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Keywords

Landscape, variability, response, Asian, megadeltas, environmental, change, GeoQUEST

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Landscape variability and the response of Asian megadeltas to environmental change

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Abstract

This chapter examines the landscape variability of the megadeltas of Asia and their response to anticipated climate change and sea-level rise. The Indus, Ganges-Brahmaputra-Meghna, Irrawaddy, Chao Phraya, Mekong, Red, Pearl, Changjiang, and Huanghe Rivers have extensive low-lying delta plains flanking their mouths. Effective management of these systems requires understanding of both the natural physical processes and their human modification at a range of spatial and temporal scales. Surface topography of each delta has become increasingly complex since postglacial sea-level rise as it has prograded over the past 6000 years, with greater discrimination of river-, wave-, and tide-dominated sectors and switching of distributaries. The Asian megadeltas have a long history of human exploitation, and have been increasingly influenced by human alterations at a range of scales. They now support large populations and there are strong urbanisation trends. Many of the largest cities are already megacities (>8 million people) and collectively they will contain over 120 million people by 2015. There has been a long history of water control in the deltas, from flood mitigation and groundwater extraction to irrigation and channelisation, exacerbating compaction, subsidence and acid sulphate soil development. Whereas human land-use changes have led to increased sediment loads in the past, construction of upstream dams and other water abstractions and diversions are now seriously reducing the supply of sediments to deltas with increased coastal erosion a widespread consequence. As these human pressures grow substantially through the 21st century, there is a need to more completely understand the spatial variability of natural processes in relation to socio-economic factors to design long-term management strategies that exploit the natural resilience of these megadeltas to the maximum extent possible.

Keywords: Megadelta; Asia; Climate change; Sea-level rise; Coastal vulnerability

10.1. INTRODUCTION

Deltas, occurring at the mouths of river systems that deposit sediments as they enter the sea, are some of the most dynamic sedimentary environments. They contain a long, and often economically significant, sedimentary record of their response to past episodes of climate and sea-level change. Geological investigation of these deposits, and the processes controlling sedimentation, provide insights into the response of deltas to environmental change, which in turn may offer rational and cost-effective strategies for the sustainable management of natural resources and land use in these dynamic systems in the face of future environmental change.

This chapter examines the megadeltas associated with the mouths of the nine largest rivers in south, southeast and east Asia, the Indus, Ganges-Brahmaputra-Meghna (GBM), Irrawaddy (Ayeyarwady), Chao Phraya, Mekong, Red (Song Hong), Pearl (Zhujiang), Changjiang (Yangtze) and Huanghe (Yellow) rivers. Most of these are influenced by the seasonal Asian monsoon, with headwaters in the Himalayan-Tibetan massif (see Chapter 4.1), and carry large, highly-seasonal sediment loads to the sea (Table 1). There are extensive low-lying sedimentary plains associated with the mouths of each of these systems, termed ‘megadeltas’, which appear particularly vulnerable to impacts as a result of any change in sea level (McLean and Tysban, 2001) and other global change (Kremer et al., 2005). Although smaller Asian deltas also share many characteristics with these deltas, the megadeltas are of special concern because they support large rural populations, and are all associated with at least one large and growing city (Figure 1).

The Asian megadeltas have responded to a variety of stimuli as they have evolved through the Holocene. They have become increasingly shaped by human influence, both through land-use change within the catchments and on the deltas themselves. The productive low-lying deltaic plains have been largely cleared of their natural vegetation, and exploited for agriculture, silviculture, aquaculture or settlement (Stanley and Chen, 1996). The economic future of these deltas in the face of global climate change, particularly sea-level rise, is inextricably linked with their environmental well-being (Milliman et al., 1989). It is the aim of this chapter to reassess and re-emphasise the interrelationships between geological evolution of deltas and sustainable economic development of the plains that characterise them. There is particular emphasis on the nine Asian megadeltas, but the principles of this analysis will be of general utility to the more numerous smaller deltas in the Asia-Pacific region as well as other megadeltas elsewhere in the world.

10.2. RECENT GEOLOGICAL EVOLUTION OF MEGADELTAS

The primary control on the development of the megadeltas of Asia is the large, highly-seasonal sediment load the rivers carry as a result of relatively rapid weathering and transport associated with active tectonism in the world's highest mountain range (Milliman and Meade, 1983). The region plays a disproportionately large role in the global land-sea flux of sediment as a result of substantial summer monsoonal rainfall and spring snowmelt caused by the seasonal northwards migration of the intertropical convergence zone. The big rivers, from the Indus to the Huanghe, carry annual suspended sediment loads of 100 to 1000 million tonnes (Milliman and Syvitski, 1992; see Table 1). It is primarily this catchment-derived sediment that has built the broad plains, although tide and wave processes can also effectively rework sediments from the delta front back onto the delta shoreline, as discussed in Chapter 4.

