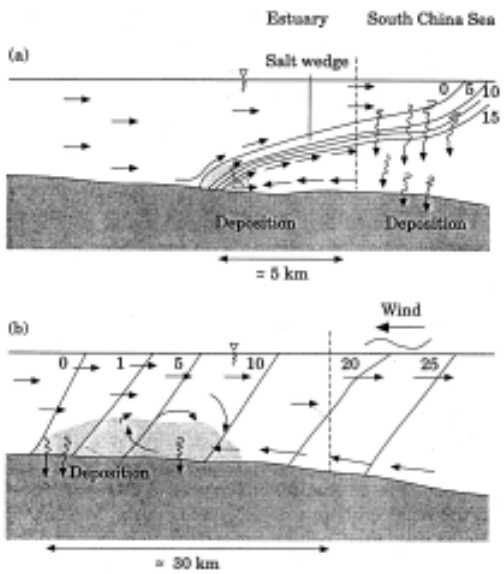


Figure 4. Seasonal change in estuarine salinity structure and associated sedimentation at the mouth of the Bassac branch of the Mekong Delta, showing: (a) the highly stratified structure during the flood season, and; (b) well-mixed conditions during the low-flow season (Wolanski et al.*, 1996).*

The numerous canals and local drainage systems allow the intrusion of seawater into many parts of the delta plain away from the main channels. In particular, saline intrusion is severe and complex within the Ca Mau Peninsula due to the convergence of contrasting tidal regimes of the South China Sea and the Gulf of Thailand, low freshwater discharge, and the interconnected nature of the waterways (Tin and Ghassemi, 1999). The convergence of the two tides also lead to stagnation of water in the waterways of this region, hindering the inflow of irrigation water from the Bassac (Tin and Ghassemi, 1999).

During the flood season, the high freshwater discharge causes the main distributaries to become fresh nearly to their mouths, where a distinct salt-wedge forms and the river discharge floats as a plume offshore (Wolanski *et al.*, 1996; Figure 4a). Tidally driven water fluctuations are experienced only as far upstream as Long Xuyen on the Bassac and Cho Moi along the Mekong (NEDECO,

1991a). Coincidence of particularly high river discharge and spring tides may lead to flooding in the lower delta.

1.2.2.6 Geologic setting

The present-day Mekong Delta is the surface expression of a major Cenozoic sedimentary basin, the Saigon – Vung Tau Basin (Fontaine and Workman, 1997). The delta is situated in a horst-graben[4] system which trends parallel to the dominant northwest-southeast structural trend common to mainland Southeast Asia (Takaya, 1974). Superimposed on this trend are northeast / southwest trending swells and faults, which effectively create a chequerboard-like series of minor basins and blocks (Xang, 1998). The faults appear to exert some control on the surface morphology of the delta: the straight course of the Bassac follows the boundary between a horst and a graben (Takaya, 1974; Xang, 1998), while an area of coastal recession in southeastern Ca Mau Peninsula corresponds to the location where another such fault crosses the coast (Le Quang Xang, pers. comm.)

The thickness of the depositional sequence overlying the basement rocks varies considerably in response to the basement structure: maximum thicknesses in excess of 800 m occur in the northern part of Ca Mau Peninsula which lies within a graben, while the area to the northeast of the Bassac, overlying a horst, is characterised by a much thinner sequence (>200 m; Le Quang Xang, pers. comm.). Basement rocks penetrate the sedimentary cover to emerge as isolated hills (monadnocks) up to approximately 500 m high in the extreme northwest of the delta and offshore along the western and southern coasts. These are mainly composed of granite and limestone and represent an extension of mountains in southwestern Cambodia.

The depositional sequence appears to consist of thick commonly silty to sandy Eocene to Pleistocene sequence overlain by Holocene sediments of variable character (Rasmussen, 1964). The depth of the Pleistocene – Holocene boundary becomes increasingly shallow to the north, and outcropping Pleistocene terraces form the boundary to the Holocene delta along its northern boundary (Morgan, 1970).

1.2.2.7 Evolution of the modern delta

The present configuration of the Mekong Delta has been attained during the Holocene epoch, or the last 10,000 years of earth's history. During the last glacial, sea levels were over 100 m lower than at present, and the shoreline was located several hundred kilometers to the east of the modern delta. The embayment within which the modern delta is located was a river valley shaped by fluvial erosion and some possible tectonic movements. This valley was subsequently inundated by the sea due to the rapid sea-level rise following the glacial (the Holocene transgression) to form a marine embayment. During the mid-Holocene, the rate of sea-level rise progressively decreased until a maximum level of between 2.5 and 4.5 m above the present was attained at 5000 – 4000 years BP (Nguyen *et al.*, 1997). This slowing of sea-level rise allowed the Mekong Delta to commence its expansion into the embayment, which has further been assisted by a slow regression (sea-level fall) since 4550 years BP, and possibly by the tectonic uplift of basement horsts (Nguyen *et al.*, 1997).

The geomorphic character of the delta has varied through the course of its seaward expansion. In the initial stages, the delta was sheltered from wave action by the sides of the embayment to the north and east, and by the bedrock monadnocks to the west. Furthermore, marine conditions penetrated deeply into the embayment due to the effects of the transgression. As a result, extensive tidal flats backed by mangrove swamps developed along the coastline of the delta. Organic-rich mangrove sediments from this period underlie large areas of the Long Xuyen Quadrangle and the Plain of Reeds (Nguyen *et al.*, 1997). In the latter stages, the delta shorelines have experienced increasing exposure to waves, as the delta infilled the embayment and commenced its advance into the South China Sea. Episodic erosional reworking of the shoreline caused the formation of a series of beach ridges in the northeastern parts of the delta. Increasing

wave exposure has also resulted in a marked southwesterly longshore sediment transport, forming the Ca Mau Peninsula. Due to the more sheltered aspect, mangroves and tidal flats continue to dominate the shorelines along southern Ca Mau Peninsula and the Gulf of Thailand. The formation of beach ridges is also likely to have been driven by cycles of minor transgressions and regressions superimposed on the general trend of long-term regression during the late Holocene.

Overbank sedimentation through the action of river flooding has created alluvial landforms such as levees over the coastal and offshore deposits originating from earlier phases of delta development in the upper and middle parts of the delta. In some areas proximal to the distributaries, channel migration has caused the erosional removal of older deposits and their replacement with more recent fluvial deposits. In areas distal to the distributaries, low rates of overbank sedimentation have resulted in the maintenance of low-lying, swampy, and, in part, saline conditions, *e.g.* in southern Ca Mau Peninsula.

1.2.2.8 Sedimentary environments and processes

The delta plain of the Mekong consists of a mosaic of distinct sedimentary environments, each characterised by distinct topography, sediment type and processes. The main types of environment within the delta are: distributary channel and mouth, levee, backswamp, tidal flat and mangrove swamp, beach ridge and swale (Figure 5).

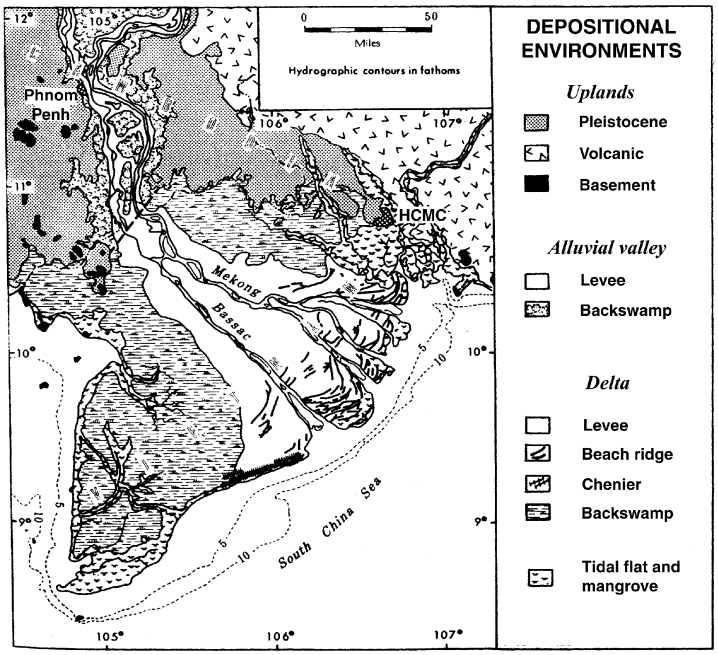


Figure 5. Sedimentary environments of the Mekong Delta (Morgan, 1970).

The distributary channels are the main conduits for the flow of water through the delta plain. They are characterised by relatively high water flow velocities, and relatively coarse, predominantly sandy, bottom sediments. A change in channel planform from upstream to downstream along each of these distributaries is apparent. The upstream reaches are characterised by a relatively high sinuosity and frequent occurrence of mid-channel bars and islands. Here, lateral channel migration is both widespread and rapid, and is accomplished through the accretion of frequently alternating point bars and mid-channel bars/islands, and the synchronous erosion of the opposite bank. Channel and bar sediments here are typically medium to coarse sand. The middle reaches of the distributaries are characterised by lower sinuosity and less frequent occurrence of elongated point bars and mid-channel bars/islands. The incidence and the rates of lateral channel migration are typically lower than in areas further upstream. Channel and bar sediments are typically fine to medium sand with variable admixtures of silt and clay. The channels are generally 10 to 40 m deep along the main distributaries, becoming much shallower (5 – 15 m) in the last 80 km or so near the mouth (Interim Committee for Co-ordination of Investigations of the Lower Mekong Basin, 1987).

Near the mouths, the distributaries develop a funnel-like morphology interspersed with numerous triangular and linear distributary-mouth bars. These bars are typically unstable when newly formed and their shifting

causes local areas of rapid accretion and erosion. Over time however, these lower reaches become increasingly stable and more akin to the middle reaches, as many of the bars coalesce and become incorporated into the delta plain and the main channels become clearly defined. Channels are extremely shallow, typically less than 5m (Interim Committee for Co-ordination of Investigations of the Lower Mekong Basin, 1987). The funnel-shaped distributary mouths are a product of the strong tidal currents resulting from the large tidal range in the South China Sea. The pattern of sediment transport and deposition in the vicinity of the distributary mouths changes seasonally; during the flood season, most (95 %) of the suspended sediment bypasses the mouth, flocculating upon encountering saltwater and being deposited offshore, whereas in the dry season, sediment is deposited within the distributary due to the effects of saline intrusion, tidal asymmetry and baroclinic circulation (Wolanski *et al.*, 1998). The last two mechanisms hinder sediment discharge to the sea by countering downstream sediment transport.

Levees constitute the highest areas of the delta plain and are best developed along the main distributaries in the upper delta (approximately 5 m local relief at Chau Doc; Takaya, 1974). Their height progressively decreases both toward the coast and with increasing distance from the channel. Away from the distributaries, they merge into backswamps. Both the levee and the backswamp experience deposition of suspended sediments delivered through overbank flooding. Minor channels act as conduits for floodwaters between these backswamps and the main distributaries. The elevation of backswamps is commonly below 1m and, in the absence of flood mitigation works, they are areas of regular and prolonged inundation during the wet season. The grain size of the overbank sediments generally decreases with increasing distance from the channel; silt and fine sand are commonly confined to the levee crests, while clay occupies extensive areas of levee slope / toe and backswamps (Uehara *et al.*, 1974; Kyuma, 1976). Backswamps which are remote from the main distributaries and are not drained by significant channels (*e.g.* the Plain of Reeds and western parts of the Long Xuyen Quadrangle) experience negligible amounts of overbank deposition. Sediments in such areas are typically organic-rich mud and peat derived from local vegetation.

Depositional environments along the coastal sections of the delta reflect the interaction between sediment supply from the river and coastal processes. The coastline throughout much of the Mekong Delta consists of tidal flats, which are a product of fine (mainly silt and clay) river-borne sediment being redistributed and deposited through tidal inundation. Unvegetated tidal flats form a continuous shore-parallel band over 5 km in width along the coast of Ca Mau Peninsula. The upper intertidal zone is colonised by mangroves, which exert considerable control on sediment deposition through the trapping of sediment and production of organic matter. Extensive areas of mangroves occur in areas of the delta distal to the main channels, where rapid aggradation of the substrate is prevented by low rates of overbank sedimentation. The largest areas of mangrove swamps in the Mekong Delta thus occur at its extremities, *i.e.* southern Ca Mau Peninsula and near the mouths of Vaico and Saigon Rivers. The larger mangrove areas are drained by a complex network of sinuous tidal creeks, which serve as important conduits for tidal drainage in the inner parts of the swamps (Miyagi, 1995). It is to be emphasised that most of the original mangrove areas of the Mekong Delta, and thus the natural processes operating within such environments, have been modified by human activities.

Along the central and northern parts of the South China Sea coast, which are comparatively exposed to wave action, periods of particularly high waves produce beach ridges, which commonly rise to an elevation of 2 – 3 m above sea level (Takaya, 1974). The ridges are typically composed of clean fine sand and are separated from each other by low swampy swales. These swales have developed from tidal flats which accrete on the seaward side of ridges with the return of normal (lower-energy) wave conditions. Tidal flat accretion continues until the next episode of high wave energy, when part of it is eroded and a new ridge forms along its seaward margin. The width of the swales progressively increases and the number of ridges decreases in the southern parts of the delta (Morgan, 1970), in response to increased shelter from storm waves.

1.2.2.9 Soils

The distribution of soil types within the Mekong Delta is largely determined by the type of sedimentary environment (Figure 6). Superimposed on this spatial pattern is the history of land use, which has played a major role in converting potential acid sulphate soils into actual acid sulphate soils.

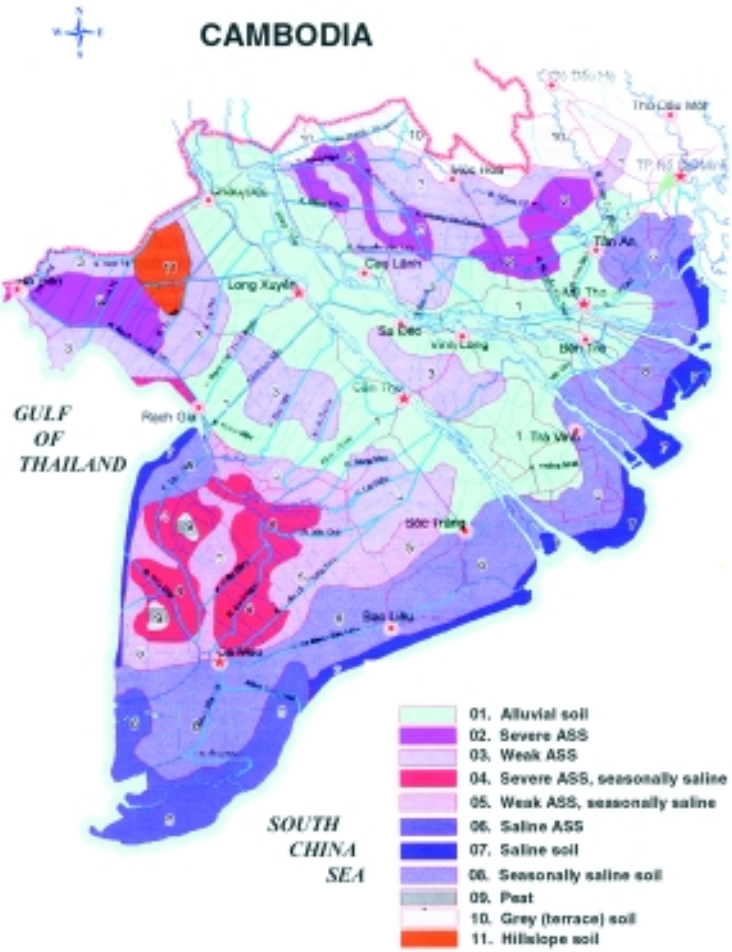


Figure 6. Distribution of major soil types in the Mekong Delta (Source: SIWRPM).

Acid sulphate soils (ASS) occupy 1.6 million ha, or over 40 %, of the Vietnamese part of the Mekong Delta (NEDECO, 1993c). The largest and the most severe occurrences of these soils are located in the low-lying backswamp areas distal to the main distributaries, *i.e.* in the Long Xuyen Quadrangle, the Plain of Reeds, and southern Ca Mau Peninsula. The main characteristic of ASS is their potential to develop high levels of acidity upon exposure to oxygen. The acidity is derived from the oxidation of the iron sulphide, pyrite (FeS_2). In the absence of oxygen, pyrite remains inert and the soils are termed potential ASS (or PASS). When PASS is exposed to oxygen through natural (*e.g.* fall in water table during the dry season) or anthropogenic (*e.g.* land drainage, excavation) causes, they become actual ASS (or AASS). Large-scale conversion of former backswamps into cropping area in recent times, such as in the Plain of Reeds, has significantly increased the relative proportion of AASS. In areas nearer to the main distributaries, occurrences of ASS usually have a lower acid-generating potential and are located at some depth below a surface capping of benign alluvial soil.

Alluvial soils occupy approximately 1.2 million ha of the delta, forming a broad ribbon along the main distributaries. As such, they are closely associated with the levees and their toes, which merge into the backswamps with increasing distance from the channels. They are a product of deposition during overbank floods. It is often claimed that the deposition of fresh alluvium by floods is significant in the maintenance of soil fertility within the delta; it is true that the highest soil fertility within the delta is associated with the levee areas especially of the upper delta (Kyuma, 1976) , *i.e.* areas of most active overbank deposition. However, several past studies have indicated that the alluvial soils of the delta are not particularly fertile compared to soils in other rice growing areas in tropical Asia, as a consequence of the low exchangeable base availability, the dominance of highly weathered kaolinite clays and low ammonification ratio of soil organic matter (Uehara *et al.*, 1974; Kyuma, 1976). Nevertheless, the alluvial soils, especially

of the levees, constitute the most fertile and intensively cultivated areas of the Mekong Delta.

Saline soils form a continuous belt of 20 to 50 km width along the South China Sea coast of the delta and occupies most of the Ca Mau Peninsula. Occurrences along the Gulf of Thailand coast north of Ca Mau Peninsula are restricted to a relatively narrow coastal fringe. The area of saline soils within the Delta amount to over 700,000 ha (NEDECO, 1993c). Permanently and strongly saline soils are found at low elevations along the coast on tidal flats and in mangrove swamps. Salinity is the result of regular tidal inundation of the ground surface and the saline groundwater. They are typically alkaline and commonly depleted in phosphorus (Kyuma, 1976). Less severe saline soils are found over a larger area, commonly in backswamps distant from the main distributaries and which lack a significant drainage network. Salinity is mainly due to the capillary rise of salt from subsurface saline intrusion. Most saline soils of the Mekong Delta are seasonal saline soils, *i.e.* salinity levels peak during the dry season (NEDECO, 1993c), when capillary action in the soil is at its most active. Saline soils over much of the Ca Mau Peninsula have acid sulphate characteristics as well. Most of these are associated with former and current mangrove environments.

Other minor soil types within the Mekong Delta includes peat, sandy, colluvial and terrace soils. Peat soils are associated with backswamp and mangrove environments, where poor drainage has permitted thick accumulations of locally derived plant matter to form. In backswamps, organic matter is usually derived from *Melaleuca*, reeds or sedges. Peat soils associated with mangroves are saline. Their extent has been severely reduced through human disturbance, which has resulted in the destruction and / or the removal of the surface peat layer. Much of the former peat soils have thus become acid sulphate soil areas. Most of the remaining peat soils are found in the mangrove forests of Ca Mau Peninsula and along the Gulf of Thailand, and in the Plain of Reeds.

Sandy soils are associated with the beach ridges of the lower delta, while colluvial soils mantle the base of hills composed of basement rocks along the northern fringes of the delta. Both are typically coarse-grained, well-drained and very low in nutrient status. Terrace soils are typically clayey and grey in colour. They are found over outcrops of Pleistocene sediments mainly to the north of the Plain of Reeds (NEDECO, 1993c). Due to the prolonged period of subaerial weathering, they are relatively low in nutrient when compared to the modern delta soils.

1.3 Natural constraints on human activity in the Mekong Delta

1.3.1 Floods

Flooding is a natural and recurrent phenomenon in the Mekong Delta. It is the very process which drives the evolution of the delta plain over geological time scales. However, floods also have represented a serious and widespread constraint to the human habitation and economic development of the delta. Damages due to flooding in the Plain of Reeds alone amount to tens of billions of Vietnamese dong (VND) per annum (Integrated Land and Water Development and Management Group Training Vietnam, 1997). Due to the low elevation and relief of the delta plain, floods in the Mekong Delta are typically prolonged and aggravate the problem of poor drainage.

Floods have been a major barrier to year-round agricultural production in the delta. In many areas affected by moderate flooding, the peak of flooding from August onward has traditionally signified the end of the growing season, cultivation resuming with the receding of floodwaters toward the end of the year. The harvest of the summer / autumn rice crop had to be timed precisely to avoid losses due to an early onset of the flooding. In areas suffering deep and prolonged inundation, rice cultivation continued during the flood season, through the use of floating (inundation depth > 1 m) or deep-water (inundation depth < 1 m) rice varieties, but nevertheless at a great risk (NEDECO, 1991c; Australian Agency for International Develop-

ment, 1998; Tin and Ghassemi, 1999). Although these traditional varieties are well adapted to the local conditions, their yields are usually about half that of the modern high-yielding varieties, and require a long growing season of up to 9 months which precludes multiple cropping (NEDECO, 1991c). Such situations commonly lead to low farmer incomes, which may have negative effects on dry-season agricultural production such as a lack of funds for inputs to boost production, *e.g.* fertilisers (Australian Agency for International Development, 1998). Although multiple rice cropping has become possible in many parts of the delta due to the construction of flood-control structures, waterlogging after periods of prolonged heavy rain during the wet season continues to cause losses through the death of young rice seedlings in poorly drained areas (Tin and Ghassemi, 1999).

Another socio-economic effect of flooding and poor drainage is an increased cost of infrastructure development and maintenance. For example, major roads need to be constructed on an embankment, and buildings on high foundations, mounds or stilts. Roads which are submerged during the flood season require frequent maintenance and the prolonged period during which they remain impassable hinders communication, trade and transportation (Integrated Land and Water Development and Management Group Training Vietnam, 1997). In addition, health problems are prevalent in flood-affected areas because of overcrowding in limited areas of high ground during the flood season, and also because the floodwaters cause overflowing and redistribution of household sewage, farm runoff and solid waste, and thus, the contamination of drinking water supply (Australian Agency for International Development, 1998; Truong Dang Quang, pers. comm.). The seasonal concentration of population and their activities may also result in land and resource use conflicts.