Evolution of each delta has been controlled directly by sea-level change as shown schematically in Figure 2. Megadeltas have developed at the mouths of these rivers during the Holocene for several reasons. Previous sea-level cycles, comprising alternate transgression (landwards movement of the shoreline) and regression (seawards movement of the shoreline), have formed low gradient plains that have provided suitable space, termed 'accommodation' space in the geological literature, for the accumulation of an extensive depositional wedge of sediment. Sand and mud have partially filled this accommodation space, forming near-horizontal plains, as a result of deceleration and stabilisation of sea level. The surface morphology of individual Asian megadeltas has formed during the past 6000 years while sea level has been relatively stable around its present highstand. There are structural controls that constrain the shape of some of the deltas; for example, the Irrawaddy fills a trough between the Araken mountain range and the Shan plateau, and similarly the

Chao Phraya occupies a structural depression in the central plain of Thailand. Inheritance from previous Quaternary landscapes also constrains the shape of modern megadeltas, with outcrops of Pleistocene terraces formed at previous sea-level highstands conspicuous as higher surfaces within, or flanking, the delta plains. Similar Pleistocene deposits underlie the modern deltas and have determined the accommodation space that has been available for deposition during the Holocene. Transgressive sediments underlie each of the deltas as a result of a fairly consistent pattern of postglacial sea-level rise across the region, but the various Asian megadeltas appear to have followed increasingly individual pathways over the past 6000 years. These two phases, the transgression associated with sea-level rise and progradation of delta landforms during the mid and late Holocene, are described below.

10.2.1 Transgression

At the peak of the last glaciation the sea was at least 120 m below present, with some evidence in the Indo-Pacific region for it having reached as much as 140 m below present (Curray and Emmel, 1982; Yokoyama et al., 2001). Postglacial sea-level rise resulted in inundation of the underlying Pleistocene surface. The position of the former shoreline is indicated by mangrove deposits, which record rapid flooding across the Sunda shelf (Hanebuth et al., 2000). In common with deltas worldwide, Holocene sedimentation began approximately 8,000 years ago as sea level inundated this underlying surface, typically encountered in drillholes at around 20-30 m below sea level (Stanley and Warne, 1994). The shoreline is recorded particularly by deposition of organic muds associated with mangrove forests in intertidal environments; for example, a pattern of landward migration of this narrow mangrove-fringed shoreline is implied by radiocarbon dating of the base of cores throughout the central plain of Thailand (Somboon, 1988). This transgressive basal sedimentary unit can also be detected on other deltas in the region (Hori et al., 2001, 2002, 2004; Tanabe et al., 2003a, b, c). The exception appears to be the GBM system, which is discussed below, where inundation of the prior surface occurred 9000-10000 years ago at depths of up to 70 m below present sea level (Umitsu, 1993; Goodbred, 2003).

Around 7000-6000 years ago, the sea level reached a level close to present, with several lines of evidence suggesting that it was slightly above present (1-2 m) throughout the region (Geyh et al., 1979; Woodroffe and Horton, 2004). Deceleration, and subsequent stabilisation of sea level marked a change from aggradational to progradational sedimentation (Chen and Stanley, 1998). At this time the delta shoreline extended to its most landward position, marking the inner extent of the delta; for example, in the central plain of Thailand the shoreline was north of the location now occupied by the city of Ayutthaya (Tanabe et al., 2003a), and in the case of the Mekong the shoreline was near the location now occupied by the city of Phnom Penh in Cambodia (Tanabe et al., 2003b). At the peak of the transgression rivers entered into the bayhead of estuarine embayments. Since that time there has been a regressive sedimentary pattern with the continued buildout of sediment seawards (Figure 2).

10.2.2 Progradation of delta plains

The Asia-Pacific region is distant from present polar ice or formerly extensive ice sheets which accumulated during the last glaciation. As a consequence the relative sea-level curve for the past 6000 years for most of the region is similar to the eustatic curve driven by ice-melt. Most melt of glacial ice terminated around 6000 years ago and for that reason sea level has shown little variation over recent millennia. In fact, in southeast Asia, radiocarbon dates indicate that the sea was relatively higher than present around 6000 years ago as a result of subtle hydro-isostatic adjustments to redistribution of mass on the earth’s surface. A series of oscillations have been inferred since then with periods during which sea level appeared higher than present around 5000, 4000 and 1500 years BP, interspersed with lower phases (Tjia, 1996; Woodroffe and Horton, 2005).

Deltas have prograded over this period. The resulting stratigraphy is shown schematically in Figure 2. During the period of sea-level rise up until 6000 years ago the mangrove fringe and associated intertidal environments migrated landwards. Since sea-level stabilisation, the shoreline has prograded with intertidal sediments such as mangrove muds and peat being deposited over nearshore shallow marine sediments. During this mid and late Holocene shoreline regression and progradation of the plains have extended distributary channels seawards such that their hydraulic efficiency has decreased and in many cases they have switched to a shorter route to the sea and a new locus of deposition (see Chapter 4.3.4 and 4.4.2).

10.3. DELTA MORPHOLOGY

The Holocene delta plain of each megadelta is defined as those areas which formed as a result of progradation. The landward margin of each can be defined as the limit of the mid and late Holocene delta plains. This maximum transgression demarcates the approximate position of the shoreline around 6000 years ago when sea level appears to have reached its present highstand in the region. The landward margin of the delta has been mapped during recent geological studies on several of the systems (Huanghe, Saito et al., 2001; Changjiang, Chen and Stanley, 1995; Hori et al., 2002; Pearl, Li et al., 1991; Red River, Tanabe et al., 2003c; Mekong, Ta et al., 2002a, b; Chao Phraya, Tanabe et al., 2003a). We are unaware of any mapping of this maximum transgression for either the Indus or the Irrawaddy, and have consequently adopted an extent as mapped by Wright et al. (1974). The extent that these authors show appears verified using digital terrain models (DTM) based on Shuttle Radar Topography Mission (SRTM, described below). SRTM analysis of those deltas for which the maximum transgression has been mapped confirms that this margin coincides with a marked change in gradient. In the case of the Ganges and Brahmaputra Rivers a large part of Bangladesh, as well as parts of West Bengal, north of the Indian city of Calcutta, comprises the GBM delta plain (Morgan and McIntire, 1959). Examining mass balances for the GBM has shown that the volume of sediment deposited within the delta in the period 10,000-8,000 years BP, termed the hypsithermal, equates to more than twice the volume presently brought down the rivers. The delta was aggradational from 11,000-7,000 years BP, implying that the rivers supplied as much as 2.5 times their present load (Goodbred and Kuehl, 2000a, b; Goodbred, 2003). The maximum transgression occurred around 23ºN in West Bengal (Bannerjee and Sen, 1988), and coincides with an elevation of around 3 m (Allison, 1998a). The extent of Holocene deposition for this system is based on a generalised margin inferred from the studies described by Allison et al. (2003), together with SRTM DTM data.

10.3.1 Plains topography

Shuttle Radar Topography Mission (SRTM) elevations, obtained by Synthetic Aperture Radar (C/X band, single pass radar interferometry), are available from the National Aeronautics and Space Administration (NASA) in a geographical projection at several resolutions (http://edcsns17.cr.usgs.gov/srtm/index.html). SRTM-1 is at 1 arc second, but the research-grade SRTM-3 was used in this study, averaged at 3 arc second, corresponding to a cell size of around 90 m on the ground. The SRTM data contain elevations to the nearest metre, with the sea surface set to zero. Data were masked using a shapefile of each delta extent defined as described above. Delta margins are imprecise because water levels rise and fall, land is eroded and deposited and in places is highly irregular. It is important to emphasise that many elements of delta surface topography encompass much variability within this 90 m cell size, for example, the ridge-basin relief on meander scroll plains (Brammer, 1996). Table 2 summarises the proportion of the elevations for each of the delta plains in a series of elevation slices, enabling a broad overview of variation in elevation of the plains, and providing insight into the complex mosaic of delta topography. The nature of the shuttle-derived topography is such that it cannot be regarded as precise; the returns for the Huanghe (especially for Jiangsu) and the Mekong both contain noise, backscatter from the sea surface and data voids. For this compilation, in order to give a broad overview of the topography of the plains, voids or outlier returns were discarded. The results for those finite values ranging from 1-20 m above sea level are summarised in Figure 3 and Table 2. Some general trends are described below for the individual deltas.

The summary of the proportions of different deltas in each of a series of broad elevation classes indicates considerable variability between deltas. The SRTM DTM for the Indus indicates that there is a general increase in elevation with distance from the coast. The Holocene history of this delta appears to have consisted of a series of delta lobes to the east of the present channel with progressive abandonment as the river has avulsed westwards (Holmes, 1968; Kazmi, 1984). The Indus delta does not reflect this delta lobe chronology in its relatively gradual shore-normal topographic gradient, in contrast to other deltas, for which DTMs show considerable variability in surface topography. For example, in the case of the GBM there are many natural levées flanking existing and former channels (Umitsu, 1985). These play an important part in channelling flow, are significant for human transport and livelihood, and influence the pathway of flood waters and the persistence of flooding. They can be clearly seen in the SRTM DTM, and coalesce to form a fluvial landscape over much of the portion of the delta north of 23ºN, meaning the northern section is considerably higher in elevation (Table 2). Furthermore, through the complex interaction of a series of factors, including subsidence, compaction and the reduced sedimentation in backwaters cut off from direct inundation, there can be extensive areas of plains that lie below flood levels (Stanley and Hait, 2000). For example the low-lying, actively-subsiding Sylhet basin, in places only 2 m above sea level, is clear in the DTM of the GBM system, and can be flooded by water that is up to 6 m deep in the wet season. The elevations cannot be used directly to infer the extent of flooding because of the variability of tidal range, which in places exceeds 5 m and the complex flood-water surfaces that vary from year to year. Nevertheless, the SRTM DTM indicates the low-lying areas flanking the former distributaries of the Ganges.