However, not all socio-economic effects of flooding are adverse. Sediment deposition effected by floods plays an important role in rejuvenating soil over geological time scales. Although it is debatable whether the annual contribution of soil nutrients through flood-related sedimentation is sufficiently significant to improve crop growth (Uehara *et al.*, 1974; Kyuma, 1976), it is without doubt that overbank flooding and the associated sedimentation contribute to improved soil properties in the long-term, through the creation of higher, better-drained land (*e.g.* along levees), by flushing out accumulated toxins in the soil, and by counteracting unfavourable changes to the physical and chemical properties of the soil, *e.g.* in the absence of replenishment with new material, the soil may become compacted and partially reduced with age, hindering root growth and nutrient uptake and increasing the possibility of H_2S toxicity (Le Quang Tri, pers. comm.).

Furthermore, the annual flooding brings increased opportunities for fisheries activities. In areas where rice fields are regularly inundated, *e.g.* in 2-crop areas of the upper delta, the harvesting of fish introduced into fields through connections with canals or the river is a major activity and a source of farm income during the flood season. However, flooding may pose problems in the case of freshwater aquaculture, whereby fish ponds are stocked prior to the arrival of the floods (College of Agriculture, 1997). The significant increase in the suspended sediment concentration of river water during the flood season (NEDECO, 1993c) results in high turbidity within aquaculture ponds throughout the delta (both freshwater and saltwater) reducing yields and increasing costs of pond maintenance, *e.g.* clearing accumulated sediment from bottom of ponds (College of Agriculture, 1997; Johnston *et al.*, 1998).

1.3.2 Droughts

The low rainfall and high evaporation during the annual dry season place constraints on human habitation and activity in the Mekong Delta, that are as equally serious as those arising from the excess of rainfall during the wet season. The dry season lasts from December to April, placing pressure on freshwater supply, especially toward the latter part of the season, as the freshwater discharge in the main river channels diminishes, surface water storages on the delta plain (*e.g.* in backswamps and ponds) become depleted and the ground water table falls. Such conditions also give rise to other problems such as salinity

intrusion in coastal areas and acidification in ASS areas. Shorter periods of dryness, which occur during the onset, or toward the end, of the wet season in some years, may also be extremely damaging to newly planted crops (SIWRPM, 1997; Tin and Ghassemi, 1999).

1.3.3 Acid sulphate soils (ASS)

The 1.6 million ha of ASS within the Mekong Delta is one of the largest single occurrences of such soils in the world. The key identifying characteristic of ASS is the high concentration of sulphides within the parent material, in most cases dominated by pyrite (FeS_2). Pyrite in coastal ASS, such as those of the Mekong Delta, is a diagenetic mineral[5] whose formation commences upon the initial deposition of the sedimentary parent material. Sedimentary pyrite forms preferentially in environments which experience regular tidal exchange with the sea, low degree of bottom sediment stirring by currents and waves, low to moderate sedimentation rates, and a sufficient supply of iron and organic matter. Under such conditions, sulphate supplied from seawater by tides is converted into sulphides by sulphur-reducing bacteria, which metabolise organic matter present within the sediment, and then combined with iron in sediment in multiple stages to eventually form pyrite (Pons and van Breemen, 1982; Pons *et al.*, 1982). Such conditions commonly occur in depositional environments such as deltas, estuaries, coastal lagoons, mangrove swamps and tidal flats.

ASS formation around the world has been profoundly influenced by long-term sea-level fluctuations during the Holocene period. During the latter part of the Holocene transgression, sedimentation in many tropical and subtropical deltaic areas kept up with the rising sea, in part due to the development of extensive mangrove swamps (Woodroffe *et al.*, 1993; Dent and Pons, 1995; Hashimoto and Saintilan, submitted). The development of mangroves in turn was likely to have been driven by the penetration of marine conditions upstream into delta plains and coastal embayments enhanced by the rising sea (Hashimoto and Saintilan, submitted). Given the ideal depositional conditions, pyrite accumulated to extremely high levels in these sediments. Hence, it is common for thick accumulations of severely acid-sulphate soils to underlie the older, more landward parts of tropical /subtropical deltas. As sea levels stabilised since mid-Holocene, deltas have expanded, veneering the earlier mangrove deposits with non-pyritic alluvium or freshwater peat and developing a prograding sedimentary wedge to their seaward. Although a mangrove fringe typically develops landward of the bare tidal flats along the shoreline on such prograding deltas, the pyrite content of the sediment is typically much lower than their earlier counterparts (Dent and Pons, 1995), reflecting the increased influence of freshwater discharge, rapid sedimentation rates and lower organic matter content of the sediments.

The general spatial pattern of ASS distribution and severity in the Mekong Delta is intimately associated with its depositional environments and history. The increase in severity with increasing distance from the main distributary channels of the Mekong and the Bassac reflects the corresponding decrease in the influence of freshwater discharge. The extensive occurrences of particularly severe ASS in the far inland areas of the delta, *i.e.* the Plain of Reeds and parts of the Long Xuyen Quadrangle, are likely to correlate with the locations of the early Holocene transgressive mangrove swamps. The moderately and weakly ASS common in the central and seaward parts of the delta are the product of deposition in mangrove swamps and tidal flats during the more recent, progradational phase of the delta. The sediments of major channels and coastal beach ridges have low or no ASS potential on the account of their high-energy depositional environment and, in the former case, due to the strong influence of freshwater. The alluvial capping over ASS in many parts of the delta are non-pyritic due to their deposition under oxidising terrestrial conditions.

The pyritic sediment, or PASS, is converted into AASS as pyrite is exposed to the air. AASS formation is often a variable and multi-stage process, but invariably results in the production of sulphuric acid:

$$FeS_2 + 15/4O_2 + 7/2H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4H$$

(Dent and Pons, 1995; Mulvey and Willett, 1996).

AASS may form naturally from PASS in the absence of human disturbance through falls in the water table, either during or after the deposition of parent sediment. Such phenomena may occur:

- seasonally, such as during the annual dry season;
- episodically, such as during droughts, or;
- permanently, in the event of a relative fall in sea-level, or a change in the course of the river.

The natural environment of the Mekong Delta is relatively favorable for the natural formation of AASS, given the extremely seasonal rainfall regime with a lengthy dry season, and a trend toward a sea-level fall during the late Holocene period, which have exposed highly pyritic early to mid-Holocene mangrove sediments.

However, most of the AASS and associated problems today in the Mekong Delta are derived from the human disturbance of PASS. Disturbance may take the form of an artificial lowering of the water table (through the draining of swamps, an increased evaporation from the soil surface, or excessive extraction of groundwater), or the direct exposure of pyritic material to the air through excavation or the placing of such material on the ground surface. Although the history of land drainage and reclamation for agriculture in the Mekong Delta dates back over three centuries, much of the conversion of PASS into AASS has taken place since the 1970s. The destruction of *Melaleuca* forests in backswamps and mangrove forests along the coast was initiated during the Vietnam (American) War through napalm bombing and the spraying of defoliants (Miyagi, 1995; Poynton, 1996; Benthem, 1998), and intensified through the government-initiated programme of agricultural expansion and settlement in underdeveloped areas of the delta since the end of the war (Poynton, 1996; Integrated Land and Water Development and Management Group Training Vietnam, 1997; Vinh, 1997). The stripping of forest cover and protective peaty topsoil has resulted in increased evaporation from the ground surface, increased penetration of air into the soil profile, and hence, in the lowering of the dry-season water table and the formation of AASS (Dent and Pons, 1995).

Since then, problems associated with AASS have been further aggravated through the implementation of large-scale water-control projects, which have resulted in the construction of numerous canals (Poynton, 1996; Integrated Land and Water Development and Management Group Training Vietnam, 1997), whose total length amounted to nearly 5,000 km in the early 1990s (Ministry of Transportation, 1993). Canals have not only resulted in the further lowering of water tables, but have also exposed large volumes of PASS to the air, along the walls of the canals and through the mounding of excavated pyritic material along their banks and in the fields for flood protection and improved drainage. The traditional use of excavated pyritic material to create raised beds for dryland crops (Sterk, 1992; Dent and Pons, 1993), applied in the more recently developed areas, has also contributed to a significant increase in acid discharge.

The most direct impacts of AASS are the acidification of soils and waterways. In the Mekong Delta, the heavy seasonal rainfall ameliorates the accumulation of soil acidity during the dry season to some degree. Nevertheless, seasonal soil acidity hinders crop cultivation over a large area of the Mekong Delta, where only acid tolerant crops such as pineapple, cashew and yam may be grown (Tri, undated). Rice crops, of both traditional and improved varieties, suffer low yields or total failure in years of severe acidification (Poynton, 1996; Tri, undated). Soil acidity, while harmful to crops in its own right, also interferes with the uptake of nutrients. In particular, acid conditions lead to the fixation of phosphorus, reduction in nitrogen mineralisation, and a low base status resulting from the exchange and leaching out of calcium, sodium and potassium ions (Kyuma, 1976; Sen, 1988; NEDECO, 1993c). Soil acidification may also lead to ecological changes, as acid-intolerant plants are displaced by acid-tolerant ones (such as *Melaleuca* spp. and *Eleocharis* spp.), reducing biodiversity.

The mass flushing of acid into waterways at the commencement of the wet season results in extreme fluctuations in water quality and chemistry, detrimental to aquatic ecosystems. Such events commonly lead to mass mortality, disease, disfigurement and reduced growth rates in fish and other aquatic life (Sammut *et al.*, 1995, 1996; Callinan *et al.*, 1996). Acid-tolerant aquatic plants may proliferate under conditions of recurrent acid discharge, choking smaller waterbodies with organic debris, thus impacting on water quality (Sammut *et al.*, 1995, 1996). Recent evidence indicates that acid discharge may also encourage the growth of toxic blue-green algal blooms, if the background nutrient loading is high (ASSAY, May 2000).

The extent and severity of acid discharge is heavily dependent on the configuration of the drainage network. In areas where the network consists of a long and complex system of canals eventually discharging into the sea or major river channels, such as in the Plain of Reeds, acid discharge takes the form of a short-lived (up to 10 days) wave of extremely acid water (pH 2.5 to 4) in and near the acid source area, which becomes diluted to pH levels of 4 to 6 as it travels into the more distant parts of the drainage network, but then stagnates over a large area for periods of over a month at time before dissipation or discharge to the sea (Government of Vietnam, 1991 [Working Paper No. 1]). On the other hand, areas where canals are shorter and simpler in terms of their network, such as the Long Xuyen Quadrangle, the acid discharge is flushed out rapidly, but in a more concentrated state, with a correspondingly more severe impact on the receiving waterbody (Poynton, 1996). The main channels of Mekong and Bassac are usually little affected by acid discharge from adjacent delta plain areas, as the discharge is rapidly diluted by large volumes of freshwater.

A serious environmental side-effect of pyrite oxidation and the associated fall in soil and water pH is the increased mobility of potential toxins. As acid is generated during the dry season, metals within the soil such as iron (in part derived from the breakdown of pyrite), manganese and aluminium become mobilised in response to the fall in pH and are concentrated at the surface to toxic concentrations through capillary action (NEDECO, 1993c). These metals commonly combine with sulphate released during pyrite oxidation, *e.g.* alum (van Mensvoort, 1993). Aluminium and iron toxicity is common in rice seedlings planted at the start of the wet season, when rainfall is still insufficient for the flushing of the metals out of the surface soil (Tin and Ghassemi, 1999). In waterways, aluminium at high concentrations causes serious toxicity in fish, and has been identified as a major contributing factor in mass mortality in ASS areas (Sammut *et al.*, 1996; Callinan *et al.*, 1996). In the Plain of Reeds, aluminium concentrations in canal water at the start of the wet season can exceed the normal tolerance in local fish by over 100-fold (NEDECO, 1993c). Acid conditions can also increase the mobility of trace metals and prolong the residence time of pesticide residues in the environment (van Mensvoort, 1993; NEDECO, 1994b). Hence, ASS may contribute to an increased biological uptake of such toxins in the environment.

1.3.4 Water and soil salinity

The problem of saline intrusion is one common to many deltaic settings. In the Mekong Delta, seasonal saline intrusion is a natural recurring phenomenon, driven by the significant decrease in surface and subsurface runoff during the dry season (Figure 7). However, as in the case of ASS, human disturbance of the natural environment has increased the extent and the severity of the problem.

Salinity problems in the Mekong Delta may be categorised into 3 main types on the basis of their mechanism: channel, subsurface and relict. The first involves the upstream intrusion of seawater within the distributaries, tidal creeks and canals of the delta. Saline water entering a single channel may be distributed over a wide area of the delta plain by its tributaries. The extent of the intrusion depends, among other factors, on the freshwater discharge, size and morphology of the channel, configuration of the drainage network, tidal conditions and the presence / absence of control structures such as sluice gates. Subsurface saline intrusion involves the penetration of saline groundwater beneath the delta plain from the coast, or

from channels containing saline water. Relict salt in sediments deposited under an earlier, marine-influenced phase causes salinisation of groundwater in some parts of the delta now located considerable distances inland, *e.g.* An Giang province.

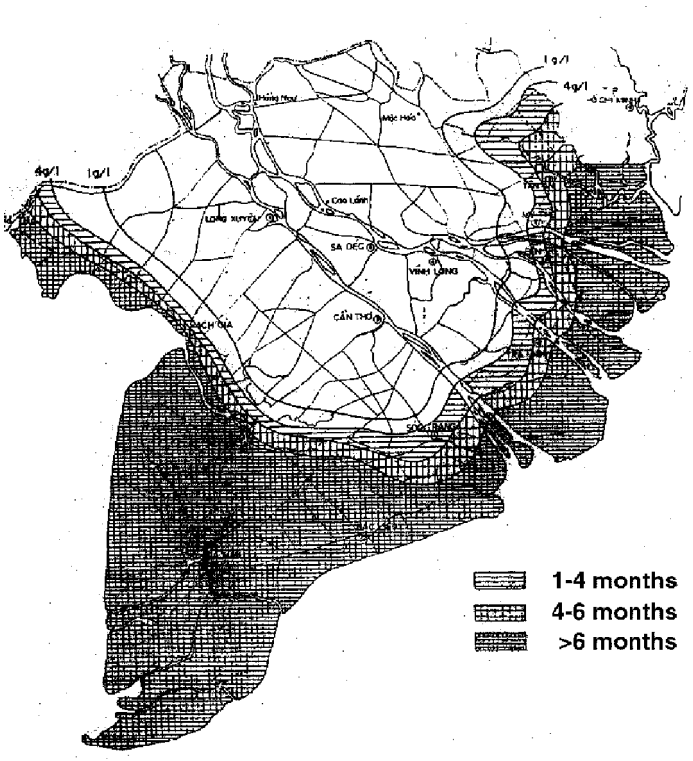


Figure 7. Distribution and duration of saline intrusion in the Mekong Delta (Source: SIWRPM).

1.3.5 Waterway development issues

Deltaic environments are typically endowed with a dense array of natural waterways. However, in their natural state, their use as a transport network and for water supply poses some problems. In the Mekong Delta, the natural configuration of channels and drainage network presented a challenge to their utilisation in the early part of the settlement. Apart from the main channels of Mekong and Bassac and their tributaries, most of the delta plain, under natural conditions, was drained by innumerable local drainage lines with low interconnectivity, high sinuosity and poorly defined flow direction. Initiatives directed at improving the waterways for transport commenced soon after the first Vietnamese settlement of the delta. Large-scale canal construction was commenced in late 19th century by the French, and by 1930, an interconnected rectilinear network of canals extended throughout much of the delta (Takada, 1984; Brocheux, 1995). A more recent phase of canal construction has commenced since 1975, when a number of irrigation /land reclamation schemes for rice production have been implemented by the central government. Today, these canals virtually incorporate all waterways within the Mekong Delta into a single network with a total length approaching 5000 km and which enables uninterrupted water transport from Ho Chi Minh City to Ca Mau Peninsula and the Gulf of Thailand coast (Ministry of Transportation, 1993).

Sedimentation and erosion also present a challenge to the human utilisation of the Mekong Delta waterways. The high sediment load of the Mekong River system, estimated at 160 million t / year (Milliman and Syvitski, 1992) results in an inherently dynamic channel system with rapid rates of change. Commonly, such changes are associated with channel migration, whereby deposition along a river bank is countered by erosion of the opposite bank. Susceptibility to channel migration and the type of mechanism responsible vary according to the location within the deltaic system. The upper delta experiences very rapid rates of channel migration (banks erosion rates are commonly up to 20 m / year), caused by the lateral accretion of point-bars and mid-channel bars / islands, and the downstream migration of mid-channel bars (Figure 8a). Mid- and lower delta channels are more stable (bank erosion rates are commonly 5-10 m / year), and channel change here is mainly caused by the slow accretion of elongated point-bars and mid-channel bars (Figure 8b). The slower current velocities and cohesive bank material, as well as the protection afforded by mangroves and nypa palms (*Nypa fruticans*) in saline reaches, are the principal reasons for the relative channel stability here. Near the mouths of the main distributaries, channel changes are common and result from the formation and shifting of distributary-mouth bars (Figure 8c).

Another group of channel change involves the abandonment of channel segments, which generally leads to their progressive siltation. At a small scale, channels separating a mid-channel or distributary-mouth bar

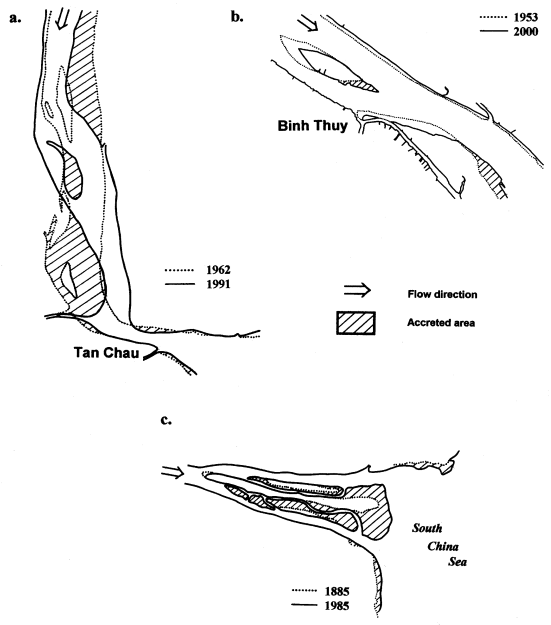


Figure 8. Channel change and associated bank erosion at: (a) Tan Chau on the Mekong branch (Anh, 1992); (b) along the Bassac branch at Binh Thuy / Can Tho City (MDDRC, 2000), and; (c) at the Bassac mouth (Anh, 1992). The contrast in channel morphology and migration mechanism between the upper, middle and lower delta, respectively, is clearly evident.

from the river bank may infill with sediment to eventually result in the coalescence of the bar with the bank. At a larger scale, individual distributaries may also become abandoned; the progressive sediment accumulation within the Ba Lai sub-branch of the Mekong is a manifestation of its impending abandonment (Anh, 1992). Also, many of the smaller *rach*-type channels in the peripheral areas of the Mekong Delta (*i.e.* Ca Mau Peninsula and the area about the mouths of Saigon and Vaico Rivers) are prone to change in position and abandonment; strong tidal asymmetry resulting from the large tidal range along the South China Sea coast results in the progressive inward transport of sediment from the sea and eventual channel infilling. Mangroves are likely to assist in sediment accumulation within these channels.

Sedimentation and erosion processes in the Mekong Delta are highly seasonal given the large annual fluctuation in both the river discharge and sediment load. Suspended sediment load of the river inflow varies from less than 100 mg l^{-1} during the dry season to 600 mg l^{-1} during the peak flood season (NEDECO, 1993c; Wolanski *et al.*, 1998). Most bedload (consisting predominantly of sandy material) is transported and deposited on the channel bed and in bars during the flood season, while the finer suspended load during this season is either kept in transport within the channel, flushed out into the ocean, or deposited on the delta plain through overbank flooding. In-channel deposition of suspended load sediments takes place during the low-flow period. In the seaward parts of the channels, deposition is aided by saline intrusion, which causes sediment flushed to sea during the flood season to be re-imported into the delta (Wolanski *et al.*, 1998). In the larger channels, much of the dry-season deposition is ephemeral, as the fine sediment is reworked during the following flood season. In the smaller channels, tidal creeks and canals, mud deposition is more likely to be cumulative over successive dry seasons.

Bank erosion is considered a serious socio-economic problem in the upper delta provinces of An Giang and Dong Thap provinces. Problems are especially severe at Tan Chau on the Mekong branch in An Giang, where erosion rates attain 30 m / year, and approximately 400 households have had to be relocated due to destruction of their dwellings through bank collapse (Figure 9). Bank erosion has resulted in major disruptions to local livelihoods, and financial burden on the provincial government (cost up to the present amounts to hundreds of billions of VND) by necessitating the relocation of inhabitants and localised bank protection works (Truong Dang Quang, pers. comm.). Losses due to bank erosion appear to have increased in the last decade, probably due to the growing urban population and the resultant concentration of activity and capital along the waterfront (Truong Dang Quang, pers. comm.). The severity of erosion at Tan Chau is largely attributable to the sharp meander-bend morphology, which focuses the river flow energy onto the concave bank (where the town is situated). The gradual downstream rotation of the point-bar on the opposite bank has resulted in a progressive downstream shift in the zone of erosion; stretches of river bank upstream of Tan Chau, which formerly experienced severe erosion are now experiencing bank accretion (Truong Dang Quang, pers. comm.).

Figure 9. Eroding banks of the Mekong at Tan Chau in August 2000. Note the foundations of ruined buildings in the river suggesting the former location of the river bank.

Other erosion hotspots further downstream within An Giang (*e.g.* at Long Xuyen) are mostly associated with the downstream migration of mid-channel bars, which creates a shifting zone of erosion downstream and to the sides of the bar, and a zone of accretion to its upstream. Large-scale bank stabilisation through hard engineering (*e.g.* concrete retaining walls, rock protection), common in countries such as Japan, has not been applied to the Mekong Delta, and is unlikely to be in future due to the prohibitive cost. Such works have, in a great number of fluvio-deltaic systems around the world, produced undesirable side-effects such as rapid channel aggradation, and exacerbated downstream erosion / sedimentation (see Section 3.2.2).

Sedimentation on the opposite bank, which accompanies bank erosion, also represents an economic cost in places, through the shoaling of navigation channels, the stranding of wharves, docks and other water transport infrastructure, and the blocking of entrances to canals. However, sedimentation in the main distributary channels is regarded by many as an economic benefit, given the predominantly sandy nature of channel sediments, and the increasing demand for construction sand driven by urban expansion. Numerous sand dredging operations exist along most of the length of both the Mekong and the Bassac branches; an individual operation may extract volumes in the order of 10^4 m^3 /year from the bed of the channels (Ky Quang Vinh, pers. comm.).