A particularly large proportion of the Mekong appears especially low-lying (note, many SRTM data voids were excluded from this delta). This is also the case with the Pearl, and the Huanghe. The abandoned former delta of the Huanghe river, along the coast of Jiangsu, contains some spurious STRM noise, but appears especially low-lying (Table 2). The Irrawaddy by contrast comprises low-lying plains that extend well inland towards the apex of the delta (Figure 3). The significance of these elevations needs to be considered in relation to the elevation of flood surfaces, whether these are high tide levels, storm surge levels or river flood levels in the wet season. However, none of these surfaces will be horizontal, so actual flooding remains a highly localised phenomenon.

Depositional coasts can be viewed in terms of the dominant processes that influence them, particularly in relation to river, wave and tide energy. Deltas have traditionally been classified into river-, wave- and tide-dominated deltas (Wright and Coleman, 1973; Galloway, 1975; Wright, 1985; Suter, 1994), summarised in a ternary diagram in which individual deltas are placed based on the balance of processes at their margins. Many of the deltas associated with large rivers are ‘river-dominated’, but the degree to which any of these factors dominate needs to be viewed relative to other processes, and it is possible to differentiate wave-dominated deltas from tide-dominated deltas. Wave-dominated sections of coastline are typically swash-aligned with a sequence of shore-parallel sandy ridges; tide-dominated sections are muddy and characteristically contain tapering and meandering tidal creeks fringed with mangrove forests. River-dominated sections of a delta are indicated by former distributary channels (paleochannels) and meander scroll bars.

The processes operating within megadeltas have become more clearly discriminated as each has evolved during the Holocene, either as a result of spatial separation of the processes that shape them, or with discrimination in time. The subaerial delta plain can be divided into an upper deltaic plain, which is dominated mainly by river processes. River domination is characterised by fluvial sediment supply and meandering and avulsing channels flanked by levées that are elevated above the general surface of the plains. The lower deltaic plain is usually within the zone of tidal influence, indicated by tapering and meandering tidal channels, or it may be dominated by waves in which case it is usually characterised by shore-parallel ridges of sand and shell. Asian megadeltas may contain different sectors dominated by different processes, as can be seen in the Red River delta (Figure 4). The western sector is wave dominated with shore-parallel beach ridges, and the eastern sector is tide-dominated with mangrove-fringed tidal creeks. The apex of this delta is river-dominated (Figure 4a), with the levées flanking active and former distributaries clearly distinguishable from SRTM DTMs (Figure 4b). These topographic trends can still be seen, although the delta plain is heavily settled with intensive land use, as apparent on the JERS image (Figure 4c).

The Indus is situated on a coast that experiences high wave energy (Wells and Coleman, 1984), and the Huanghe, emptying into the Bohai Sea with minimal tides, experiences wave reworking of the shore (Saito et al., 2000). In the case of most of the other Asian megadeltas, wave energy is relatively low, and the abandoned delta is tide-dominated. The delta can be divided into active sectors and abandoned sectors, as shown by Wright et al. (1974), and tide-domination becomes particularly apparent along the margin of the abandoned delta. The GBM shows the characteristics of an active delta plain, the Meghna Delta plain to the east is river-dominated, and an abandoned delta plain (or ‘moribund’ delta), the Gangetic Tidal plain to the west is tide-dominated. The distributaries draining into the Sundarbans which is a mangrove reserve covering most of the Gangetic Tidal plain carry less than 4% of the flow, and the plain is dominated by tides (Figure 5). There is an intricate network of tidal creeks. These are prominently tapered, and diverge into sinuous channels that meander though the mangrove forests (it is likely that the dense canopy of these mangrove forests has been detected by SRTM radar along the central portion of the delta front, west of the Haringhata River and south of Khulna, to record the uncharacteristically high returns in contrast to the surrounding low-lying tidal plain seen in Figure 3). This abandoned part of the plain, no longer receiving direct river-borne sediment, but continuing to subside in response to the loading of the shelf by sediment, is actively receding. For example, 100 km^2 has been lost from the Sundarbans in the past 30 years, with erosion concentrated on the southern shores of islands (Allison and Kepple, 2001), in contrast to the Meghna Delta plain which has prograded (Allison, 1998b).

The stratigraphy and Holocene progradation of the Mekong Delta has become clearer as a result of a series of recent studies. Sandy ridges have been formed episodically in the eastern side of the delta over the past 3000 years (Nguyen et al., 2000). Stratigraphy and chronology suggests that the delta has changed from a more estuarine and tide-dominated system, prograding seaward at around 30-35 m a^{-1}, to a more wave-dominated delta, as the offshore gradient became steeper, prograding at 11 m a^{-1} (Tanabe et al., 2003b). This represents an intrinsic threshold within the development of the delta. After the delta has infilled the initial extensive accommodation space, it has built into deeper water consequently developing a steeper shoreface (Ta et al., 2002a). Other intrinsic thresholds in delta development include the transition from mangrove forests to freshwater vegetation as the plains accrete vertically beyond the level at which they are influenced by saline or brackish water. Pollen diagrams from several of the deltas in the region record this transition (Woodroffe, 1993).