[1] Vietnamese for "…*small water courses without any permanent source*…" (Brocheux, 1995) of diverse geomorphic origin, including tidal creeks, abandoned distributaries, and crevasse or backwater channels.

[2] A state of salinity structure in estuarine waters whereby mixing between fresh- and saltwater occurs incrementally in the upstream-downstream direction, creating a relatively gentle salinity gradient.

[3] Any state of salinity structure in estuarine waters involving the convergence of fresh- and saltwater along a relatively sharp front or gradient, with the former floating on top of the latter as a plume prior to mixing.

[4] Horsts and grabens are blocks of rock displaced upward and downward, respectively, relative to adjacent rocks by movement along (sub)parallel faults on either side of the blocks.

[5] A mineral that forms in sediment soon after deposition.

2. INFRASTRUCTURE DEVELOPMENT IN THE MEKONG DELTA AND ITS IMPACTS ON THE BIOPHYSICAL ENVIRONMENT

2.1 Introduction

It is apparent from the preceding sections that the natural environment of the Mekong Delta provides both abundant opportunities for, and constraints to, its human utilisation. As a result, the delta has undergone progressive environmental modification since the arrival of the first Vietnamese rice growers over 300 years ago. However, it is in relatively recent times, in particular since 1975, that the pace and the spatial scale of environmental transformations have increased markedly, a trend chiefly driven by political and economic forces. Such transformations have taken the form of infrastructure development projects, which range in spatial scale from that of individual farms to the entire delta, and which represent the product of decision making at individual, through provincial to national and international levels. Although many of these have generated positive economic effects, in accordance with their original aims, their environmental impacts have often remained unaccounted for, while new interventions continue to be planned and implemented. Furthermore, the co-existence of numerous activities within the delta, commonly with conflicting interests, leads to concerns over their cumulative impacts and effects on each other.

This section explores the origins, mechanisms and implications of actual and potential environmental issues arising from recent infrastructure development interventions within the Mekong Delta. Analysis and discussion will be focussed on two case examples, namely large-scale water-control projects, and the development and biophysical transformation of the coastal zone associated with shrimp aquaculture, mangrove forestry, and irrigated rice cultivation.

2.2 Large-scale water-control projects

2.2.1 History and rationale

Rice cultivation is the most important economic activity in the Mekong Delta today. Over 90 % of the agricultural land of the delta is utilised for rice. Mekong Delta rice is a significant contributor to the national economy, producing approximately half of the national rice production and forming the bulk of rice export (NEDECO, 1991c). Rice cultivation was introduced into the delta by pioneer Vietnamese settlers in the early 18th century, and spread throughout much of the delta with the rapid development of the canal system between the mid-19th and mid-20th centuries (Takada, 1984; Sanh *et al.*, 1998). However, no systematic irrigation schemes were implemented until the collectivisation of agriculture after the end of the Vietnam (American) War, such that rice cultivation in the delta, until relatively recent times, was constrained by the natural patterns of rainfall and flooding. Some 1000 traditional varieties of rice, featuring different maturity time and flood tolerance, were used often in conjunction with transplanting techniques to avoid damage during the peak flood season (Tanaka, 1995; Sanh *et al.*, 1998). In areas prone to deep, prolonged flooding, such as the Long Xuyen Quadrangle and the Plain of Reeds, floating rice varieties were cultivated (Sanh *et al.*, 1998), while early-maturing varieties with single transplanting were utilised in coastal areas in order to avoid damage from saline intrusion at the beginning of the dry season (Tanaka, 1995). Such cultivation of traditional varieties, which dominated the delta up to the early 1970s, was typically characterised by a single crop per year and low yields (usually 1.5 - 2.0 t ha-1; NEDECO, 1991c).

The introduction of high-yielding varieties in 1966 and the spread of mechanical (low-lift) pump for local-scale irrigation heralded the beginning of the intensification of rice cropping within the Mekong Delta. During the late 1970s and 80s, intensive rice cultivation spread rapidly throughout the delta, a trend further emphasised by the country's reorientation toward a market economy since 1986 (NEDECO, 1991c, e).

Large areas of ASS in the Plain of Reeds, Long Xuyen Quadrangle and Ca Mau Peninsula, hitherto excluded from regular agricultural use, were turned over to rice production through the expansion of the canal network, the establishment of farming collectives, and a government program of resettling impoverished farmers from other areas (MDDRC, 1993; Sanh *et al.*, 1998). The rapid spread of intensification is well illustrated by the increase in the total area of irrigated rice within the delta, which nearly quadrupled between 1975 and 1995 to 1.1 million ha (Son, 1998). Much of the delta now produces 2 rice crops in a year and triple cropping is possible in parts.

Although the replacement of traditional varieties with improved varieties, and the increased application of chemical fertilisers, agro-chemicals and farming technology played a role in the increase in yields, it was the implementation of large-scale dry-season irrigation and wet-season flood- and drainage-control measures which permitted the application of intensive rice cultivation methods to most parts of the delta. The spread of water-control measures throughout the delta was facilitated by the existence of an extensive canal network, integrated into a well-developed hierarchy from primary (regional-scale) through to tertiary (local- / farm-scale) canals.

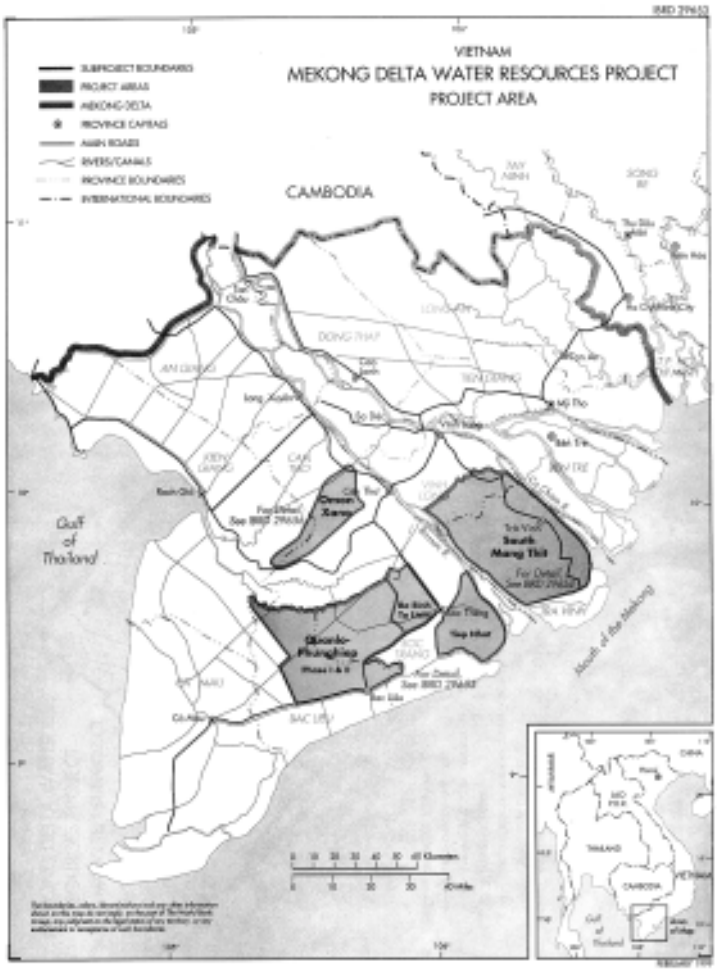


Figure 10. Location of large-scale water-control project areas comprising the Mekong Delta Water Resources Project (World Bank, 1999).

Before the 1990s, water control within the delta was implemented in a highly fragmented manner. Typically, flood-control measures were applied to areas in the order of 10^2 - 10^3 ha, usually enclosed by primary and secondary canals, while individual irrigation and drainage-control measures were applied to areas of less than 10^2 ha, served by tertiary canals (NEDECO, 1991b). Water-control activities have subsequently become more coordinated under the Mekong Delta Master Plan, which has established sub-projects with clearly defined boundaries and individual areas of 10^4 - 10^5 ha. At present, these sub-projects are: South Mang Thit, Quan Lo Phung Hiep, Ba Linh Ta Liem, Tiep Nhat and O Mon Xa No (World Bank, 1999; Figure 10).

The main components of hard infrastructure in water-control activities in the Mekong Delta are canals, dykes and sluice gates.

Canals in the Mekong Delta are channels excavated into the underlying sediments with a minimal use of hard bank stabilisation techniques (*e.g.* concrete). In areas with well-defined natural drainage, a significant proportion of the canal network consists of modified natural channels, evidenced by their irregular planform, *e.g.* southern Ca Mau Peninsula. In backswamps and other parts of the delta lacking well-defined natural drainage lines, canals are more straight and form a rectilinear network, *e.g.* in the Long Xuyen Quadrangle and the Plain of Reeds.

The canals have multiple functions, namely as conduits for irrigation water from the main channels to cropping areas, for the drainage of local runoff and floodwater away from cropping areas into channels or the sea, as pathways for water transport, and for waste disposal. Under water-control schemes in recent times, many canals have been designed or modified to hasten the removal of acid water originating in ASS areas. In coastal areas, canals also allow the ingress of saline water necessary for aquaculture and mangrove forestry activities. An added economic benefit of canals is the increase in potential for fishing activities, which may be a significant supplementary source of local income especially during non-cropping periods. They vary enormously in size, from primary canals which allow the passage of boats of over 2000 t to ditch-like on-farm canals. The primary canals act as conduits for water between natural water bodies, *i.e.* the main channels and the sea, and the general area of water control, while the secondary canals form the interconnections between the primary canals. Tertiary canals act as the pathway for water to and from the fields.

The dykes are usually composed of sediment excavated locally during canal construction and line natural channels and primary / secondary canals. Their function is to prevent or delay the inundation of fields through overbank or coastal flooding. Many of the larger dykes also serve as road embankments, and are significant in the development of land transport networks in the less developed areas. Some tertiary canals also have dykes, but they are much smaller in dimension and have a limited role in delaying flooding (NEDECO, 1991b). The highly interconnected nature of canals has meant that dykes have effectively divided the delta plain into an agglomeration of individually enclosed polders. The height of the dyke and the location within the delta determine the degree of protection from flooding offered by the dykes, and hence, the type of agricultural activity possible. In areas where the dykes are lower in height than the mean peak flood level, they allow rice cropping into the early part of the flood season until the flood level attains the top of the dyke. Such areas are usually double rice cropping areas, and the inundated fields are utilised for fishery activities during the peak flooding season. Areas with dykes higher than the mean peak flood level are considered to have year-round flood protection, which allows triple rice cropping to take place.

Water flow in and out of canals is regulated by the sluice gates. Their exact function depends on location within the delta. In the upper delta where overbank flooding is deep and prolonged, sluice gates control the influx of water from the main river channels during the early part of the flood season in order to keep the rising water out of the fields until after the harvest of the summer / autumn rice crop. They are opened after the harvest, usually by mid-August, after which the dykes are overtopped in double rice cropping areas. The sluice gates are also opened in many of the triple rice cropping areas (*e.g.* parts of Long Xuyen Quadrangle, North Vam Nao Island between the Bassac and Mekong channels in An Giang province) during the peak flood season in order to allow overbank sedimentation in the fields, to flush out agro-chemical residues, and to permit fishing within the fields. The sluices are generally located on the larger canals, and water flow control along tertiary canals and on farms are commonly carried out with temporary earth banks and dyke breaches. A contrasting situation is presented by sluice gates in the coastal areas, which have a double function of controlling the flow of floodwater and local drainage during the wet season, and saline intrusion during the dry season. Gates occur both along main canals and tertiary canals which face the main channels or the sea; this is necessitated by the saline intrusion. Gate operation may be highly complex due to great variability in conditions resulting from fluctuations in local runoff and tidal regime, although gates are generally closed during the dry season to prevent saline intrusion. Furthermore, the efficiency of gates and irrigation systems appears to be curtailed by low levels of maintenance and coordination of infrastructure operation (Miller, pers. comm.).

It needs to be reiterated that the greater part of the canal network in the Mekong Delta was established well before the spread of irrigated rice cultivation. Nevertheless, the implementation of water-control projects under the Mekong Delta Master Plan has heralded a new era of extension and upgrading of water-control infrastructure. The extension of the secondary canals network has been crucial in the spread

of irrigated rice cropping to previously marginal areas in the Plain of Reeds, Long Xuyen Quadrangle and Ca Mau Peninsula (NEDECO, 1994a; SIWRPM, 1997). In areas with a pre-existing network of canals, many have been restored to their original capacity or enlarged through dredging and excavation. The number of sluice gates throughout the delta has increased dramatically since the 1990s; the number of gates within each water-control project area has typically tripled or quadrupled through the course of project implementation (NEDECO, 1994b; SIWRPM, 1997; Australian Agency for International Development, 1998).

2.2.2 Environmental impacts and concerns

2.2.2.1 Hydrological impacts: flood season

The proliferation of structural modifications associated with recent water-control interventions means that contemporary hydrological processes within the Mekong Delta little resemble those under original conditions. The overall effect of modifications, such as canal and dyke construction, has been to fragment and complicate the pattern of channel and overbank flow of water within the delta.

Under natural conditions, wet-season flooding in the Mekong Delta is a gradual process, which commences in the upper delta and moves progressively downstream. Water levels progressively rise in the main channels until breaches in levees and flood channels allow overbank flow over the delta plain. Thereafter, much of the delta plain acts as major pathways for the general downstream flow of floodwater. Water-control structures have lead to the disruption of this process in two major ways.

First, the delaying or the complete prevention of overbank flooding results in an increase in discharge through channels and ungated canals (*e.g.* primary canals). Within natural channels, the likely consequential increase in flow velocities may alter channel morphodynamics, *e.g.* by increasing bank erosion, or by increasing the delivery of sediment to areas further downstream, thus increasing siltation problems in these parts. Under conditions of minimal water diversion from the main channels, the frequency and / or depth of flooding in the lower delta may also increase; here, only a slight increase may have significant impacts, as many lower delta areas do not usually experience significant overbank flooding and flood protection is often effective for relatively low flood heights. In canals, high flow velocities contribute to bank erosion and enhanced transport of sediment in the main canals. Upon entering the smaller tertiary canals, much of this sediment is deposited due to an abrupt drop in flow velocities, adding to the cost of canal maintenance.

The second group of impacts pertains to the flow of water once it enters the overbank areas. In the upper delta, canals and dykes generally trend normal to the orientation of the main channels. Under natural conditions, the overbank areas of the upper delta functioned as major pathways for the downstream (*i.e.* subparallel to the main channels) flow of floodwater. The structures therefore represent major obstacles to the natural overbank flow of floodwater. Across the border in Cambodia, flood-control structures are largely absent, such that those on the Vietnamese side could potentially contribute to aggravated early season flooding here by effectively damming the downstream-travelling floodwave. Even when the dykes are overtopped, as in double rice cropping areas during the peak flood season, they continue to hinder overbank flow by increasing the effective surface roughness of the delta plain. In the event of an extreme flood, such as that which affected the delta in September and October 2000, the consequences may be grave, as they may increase the duration and the depth of inundation. Indeed, evidence suggests that local flood heights have generally increased in recent years, since the construction of numerous water-control structures (Tin and Ghassemi, 1999), and that the proportion of floodwater throughflow has decreased (MDDRC, 1996).

2.2.2.2 Hydrological impacts: dry season

Under natural conditions, the recession of water levels in the main channels after the peak flood season results in the reversal of the direction of water transfer between the main channels and the delta plain. The outflow of water maintained in overbank storage from the flood season thus supplements freshwater flow in the main channels during the earlier part of the dry season. The overall impact of canals and the proliferation of irrigated rice cropping on the dry-season flow regime has been a reduction in discharge within the main channels. The effect of water abstraction from the main channels by primary canals is cumulative, such that discharge in the main channels decreases progressively with increasing distance downstream. This contrasts with the regime under natural conditions, whereby downstream losses of discharge were minimal. In this regard, the recent expansion and intensification of cultivation in the extensive backswamp areas of the upper delta (such as the Plain of Reeds and the Long Xuyen Quadrangle) is likely to have a significant impact by further increasing the proportion of discharge abstracted in the upstream section of the channels.

An immediate effect of such a lowering in discharge within the main channels is the increased duration and extent of saline intrusion in the lower delta. Data indicate that saline intrusion in the Bassac and Mekong channels since the 1980s has generally increased only in duration (Tin and Ghassemi, 1999), but the likelihood of an upstream extension of the intrusion remains high given that the construction of new water-control structures will continue into the foreseeable future, and that the increasing population, urbanisation and industrialisation within the delta will place increasing pressure on water resources. The occurrence of water abstraction points along reaches of the main channels affected by seasonal salinity implies that the viability of some downstream irrigation projects may be threatened, should there be a significant extension of the intrusion due to continued water-control interventions upstream. A further and growing threat is posed by infrastructure development in the catchment upstream of the delta, notably the rapidly increasing number of dams.

Another hydrological effect of water-control projects, which becomes aggravated during, but not restricted to, the dry season, is poor flushing of water within canals. One cause of water stagnation in canals is the poor geometry of canal network. For example, the channel-normal orientation of canals which traverse the extensive backswamp areas of the Plain of Reeds and the Long Xuyen Quadrangle, is highly conducive to water stagnation, as the flow velocity of water is significantly dampened upon entry into the canal from the main river channels by the sharp accompanying deflection. Furthermore, in the Long Xuyen Quadrangle, tidal inflow from the Gulf of Thailand acts to hinder the outflow of water, especially during late dry season, when the inflow of freshwater from the Bassac is weak (Tin and Ghassemi, 1999). In Ca Mau Peninsula, the configuration of the canal system featuring numerous shore-normal canals along the South China Sea and Gulf of Thailand coastlines, interconnected within the interior of the Peninsula by cross canals, is particularly susceptible to the formation of stagnant zones, as the incoming tidal waves meet in canals within the interior of the Peninsula. The installation of numerous sluice gates for the control of dry-season salinity has also contributed significantly to water stagnation in some areas, such as the Plain of Reeds (NEDECO, 1994a).

The still conditions enhance sedimentation within canals, resulting in an elevated cost of maintenance. (The impacts of water-control interventions on sediment dynamics within the delta are discussed in the following section.)

2.2.2.3 Impacts on sediment dynamics and deposition

Under natural conditions, much of the delta plain experienced sediment deposition annually through overbank flooding. In recent years, flood deposition over much of Mekong Delta has been restricted or completely prevented through the exclusion of floodwaters by flood-mitigation structures such as dykes. The most immediate effect of such cessation of regular overbank sediment deposition is the possibility of

decline in soil productivity, and hence in agricultural yields. Although the actual annual contribution of soil nutrients through overbank deposition may not be as significant as it is sometimes claimed to be (see Section 1.3.1), it is highly likely that the annual addition of new sediment to the delta-plain surface has a maintaining or a protective effect on soil fertility and structure, namely by retarding the leaching of nutrients from the existing soil attributable to subaerial weathering, and by preventing excessive compaction of the near-surface soil, which may lead to poor soil aeration and H_2S toxicity in crops.

In many areas, annual overbank flooding has not completely been prevented due to the overtopping of the dykes during the peak flood season. However, even here, overbank deposition is likely to have been significantly reduced due to the obstruction of free overbank flow over the delta plain by the dykes. In effect, these dykes have converted the delta plain into a series of settling basins, such that the floodwaters lose much of their sediment load rapidly upon entering the overbank area, and little deposition takes place as they advance further away from their ingress points. Such an effect is apparent in the marked difference in the turbidity of water in the flooded fields and that in the main channels and canals (the latter is more turbid) that is commonly observed from high vantage points.

Figure 11a. Some factors contributing to enhanced sediment trapping in canals: constrictions and poor layout geometry (Tam Phuong Irrigation Area, South Mang Thit Subproject).

The practice of allowing floodwaters onto the fields during the peak flood season in some full-flood protection areas is often regarded as an insurance against a decline in soil productivity that may take place under conditions of total exclusion of overbank deposition. However, there is a need to question its effectiveness, as in many cases, the bulk of sediment may become trapped in the canals before the water can reach the fields, due to the complex geometry of the canal systems retarding flow velocities (see below). In addition, it is the preliminary flood wave arriving from the catchment, which often carries the greatest concentrations of sediment, rather than the waters of the peak flood season which is introduced into the fields (Miller, pers. comm.).

Figure 11b. Some factors contributing to enhanced sediment trapping in canals: construction of dwellings and other structures along banks (Can Tho City).

Although water-control projects have had the overall effect of restricting overbank sedimentation, the delta plain has retained its role as a major sediment sink through the trapping of sediment in the extensive canal network which traverses it today. The chief cause of sediment trapping in canals is the stagnation of water flow, which may arise from a variety of causal factors (see preceding section). Sediment trapping is especially problematic in the smaller canals, *i.e.*, those at secondary and tertiary levels, due to the commonly large distances from ingress points along the main channels, small cross-sectional capacities, the frequent occurrence of flow-disruptive geometries (junctions, constrictions, corners and dead-ends; Figure 11a), proliferation of dwellings and other structures along the banks (Figure 11b), and the growth of

aquatic vegetation, which all contribute to slowing flow velocities. In ASS areas, the flocculation of fine particles under acid conditions assists sediment trapping within canals.

Fast flow velocities render the larger canals less efficient sediment traps. However, those canals which provide a relatively direct connection between the main channels and the sea, or between the main channels, can divert large quantities of sediment away from the source channel. For example, a significant quantity of fine sediment from the Bassac appears to be redirected by the primary canals of the Long Xuyen Quadrangle to the Gulf of Thailand. A high proportion of the diverted sediment, however, seems to be trapped within the dead-water zones in canals created by the convergence of tidal inflow and freshwater outflow. In areas where diversion canals replicate existing natural channel systems, the canals may reduce the flow through the natural channels, triggering increased sedimentation and, in the worst case scenario, abandonment of the latter. An instructive case is presented by the Vam Nao River, a natural connection between the Mekong and the Bassac branches, which has experienced progressive infilling since the construction of several Mekong-Bassac transfer canals (Anh, 1992).

Most of the sediment trapped within canals in the Mekong Delta is fine suspended load material. As a result, the effects of canals on the quantity of bedload travelling through the main channels are likely to be relatively small. However, canals are likely to have some impact on the hydrodynamics of the channels. Voluminous diversion of main channel flow into numerous primary canals may reduce flow velocities in the former, retarding bedload transport, and hence trigger an increase in the accretion of bars and bottom shoaling. The effect would be most pronounced in the lower reaches of the Mekong Delta, where the reduction in flow velocities is at its greatest due to low channel gradients and progressive water abstraction along the upper reaches. It should be borne in mind that the very large wet-season flow, when most of the bedload transport takes place, and the possibility of an increase in early flood-season discharge in the main channels due to the exclusion of floodwaters from overbank areas by dykes, may largely ameliorate the aforementioned effect.