10.3.2 Distributary switching

Distributary switching occurs when, after some time of building seaward, a delta distributary has become over-extended and may adopt a shorter, alternative course to the sea. It is generally an intrinsic change triggered by the stage of delta development, although floods or earthquakes can also induce distributary avulsions. The Huanghe shows the most extreme of these avulsions (see Figure 1); it adopted a course discharging into the Yellow Sea in North Jiangsu in 1128 AD, and then readjusted to again flow into the Bohai Sea in 1855 AD (Saito et al., 2000). The muddy coast of the abandoned Hunaghe delta in Jiangsu has been rapidly eroding at a decelerating rate, from 147 m a^{-1} in 1855 to rates of around 27 m a^{-1} in the 1980s, and 20 km and 1400 km^2 of delta plain has been lost since 1855 (Li et al., 2004)

Distributary switching appears to have occurred repeatedly in the GBM system with active distributaries migrating eastwards with the successive abandonment of distributaries such as the Hooghly and Gorai (Figure 5). Levées persist as topographic irregularities in the system, and SRTM DTM shows that levées remain as high ground adjacent to abandoned paleochannels (Umitsu, 1985). SRTM DTMs also show prominent levées, giving considerable local variability to the topography for other deltas, for example the Red River, whose paleochannels can be seen in Figure 4c.

10.3.3. Delta morphodynamics at different time scales

It is clear that there are a range of processes in operation and that different processes operate over different time scales. This is summarised in Figure 6; insight into past geological processes can be most effectively reconstructed on millennial time scales, because stratigraphy and radiometric dating provide control on rates of change at millennial time scales. Thus the pattern of sea-level rise and the aggradation of deltas up to around 6000 years ago, which occurred synchronously throughout the region, can be studied by coring through the delta and deciphering the sedimentary sequence within cores. By contrast, the details of development of the plains over the past 5000 years are less clearly understood and require more detailed coring at a variety of sites, using a range of techniques. Dating of beach ridge sequences is beginning to constrain the pattern of coastal buildout (Ta et al., 2002a). Similarly the fluid dynamics and processes of sedimentation on short time scales (<years) are reasonably

understood; application of dating techniques such as ^{210}Pb and ^{137}Cs has clarified recent change in the GBM and Changjiang (cf. Kuehl, et al., 1989; Chen et al., 2004), but there remains a gap between the these dating techniques and radiocarbon timescales, resulting in uncertainty about patterns of change at decadal to century time scales. This constrains the effectiveness of forecasting change, with the way in which a delta will evolve becoming increasingly uncertain into the future.

Associated with the substantial sediment input has been subsidence of parts of the delta. Localised subsidence and associated consolidation, dewatering and compaction of sediments were identified as major issues for the GBM by Milliman et al. (1989) and for the Changjiang estuarine depositional sink (Chen and Stanley, 1993, 1995; Chen et al., 2000). Under natural circumstances the delta may have some propensity to offset this local subsidence by deposition of fluvial sediment, but this is considerably reduced when flows are constricted within embankments and levées. As will be illustrated below (see Figure 8) the pattern of subsidence is likely to vary spatially, as is the degree to which it is offset by the availability and accretion of sediment.

10. 4. THE HUMAN LANDSCAPE

The expansion of low-lying Holocene deltas appears to have coincided with, and is regarded as a trigger for, the appearance of urban centres of population in semiarid areas, because these societies could be supported by agriculture on the productive, seasonally-flooded plains (Stanley and Warne, 1993). By contrast, it has been suggested that the tropical Asian deltas were less favoured for human settlement as a result of their inaccessibility because of seasonal flooding and malaria (Büdel, 1966). However, the extent of early human use of the Asian megadeltas may have been underestimated. There are known to have been civilisations associated with the Indus Valley (Harappan period, around 6000 BP) and the Changjiang (Majiabang culture, around 7000 BP). In these cases, as with the deltas of the Nile and Mesopotamia, occupation began around the time that the deltas started prograding. In view of the prolific sedimentation and rapid vegetation growth, evidence of human use of the

Asian deltas has not been well-preserved; archaeological remains are less obvious, less well-preserved and less studied in these monsoonal, well-vegetated, and highly-active deltas. An exception is the Changjiang delta, where the earliest human occupation and agricultural cultivation has dated to around 7000 years BP on the southern delta plain (Stanley and Chen, 1996; Chen and Stanley, 1998). Numerous well-preserved Neolithic sites coincide with delta initiation (Chen et al., 2005). Preliminary prehistoric evidence has also been reported from the Mekong Delta extending back at least two millennia, to prior to the rise of the Angkor civilisation (Higham and Lu, 1998), and further evidence may remain to be discovered from the other wetter Asian deltas.

Associated with occupation of the river catchments, and the evolving deltas, human impacts have been both direct and indirect. Direct impacts result from exploitation of resources within each delta, including widespread land-use change to agriculture, silviculture and aquaculture in the rural areas, and more recent urbanisation. Indirect impacts have occurred through land-use and water-management changes within the catchment (Nilsson et al., 2005). The 20th century saw an escalation of human impacts across Asian megadeltas, and a further intensification seems inevitable as populations continue to increase and the Asian economies expand through the 21st century. On the delta plains, land use varies from subsistence agriculture particularly for rice, but also for other crops such as jute, to more intense aquaculture, such as shrimp farms, to the growth of major cities. Along the delta front of most megadeltas, extensive areas of the coastal fringe, supporting mangrove forests or saltmarshes have been destroyed to make way for short-lived shrimp farms, many of which do not appear sustainable. The deltas are important for local fish production, and major offshore fisheries are sustained by nutrient output from the distributaries.

Indirect human impacts have led to substantial changes in sediment load on many of these systems, simultaneously increasing sediment supply by enhanced erosion on some rivers and reducing it through retention in dams on others (Syvitski et al., 2005). The most extreme example is the Huanghe River, called the Yellow River because of its enormous sediment load that results from human clearance of vegetation in the loess plateau and consequent soil loss, increasing suspended load 2-10 times over the past 2000 years (Ren and Shi, 1986; Milliman et al., 1987; Jiongxin, 2003). Similar land-use changes have increased sediment loads at least 2 times on the Changjiang and Red River (Saito et al., 2001), and led to enhanced loads on other rivers (see Chapter 4).

The spread of wet-rice cultivation transformed these deltas into the rice bowls of Asia, once mastery of the floods was established. Flooding has been controlled to some extent, through engineered levées and embankments and with the spread of irrigation. Exclusion of natural flood waters from many areas of the delta plains has had some less desirable consequences, such as compaction and acid sulphate soil development, examined below. The redirection of nutrient-rich waters and their sediments have also had major implications for the productivity of deltas (see Chapter 4).

Patterns of flooding are not the same from year to year, but vary widely with climatic factors, and may show gradual trends as a result of human influence. For example, increased flooding has been observed in Vietnam, as a result of a combination of upstream deforestation, heavy rains, sea-level rise and blocking of lagoonal inlets and river mouths (Thanh et al., 2004). Flooding can be severe when river floods coincide with spring tide or surges. The August-October floods on the Mekong were especially extensive in 1991, 1994, 1996 and 2000, with severe consequences for rice production (Wassman et al., 2004) and waves broke dykes on the Red River delta in 1955 and 1996. Increased saline intrusion has been noted in tide-dominated distributaries of many of the deltas (Aung, 1993; Douglas, 2005).

Delta fronts along many of these megadeltas are undergoing a lowering of the surface and a landward retreat of the margin. Whereas in many instances this may be the result of natural processes in the abandoned delta plain, it has been exacerbated by human action. A further problem can arise where groundwater is extracted as is occurring for many of the big cities. Rapid subsidence associated with groundwater extraction was resulting in subsidence of parts of Shanghai at rates of up to 28 mm a^{-1}, but this has been reduced to 3-4 mm a^{-1} by regulating withdrawal (Han et al., 1995). Nevertheless, that has left central Shanghai such that it lies 2-3 m below storm surge levels, and dependent on the embankment built around the city to an elevation believed to correspond to the 1 in 1000 year flood level (6.9 m above the Wusun Datum, Chen and Wang, 1999). This contrasts with dykes on the Pearl River which are built for the 1 in 20 year flood level, and which do not have freeboard for sea-level rise. Similar restraints on groundwater extraction may slow subsidence rates within other cities on Holocene deltaic sediments such as Bangkok and Hanoi. Much of the erosion along the Gulf of Thailand may result from the relative sea-level rise due to compaction following ground water pumping (Phienwej and Nutalaya, 2005). As the morphodynamic behaviour of a delta is responsive to human intervention, an understanding of the distribution of population and their activities within each delta is necessary. The population characteristics of the megadeltas are described below; regional trends in population growth and urbanisation, and globalisation, are described in more detail in Chapter 7).

10.4.1 Delta populations

The Asian megadeltas now support enormous populations. In part this reflects the burgeoning populations of the two most populous nations on earth, China and India (see Chapter 7.2), but it is clear from gridded maps of population density that people within those countries are disproportionately concentrated within the river valleys and on the deltas of the large rivers (Small and Nicholls, 2003). The extensive subaerial delta plains of the Ganges and Brahmaputra rivers have a surface area in excess of 110,000 km^2, and almost the entire population of Bangladesh, comprising over 140 million people, as well as many millions in West Bengal in India, live on the delta plains built by these rivers. Excluding the uplifted fault blocks comprising the Barind Tract and the Madhupur Terrace on which much of Dhaka lies, the population of the GBM delta is more than 129 million.