Changes in the main-channel flow geometry at canal junctions have had more certain effects on bedload deposition, at least at a local scale. Flow separation and the consequential creation of slackwater zones common at the confluence of canals with the channel are conducive to the initiation of bar deposition, often at locations which have been erosional under natural conditions (*e.g.* on the concave bank of a river bend). The initiation of new bars would result in the initiation of erosion on the opposite bank. Furthermore, some bedload may be diverted with the flow away from the channel and into canals, where the slower flow encourages rapid deposition. In either case, the supply of bedload to existing bars and other temporary sinks of bedload is diminished, causing a slower rate of accretion or erosion in these areas. Such a change in the zonation of deposition and erosion within the channels may be detrimental to the maintenance of water transport infrastructure. The situation may be complicated by an increased sediment release to the channel through bank erosion during the early flood-season, when the confinement of flood discharge to the channels and ungated canals result in increased flow velocities and enhanced bank scour (see Section 2.2.2.1).

The proportion of suspended load sediment trapped within Mekong Delta is likely to increase, as intensified rice cultivation continues to expand and the density and complexity of the canal network increases. Besides increased sediment trapping by canals, an increase in dry-season water abstraction for irrigation is likely to enhance the transport of suspended sediment from the coast into the lower reaches of the main distributaries by baroclinic currents (Wolanski *et al.*, 1998). This increase in the dry-season sediment deposition, combined with an increased flow diversion by canals throughout the year, may turn the lower reaches of the main distributary channels into a zone of net fine-sediment accumulation. The controversial plans to divert a significantly larger proportion of the Bassac flow to the Gulf of Thailand through canals still remains a possibility. Under such a scenario, a significant decline in the discharge of suspended sediment to

South China Sea is to be expected, leading to an increase in the incidence of coastal erosion. The effect is likely to be most pronounced along the coastline of Ca Mau Peninsula, where sediment is almost entirely supplied by the longshore transport of suspended load discharged at the distributary mouths. (The direct impacts of canals on the coastal environment is discussed in Section 2.3.2.2.)

2.2.2.4 Impacts on ASS and acid discharge

Although an improvement in the flushing of acidity from ASS areas has been one of the principal aims of many water-control projects within the Mekong Delta, the production of acid discharge *per se* has, in many cases, increased as a result of these projects. The construction of additional canals has resulted in the further exposure of PASS material to the air, hence their conversion to AASS, through several means: the excavation of PASS material during canal construction; use of excavated PASS material for dyke construction; improved drainage and a fall in the watertable (especially during the dry season); installation of sluice gates which have resulted in prolonged conditions of low water levels or a reduction in tidal fluctuations within canals. In addition, land reclamation associated with water-control projects have sometimes resulted in the destruction of remnant *Melaleuca* forests in backswamps and mangroves near the coast, together with their protective peaty topsoil, all of which have contributed to the further creation of AASS. Peat decomposition has also contributed to the eutrophication of some canals (MDDRC, 1996). Actual observations and field experiments indicate that the severity of acid discharge rapidly decreases within the first few years of PASS disturbance, but acid discharge at moderate levels continues for some years after the initial disturbance (Sterk, 1993; Tin and Ghassemi, 1999).

In accordance with their original aims, water-control projects have decreased the severity and the duration of water acidification in some parts of the Mekong Delta, through improved drainage and increased freshwater throughput from the main channels. This has been the case especially in the Plain of Reeds, where the area affected by acidity has decreased to less than one-quarter of its extent in 1980, and the duration of acid conditions has decreased from typically over 6 months to less than 3 months (Tin and Ghassemi, 1999). However, it is imperative to bear in mind that the amelioration of acidity pertains to local in-field conditions, and that the construction of canals, which has brought about these improvements at a local scale, has *increased* the total volume of acid generated in ASS areas. In addition, this acidity is exported to areas downstream and results in severe impacts on the receiving waters if it is not diluted appreciably during transport. Thus, in the Plain of Reeds today, freshwater inflow from the Mekong flushes acidity away from the western areas, incorporating more acidity during its passage through the eastern parts, prior to discharging into the West Vaico River (NEDECO, 1994a; Tin and Ghassemi, 1999). Predictably, the level of impact of acid discharge on the latter river system has increased since the implementation of water-control projects (NEDECO, 1993c).

In some areas where zones of stagnant water have formed through water-control interventions (*e.g.* due to installation of sluice gates, poor canal layout), acidity problems have not improved or have been aggravated. Sluice gates may have a negative ecological impact by causing a sudden efflux of acid water upon opening; the frequency and the timing such events are at the mercy of local operators of irrigation systems, and may lead to frequent water-quality fluctuations of high magnitude.

2.2.2.5 Other water quality and pollution impacts

Water-control projects have impacted water quality in the canals and smaller channels of the Mekong Delta through changes in hydro- and sediment dynamics, and the expansion and intensification of human activities, especially rice cropping, which have followed the implementation of the projects. In many cases, the cumulative effect of the different types of impacts has resulted in a severe deterioration of water quality.

Dominant pollutants in the Mekong Delta waterways, excluding those associated with ASS, are organic

matter, nutrients (nitrogen and phosphorus), pesticides and pathogens (such as faecal coliform), derived from farm runoff and domestic effluent. Much of the surface water in the delta is eutrophic to varying degrees, indicating a relatively heavy loading of organic matter and nutrients in the majority of waterways, except in the main channels (NEDECO, 1993c).

The construction of new canals associated with water-control projects has stimulated further ribbon development along Mekong Delta waterways. In the majority of cases, dwellings which line the canals are unsewered and discharge domestic effluent directly into the canal. From this perspective, canal construction is a source of pollution in its own right.

As with acid discharge from ASS areas, the formation of stagnant zones within canals, such as that arising from the installation of sluice gates or a poor canal network layout, has been the principal cause of excessive local-scale pollutant accumulation in waterways. In areas where sluice gates control dry-season salinity intrusion, such as in the Quan Lo Phung Hiep project area in Ca Mau Peninsula and the South Mang Thit project area in Tra Vinh Province, the coincidence of lengthy periods of gate closure with low freshwater runoff have resulted in chronic seasonal water quality deterioration (NEDECO, 1994b; SIWRPM, 1997). The combination of stagnant water and heavy nutrient loading is conducive to excessive vegetative growth, which may cause further pollution through the decay of organic matter produced, and lead to health problems in the local population by encouraging the breeding of disease-carrying organisms such as malarial mosquitoes.

The spread of intensified rice cropping, triggered by water-control projects, has resulted in a greater application of chemical fertilisers and pesticides, thus increasing the pollutant flux into waterways. There are particularly serious health and ecological concerns regarding the increased pollutant loading of pesticides, trace metals and other toxic substances, many of which are dispersed and stored within the environment through adsorption to fine sediment and organic particles. The trapping of sediment in canals, due to the creation of stagnant conditions, has the effect of concentrating such pollutants within the canal environment, and if this coincides with periods of acidification due to the formation of AASS, chemical conditions favourable for the mass biological uptake of these toxins can arise.

Figure 12. Compartmentalisation of the delta plain by water-control infrastructure such as dykes, which commonly results in the stagnation of floodwaters in the overbank areas and aggravated pollution problems (near Chau Doc, An Giang Province).

The negative effects of water-control projects on water quality are not restricted to canals. The retardation of water flow in the overbank areas, as a result of the compartmentalisation of the delta plain by dykes (Figure 12), has had a similar effect to the creation of dead-water zones in canals. During the peak flood season in partially flood-protected areas, floodwaters enter fields and entrain household effluent, solid waste and other pollutants, but their outflow is restricted by dykes. As a consequence, local inhabitants are forced to live in the polluted water for the duration of overbank flooding, resulting in health problems. In this light, it is also dubious whether annual flooding is entirely effective in removing pesticide residues from the soils of the fields, as it is commonly believed.

2.2.2.6 Ecological impacts

The foremost ecological impact of large-scale water-control projects within the Mekong Delta is the reduction in the remaining area of relatively natural ecosystems. Some of the last remaining tracts of freshwater wetlands (mainly consisting of *Melaleuca* woodlands and swamp grasslands) in the peripheral parts of the delta plain, *i.e.* the Long Xuyen Quadrangle and the Plain of Reeds, which had traditionally deterred human utilisation through hostile environmental conditions such as ASS, poor drainage, prolonged and deep flooding, and the coastal wetlands of Ca Mau peninsula, with their near-impenetrable growth of mangroves and saline conditions, were opened to human modification and use as a consequence of these projects. Those few areas of natural ecosystems which have thus far escaped modification have come under increasing environmental stress and risk associated with the encroachment of human activities, particularly as a result of their occurrence as "islands" within a "sea" of human-modified landscapes. Many of these remnant ecosystems are under national protection today, but nevertheless continue to be threatened by the impacts of human activities in the surrounding areas, such as changes in river flow and flooding regime and sedimentation patterns brought about by the continued implementation of water-control measures, increasing pollutant loading, poaching activities and escaped fires from burn-offs (Vinh, 1997).

The installation of numerous structures associated with water-control projects has resulted in an overall compartmentalisation of the ecosystems of Mekong Delta. These structures have obstructed the natural environmental flows, such as the transfer of water, sediment and nutrients, and the migration and dispersal of organisms and plant propagules, between the diverse biophysical environments of the delta. Flood-control dykes inhibit the free movement of fish between channels and delta plain during overbank flooding, which is especially significant for the so-called "white" fish species, which spawn on the flooded delta plain, but live within the channels during the dry season (NEDECO, 1991d). Sluice gate closures not only hinder the movement of biota and material between the freshwater and saline aquatic environments, but also eliminate the transitional brackish environments, along with species which cannot tolerate prolonged fresh or fully saline conditions such as the nypa palm (*Nypa fruticans*). The widespread loss of nypa, a highly valuable resource in the local economy, has increased the pressure placed on remaining resources, to the extent that dead clumps, apparently due to over-harvesting, are a common sight in many coastal areas.

Apart from those associated with the installation of structures, water-control projects have brought about changes to the character of habitats within the biophysical environments of the delta. The straightening of natural channels and the repeated dredging of canals are some examples of direct modification of pre-existing natural habitats, while more indirect effects have been brought about by changes in the river flow regime, duration, extent and depth of wet-season flooding, sediment dynamics, and acid discharge from ASS areas. Habitat diversity has generally decreased; for example, the alternating riffle and pool sequence typical of natural channels has been replaced with a rectangular channel of uniform depth. Furthermore, the degree of habitat stability has been altered, typified by the repeated and frequent disruption to aquatic ecosystems in canals through dredging, or the periodic flushes of acid discharge from the increased area of AASS. Although the increase in the area of aquatic habitats resulting from canal construction has often been cited as an ecological benefit of water-control projects (and indeed, fisheries resources offered by canals are an integral part of the local economy throughout the delta), this claim needs to be questioned given the typically low diversity and stability of habitats offered by canals. Such ecological conditions pave the way for a decline in regional biodiversity, as only the most adaptable and gregarious species are allowed to survive at the expense of the others.

Increased pollutant loading in the environment resulting from water-control interventions, whether it be due to an increase in the use of agro-chemicals associated with expanding irrigated rice production, an increased area of AASS and acid discharge, a reduced flushing capacity of waterways, or an increase in local population, has affected ecosystems directly through mortality in biota, diminished biological produc-

tivity, decreased resistance to disease and lowered biodiversity (MDDRC, 1996). A matter of particular concern is the potential for a progressive accumulation of toxins in the natural environment, since water-control projects have not only increased the pollutant loading, but have generally increased the potential for pollutant trapping within the environment, and their uptake by organisms. The restriction of overbank flooding on the delta plain, obstruction of overbank flow, increased acidification of soil and water due to AASS formation, water stagnation and enhanced sediment trapping in canals, lowered dry-season flow in the main channels due to water abstraction and the consequentially enhanced in-channel sedimentation within the lower delta, are some of the impacts which could all contribute cumulatively to the slow and progressive poisoning of the delta.

The impacts of water-control projects have the potential to undermine the long-term sustainability of agricultural production within the Mekong Delta. The increased levels of environmental stress and reduced biodiversity brought about by these impacts reinforce the general trend toward the domination of the delta by a handful of high-yielding rice varieties. Ecological balance is unlikely to be established within the newly formed agricultural landscapes of the delta, and, in the absence of natural controls, pest and disease out-breaks and fluctuations in environmental conditions will increasingly pose a threat to agricultural production. In addition, many traditional varieties of crop plants and livestock, as well as their ancestral or related species occurring naturally within the Mekong Delta, *i.e.* those under threat from the effects of the water-control projects, have higher environmental tolerances than the more recently introduced varieties, and could hold the key to the future development of more robust varieties for the local environment (Hirata, 2000). The absence of such genetic resources within the region will establish a feedback loop of perpetual reliance on costly inputs of agro-chemicals and new imported varieties, and continuing environmental and ecological degradation.

2.3 Development of the coastal areas of the Mekong Delta

2.3.1 History and rationale

2.3.1.1 Introduction

The coastal areas of the Mekong Delta present some of the most challenging environmental conditions within the entire delta for human settlement and utilisation. Here, many of the major environmental constraints to economic development within the delta converge, such as salinity, ASS, and poor drainage. In areas such as southwestern Ca Mau Peninsula, which are removed from the direct influence of the fresh-water flow of the main channels, a seemingly paradoxical situation of freshwater shortage in a swamp land kept the area largely undisturbed by human activities until comparatively recent times. The only impacts on the environment were derived from scattered communities which subsisted on fishery activities, mangrove wood collection for fuelwood and charcoal production, shifting cultivation and salt manufacture (Hong and San, 1993; Sanh *et al.*, 1998). In areas endowed with more freshwater resources, traditional land utilisation methods operated in tune with the natural seasonal fluctuations in environmental conditions. Such adaptation is apparent in the formerly widespread mixed system of wet-season rice and dry-season shrimp cultivation, based on the opportunistic utilisation of seasonal alternations of fresh and saline conditions. Such traditional systems of landuse also minimised the generation of adverse environmental effects. For example, the saltwater inundation of rice fields during the dry season for shrimp cultivation prevented the formation of AASS and associated soil toxicity and acid discharge, and excessive compaction of the soil surface (Miller, 2000). This not only brought benefits to the natural environment but also to farmers, in that the labour input as well as the risk of crop failure due to soil toxicity at the start of rice planting in the wet season were minimised.

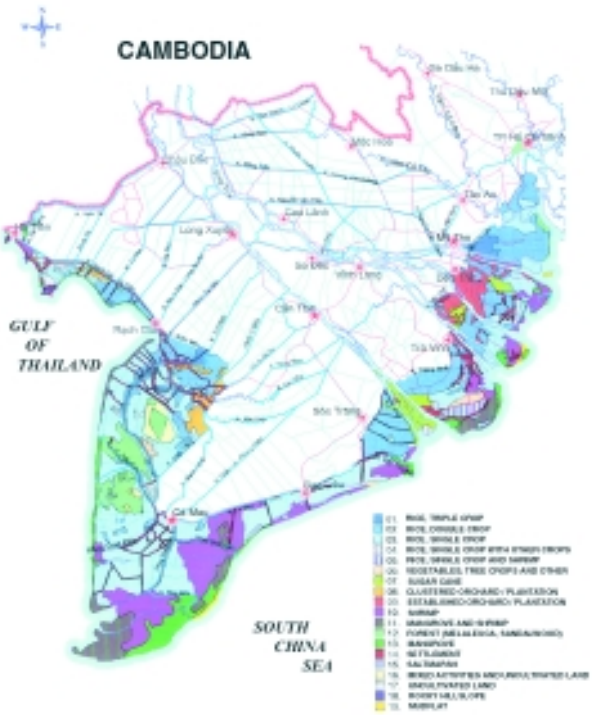


Figure 13. Land use in the coastal areas of the Mekong Delta in 1998 (Source: SIWRPM).

As part of the large-scale water-control projects initiated within the Mekong Delta in recent times (see Section 2.2.1), a large proportion of the seasonally saline coastal areas have become devoted to irrigated rice cultivation through the year-round maintenance of fresh conditions by sluice gates (Figure 13). A contrasting approach to the utilisation of seasonally and permanently saline environments exists in the coastal fringe of the delta, lying between the coastline and the seaward boundaries of irrigated rice areas. Here, salinity is regarded as a resource for economic production, and the main land development in recent times has taken the form of aquaculture, dominated by shrimps, and mangrove forestry (Figure 13).

2.3.1.2 Shrimp aquaculture and mangrove forestry

Aquaculture has been an integral component of many traditional farming systems within the Mekong Delta. The traditional combined system of raising fish and/or shrimp in fallow dry-season rice fields has developed more or less concurrently with the expansion of rice cultivation into the seasonally saline areas of the delta since early 20th century (Sanh *et al.*, 1998). Pond culture techniques of shrimps outside rice-growing areas developed around the same time, involving the damming of tidal creeks and their enclosure with earth banks (Hong and San, 1993). Such systems are extensive, relying on the natural recruitment of seedstock and food supply.

Since 1980, there has been a rapid expansion in shrimp aquaculture throughout most of the coastal areas of the Mekong Delta, driven by economic liberalisation, high prices on the international market, and active government promotion of the activity for national economic development (NEDECO, 1991d; Hong and San, 1993; Koopmanschap and Vullings, 1996; Johnston *et al.*, 1998). Shrimp farming outgrew its original status as an ingenious solution to the utilisation of seasonal salinity, instead becoming a year-round economic activity for farmers involving considerable investment in infrastructure. By mid- to late-1990s, the total area of shrimp aquaculture and annual production within the delta approached 200,000 ha and 50,000 t respectively (Phuong and Hai, 1998). The high and quick returns in the early days of shrimp aquaculture expansion attracted numerous migrants from both within the delta and other provinces of Vietnam, many of these displaced or impoverished farmers, further fuelling the growth of the activity (Hong and San, 1993; MDDRC, 1996; Benthem, 1998). In addition, the initial apparent success caused numerous local households to abandon their original economic activity in favour of shrimps; in this manner, many productive rice fields were converted to shrimp ponds (Koopmanschap and Vullings, 1996).

Nearly all of the early growth in shrimp aquaculture was founded on extensive methods, entirely reliant on natural inputs and tidal water exchange. Ponds are used for repeated recruitment, growth and harvest, over relatively short cycles of 15 to 30 days (Hong and San, 1993). Under such management techniques, yields from individual ponds progressively decline over time due to the depletion of natural seedstocks and nutrients, and worsening pond water quality due to the formation of AASS from the excavated material, incomplete flushing and pond bottom fouling due to organic matter accumulation (NEDECO, 1991d; Hong

and San, 1993; Koopmanschap and Vullings, 1996). To a large extent, this decline is a direct consequence of the clearance of mangroves for pond construction, as mangroves provide nursery areas for shrimp larvae and a high percentage of nutrient requirement for their growth (NEDECO, 1991d; Linh and Binh, 1995). Another factor is the poor design and management of the ponds, leading to sub-optimal conditions for the growth of shrimps. For example, many ponds are too shallow, which results in large fluctuations in water temperature (Koopmanschap and Vullings, 1996; Johnston *et al.*, 1998), while others are excessively deep or have too few sluice gates to allow for sufficient water exchange (Hong and San, 1993). Some farmers have often offset the decline in productivity by constructing new ponds and abandoning the old ones. As a consequence, large areas of mangrove, in many cases still in the process of regeneration after destruction during the Vietnam (American) War, were converted to wasteland only capable of supporting a scrubby regrowth of species such as *Acanthus illicifolius*. The halving of the area of mangrove in the former Minh Hai province (presently separated into Ca Mau and Bac Lieu provinces) between 1983 and 1995 (from 117,745 to 51,492 ha; Phuong and Hai, 1998) is a graphic illustration of the detrimental effects of expansion in shrimp farming within the delta.

By early 1990s, the effects of the proliferation of shrimp ponds and the consequential decimation of mangrove forests were becoming apparent at the regional level. Despite the continued increase in the area devoted to shrimps, shrimp production showed signs of decline. Production was further reduced through recurrent outbreaks of viral infections, such as the white-spot disease, whose spread has been encouraged by the sub-optimal conditions within the ponds and the sharing of common waterways by numerous shrimp farms for both water intake and effluent discharge (Koopmanschap and Vullings, 1996; MDDRC, 1996; Benthem, 1998; Phuong and Hai, 1998).

The declining yields provided impetus for the development of shrimp farming systems with a decreased reliance on natural inputs. Improved extensive and semi-intensive systems, relying on tidal water exchange, but with artificial inputs of shrimp seedstock (at densities of 1-3, and 3-6 juveniles per m^2 respectively; Phoung and Hai, 1998) and low-grade feed, have been adopted by some farmers, while a limited number of intensive systems reliant on costly input of seedstock, high-quality feed and mechanical water pumping were established through the input of foreign finance and expertise (Koopmanschap and Vullings, 1996; Phuong and Hai, 1998). In particular, the rapid spread of improved extensive and semi-intensive systems within the region has occurred in the absence of clearly defined management plans, such that they coexist intermingled with the extensive systems throughout much of the coastal zone of the delta. However, in many cases, intensified systems have been plagued by the same problems affecting the extensive systems, such as low yields and mass mortalities (Koopmanschap and Vullings, 1996), as a result of high background levels of water pollution, regional ecological impoverishment and farmer inexperience (Johnston *et al.*, 1998).

Mangrove forestry is not a recent concept in the Mekong Delta. The French colonial government established plantations in Ca Mau Peninsula for the reafforestation of areas logged for timber, fuelwood and charcoal in the 1940s, while large-scale replanting of areas decimated through herbicide spraying was initiated after the end of the Vietnam (American) War by the central government, mainly in Ca Mau Peninsula and at Can Gio, near Ho Chi Minh City (Hong and San, 1993; Miyagi, 1995). However, the increasing degradation of natural environments in the coastal areas of the delta as a result of human activities during the 1980s and early 1990s, to a large part due to the uncontrolled spread of shrimp aquaculture, instigated the central and provincial governments to promulgate a series of regulations to protect forests and wetlands of coastal areas, and to initiate mangrove plantation programmes (Hong and San, 1993). In addition, several foreign-funded projects dealing with the rehabilitation of mangrove areas were established under the Mekong Delta Master Plan (1993) during the 1990s (Benthem, 1998).