Table 3 lists the populations of the other deltas calculated using the delta margins defined by the maximum Holocene transgression, and using the gridded population density estimates. The gridded population datasets are based on census returns distributed within administrative units, using a mass-conserving algorithm (Tobler et al., 1997). The updated and expanded GPW-3 (beta version), produced by the Center for International Earth Science Information Network (CIESIN), is adjusted to UN estimates of country total populations. These data include population estimates for 1990, 1995 and 2000, and an estimated population for 2015 using country-specific growth rates. Population densities have been interpolated assuming population to be uniformly distributed across each administrative unit. Data are gridded using 2.5 arc minute cells (4.6 km at equator). The geographic projection of these data, using latitude and longitude, means that the size of the cell on the ground varies with latitude, and population density figures need to be weighted for area using a further grid from CIESIN (http://sedac.ciesin.columbia.edu/gpw). Coastal grid cells have been given an area based on the proportion of that cell that is land. Spatial uncertainties in population distributions are generally larger than boundary uncertainties, and an example of the vagueness of the landward boundary is illustrated by the details of the Red River outlined by Tanabe et al (2003c, see their Figs. 2 and 3) who portray slightly different boundaries in consecutive figures of the delta. Delta populations for 2000 and 2015 shown in Table 2 were derived using ArcGIS raster calculator.

After the GBM system which stands out by its size and population, the next largest delta population consists of nearly 26 million associated with the Changjiang. The population on the Holocene plains deposited at the present mouth of the Huanghe consists of around 14 million, but the coast of Jiangsu on the abandoned Huanghe, adjacent to the Changjiang, has nearly 20 million. The Indus has the smallest population with around 3 million, and the other deltas each have 10-15 million. It is noteworthy that several of these estimates appear lower than some previous figures, for example those reported for Vietnamese deltas by Thanh et al. (2004), which presumably results from our stricter definition of the delta as defined by the Holocene maximum transgression.

The gridded population data are only an approximation of the spatial distribution of people within the deltas. Proportional allocation population estimates have generally been shown to be more reliable in denser population areas, such as the deltas, because there are usually more collection districts and topographic expression of delta margin also often coincides with administrative boundaries. However, the spatial resolution of census data does pose a fundamental constraint on the conclusions that can be drawn and is a limitation on calculating population in the near-coastal zone (see Figure 4d). Extrapolations of populations based on GPW2015 show a scenario of population at a sub-national resolution for 2015 (Table 2). These should not be considered projections because they are determined assuming continuation of recent geometric demographic patterns of growth between 1990 and 2000 censuses, adjusted at national level to UN 2015 population projections. They are presented only to emphasise the often dramatic patterns of continued growth. Urbanisation is the most significant contributor to growth (as described in Chapter 7.3); rural populations are expected to remain constant as illustrated by Jiangsu, where there is no major city, and where population is projected to decrease.

Although the gridded population data enable updated estimates of populations for each delta based on administrative units, it is important to recognise that people within the deltas are generally in highly nucleated settlements, and the spatial resolution of the gridded cells does not capture the concentration of settlements along higher ground, such as levées and beach ridges as can be seen in the case of the Red River delta in Figure 4. The scale of administrative units on which data are based is a major constraint, which although not known for the Red River delta, averages 25 km for Vietnam as a whole. Nevertheless this approach was preferred over alternatives, such as the modelled Landscan (Oak Ridge) or the global city lights dataset, each of which has their own constraints. As discussed below (see Figure 8), natural processes operate at different spatial scales, and so also do socio-economic processes; for example land tenure is often very fragmented, and individual holdings may involve properties of 1-2 ha spread across small plots in several dispersed places. It is critical to emphasise that, in common with the topographic summary above, the population data are not at sufficient resolution for detailed hazard analysis, or local vulnerability assessment. The rural-urban distribution of population is a major issue in these deltas; it is the subject of further development of the global gridded population data set using a GIS layer of urban extents, as part of a CIESIN project called, GRUMP, but present data do not allow resolution of this issue, which is discussed below, and in Chapter 7, based on more traditional assessments of city population data.

10.4.2 The emergence of megacities

Table 4 shows the rapid growth of several actual and emerging megacities in the region (cities of more than 8 million people, Nicholls, 1995), and their projected growth to 2015. Almost all the large urban agglomerations in the Asia-Pacific region are on the coast (see Figure 1 in Chapter 7), and many of the cities occur in one of several settings within, or adjacent to, the megadeltas. Shanghai, Guangzhou and Bangkok are each located on the Holocene plains in mid delta. Dhaka lies in mid delta, but sits largely on the Madhupur terrace, an uplifted section of mid-Holocene delta deposits (Brammer, 1996), meaning it is a little more elevated than the adjacent settlements. Also on the margin of this same delta is Calcutta, on the Hooghly River, a former distributary of the Ganges. Karachi, Ho Chi Minh City and Rangoon are similarly on the coastal margin of their respective deltas, whereas Tianjin is on the inland margin of the Huanghe. It is often the case that significant cities develop at the apex of the delta. Such is the case for Hanoi. In the case of the Mekong its margin has been considered to coincide with the border between Vietnam and Cambodia, mainly because Quaternary mapping of plains in southern Cambodia has not been undertaken; Phnom Penh occurs near the apex of the Mekong Delta, and other smaller cities also occupy such a position, such as Zhengjiang on the Changjiang. Populations of cities have been obtained from UN/DESA 2002. Collectively, the projected population of these cities for 2015 exceeds 125 million. The city of Dhaka is the most rapidly expanding in the world and is projected to expand by a further 71% by 2015, to exceed 22 million. Megacities are considered in greater detail in Chapter 7.