In recent times, plantations have also been established on land under private tenure as a source of income for local communities. In particular, growing concerns over forecasts that the mangrove forests of the delta

Figure 14. A combined mangrove-shrimp farming system in Bac Lieu Province, integrating an improved extensive method of shrimp aquaculture with the plantation forestry of Rhizophora apiculata.

will no longer be able to meet demands for timber and charcoal by the beginning of the 21st century, should the rate of their destruction be maintained (Johnston *et al.*, 1998), and over declining shrimp productivity linked to mangrove loss, paved the way for the development of combined shrimp-mangrove farming systems (Figure 14). Under such a system, mangrove cover was to be maintained over 70 % of the area, with the remainder being available for shrimp aquaculture and other farming activities. Several designs of such combined systems exist: systems featuring clearly separated areas of aquaculture ponds and plantations; integrated systems in which mangroves are planted within and around ponds; systems featuring ponds located within plantations (Hong and San, 1993; Linh and Binh, 1995).

The establishment of mangrove plantations has brought numerous positive environmental and socio-economic benefits. A reduction in soil acidity and an improvement in soil texture and organic matter content have been noted in some AASS areas which have been reafforested. There have been signs of recovery in degraded aquatic and coastal ecosystems, and a corresponding increase in fisheries productivity, in areas such as Can Gio, where plantations have been established for some decades (Hong and San, 1993). Mangroves in and around shrimp ponds have improved the conditions for shrimp growth through the production of nutrient-rich organic litter and by providing shade, which prevents the excessive rise in water temperature inside the ponds. On the other hand, mangrove plantations have also been a source of economic dissatisfaction for farmers, as excessive shading of aquaculture ponds by mangroves results in reduced shrimp yields (Linh and Binh, 1995), and returns from plantation mangroves are slow and low in comparison with those derived from aquaculture (Johnston *et al.*, 1998). A typical rotation period between planting and harvest is in the order of 20 years (Hong and San, 1993; Johnston *et al.*, 1998). As a consequence, much illegal cutting and mismanagement of plantation mangroves took place, which resulted in the introduction of tightened regulations, such as the total ban on mangrove cutting in Ca Mau province declared in 1996 (Johnston *et al.*, 1998). Concerns over the tenure of land devoted to mangrove forestry, and the widespread perception that land under private tenure should be devoted to farming activities, have also been factors contributing to the relatively low success rate of mangrove plantation schemes (Miller, pers. comm.).

2.3.1.3 Irrigated rice cultivation

Although the area of land under shrimp aquaculture has generally increased in recent times, it is being displaced from the more landward parts by the progressive expansion of irrigated rice cultivation. Within the Quan Lo Phung Hiep water-control project area in the interior of Ca Mau Peninsula, shrimp aquaculture is being replaced in increments from the northeast to the southwest of the project area. In this particular case, socio-economic problems have arisen due to the creation of a weakly brackish zone at the front of the expanding irrigation area; here, the salinity levels are too low for shrimp aquaculture, yet too high for rice, undermining the livelihoods of many former shrimp farmers.

The area of irrigated rice cultivation is expected to continue its expansion into the near future. The general government policy appears to be directed toward a maximisation of the area under irrigated rice cultivation.

In some areas, such as Bac Lieu province, there are plans to extend irrigated rice cultivation into permanently saline areas seaward of the large-scale irrigation areas (*e.g.* Quan Lo Phung Hiep) through the establishment of small-scale individually enclosed polders with dedicated sluice gates to exclude salinity. Only the coastal fringe, in the case of Ca Mau Peninsula, seaward of the coastal protection dyke under construction extending along most of the South China Sea coastline, is excluded from potential future land reclamation. This coastal buffer strip is dedicated entirely to the growth of natural and plantation mangroves, in order to boost the defence capability of the coastal protection dyke against storm surges and king tides.

2.3.2 Environmental impacts and concerns

2.3.2.1 Hydrological impacts

The overall hydrological effects of canal construction associated with large-scale water-control projects in the Mekong Delta have been discussed at length in Sections 2.2.2.1 and 2.2.2.2. Impacts of water control in the coastal areas of the delta chiefly involve changes in the extent of saline intrusion and salinity gradient, local tide range within canals, tidal current velocities, and degree of tidal exchange and water circulation.

The obstruction of saline intrusion by sluice gates has commonly increased the tidal range within the section lying seaward of the gate, due to amplification effect at the end of the tidal section of the canals. In situations where the incoming tide propagates into several canals at the coastline, as is the case in Ca Mau Peninsula, tidal amplification may be further enhanced by the convergence of the propagating waves where the canals join one another. Such an increase in the tide range may have undesirable localised impacts such as flooding, poor drainage and waterlogging of soils, and enhanced erosion of canal banks. In addition, sluice gate closure leads to the formation of dead-water zones on either side of the gate, with negative consequences for water quality in the canal.

On the other hand, saline intrusion may become aggravated along canals in which branch canals on both sides are simultaneously closed by sluice gates. Such situations commonly arise where a canal lies between two separate water-control project areas.

In the coastal zone of the Mekong Delta, modification to the natural topography has been extensive. Local relief has increased and the topography has generally become more complex due to the construction of shrimp ponds, with their associated dykes/bunds, spoil heaps, and inflow and outflow channels. The typical coexistence of different land uses within a small area has contributed significantly to the increased complexity of topography. Furthermore, the drainage network has been extensively modified. The broad expanses of swampy terrain traversed by a maze-like network of typically sinuous tidal creeks has been replaced by a clearly defined network of interconnected canals and straightened channels. The effects of these structural modifications to the delta plain are highly variable spatially; on one hand, drainage and tidal exchange of some areas have improved due to the establishment of canal systems, but structures such as dykes and spoil heaps of dredged sediment have impeded such processes in other parts. Stagnation of local runoff is particularly common adjacent to dykes, which can lead to unnaturally prolonged fresh conditions, accumulation of pollutants and aggravated local flooding during the wet season. The possible future proliferation of small-scale rice polders in the coastal fringe will undoubtedly increase the impact and complexity of hydrological changes.

2.3.2.2 Impacts on sediment dynamics and deposition

The overall environmental effect of canal construction on sediment dynamics within the coastal areas of Mekong Delta differs somewhat from that in the more upstream areas as it has not been widely accompanied by the installation of large-scale flood-protection dykes, and due to the difference in the direction of

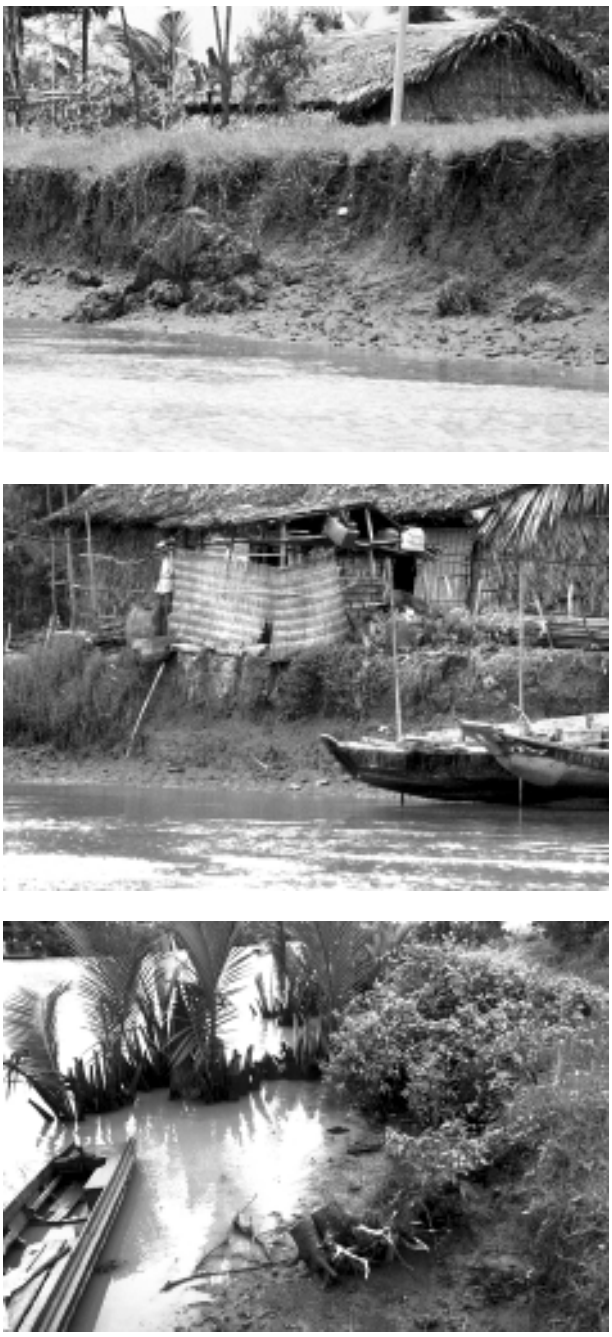


Figure 15. Severe bank erosion along Cai Cung Canal, Bac Lieu Province (August, 2000). Note the oversteepened banks, concentration of human activity along the banks, and evidence of over-harvesting of nypa clumps.

sediment flux. Coastal canals have increased the number of conduits for tidal sediment transport from the South China Sea, such that they are likely to have increased the supply of sediment to the delta plain. Although the canals themselves trap a significant proportion of the sediment input, the proportion of in-channel sediment storage is relatively low compared to natural sinuous channels, in which sediment is stored in numerous point-bars. Moreover, the straight form of canals results in higher flow velocities, contrasting with the slower flows within natural sinuous channels. Thus, canals cause a more efficient inward transport of sediment, which results in an accelerated rate of delta plain aggradation. In mangrove areas, this signifies a hastened rate of increase in the elevation of the substrate, and a potentially shortened lifespan of the ecosystem at a given location. In shrimp aquaculture, it accounts in part for the often unexpected rapid rates of pond siltation.

The installation and closure of sluice gates for the prevention of saline intrusion has increasingly restricted the inward transport of sediment from the sea in recent times, in the more landward parts of the coastal belt. These gates have enhanced local sedimentation rates on their seaward side through: the direct trapping of sediment against the gates; the creation of dead-water zones during periods of gate closure; and the enhanced flocculation of clay minerals in the initial stages of gate opening, as the abrupt convergence of two water masses of different salinities takes place. Thus a significant shift in the sedimentation pattern within canals, shrimp ponds and mangrove areas is likely with future sluice gate closures associated with both large-scale water control projects and small-scale polder construction.

Bank erosion is widespread along canals in the coastal areas of the Mekong Delta (Figure 15). Erosion observed along the canals facing the South China Sea coast is possibly amongst the worst within the entire delta, due to the coincidence of a large tidal range, strong tidal currents and the predominance of soft wet clays as bank material. This leads to geotechnically unstable bank conditions favouring collapse through rotational slump, creep and flow mechanisms. The destruction of nypa clumps and mangroves along the canal banks, due either to hydrological changes brought about by water-control interventions, pollution, or over-exploitation, in addition to the physical disturbance of the banks resulting from concentration of human activity along the banks, and the high density and speed of boat traffic within the canals, have all contributed further to the problem.

It appears that bad design and management practices are causing unnecessary and costly aggravation of

bank erosion and siltation problems of canals in the coastal (and probably other) areas of the Mekong Delta. One of the reasons for widespread bank erosion along canals is the steepness of the dykes or banks bordering the canals. Most such embankments feature a slope exceeding the generally recommended value of 1:3 to 1:2 (Ministry of Transportation, 1993). This may be a result of: construction not being carried out in accordance with the plan; construction pre-dating the establishment of general specifications for embankment slope; or modifications to the embankment after construction. Furthermore, many of the external factors contributing to bank erosion could be ameliorated through an improved regulation of land use along the banks of canals, boat traffic in canals, and the use of bank vegetation. Erosion accelerates canal siltation, and hence increases the need for maintenance dredging. Ironically, careless dredging practices appear to be resulting in a positive feedback loop, in which dredging necessitated by bank erosion is leading to further bank erosion. First, dredging appears to be taking place too close to the banks, resulting in the oversteepening of the subaqueous bank profile. Second, the dredge spoil is usually placed as near as possible along the top of the bank/dyke, creating a tall and steep bank profile above water level. This reflects the short length of the discharge pipe that is used by dredges, but in effect, also caters for the common local preference for tall and steep canal banks, which facilitate the placement of dwellings and wharves directly on the banks. Oversteepening of canal banks through dredging also diminishes the ability of any remaining bank vegetation to stabilise them. Repeated dredging has resulted in the unintentional widening of many canals, which may result in the exposure of PASS material. The placement of dredge spoil along the banks may also act to recycle pollutants, which are washed into canals and are adsorbed onto fine sediment particles forming the bottom sediment.

Figure 16. Initiation of gully erosion on the tidal flat next to Cai Cung Canal, Bac Lieu Province. Note the steep drop separating the surfaces of the tidal flat and water in the canal at low tide.

Shoreline stability may be directly affected by coastal canals. The canals along the South China Sea coast of Ca Mau Peninsula are of particular concern as they represent disruptions to the longshore drift system, *i.e.* they act as sediment sinks, progressively diminishing the volume of sediment supplied downdrift. The net volume of sediment lost from the drift system would be substantial, given the strength of tidal inflow into these canals resulting from a large tide range and strong tidal asymmetry. Furthermore, there is evidence to suggest that canals have had a negative impact on mangrove growth along prograding shorelines. For example, in the vicinity of the outlet to Cai Cung Canal in Bac Lieu province, mangrove colonisation of the newly formed tidal flat surface appears to be retarded compared to shorelines more distal to the canal. Although the exact cause of the poor growth remains unknown, it is likely that canals create harsher conditions for mangrove seedlings by increasing exposure to wind, sun and tidal currents. Furthermore, the steepness of the canal banks appears to be initiating erosional gullies which are incising into the surface of the tidal flats (Figure 16). The persistence of bare tidal flats around canal outlets increases the likelihood of shoreline erosion, in the absence of protection afforded by mangroves.

Given the extent of their proliferation throughout the coastal areas of the Mekong Delta, shrimp aquaculture ponds have had a high degree of impact on the sediment dynamics of the delta plain. Ponds form areas of negative relief on delta plain

surface, which has the effect of creating extra accommodation space for sedimentation. As there is a general tendency for the coastal parts of the delta plain to aggrade relatively evenly through sedimentation over time, this results in an accelerated rate of sedimentation within the ponds. Hence, frequent dredging is necessitated, since the yields of pond-cultured shrimps appear especially sensitive to the maintenance of a reasonable water depth (Johnston *et al.*, 1998). Such high cost of pond maintenance is a frequent cause of economic hardship among the rural inhabitants of the coastal areas, who are among the poorest within the Mekong Delta. Furthermore, after several years of repeated dredging, excessive local accumulation of spoil takes place. If stored around ponds as dykes, the spoil impedes local drainage as mentioned in Section 2.3.2.1. Spoil is also stored as linear banks inside ponds, which contribute further to sedimentation in ponds by increasing sediment trapping potential (e.g slowing water flow, creating zones of flow separation) and by being eroded back into the pond. Moreover, excessive spoil accumulation may necessitate removal by transportation, further adding to the maintenance cost of ponds.

At a larger scale, the cycle of sediment trapping in ponds, dredging and storage of spoil on delta plain surface has the effect of increasing the proportion of suspended-load sediment sequestered by the delta plain than otherwise would be the case. Such an increase may be offset by a corresponding reduction in sediment deposited along the delta shoreline, resulting in imbalances within the coastal sediment budget. Where shrimp ponds have been constructed on the bare intertidal flats along the shoreline, or in the natural mangrove forests immediately to their landward, the ponds have generally increased the risk of shoreline instability or recession. First, ponds provide points of weakness along the shoreline, which facilitates the onset of erosion. The effects are magnified if pond construction has resulted in the removal of protective mangroves. Second, structures associated with ponds such as dykes tend to channelise surface runoff, which can erode the surface of the intertidal flat through the formation of gullies and micro-cliffs. Third, the structural modification of the intertidal flat surface prevents its continued vertical aggradation and colonisation by mangroves (MDDRC, 1996).

In addition, shrimp aquaculture may contribute to bank erosion problems in canals, as effluent discharge from ponds commonly takes form of a high-velocity jet of water running down the bank. Finally, the spread of intensive shrimp aquaculture is likely to intensify environmental problems associated with the construction of canals in the years to come.

The effects of mangrove forestry activities on geomorphology and sediment properties will be discussed in Section 2.3.2.5 below.

2.3.2.3 Impacts on ASS and acid discharge

Many coastal areas of the Mekong Delta are underlain by PASS. Most infrastructure development activity in these areas has involved the excavation of such material, therefore the increasing the extent and severity of ASS problems, *e.g.* canal and dyke construction. Increased closure of sluice gates has aggravated AASS formation in some cases by causing a significant fall in dry-season water level on the freshwater side of the gate. The practice of using PASS material excavated during the construction of shrimp ponds for dykes and earth banks has not only accelerated the formation of AASS, but has caused problems with acid build up in ponds and resultant mortality in shrimps (Hong and San, 1993). Acidity in soil and water has also impacted mangroves, causing restricted growth and inhibited regeneration in both mixed shrimp-mangrove systems (MDDRC, 1996) and independent stands. The problem is exacerbated by the organic enrichment of sediment accumulating at the bottom of the ponds leading to the formation of sulphides, *i.e.* an additional source of acidity.

2.3.2.4 Other water quality and pollution impacts

The effects of sluice gate closures on water quality in coastal canals have been discussed in Section 2.2.2.5. Another factor in the overall deterioration of water quality in the coastal areas of the Mekong Delta is the proliferation of aquaculture ponds. Due to inadequate design or natural constraints, most ponds have poor flushing characteristics, such that waters become enriched in pollutants such as organic matter, derived from biological activity within the pond and from organic-rich mangrove sediments forming the confines of the pond, and toxins released under acid conditions from ASS. Such a build up of pollutants is detrimental to shrimp and other organisms which inhabit the ponds, and add to the pollutant loading in canals and coastal waters upon discharge. Under present-day conditions, the predominance of extensive systems in the delta has maintained the degree of pollution from pond discharge at a relatively low level. Admittedly, the background pollution loading of canals and rivers is often at such elevated levels that there is no discernible difference in water quality inside and outside the ponds (Johnston *et al.*, 1998). However, in areas where a number of shrimp ponds rely on a common canal for the exchange of pond water, the cumulative impact of the discharge has resulted in a serious water quality decline.

Furthermore, such a situation results in conflict among the individual farmers, as successive discharge of pond effluent along the canal causes a progressive deterioration in the quality of water supply to ponds of farmers located further downstream along the canal. Furthermore, such problems are expected to increase in future as more farmers adopt semi-intensive and intensive systems of shrimp aquaculture, which involve the application of feed. Under such systems, a substantial proportion of the feed is wasted (NEDECO, 1994b; Koopmanschap and Vullings, 1996) and contributes to the nutrient enrichment of pond water and bottom sediment. In order to combat the decline in pond productivity associated with increasing water pollution, there are plans in some parts of the delta to construct two-way canal systems, whereby the water supply to the ponds is separated from the outflow of effluent discharged from ponds (Lai Thanh An, pers. comm.). Although beneficial at a local scale, such interventions do not necessarily alleviate the overall pollution loading in the environment, and may serve to further increase environmental problems associated with canal construction and maintenance.

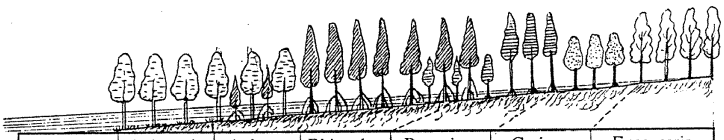
Nevertheless, the increasing area of irrigated rice cultivation is likely to make shrimp aquaculture as much of a loser as the natural environment in future. The heavy application of chemical fertilisers and pesticides associated with the introduction of high-yielding rice varieties, has resulted in an increasing chemical pollution load on waterways throughout the delta. Some of the commonly used pesticides, such as pyrethroids and methyl-parathion are highly toxic to shrimp, small fish and zooplankton at very low residual concentrations of 0.0005 mg l^{-1} or less (NEDECO, 1994b). Furthermore, irrigated rice and shrimp aquaculture frequently occur in contiguous areas, a phenomenon which will become more common with the establishment of small-scale rice polders in the permanently saline areas. Hence, there is high probability that shrimp aquaculture will suffer increasing future losses in productivity due to chemical pollution. Naturally, such chemical pollution will also widely impact on aquatic and terrestrial ecosystems in general, and the ever-increasing domestic and agricultural water demand.

2.3.2.5 Ecological impacts

Due to the characteristics of the natural environment, the coastal areas of the Mekong Delta were one of the last refuges of relatively pristine natural ecosystems. In particular, the mangrove forests of the Mekong Delta boasted the highest biodiversity and structural complexity within entire Vietnam (Hong and San, 1993), as reflected in their impenetrable jungle-like appearance, which historically deterred human attempts at clearance. However, years of warfare, followed by rapid infrastructure development in recent times, especially that related to shrimp aquaculture, have resulted in their decline at a remarkably rapid rate. The most dramatic changes have occurred in southern Ca Mau Peninsula, where a near full tree cover of the

land surface in the mid-1960s (consisting mainly of mangroves and *Melaleuca*) was reduced to less than 30 % by the mid-1990s (Benthem, 1998). The extent of recent disturbance has been such, that nearly all existing stands of natural mangroves today may be classified as secondary growth.

The degree of fragmentation of the biophysical environment due to recent infrastructure development interventions within Mekong Delta is probably the highest in the coastal areas. Nowhere else in the delta does such a diverse range of land uses, commonly with conflicting objectives, coexist within such a relatively limited area (Figure 13). Furthermore, the extent of structural modification to the original geomorphic characteristics of the land surface has been greater here than in other parts of the delta. Under natural conditions, ecosystems within the coastal areas of the delta were organised into approximately shore-parallel zones, reflecting the progressive increase in land surface elevation and a corresponding decrease in salinity levels with increasing distance from the shoreline. On Ca Mau Peninsula, for example, a typical pattern of zonation observed from the shoreline inland consisted of: bare intertidal flat; frontal mangrove zone of *Avicennia alba*; lower mangrove zone of *A. alba* / *Rhizophora* spp.; middle mangrove zone of *Rhizophora* / *Bruguiera* / *Ceriops* spp.; upper mangrove zone of *Excoecaria agallocha* / *Thespesia populnea* and other species; brackish anf freshwater wetlands of *Melaleuca* spp., *Phragmites karka* and other species (Hong and San, 1993; Binh, 1994; Figure 17). The overall effect of infrastructure development has been to completely alter these relationships through changes in land surface elevation, either due to requirement for level land of specific elevation or due to the installation of hard infrastructure such as dykes, earth banks and ponds, and through changes in salinity levels or freshwater input. For example, the construction of shrimp ponds in mangrove areas has created large areas of water which are too low in elevation for mangrove colonisation, and rimmed by earth banks which are, by contrast, too high. Naturally, mangrove recovery is poor upon the abandonment of ponds, which commonly occurs due to a progressive decline in productivity with time, or due to the selection of unsuitable land, *e.g.* in the highest parts of the mangrove zone where tidal exchange is limited (Linh and Binh, 1995). Ponds created on bare tidal flats and at the front of the mangrove fringe along the coast have effectively prevented the colonisation of the substrate by mangroves.



Mangrove stands	Avicennia alba	Avicen-nia + Rhizoph-ara	Rhizopho -ra apiculate	Bruguiera parviflora & B. sexangula	Ceriops spp	Excoecaria spp
Tidal action	Flooded at low tides		Flooded at moderate tides		Flooded at very high tides	
Soil types	Saline soil		Potential sulphate saline soils			
	Loose mud	mud	soft clay	clay	hard clay	
Farming systems	Shrimp excl. under/protect -ion of mangroves	Sh.+ Rhiz comb	Rhizophora + Shrimp(Rhiz. plantation combined with shrimp culture)		Rhiz. + Shrimp (Lowering soil surface necessary)	

Figure 17. Natural ecosystem zonation and forestry use of mangrove areas in southern Ca Mau Peninsula according to Binh (1994).

An aggravating factor in the human modification of biophysical environments in the coastal areas has been the frequent occurrence of land uses with different elevation and salinity requirements, *e.g.* shrimp aquaculture and irrigated rice, in close proximity and in an intercalated spatial pattern. As a result, much of the coastal zone of the delta today is a patchwork of diverse land uses and ecosystems featuring complex changes in elevations and salinity levels. Under such spatial constraints, ecosystems experience far greater levels of environmental stress and are more susceptible to the adverse effects of future environmental change (see Section 3).

Much ecological degradation within the coastal zone of the delta has been caused by the structural obstruction of regular tidal water exchange and the associated decline in water quality. Areas of mangroves and tidal creek systems, where water formerly circulated freely with tidal fluctuations and surface runoff, has now been replaced by the stagnant water of shrimp ponds, in which only the hardiest species survive. This

is reflected in the usually low species diversity and density of zoobenthos in ponds relative to that in nearby waterways (MDDRC, 1996). Although poor pond design and management contribute significantly to poor pond water quality, their improvement is unlikely in the near future due to lack of finances, supporting infrastructure and expertise (Johnston *et al.*, 1998). The high level of ecological stress placed on biota by the pond environment is apparent in the recurrent outbreaks of disease and widespread mass mortalities in aquaculture shrimps (Linh and Binh, 1995; MDDRC, 1996; Phuong and Hai, 1998). Poor conditions within shrimp ponds also pose a threat to the aquatic ecosystems outside, as they act as nursery for bloom-forming algae, which can spread with the discharge of effluent to other areas, causing deoxygenation and H_2S and ammonia toxicity upon their death and decay (MDDRC, 1996). Conditions are not significantly more favourable in the canals, whose water quality suffers from the cumulative impacts of effluent discharge from numerous shrimp ponds, chemical pollution from rice cultivation, and poor flushing resulting from the tidal regime and sluice gate closures. Thus, much of the aquatic and intertidal habitats within the coastal zone of the delta have been rendered ecologically impoverished.

The ecological impacts of canal construction, sluice gate closures and increased chemical and ASS pollution have been discussed in Section 2.2.2.6.

Outside shrimp ponds and canals, the ponding of stagnant water caused by earth banks of shrimp ponds and canal dykes, especially in combination with increased pollution from pond effluent and acid leaching from excavated PASS material, has been detrimental particularly to mangroves, both natural and planted, resulting in stunted growth or dieback. For similar reasons, the coastal protection dyke under construction along the South China Sea coast of Ca Mau peninsula is likely to have a widespread impact on the health of local mangroves, much of these planted for the added protection of the dyke.

The spread of shrimp aquaculture has resulted in the depletion of shrimp stock in the local waters due to over-recruitment for stocking ponds and the widespread destruction of mangroves. Depletion is especially severe in the inner, or upstream, parts of tidal creeks and canals, due to the progressive recruitment of shrimps entering with the incoming tide by shrimp farms situated along the waterway (Linh and Binh, 1995). Ironically, the decline in shrimp recruitment in individual ponds seems in part due to the barrier to free movement of aquatic biota imposed by the construction of infrastructure such as ponds, earth banks, canals and dykes (Hong and San, 1993). Decline in shrimp numbers is apparent in the outside waters as well; total annual shrimp catch off the coast of the former Minh Hai province has been reduced by more than half between 1978 and 1990, despite an increase in the size of the fishing fleet (Linh and Binh, 1995). A similar correlation between the size of shrimp catch and mangrove area has been noted in a number of tropical areas, such as Indonesia and the Philippines (Linh and Binh, 1995). Hence, the ecological imbalance created by the depletion of shrimp stock has the potential to impact ecosystems at a spatial scale of the entire Mekong Delta or greater.

Given the immense scale of mangrove destruction as a result of warfare and shrimp farming, the role of recent mangrove forestry initiatives in arresting the rapid downward spiral in the area of mangrove is to be commended. The decline in the area of mangroves within Ca Mau Peninsula has significantly stabilised since the early 1990s (Benthem, 1996) and some areas, such as Bac Lieu, have been experiencing a net increase in recent years (Truong, Bac Lieu Forestry Division, pers. comm.). The rehabilitation of mangroves has brought abundant environmental and socio-economic benefits, as previously mentioned in Section 2.3.1.2.

However, the recent mangrove forestry activities are not without some environmental concerns. Perhaps the most serious of these is the trend toward monoculture with the emphasis commonly on economically valuable *Rhizophora apiculata* (Benthem, 1998). Plantations have been established over a wide range of intertidal elevations, which has necessitated the lowering and grading of the land surface to cater for the

substrate elevation required by the species for successful growth (Figure 17). Poor growth of planted mangroves has resulted in some cases, particularly with combined mangrove-shrimp farming systems, through the raising of ground surface due to dumping of material excavated from shrimp ponds (MDDRC, 1996).

Furthermore, mangrove plantations are often established to replace existing mangrove forests, some of which are classified as degraded. Existing trees are mostly clear-felled, and replaced with a mono-specific planting. If some trees are retained, they are of the same species as the plantation (Hong and San, 1993). Thus, in its current form, mangrove forestry actively contributes to a reduction in the biodiversity of mangrove ecosystems within the delta, rather than to its restoration. The substrate is often prepared prior to planting by clearing organic litter which may remain from the original forest cover, and by ploughing. Ploughing causes the oxidation of the typically peaty topsoil, and together with the removal of litter, contributes to loss of nutrients from the ecosystem. Furthermore, removal of the protective topsoil may cause the formation of AASS, with negative consequences for both the mangroves and nearby ecosystems. The uniform physical structure of the forest, derived from simultaneous planting over a large clear-felled area, and maintained through thinning, pruning and weeding out of unwanted species, while important for the production of commercially valuable timber, contributes little to the restoration of a viable, robust and diverse ecosystem. The ecological uniformity of mangrove plantations renders them susceptible to damage from adverse weather conditions, insects and diseases; the rapidity of spread of potential pests and diseases in homogenous plantations calls for constant monitoring (Mr Truong, pers. comm.).

Another concern revolves around the ecological implications of the long-term management of plantation mangroves. Mangroves in the Mekong Delta are opportunistic colonisers of substrates undergoing progressive aggradation. As such, the mangroves are an ephemeral ecosystem in a constant state of change, to be eventually succeeded by the *Melaleuca* forest or swamp grassland ecosystem (see Section 3.2.3). Monospecific plantations of mangroves are likely to suffer a progressive decrease in productivity over time, as the substrate aggrades to elevations beyond the range of tolerance of the species employed. Such changes may occur over time scales of 10^0 to 10^1 years, especially if sedimentation due to large flood events cause catastrophic aggradation of the substrate. In addition, changes in sediment dynamics due to other infrastructure development interventions within the coastal areas of the delta are likely to cause an increase in sedimentation rates in some areas (see Section 2.3.2.2), further shortening the viable life of plantations.

Finally, the regulatory aspects of mangrove forestry, namely the prohibition of cutting prior to the end of the rotation period, and the policy requiring the maintenance of 70 % mangrove cover within mixed mangrove-shrimp farming systems, although contributing positively to the preservation of plantation mangroves, appear to be resulting in the over-exploitation of natural mangrove stands along canals and rivers. Such cutting, together with the over-exploitation of nypa palms due to the effects of salinity control projects (see section 2.2.2.6), is a major cause of aggravated bank erosion along the waterways of the coastal areas of the Mekong Delta.

3. SYNOPSIS

3.1 Environmental problems in the Mekong Delta — a systems approach to their analysis

3.1.1 Disruption to sources, sinks and transfer pathways

Many of the environmental problems resulting from large-scale infrastructure development interventions in the Mekong Delta may be viewed as a consequence of failure to recognise the delta as an environmental system. At a larger scale, the entire delta may be viewed as a component of the Mekong River catchment system. In this context, the delta is a sink and a transfer zone for matter derived from the more upstream parts of the catchment and transported downstream. At the delta scale, the diverse biophysical environments found here are all components of a network of temporary sources and sinks for matter such as sediment, water, carbon and sulfur, linked by numerous transfer pathways. For example, the backswamps of the delta plain act as temporary storages for flood waters travelling from the catchment to the ocean. During storage, much of the suspended sediment transported from the catchment is deposited, such that backswamps also function as sediment sinks. The ASS which underlie these backswamps represent sinks for sulphur, introduced into the sediments of the deltaic system by seawater at an earlier phase in its geomorphic evolution.

The modifications to the natural environment accompanying infrastructure development interventions have altered the status of sources and sinks within the deltaic system. Returning to the examples above, in terms of overbank sediment deposition in backswamps, flood-mitigation dykes have reduced the proportion of suspended sediment being sequestered by backswamps. To a large extent, canals have replaced the natural sediment sinks of the delta plain. However, these artificial sediment sinks do not fully assume the function that delta plains formerly fulfilled prior to the construction of dykes, since deposition is confined to the trough of the canal. Thus sediment formerly distributed over a large area of the delta plain is now accommodated in canals, which manifests itself in rapid siltation rates and high cost of maintenance of canals. In the case of sulphur stored in PASS beneath backswamps, the drainage of backswamps and canal excavation have converted these former sinks into major sources of sulphur, re-released into the deltaic system as sulphuric acid. The consequential decrease in pH has triggered a concurrent release of aluminium, iron and other chemical substances from their former sinks in delta soils as well, while the desiccation of surface peat cover has reversed the role of backswamps from being net sinks to sources of carbon. In addition, the increase in the pollutant loading of delta environments may also be viewed as a form of creation of new sources of input within the deltaic system arising from infrastructure development.

Furthermore, the transfer of matter within the deltaic system has been disrupted through changes in pathways as a result of environmental modifications. Such changes inevitably result in impacts to environments located further down the transfer pathways since the delta is a dynamic system, *i.e.* the biophysical environments within the delta are maintained by a sustained flux of matter through them. Thus, changes in the upper delta result in the propagation of impacts downstream to the lower delta, and changes within the main channels may propagate along pathways transferring matter away into the distal parts of the delta plain, impacting areas such as backswamps.

The dry-season diversion of river flow from the main channels to canals for irrigation is perhaps the most obvious example in this respect. The resultant decrease in discharge within the main channels triggers a reaction of increased extent and duration of saline intrusion downstream, and, in turn, the geomorphic response of decreased sediment discharge to the coast and possible shoreline recession.

In some cases, measures have been undertaken to ameliorate the effects of such changes in the transfer

pathways of matter. However, rarely do they effectively replicate processes under natural conditions. For example, the increased length and geometric complexity of the transfer pathway (*i.e.* the canal network) and the decreased residence time of flood waters on the delta plain render the controlled inundation of fields far less efficient than natural flooding processes in redistributing sediment from channels to the delta plain (see Section 2.2.2.3).

3.1.2 Environmental fragmentation

In many ways, the alterations to transfer pathways of matter within the Mekong Delta resulting from infrastructure development have had the effect of fragmenting the biophysical environment. Under natural conditions, the diverse biophysical environments within the delta were generally separated from each other by gradational boundaries reflecting the natural environmental gradients in parameters such as salinity levels, sedimentation rates and energy of the river flow. Structural modifications, such as dykes and sluice gates, have converted these gradients into abrupt boundaries across which the transfer of matter is hindered. The progressive exclusion of saline influence from coastal areas of the Mekong Delta for the expansion of irrigated rice cultivation has, for example, eliminated the transitional brackish environments, and has prevented the transfer of biota, nutrients, sediment and other matter between the freshwater and marine environments.

In addition, the conversion of natural gradients into sharp boundaries has often resulted in a situation of excess on one side and depletion on the other side of the boundary. Matter such as sediment and nutrients, which used to be deposited or dissipated in a diffuse manner within a broad zone is now forcibly restricted to one side of the boundary, such that it accumulates to a level exceeding that under previous conditions. Thus problems arise, such as the high maintenance cost of many sluice gates due to excessive silt accumulation on one side, and the eutrophication of canal water dammed by the gate.

The creation of sharp environmental boundaries has had detrimental ecological effects. First, they can represent a physical barrier to the movement of biota requiring the utilisation of environments on both sides of the boundary during their normal life cycle. An example common through much of the delta is restriction of fish migration between the river channels and the backswamps by flood-control structures. In addition to changes in species diversity and ecological health, this has resulted in significant repercussions on the productivity of floodplain fisheries and the rural economy. Second, transitional environments created by natural environmental gradients, such as brackish water environments, have been eliminated altogether, leading to local extinction of species specifically adapted to such environments. An example is the widespread dieback of nypa palms along canals due to the installation of sluice gates. Finally, sharp boundaries have restricted the transfer of matter, significant as inputs to ecosystems, between the environments on either side. An example in this regard is the reduction in the transfer of terrestrial carbon from backswamps and mangrove areas to channels and the sea, due to obstruction by water-control structures. Since organic carbon is an important component of energy input to the aquatic ecosystems, such a change would have far-reaching negative consequences.

Another ecological concern centred on the replacement of natural gradients with sharp boundaries is the destabilisation of environmental conditions. In many cases, the boundaries comprise structures which may be opened, in effect causing an immediate disappearance of the environmental boundary. In the case of sluice gates, their opening can cause the rapid propagation of a freshwater plume into the saline zone, and / or that of a salt wedge into the freshwater zone. Under natural conditions, the convergence of salt- and freshwater would have taken place over a broad transitional zone, and changes in salinity levels incrementally. The ecological consequences are far more catastrophic in the case of sluice gates separating water acidified by PASS drainage from non-acidified water.

In addition, changes in environmental conditions, such as salinity levels, were commonly a cyclical or a

seasonal phenomenon driven by fluctuations in the river discharge and tidal regimes. Changes in conditions resulting from the opening of gates, on the other hand, are more often than not driven by human demand and do not necessarily coincide with the natural periodicities. The overall effect has thus been a change in the timing, frequency and magnitude of environmental fluctuations.

Such erratic environmental conditions are likely to reduce ecological diversity as only the more adaptable species are allowed to persist. Other species, if not eliminated, suffer elevated environmental stress. Experience from ASS areas of eastern Australia indicates that such conditions render the ecosystem open to invasion colonisation by noxious species, which not only pose an ecological threat but may also have negative economic effects. Here, the proliferation of the African waterlily (*Nymphaea caerulea var. zanzibarensis*) in estuarine waterways has been directly linked to recurrent acidification, and has been the cause of excessive organic matter accumulation, which has increased the cost of canal maintenance as well as causing the deterioration of water quality (Sammut *et al.*, 1996).

3.2 Environmental problems as a consequence of disruption to a dynamic biophysical system

3.2.1 Disruption to natural evolutionary trends of the biophysical environment

Given the inherent role of deltas as sediment sinks, and the rapid rates of geomorphic processes driven by a large river discharge and sediment load, the Mekong Delta is a highly dynamic biophysical environmental system. As such, the delta is in a constant state of evolution. Such environmental change is apparent at many different spatial scales, for example, a mid-channel bar undergoes accretion and downstream migration within a channel system, which evolves through channel shifts within the meander belt and occasional avulsions[1] , and which itself is part of the expanding delta system. Trends in geomorphic evolution may be progressive, cyclical or episodic, and there is commonly a link between the spatial and temporal scales of evolution; namely, that small-scale geomorphic features, such as mid-channel bars, evolve over short time scales while the evolution of larger-scale features, such as the channel, and the encompassing delta system takes place over longer time scales. Analogous relationships may be observed in the biological environment; for instance, the time required for the establishment of a viable forest ecosystem far exceeds that required for the establishment of individual trees which compose it.

Infrastructure development interventions within Mekong Delta have disrupted the natural evolutionary trends of the biophysical environment through changes in the rate and direction of evolution or, in some cases, through the total suppression of evolution.

The construction of structures with negative relief such as canals and shrimp ponds on the delta plain surface could be viewed as a temporary forced reversal of the natural trend, as it works against the natural trend for the delta plain surface to progressively aggrade through overbank and tidal sediment deposition. However, in this case, the direction of the trend remains unchanged, *i.e.* aggradational. This explains why rapid siltation is such a persistent problem in the maintenance of ponds and canals, as the delta system responds through locally enhanced rates of sediment deposition, in an attempt to re-attain its original degree of delta-plain evolution.

Coastal erosion, which is likely to arise from a continued decrease in sediment and river discharge to the coast due to water-control interventions, is an example of human impacts resulting in the reversal of the evolutionary trend itself. The increase in channel and delta plain salinity levels likely to accompany a regime of progressive coastal recession, which contradicts the natural trend of freshening conditions over time, illustrates the point that an induced change in the evolutionary trend is likely to trigger changes in the evolution of other parts of the delta system.

The prevention of overbank sedimentation by flood-control structures and the destruction of peat-accumulating *Melaleuca* and mangrove forests have in effect terminated the natural evolutionary trend toward progressive aggradation and an increase in the elevation of the delta plain. In the low-lying parts of the delta, such aggradation has been an important process in the formation of a protective sediment cover over ASS and saline soils, and the general progression in environmental conditions from saline to freshwater. In the absence of such an ameliorating natural mechanism, there is little hope that the delta will ever be freed from the environmental and economic problems associated with ASS and saline soils.

It is imperative to note that, although disruption to natural processes tends to occur through local-scale interventions, the impacts commonly transcend the scales to affect the evolution of the entire delta system, due to: first, the cumulative effect of numerous such interventions spatially distributed throughout the delta system; second, the interconnections between small-scale geomorphic evolution of the delta sub-environments and the large-scale evolution of the delta system. Thus, the forced formation of a sand bar at a junction of a canal with the main channel will change the sediment delivery rate of the channel at its mouth if repeated at numerous locations along the channel system, eventually impacting the rate of delta-front progradation into the sea. The large-scale impacts typically do not become apparent for some time due to lag effects (*i.e.* the time required for the impact to propagate through the system), or to the effects of environmental thresholds (*i.e.* a saturation level of disturbance needs to be attained before a response takes place). Thus, returning to the aforementioned example, the effects of increased bar formation in channels may not become apparent at the delta front for several years or decades after the construction of the canals.

3.2.2 Catastrophic response: a possible consequence of environmental disruption

Of particular concern regarding lags in the manifestation of environmental impacts is the increased likelihood of catastrophic environmental change. Under natural conditions, environmental change generally proceeds in increments, such that the biophysical environment never remained in a state of disequilibrium with the ambient conditions for extended periods. On the other hand, human modifications to the environment, which suppress or oppose the natural trends in evolution, tend to maintain a state of disequilibrium within the environment, which may trigger a catastrophic response when the disequilibrium can no longer be maintained. Lessons may be drawn from numerous other deltaic systems around the world (*e.g.* Yellow River in China, Mississippi River in the United States, Red River in northern Vietnam, Tone and Kiso Rivers in Japan), where the suppression of channel migration and overbank sedimentation resulting from the hard engineering of the river channel has resulted in the accelerated aggradation of the channel bed and super-elevation of the river water level relative to the delta plain. In addition, such engineering interventions have increased the flood height within the river channel through the consequential confinement of flood flows to the channel. The unfortunate coincidence of channel bed aggradation and increased flood heights has often resulted in the eventual restoration of equilibrium through catastrophic channel avulsion during exceptionally large floods, with great losses of life, property and economic production. Although Mekong Delta is, by geomorphic standards, a relatively stable system due to the negligible rates of delta plain subsidence and a relatively low proportion of bedload in the sediment supply (and indeed, there is little evidence for substantial channel bed aggradation in recent times), a future increase in the area of full flood protection during the wet season, combined with an increased diversion of river discharge away from the main channels during the dry season, may have a similar cumulative effect to that produced by the hard-engineering of the channel as in the examples presented above. The large discrepancy between the discharges of the Mekong and the Bassac branches renders the upper delta, in particular, susceptible to avulsive channel behaviour.

3.2.3 Effects on ecosystems

The disruption of natural evolution of the biophysical environment is detrimental ecologically, as deltaic ecosystems have generally developed through the opportunistic occupation of ecological niches, which are created through the appearance, development and disappearance of diverse environments within the delta during the course of its evolution. Feedback effects are often significant in the evolution of deltaic ecosystems. Positive feedback plays a crucial role in the initial establishment and the subsequent maintenance of a stable ecosystem within an inherently dynamic physical environment. For example, the initial colonisation of newly deposited intertidal flats at the delta front by pioneer mangrove species, such as *Avicennia alba*, fulfils the function of protecting the substrate from erosion and AASS formation, thus creating suitable conditions for further colonisation by other mangrove species. On the other hand, negative feedback effects may lead to the creation of unfavourable conditions and the eventual displacement of ecosystems, *e.g.* prolonged peat accumulation in mangrove swamps will eventually raise the substrate to supratidal elevations unsuited to mangroves.

Another important concept in understanding the nature of deltaic ecosystems is that of ecosystem succession. As the physical environments of the delta evolve, the ecosystems undergo concurrent changes which follow a relatively predictable pathway. At a general level, the pattern of ecosystem succession is driven by a progressive increase in the substrate (land surface) elevation and a decrease in environmental salinity levels. This is clearly illustrated by the typical succession pattern observed with progressive sediment accretion in the coastal areas of Mekong Delta, from bare intertidal flats, through frontal / lower / middle / upper mangrove zones, to brackish and freshwater wetlands (see Section 2.3.2.5).

The effects of disruption to the natural evolution of the physical environment have been to change the pattern of ecosystem succession and the degree of ecosystem stability. It should be reiterated that, in the greater part of the Mekong Delta, disturbance to natural patterns of ecosystem succession commenced well prior to the implementation of recent infrastructure development interventions. However, at no time during the history of human utilisation of the delta environment has the rate of ecosystem modification been as rapid as in recent times.

The coastal areas of Mekong Delta have suffered perhaps the most extensive and severe disruption to processes of ecosystem succession due to recent infrastructure development. It is ironic that this is also where geomorphic evolution is at its most rapid within the delta system and where successional processes have been most active. Replacement of the original shore-parallel ecosystem zonation with a haphazard mosaic of diverse landuses, such as shrimp ponds, rice fields, mangrove plantations and remnant natural ecosystems, together with the associated destruction of well-defined elevation and salinity gradients, have rendered the continuation of successional processes difficult. In combination with the effects of fragmentation, it may lead to the eventual demise of the remaining areas of natural ecosystems. Furthermore, structural modification (*e.g.* canal outlets, shrimp pond dykes) has created difficult conditions for the colonisation of intertidal flats along the shoreline by mangroves. Given the importance of positive feedback effects resulting from this initial colonisation in the further development of the mangrove ecosystem, there is a danger that natural ecosystem succession will not be able to commence on newly formed intertidal flats in future. Naturally, in the first instance, the difficulty in initial colonisation may also curtail the formation of new intertidal flats in the absence of the stabilising effects of mangrove growth on the substrate, such that the available area for the establishment of mangroves will decrease.

Ecosystem stability is likely to be affected by changes in the evolutionary pace of the biophysical environment. Full development of ecosystems characterised by high species diversity and stability may not occur if there is an increase in the rate of background environmental change. Under such conditions, only the most environmentally adaptable species will remain to form a typically impoverished and unstable ecosystem. In this regard, the effects are similar to those of an increased variability in environmental conditions (see

Section 3.1.2). On the other hand, a decreased rate of environmental change may equally encourage ecological instability, for example, if ecosystems are dependent on such change for the input of energy (*e.g.* nutrients associated with fresh sedimentation), or in the regulation of ecologically harmful processes (*e.g.* prevention of PASS oxidation in the substrate through sustained sedimentation).

3.2.4 Implications for human activity

Disruption to the natural evolutionary trends of the environment has also been the cause of numerous negative impacts on human activities arising from recent infrastructure development in the Mekong Delta. In some cases, the impacts have adversely affected the very projects which lie at the source of the problems, as illustrated by the chronic problem of siltation in canals and shrimp ponds (see Sections 2.2.2.3 and 2.3.2.2). This example is a clear illustration of problems associated with human activities which oppose natural environmental trends. Change, especially an increase, in the rate of evolution of the natural environment also interferes with human activities. For example, an increase in bar formation and accretion rates in the river channel, as might originate from flow diversion, is likely to increase the cost of waterway infrastructure maintenance and the rate of land loss due to bank erosion. Even the conversion of PASS into AASS resulting from various infrastructure development interventions may be regarded as a form of an increased pace of delta evolution; partial oxidation of PASS is part of the natural pedogenic maturation process of the delta plain, albeit at a much slower rate. As discussed in Section 1.3.3, the detrimental effects of PASS oxidation on human activities are innumerable.

3.3 Issues of scale

3.3.1 Spatio-temporal scales of environmental problems in the Mekong Delta

There are several scale issues to be considered in the examination of environmental issues arising from recent infrastructure development interventions within the Mekong Delta. The previous section has illustrated the system nature of the biophysical environment of the delta, which may be examined at spatial scales ranging from the entire catchment, the delta, the deltaic sub-environments (*e.g.* channels) and the individual geomorphic features (*e.g.* bars within the channel). Hence, the environmental impacts may be examined at different scales, ranging from local through to delta-wide. It has also been noted that the majority of impacts originate from environmental disturbance which takes place at a local scale, but which transcends the scale to produce impacts at larger spatial scales. There is often a relationship between the spatial and temporal scales of environmental processes and impacts; the time scale at which trends in the evolution of the biophysical environment and impacts of development interventions become apparent increases with the spatial scale considered. Therein lies a considerable peril, in that a significant proportion of environmental impacts arising from existing infrastructure development interventions are still in the process of emerging, and are likely to produce aggravated cumulative effects when they combine with the shorter-term impacts derived from other future development interventions. Unexpected long-term and large-scale impacts are likely to emerge, given that the degree of difficulty in impact prediction increases with the spatio-temporal scale, due to increased complexity resulting from feedback mechanisms, lag effects, or cumulative effects produced by the convergence of numerous, often conflicting, impacts.

3.3.2 Temporal scales of infrastructure development and environmental change: perceptions and reality

An inadequate perception of temporal scale pertaining to the rate environmental change appears to be at the core of many problems, both environmental and socio-economic, associated with recent infrastructure development interventions in the Mekong Delta. Many of the interventions are based on the implicit assumption that environmental change will take place over longer time scales than that of the implementation

and operation of the interventions.

For example, the planning process in the establishment of mangrove plantation schemes, in most instances, does not appear to take into account the effects of the inherent natural tendency toward substrate aggradation and the consequential decline in forest productivity. Given the high sediment supply characteristic of the Mekong Delta, such a process is likely to affect production over time scales of several years to decades, well within the time scale of project planning. Substrate aggradation rates are likely to be further enhanced by the effects of other infrastructure development within the delta such as shrimp farming and canal construction. Therefore, the rotation period of approximately 20 years between planting and harvest, and replanting or natural regeneration of the same species thereafter (Hong and San, 1993), planned for the existing plantations may not be tenable ecologically. Premature failure of mangrove plantations before the end of the rotation period would have a disastrous economic impact on farmers, who do not economically benefit from them until harvest.

Even if the planning process recognises the natural evolution of the delta system as a factor which affects a project's environmental and socio-economic viability, there is often an implicit assumption that the rate of environmental change will remain constant. Yet, rates of change are typically variable in deltaic environments as a result of natural trends in evolution and feedback / cumulative effects. The rate of sedimentation on the delta plain varies naturally as it evolves through geomorphic stages, from coastal intertidal flats through mangrove swamps, to backswamps and, finally, levees, as the source and direction of sediment flux, and the type and strength of depositional processes vary. Channels in the process of natural abandonment experience a progressive increase in the rate of sedimentation and a corresponding decrease in water throughflow. At a more local scale, sediment flux along a stretch of river bank varies from net depositional to net erosional in response to the growth, decay and movement of point- and mid-channel bars within the channel. Such changes may potentially lead to an unexpected rise in the maintenance cost of the project, a progressive decrease in project benefits and efficiency, or a progressive aggravation of the environmental impacts of the project after its implementation. Shifts in the rates of environmental change may be further induced by the effects of human modifications to the environment in recent times.

Although widely recognised as a potential threat, the design of most infrastructure development interventions does not appear to be taking into consideration the possible effects of environmental change driven by external forces, in particular, those arising from increased human activities in the upstream catchment and global change in climate and sea level. Although the lag between the timing of catchment disturbance and that of the manifestation of its environmental effects downstream is typically long for a large catchment such as the Mekong, it is still well within the time scale of infrastructure development. Examples from other large catchment systems, such as the well-documented case of decline in sediment supply to the Nile Delta due to the construction of the Aswan High Dam in 1970, suggest that the lag involved in downstream impact propagation is in the order of 10^0 - 10^1 years. There is also little doubt that the global sea-level rise predicted with climatic warming is sufficiently rapid for environmental change to occur within time scales of decades or less; predicted rates of sea-level rise in the coming century are comparable with those in the latter stages of Holocene postglacial transgression, a time of rapid large-scale geomorphic and ecosystem change in coastal areas around the world.

3.3.3 Socio-political scale and environmental problems

Scale considerations are also important when assessing the socio-economic distribution of the environmental impacts arising from recent infrastructure development interventions in the Mekong Delta. Although the decision-making, planning and implementation processes regarding infrastructure development, at least in the case of large-scale projects, take place at the higher levels of political scale, *i.e.* at national and provincial levels, the resultant environmental impacts appear to be disproportionately concentrated at the local

level, *i.e.* the communities and the individuals. Such inequality seems to be a consequence of the natural characteristics of the environment, project design, implementation and maintenance procedures, as well as the administrative structure of project management responsibilities.

An example is offered by the problems regarding siltation in canals. The frequency of required maintenance dredging of canals generally increases with a decrease in the size of canals, due to the hydraulic geometry of canal systems. The maintenance responsibility of tertiary canals lies at the individual and community level, such that a high proportion of the maintenance cost of the entire canal network is borne by the farmers. In addition, the maintenance of secondary canals, whose responsibility lies usually at the provincial or project-area level, is commonly part-financed through farmer taxes, thus further directing the cost of maintenance at the local level. Poor canal design and dredging practices, in addition to the lack of legislative structure to protect the use of canal banks and their vegetation, result in the unnecessary acceleration of siltation rates in secondary canals (see Section 2.3.2.2), to add to the cost. Furthermore, local-scale siltation rates within canals and aquaculture ponds may change as a consequence of future national- or provincial-level decisions, *e.g.* through the installation of new sluice gates, such that the cost is subject to instability, and results in local-scale socio-economic inequality, *e.g.* as a zone of high sedimentation rate shifts along the canal with the installation of a sluice. Hence, although canal siltation *per se* is essentially a product of natural processes within the environment, its socio-economic impact is magnified by the administrative structure and maintenance procedures.

Some other examples illustrating the high environmental cost of infrastructure development borne at the local level include the loss of floodplain fisheries due to flood-control structures, the degradation of fishery resources in canals due to the increased application of agro-chemicals in rice cultivation, and the loss of nypa stands along waterways due to sluice gate installation. In all of these examples, the losses involve resources important to local subsistence and economy. It is also important to note that such traditional resources commonly furnish the greater part of the income of the poorest members of local communities, *e.g.* landless farmers (Miller, 2000). Furthermore, losses of such resources undermine the degree of self-sufficiency of local communities, which has already been weakened by the expansion of export-oriented agriculture and aquaculture throughout the delta. Thus, the environmental impacts of infrastructure development remain at the local level while the benefits, in the form of production, is exported to urban and overseas markets.

Spatial pattern of infrastructure development is another factor behind the inequality in the socio-economic distribution of environmental impacts. At the delta scale, inequality has arisen due to the coexistence of discrete project areas designated for infrastructure development, separated by areas not currently under any development schemes. Areas which lie between two or more separate project areas have tended to become convergence zones for environmental effects emanating from the project areas, and as such often suffer greater impacts than within the project areas. For example, flooding and salinity intrusion around the town of Soc Trang on Ca Mau Peninsula have worsened since the establishment of two salinity-control project areas on either side of the canal connecting the town with the coast (Olivier Joffre, pers. comm.). Such impacts are often unnecessarily aggravated by the lack of coordination in the operation of infrastructure between different project areas.

Further inequality exists at the scale of individual project areas. Typically, the project areas are demarcated by canals, roads, administrative boundaries or other anthropogenic boundaries rather than by natural environmental boundaries and gradients, such that inequalities in the distribution of environmental impacts and the degree of socio-economic benefit brought about by the project inevitably arise within the local community. For example, irrigation projects encompassing both ASS and non-ASS areas have brought local benefits to the ASS areas through the removal of acidity and soil toxins, but have resulted in negative environmental and socio-economic impacts upon the passage of acid discharge through the non-ASS

areas. In some cases, the number of rice crops that may be cultivated in a year varies within the project area due to topographic differences, but those areas which cannot reap the full benefits of irrigation through year-round rice cropping are no longer able to resort to the traditional dry-season economic activities such as extensive shrimp aquaculture due to the effects of agro-chemical pollution from year-round cropping areas. Problems are also created when project implementation takes place in areal increments, *i.e.* the project area is subdivided and the project interventions are effected step by step over a period of several years. Thus, until the full implementation of the project, a situation not unlike that at the delta scale can exist within each project area, whereby the negative environmental impacts originating from those areas, in which project interventions are already underway, are passed to areas awaiting project implementation. The local-scale conflict which has developed between farmers practising irrigated rice cultivation and shrimp farming in the Quan Lo Phung Hiep project area in Ca Mau Peninsula (see Section 2.3.1.3) is an illustration of such inequality which commonly emerge within a project area.

Inequality also arises along upstream-downstream and channel-delta plain gradients, reflecting the transfer pathways of matter and energy within the delta system. The environmental and socio-economic impacts tend to progressively intensify through cumulative effects with increasing distance along these gradients, such that they become focussed on resource users at the lower extremity of the gradients, *i.e.* in the lower delta, coastal areas and distal parts of backswamps. These areas constitute some of the most socio-economically disadvantaged within the delta, even in the absence of such impacts, due to the adverse conditions for human settlement and utilisation of the natural environment, *e.g.* ASS, severe seasonal flooding, saline soils. Thus, progressive water diversion from the main channels at successive abstraction points will progressively decrease freshwater discharge with increasing distance downstream along the channels, leading to a concurrent rise in problems with water shortage, pollutant stagnation, saline intrusion, channel and canal siltation and so on. Along individual canals conveying water away from the main channels, the same problems manifest themselves with increasing severity, as the distance from the abstraction point on the channel increases. Cumulative effects of progressive water abstraction on water pollution may be particularly severe in canals. Here, as the volume of water available for pollutant flushing progressively decreases, the cumulative volume of entering pollutants (*e.g.* acidified water, agro-chemicals, farm and household effluent) increases. Such a scenario may unfold over relatively small spatial scales to result in local socio-economic inequality; for example, the inhabitants of lower sections of a canal may be forced to purchase drinking water, while those living upflow are able to use canal water for the same purpose without incurring any financial cost.

As an increasing amount of capital through foreign aid and investment flows into the regional economy of the Mekong Basin, the number of large-scale infrastructure development schemes, as well as the degradation of the natural environment associated with changes in the patterns of resource use, in the catchment upstream of the Mekong Delta will continue to grow. Under such a trend, the downstream transfer of environmental impacts at the catchment scale will exert an increasing influence on the environmental and socio-economic well-being of the delta and its inhabitants. The position of the delta, and its role as a major sink for sediment and other material derived largely from the catchment, render it highly susceptible to a disproportionate concentration of environmental and socio-economic impacts originating from activities upstream. Hence, the victims of inequality within the delta are, in a true sense, the "losers among the losers". (The effects of environmental change in the upstream catchment will be discussed in detail in the Section 3.4.2.)

In summary, inequality in the socio-economic distribution of environmental impacts resulting from recent infrastructure development within the Mekong Delta is as much of a political issue as it is the outcome of human disturbance of natural environmental processes. A large part of this inequality seems to be the product of the fragmented spatial implementation of infrastructure development interventions within the delta, *i.e.* the establishment of multiple project areas, each with individual aims pertaining to the local area

and without coordination of activities with, and the consideration of adverse environmental impacts on, other areas within the delta. Such a sacrificial approach to infrastructure development serves to widen socio-economic gaps between those who benefit from the development interventions and those who do not.

3.4 Impacts of future environmental change on the Mekong Delta

3.4.1 An environment under siege from the inside and out

Discussion thus far has concentrated on environmental issues originating from infrastructure development interventions within the bounds of the Vietnamese Mekong Delta. Certainly, the most apparent environmental change and impacts in recent times have resulted from activities within the delta. However, some of the greatest future threats to the environmental integrity of the Mekong Delta are likely to be posed by factors outside the delta itself. In addition, the rapid changes to the socio-economic environment of the Mekong Delta are likely to intensify the environmental pressures emanating from within the delta in the years to come. The juxtaposition of such extrinsic and intrinsic forces is likely to result in an increased incidence of unforeseen cumulative effects and complexity in the environmental impacts of future infrastructure development interventions. Such an increase in the pressure placed on the biophysical environment of the delta comes at a time when resilience of the environment to changing conditions has already been diminished by the impacts of existing infrastructure development interventions.

3.4.2 External environmental threats

The two main external environmental threats to the Mekong Delta are the increasing human disturbance of the natural environment in the upstream catchment of the Mekong River, and global change in atmospheric circulation (*i.e.* the *greenhouse* effect) and the associated predicted sea-level rise.

Since the early 1990s, there has been a sharp increase in the pressure placed on natural resources within the Mekong Basin as a result of rapid regional economic development driven by major geopolitical changes and the inflow of capital derived from foreign aid, investment and trade (Hirsch, 2000). The creation of an integrated regional economy and its incorporation into global trade has heralded an unprecedented era of large-scale infrastructure development projects being implemented within the basin. A number of dams and water-transfer schemes (including those of inter-basin nature), for hydroelectric power generation, irrigation and urban / industrial water supply, have either been established or are in plan, predominantly in the headwater areas within China (Yunnan Province), Lao PDR, Thailand and Vietnam. Meanwhile, increased extraction of timber destined for export has contributed to deforestation across wide areas of the catchment. Although supporting data are scarce, the cumulative effect of such numerous and large-scale interventions would undoubtedly disrupt the natural transfer of water and sediment through the catchment. Dams would not only alter the discharge reaching the delta, but act to hinder the transfer of sediment from the headwaters to the lower catchment. The location of the majority of the dam projects in the headwater areas of the catchment, where, incidentally, the majority of sediment production within the catchment takes place, is unfortunate from both the environmental and project perspectives; the dams are likely to significantly reduce the supply of sediment to downstream, while the lifespan of the dams is likely to be shortened through rapid sediment accumulation behind the dam wall. The effect of the dams would be greatest on the coarser fractions of the sediment load, whose heavier particle mass renders them particularly susceptible to trapping. In view of the adverse environmental effects of dams on the delta, it is somewhat ironic that additional upstream dam construction has recently been advocated as a flood-mitigation measure for the delta (KOWACO, 2000).

The effect of catchment deforestation would be to increase surface runoff during the wet season at the

expense of infiltration, while decreasing the dry season river flow through a diminished contribution of groundwater outflow. The increase in the wet-season runoff is also likely to be accompanied by a decrease in the delivery time of runoff to the river channel, leading to more "flashy" flood characteristics, *i.e.* a more rapid rise in water level at the commencement of floods. Such floods commonly result in more losses due to the shorter time available for warning local populations.

The change in the composition of the earth's atmosphere through increased global emissions of the so-called *greenhouse* gases is likely to bring about significant shifts in climatic conditions in the next century. Not only will there be changes to mean temperatures and rainfall, but also the possibility of changes to climatic seasonality as well as to the frequency and magnitude of extreme events. The thermal expansion of seawater combined with the additional introduction of melting of ice in polar and alpine regions will result in a global sea-level rise of up to 1 m during this century (IPCC, 1995). In deltaic systems, such as that of the Mekong, such global-scale environmental changes will produce impacts from both upstream and downstream directions. Changing regional climatic trends would affect the river discharge regime mainly through changes in rainfall characteristics over the catchment, including the amount of total annual rainfall, seasonal distribution, intensity and interannual variability. Sea-level rise would affect a large proportion of the Mekong Delta, given the low surface elevations. The coastal areas would be directly impacted by shoreline recession, leading to the landward retreat of mangrove and brackish ecosystems. Shoreline recession would be particularly rapid if sediment discharge to the coast has been diminished through changes in sediment supply from the upstream catchment and / or in sediment transfer patterns within the delta due to human modifications, and regional climate change has increased the storm frequency / intensity or ocean wave height. The exact response of mangrove communities to a sea-level rise depends on the rate of rise and the rate of sediment supply to the substrate (Figure 18); under conditions of slow sea-level rise relative to the rate of sediment supply, mangroves may be able to prevent landward translation of their habitat through substrate aggradation (Figure 18a). Similar considerations may be applied to other parts of the delta plain; sufficiently high sedimentation rates would result in an aggradational response allowing the delta plain to keep up with the sea-level rise, whereas relatively low sedimentation rates could lead to the submergence of parts of the delta plain. The effects of the sea-level rise would propagate inland in the form of increased flood risks during the wet season (duration, extent and height), increased saline intrusion during the dry season, and rising water tables which may result in the transformation of formerly well-drained land into swamps or lakes. Within channels of the delta, the rising sea level is likely to trigger sedimentation in the form of bed aggradation and bar formation. A consequential reduction in channel stability is likely; channels become more prone to avulsions during floods if the pace of bed aggradation outstrips that of delta plain aggradation, while an increase in bar formation will result in increased lateral channel migration and bank erosion.

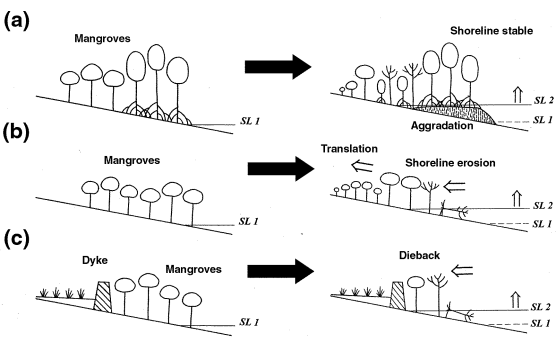


Figure 18. Some possible types of response of mangrove ecosystems to a future sea-level rise: (a) habitat maintenance through substrate aggradation; (b) habitat relocation through landward translation; (c) habitat disappearance as a result of structural impediment to relocation.

3.4.3 Future socio-economic change and its effects on the environment

The development of an integrated regional economy within the Mekong Basin is still in its infancy. As such, it is reasonable to expect that infrastructure development within the region will not only continue into the foreseeable future, but intensify. Within the Mekong Delta, the current trend toward intensification of rural landuse, whether it be the replacement of traditional single-crop rice with irrigated high-yielding multiple-

crop types, or seasonal extensive shrimp culture with year-round intensive systems, is likely to continue, necessitating further modification to the biophysical environment. Further pressure on the environment will be placed by the rapidly increasing population, as well as the regional trend toward increasing urbanisation and industrialisation. This will stimulate the development of a new suite of infrastructure in a region which has up to now largely remained rural. For example, the demand for water and land transport infrastructure will increase, as the regional dependency on imported material and export-oriented production increases. Demand for resources such as construction sand will increase, which may be supplied locally from river channels. Such extraction will further alter the natural pattern of sediment dynamics within the delta. Hard engineering of river banks may become more common as urban areas spread; such structural modification of rivers would have far-reaching consequences for sediment dynamics and channel stability.

Imbalance between the growth of population and economic activities, and the creation of accommodating infrastructure will result in aggravated environmental impacts, such as water pollution. Indeed, such problems are already prevalent across much of the delta, as evidenced by the uncontrolled discharge of household effluent into waterways and the accumulation of non-biodegradable solid waste, both on land and in waterways. Increased poverty and socio-economic inequality, resulting from intensified competition for environmental resources, is likely to result in further negative impacts on the environment, *e.g.* through an increase in illegal settlement along canals, which inevitably results in increased water pollution and sediment trapping in canals (due to retardation of water flow along the banks by dwellings).

3.4.4 A stressed environment in the face of future change

One concern regarding the environmental effects of future and large-scale change on the delta is the diminished capacity for the biophysical environment to adapt to such changes. The **fragmentation** of biophysical environments within the delta (see Section 3.1.2) has placed obstructions to free change in their spatial distribution, which has permitted their adaptation to changing environmental conditions throughout geological history. From an ecological point of view, this has signified a reduction in available refuge areas. For example, the widespread proliferation of dykes and canals around areas of mangroves (either planted or natural) would serve to hinder the landward relocation of the mangrove habitat under a rising sea level, such that the mangroves would eventually die out locally unless they are able to maintain their substrate through sufficiently rapid sedimentation (Figure 18c). In the absence of such structural obstructions, areas to the landward of the mangroves would have served as a refuge during a sea-level rise. Fragmentation also increases the level of background environmental stress placed on ecosystems, as it facilitates the convergence of negative impacts of activities in the surrounding areas, and limits the potential for reproduction, feeding and symbiosis through a low background population of individual species. A future environmental change merely serves to further increase the level of stress placed on these ecosystems, increasing the likelihood of their collapse.

Simplification is another factor contributing to reduced adaptability of ecosystems to future change. When natural or traditional rural ecosystems are modified through human activity, species composition and age / physical structure of ecosystems commonly become simplified. Recent infrastructure development interventions in the Mekong Delta have strongly encouraged such a tendency, directly through the replacement of stratified, highly diverse ecosystems with uniformly structured monocultures (*e.g.* irrigated rice, mangrove forestry, intensive shrimp aquaculture), or indirectly through degradation of natural ecosystems. Adaptability to changing conditions is reduced in such an ecosystem as the collective resilience to environmental adversities, such as weather, pests, diseases and human exploitation, is weakened. Indeed, the initial symptoms of reduced ecosystem adaptability are already apparent within the delta, such as the elevated level of damage caused by pest attacks in mangrove plantations (see Section 2.3.2.5).

Further threat to the survival of ecosystems through future environmental changes is posed by the high

background environmental stress placed by the **cumulative effects** of numerous human activities, such as increased agro-chemical pollution from intensified rice culture, eutrophication caused by effluent discharge from shrimp ponds, or overexploitation by the local population. Stressed ecosystems are typically more susceptible to damage or collapse under adverse or changing environmental conditions. For example, unhealthy mangrove ecosystems may not be able to maintain a sufficient level of biomass production to permit appreciable organic matter accumulation to take place on the substrate, thus curtailing their ability to maintain their habitat during a sea-level rise through substrate aggradation.

Such a reduction in the ability of the environment to withstand future change is not limited to the biosphere. Geomorphic and geochemical processes have widely been altered through the effects of existing infrastructure development interventions within the Mekong Delta, such that the threshold of tolerance of the physical environment to changing conditions has been lowered. In other words, for a given degree of change in environmental conditions, the magnitude of response of the physical environment would be increased in comparison to pre-disturbance conditions. Returning to the scenario of a future sea-level rise, it is suspected that the overall capacity for the delta plain to keep up with such a change has been greatly reduced due to the cumulative effect of human modifications to the environment in many disparate areas of the delta and catchment system, including:

- a diminished area and health of mangrove ecosystems, and the consequential decline in organic matter accumulation and aggradational capacity of the substrate;
- a dramatic increase in the interconnectivity and density of drainage network across the delta plain due to canal construction, facilitating the incursion of seawater under a sea-level rise and an increased likelihood of submergence;
- a reduction in sediment discharge to the coast, and hence, the ability of the shoreline to resist recession, resulting from a reduction in river flow, sediment trapping in canals, diversion of sediment discharge to other coastlines, increased sand extraction from channels *etc.*;
- a greatly reduced rate and extent of overbank sediment deposition, due to the effects of flood-control projects;
- a diminished area and health of peat-accumulating freshwater ecosystems, such as backswamp *Melaleuca* forests.

In the extreme case scenario, the cumulative effect of flow and sediment diversion from the main channels within the delta, including the possible large-scale diversion to the Gulf of Thailand and/or West Vaico River, may render the delta system incapable of adjustment to the impacts of future environmental changes originating in the upstream catchment, as well as due to a rise in sea level, such that the presently active delta front may become abandoned. In many ways, the current problems of delta-plain decay in the Mississippi Delta (Figure 19), a process driven by a combination of human disturbance to the river flow regime and sediment supply, and a rapid relative sea-level rise attributable to natural subsidence, closely resembles this hypothetical future scenario for the Mekong Delta. The magnitude of ensuing environmental and socio-economic losses (including the permanent loss of over 4000 km^2 of coastal wetlands due to marine inundation; Coreil, 1999) in the Mississippi Delta, would spell a catastrophe of national, if not regional, scale if replicated in the Mekong Delta.

The cumulative effect of future large-scale environmental change and intensified use of environmental resources within the delta may undermine the viability of many existing infrastructure development interventions. A sea-level rise would render some irrigation projects in the coastal parts of the delta inoperable if the abstraction points of freshwater along the main channels become affected by the upstream migration of seasonal saline intrusion. Sluice gates become inadequate on their own in excluding salinity, as they become circumvented through subsurface saline intrusion (which may be enhanced by a rise in water table) and a rise in canal water levels. Overtopping of flood-protection dykes may become increasingly frequent, as

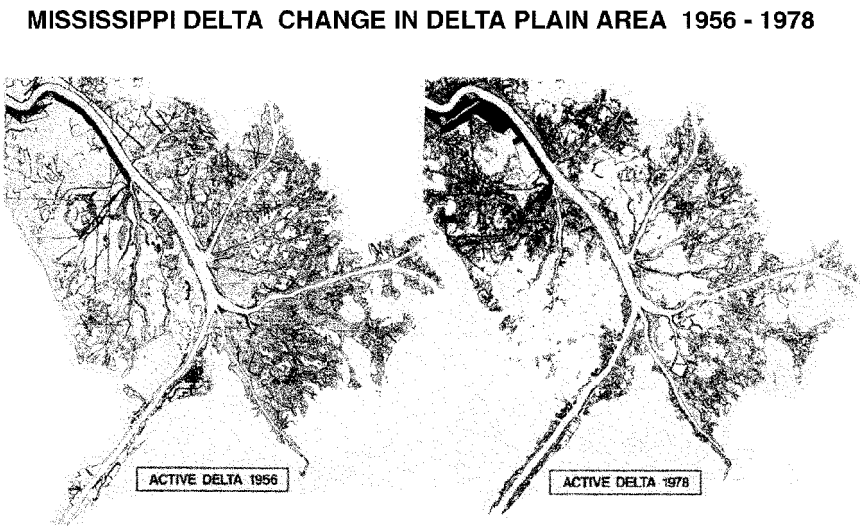


Figure 19. Submergence of the delta plain in the active lobe of the Mississippi Delta, triggered by changes in sedimentation patterns resulting predominantly from engineering works carried out since the early 20th century. These works, aimed at protecting the delta plain from floods and at maintaining a navigable channel, have effectively terminated the supply of sediment to the delta plain, curtailing its ability to keep pace with natural subsidence through aggradation. As a consequence, the delta's natural evolutionary tendency toward expansion has been reversed, rendering it especially vulnerable to a future acceleration in the rate of sea-level rise (Source: US Fish and Wildlife Service, National Wetlands Research Center).

river water levels rise in response to a higher sea level, and environmental change in the upstream catchment alters the river discharge regime. Worse still, dykes may fail due to an increased tendency toward bank erosion or channel avulsion driven by increased channel sedimentation. Costs of infrastructure maintenance are likely to rise, while the risk of project failure and its catastrophic socio-economic consequences grows. Additional costs are to be incurred through the development of supplementary infrastructure, if the existing infrastructure is to be upgraded to withstand the changes in environmental conditions. Such upgrades are an inevitable consequence of a "defensive" underlying approach to development, whereby human activities are "protected" against the perceived risks through the control of the natural environment (Miller, 2000), and which leads to a perpetual dependence on the installation of additional infrastructure under changing environmental conditions. Naturally, such developments are likely to lead to further environmental impacts in the years to come. It should be emphasised that the scenarios presented here are predictions, and a high degree of uncertainty surrounds the actual impacts of both the infrastructure development interventions and externally forced environmental change. However, it is to be hoped that they will provide a basis for a precautionary approach to further infrastructure development within the delta, in order to avert potential future environmental and socio-economic catastrophes.

[1] A mechanism of channel migration involving an abrupt change in the position of the active channel.

4. CONCLUSIONS

4.1 Summary

The Vietnamese part of the Mekong Delta has experienced an unprecedented pace of infrastructure development in the last few decades. Although such development has contributed significantly to economic growth within the delta and nationally, it has also resulted in the genesis of innumerable adverse impacts on the natural environment. Many impacts have originated from the failure to recognise the delta as a dynamic biophysical system, and an emphasis on rapid economic development based on export commodity production. Furthermore, the environmental impacts have translated into escalating socio-economic tension, in the form of: poverty aggravation, due to disproportionate impact at the local level and on the poor; and decreased community self-sufficiency, due to the loss of traditionally important resources and the replacement of environmentally attuned traditional land use strategies with intensive and environmentally costly ones. Although many of the environmental impacts of the recent infrastructure development interventions have become apparent within a short period, it is likely that the delta is resting on an environmental "time-bomb" of unforeseen and unpredictable long-term and cumulative impacts. There is a real danger that the stress currently being placed on the biophysical environment will render the delta incapable of withstanding future environmental changes, arising from intensifying development activities in the delta and its upstream catchment, or from global climate change and the associated sea-level rise. Given the extent of development within the delta, it may largely be too late to reverse the tide of environmental damage arising from infrastructure development interventions which have been implemented thus far. However, based on the discussion within this report, some recommendations for the future can be made, in an attempt to divert infrastructure development in the delta from continuing along the path of high environmental and socio-economic cost.

4.2 Recommendations

First and foremost recommendation is that future infrastructure development should incorporate a greater appreciation of the **system characteristics** of the Mekong Delta. An activity in one part of the delta will generate impacts in other areas. The analysis of environmental and socio-economic costs of a proposed project will need to be carried out, not only for the project areas, but for the entire delta. An **improved coordination** of activities between the discrete project areas, promoted in the first instance by an increased level of inter-provincial cooperation, would minimise the generation of cross-project and cumulative impacts.

The prediction and gauging of environmental impacts arising from infrastructure development in the Mekong Delta are often hampered by the lack of adequate **baseline** and post-implementation **monitoring data**. Monitoring of existing projects will assume increasing importance in providing input for future projects, as the increase in the number of projects within the delta will bring about a corresponding increase in cumulative impacts. It is not to say that data do not exist; a number of studies have been carried out by various government agencies and institutions both within and outside the Mekong Delta region, but their temporal coverage is often too short to enable trends to be identified. Data collection may not be of benefit initially, but their utility grows with time. There is also an urgent need to improve the coverage of environmental data on the Mekong River catchment. This is especially important in light of uncertainty over the effects of current and future dam construction on the delta.

There needs to be a fundamental change in the planning and design of projects, namely a move away from the "defensive" approach that pervades many recent infrastructure projects. Instead of total control, prevention and elimination, emphasis should be placed on partial control, amelioration and, in general, **adapta-**

tion to the natural environmental conditions. For example, there is more long-term benefit in replacing the current approach of flood-control, involving much investment in hard infrastructure for defending the delta plain from overbank flooding, with strategies which involve re-routing overbank flow and partial protection. In this regard, flood-protection strategy in the 2 rice-crop areas of the delta, which allows for a lengthened growing season but not a total exclusion of flood waters, is preferable to full-flood protection which many water-control projects are striving to achieve. Dykes should be fitted with numerous gaps (which may be sealed with temporary earth or straw banks) to allow free throughflow of flood waters during peak flood season and overbank sediment deposition, which assists in maintaining the soil quality. Designated floodways and detention basins could be established in the lowest parts of the delta plain to re-direct flood waters around dyke-protected fields in the early part of the flood season, instead of channelising flood flow through canals. These floodways and detention basins may be utilised for re-establishing *Melaleuca* forests, which have the added advantages of supplementing local incomes, preventing AASS formation by maintaining a high water table, and conserving groundwater, thus increasing water availability during the early part of the dry season, and reducing the need for water abstraction from the main channels. Such an approach conforms more to the traditional philosophy of living in harmony with the flood, or *song chung voi lut* (Miller, 2000), minimising environmental impacts associated with changes in hydrology and sediment dynamics. In practice, however, the high density of population and land use would pose a significant challenge to the implemention of such changes in many parts of the delta.

The adoption of such a "soft" approach to the utilisation of the biophysical environment of the Mekong Delta requires **diversification** of economic activities, and a move away from the emphasis placed on intensive monoculture. The drive to expand the cultivation area of irrigated rice has been particularly harmful to the environment. To this end, the development of agro-forestry and silvo-fishery systems within the delta, such as the combined mangrove-shrimp systems, could make a significant contribution in the years to come. Such diversification has numerous advantages, including:

- a reduction in the cost of inputs, *e.g.* pesticides;
- the creation of more ecologically viable habitats;
- a reduction in the risk of productivity decline or failure due to climatic conditions, pests, diseases, and future environmental changes arising from increased catchment disturbance and global change.

The active utilisation of local knowledge and genetic resources, such as traditional crop and livestock strains in the diversification process would further reduce the risks associated with adverse conditions and environmental change.

Furthermore, more flexibility needs to be introduced into land use in the Mekong Delta, in order to accommodate the inherently **dynamic natural environment** of the delta. In part, this may require a shift in the focus of development from investment in costly and permanent infrastructure to that of more temporary character. In mangrove forestry, plantings of *Rhizophora apiculata* should not be planned as being permanent, but instead, an opportunistic use of a suitable substrate. With the eventual aggradation of the substrate to elevations too high for *R. apiculata*, natural succession to a forest of mixed species should be allowed to take place, perhaps assisted by underplanting *R. apiculata* with other species adapted to higher substrates. Such mixed forests many continue to provide economic benefits to the local communities, through the provision of traditional resources. In the case of siltation and dredge-spoil management in canals and shrimp ponds, chronic problems arise largely due to the positive feedback effect of dredging, which encourages further sedimentation. The volume of spoil produced could be considerably reduced if dredging in canals were restricted to maintaining a navigation channel, and shoals and bars were allowed to form along the banks, and if sediment input into shrimp ponds were to be reduced by the incorporation of settling ponds and mangrove filter strips in the design. (In reality, the typically small farm sizes may render the application of such designs difficult.) The ponds themselves may be designed to enable the use of the

land for mangrove forestry, upon their eventual infilling.

Given the scale of their recent degradation and simplification, there is an urgent need for the **restoration and diversification of ecosystem**s in the Mekong Delta. Not only is this of crucial importance to the maintenance of regional biodiversity, but also in order to reduce the risk of losses in agricultural, forestry, fisheries and aquaculture production from environmental adversities and change, and to restore locally important environmental resources diminished through the effects of recent infrastructure development. Furthermore, healthy and diverse ecosystems can assist in the amelioration of some of the impacts of human activities on the environment. There appears to be a common belief that human-modified environments do not require the equivalent level of environmental consideration as the less disturbed ones, as exemplified by the following comment in an environmental impact assessment for a water-control project within the delta:

"The project area does not contain sites for nature protection, and no unique flora and fauna communities requiring protection can be found. The proposed project interventions will thus [not] *entail any negative effects on natural flora and fauna..."* (NEDECO, 1994b, p. 36).

However, the limited area of undisturbed ecosystems remaining within the delta today implies that human-modified environments, such as rice fields and canals, have the potential to offer important additional ecological habitats to the biota of the delta. They may also act as important ecological corridors connecting the widely separated areas of less disturbed ecosystems. Infrastructure such as canals should be designed to increase the diversity of ecological habitats, *e.g.* a canal featuring vegetated bars and deep pools has a far greater value as habitats than a straight, rectangular trough that is regularly disturbed through dredging. An additional benefit may be a decrease in the pollution levels of canal waters; there is evidence to suggest that a heterogenous channel morphology is important in the natural assimilation of pollutants in rivers (Petrozzi, 1998). As with the diversification of land use, a significant contribution to the creation of varied ecological habitats within the delta could be made through the development of agro-forestry and silvo-fishery systems.

Although it is fundamentally the conceptual basis behind infrastructure development which requires change if it is to strike a balance with the natural environment, much can be achieved through the **improved design and management** of existing infrastructure. For example, simple morphological modification of the canal network, such as the elimination of sharp bends, excessive branches or dead-ends, may substantially decrease sedimentation and associated hydrological problems caused by canals, while the enlargement of culverts and water intakes/outlets along dykes may be all that is required to improve the throughflow of flood waters on the delta plain, thus ameliorating problems associated with flow stagnation and obstruction of overbank sediment transport. The solution to bank erosion problems in the canals may lie in appropriate dredging practices, bank design and community education on the use of canal banks and vegetation.

Rivers and deltas have had a long and inseparable association with humans. Their rich environmental resources have not only supported human survival and existence, but have nourished the development of human society and culture since time immemorial. At the same time, their imprudent use has resulted in costly environmental and socio-economic impacts, whose legacy continues to burden inhabitants today, many years after the initial disturbance to the environment. The Mekong Delta has a relatively recent history of environmental disturbance. However, the delta is rapidly approaching a point of saturation in terms of environmental stress. The decisions in the next few years regarding development strategies within the Mekong Delta will be an important turning point in deciding whether the delta will be rendered yet another great delta of the world sacrificed in the name of development, or whether it will continue to bless its inhabitants with its natural bounty for many generations to come.

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6. GLOSSARY

Aggradation	Vertical accretion of substrates resulting from sediment deposition.
Avulsion	A form of channel migration mechanism in alluvial and deltaic rivers, whereby the position of the active channel changes catastrophically, most commonly during floods. After such an event, the former active channel usually becomes abandoned, progressively infilling with sediment.
Baroclinic flow	A current generated by the horizontal pressure gradient arising from spatial variability in the vertical density distribution of the water column (Baretta-Bekker *et al.*, 1998), as may occur when fresh- and saltwater masses meet along a sharp front within an estuary.
Bedload	The coarse-grained portion of the sediment load carried by rivers, coastal currents *etc.* which is predominantly transported along the substrate, or the bed. It usually consists of sand- and /or gravel-sized particles.
Cenozoic	The most recent era in geologic time, consisting of the Tertiary and the Quaternary periods.
Distributary	A branch within a divided channel system of a river, especially in deltas
Distributary-mouth bar	A deposit of sediment forming a shoal at the mouth of a deltaic distributary, which, if stabilised, may eventually develop into an island around which the channel bifurcates.
Diurnal tides	A tidal regime with high and low water occurring once during a period of approximately one day.
Eocene	An epoch in geologic time lasting from approximately 58 to 37 million years before present. It is one of the epochs of the Tertiary, a period within the Cenozoic era.
Eutrophication	Enrichment of surface water bodies with inorganic nutrients such as nitrates and phosphates, which stimulates the growth of phytoplanktons and commonly leads to the formation of algal blooms.
Glacial	An ice age.
Holocene	The most recent epoch in geologic time, comprising the last 10,000 years of the Quaternary period and continuing to the present.
Horst and graben	Blocks of rock displaced upward and downward, respectively, relative to adjacent rock by movement along (sub)parallel faults on either side of the blocks.
Mid-channel bar	A deposit of sediment forming a shoal in the middle of a river channel, which may eventually develop into an island around which the channel bifurcates.
Monadnock	An isolated hill originating as an erosional remnant, *i.e.* a mass of more resistant rock left behind after the surrounding rock has been eroded away.

Overbank flood	A type of flood whereby the floodwaters overtop river banks and inundate the flanking alluvial or delta plain, commonly resulting in sediment deposition.
Point bar	A deposit of sediment attached to the convex bank of a river channel at a meander bend. Continual accretion of sediment onto a point-bar results in the progressive growth of the meander bend and lateral channel migration.
Pleistocene	An epoch within the Quaternary period and preceding the Holocene, lasting from approximately 2 million to 10,000 years before present.
Polder	Land reclaimed from the sea, lake or swamp, protected from inundation by enclosing dykes.
Progradation	The advance of a margin of depositional landforms, such as a shoreline or a delta front, due to sediment deposition.
Quaternary	The most recent period of the Cenozoic era, spanning the last 2 million years of the geologic time, and consisting of the Pleistocene and the Hololcene epochs.
Rach	Vietnamese for "*…small water courses without any permanent source…*" (Brocheux, 1995) of diverse geomorphic origin, including tidal creeks, abandoned distributaries, and crevasse or backwater channels of deltas.
Regression	Also called a marine regression, a large-scale retreat of the sea and the consequential expansion of land due to a relative fall in sea-level. Some authorities also apply the term to denote the sedimentation-induced expansion of land, such as that associated with shoreline accretion, which may, or may not, be independent of the sea level.
Salt wedge	Under highly stratified conditions (in terms of salinity structure) in estuaries, little appreciable mixing between the fresh- and saltwater takes place, such that the latter forms a clearly defined wedge-shaped intrusion, called a salt wedge, beneath the outflowing freshwater plume.
Semi-diurnal tides	A tidal regime with high and low water occurring twice during a period of approximately one day.
Stratified	In estuarine salinity structure, any state involving the convergence of fresh- and saltwater along a relatively sharp front or gradient, with the former floating on top of the latter as a plume prior to mixing.
Suspended load	The fine-grained portion of the sediment load carried by rivers, coastal currents *etc.* which is predominantly transported in suspension, *i.e.* the particle travels for extended periods through the water column without touching the substrate. In most cases, clay and silt particles predominate the suspended load.
Tidal asymmetry	Inequality in the length of the rising and falling limbs of a tidal cycle, resulting from the deformation of the tidal wave as it propagates from the ocean into an coastal embayment. In estuaries, progressive shoaling and narrowing in the upstream direction commonly results in a much faster rate of rise than

	fall, resulting in flood-tide currents which are stronger than those of the ebb tide.
Transgression	Also called a marine transgression, the inundation of a large area of land due a relative sea-level rise, such as that following the end of a glacial.
Well-mixed	In estuarine salinity structure, a state whereby mixing between fresh- and saltwater occurs incrementally in the upstream-downstream direction, resulting in a relatively gentle salinity gradient.