10.5. RESPONSE TO CLIMATE CHANGE

Anticipated impacts associated with climate change and concomitant sea-level rise involve coastal erosion, inundation of low-lying areas, saltwater intrusion, habitat loss, and flooding by river and storm surges. On Asian coasts these have implications for human populations, including displacing people, requiring land-use changes, and complicating water management, navigation and waste management (Paw and Thia-Eng, 1991). Regional forecasts of climate change, based on intercomparison of model-based projections using the latest IPCC emission scenarios provide only broad indications of what might occur. Scattergrams of the range of model predictions for the regions South Asia, Southeast Asia and East Asia, plotting temperature change against precipitation change, have been prepared by Ruosteenoja et al. (2003). These show that for Southeast and East Asia all models predict that temperatures will be warmer and that it will be wetter during each of the seasons through the 21st century. For southern Asia, models predict that it will be warmer, but they show a greater spread of predictions about rainfall, including some model predictions that show it decreasing.

Whatever present-day patterns of sedimentation are, these are dynamic and changeable, showing substantial variations spatially and temporally; these are already impacted by human adjustments. Future changes should be anticipated, although the consequences may not become apparent until some unanticipated outcome alerts coastal planners to a problem. Even without sea-level or rainfall changes, the deltas can be expected to continue to evolve and to show geographical and year-to-year variability. The challenge is to disentangle human impacts from natural adjustments, particularly intrinsic changes within the system itself. This becomes still harder where some of the physical constraints on the delta may be indirectly influenced by human factors, obscuring the magnitude of natural processes. Whereas erosion occurs because waves reach the shore having been generated by offshore wind, this is the proximal cause, but the underlying issues may be human activities in terms of changes to sediment budgets, subsidence or other causes. In this section, four issues are considered; the impact of sea-level rise, vulnerability to flooding, the effect of dam construction on sediment supply to megadeltas, and the role of extreme events.

10.5.1 Sea-level rise and inundation

Average global sea-level rise over the second half of the 20th century has been 1.8 ± 0.3 mm a^{-1} (White et al., 2005), and sea-level rise of the order of 2-3 mm a^{-1} is considered likely during the early 21st century as a consequence of the greenhouse effect. However, the regional expression of this is geographically variable, and as has already been stressed must be considered in conjunction with highly variable rates of subsidence within each megadelta. Local subsidence exacerbates sea-level rise projections, so for example rates of observed sea-level rise in Vietnam are already 2.24 mm a^{-1} (1957-1989) (Thanh et al., 2004). For the Chinese coast, relative sea-level rise predictions allowing for subsidence are of the order of 40-100 cm by 2050, which is much higher than the IPCC global-mean projections (Li et al., 2004).

Although the past provides some insights into how the plains that characterise each of the megadeltas has evolved, it is not a perfect analogue for what will happen if the sea rises in the future even allowing for increased human modifications. During the long period of more-or-less stable sea level over the past 6000 years, low-lying delta plains have built out, and the surface elevation of these deposits has been lowered in relation to current sea level through a series of processes, such as subsidence, flexure of the underlying plate in response to sediment loading, compaction of sediments, and dewatering. This is shown schematically in Figure 2, where it is clear that a rise of sea level across the broad prograded delta plains that now exist will differ from the aggradation of coastal environments during the postglacial transgression (e.g. stages 1 and 5 in Figure 2 are not directly analogous). Geomorphological reconstruction gives some guide to anticipated changes, but modern delta morphology includes extensive areas that are extremely low-lying. Some parts of delta plains may be below the elevation reached by the sea at high tide on the coast, but may not be subject to inundation at present because of subtle topographic variations of the plains surface not distinguishable from SRTM DTMs or attenuation of high-tide level through complex tidally-influenced channels. Hence, a complex pattern of land loss and inundation seems likely in response to sea-level rise.

In considering possible impacts and adjustments to sea-level rise, Broadus (1993) promoted the concept of a shore-parallel retreat as the sea rose to facilitate analysis of possible impacts. In the case of Bangladesh, he estimated that a 1 m rise of sea level would cover 7% of the habitable land, involving 5% of the population, with a 5% decrease of GDP. This approach has been widely adopted, despite the provisos and caveats that Broadus advocated, namely the uncertainty about sea-level rise, the fact that it would be gradual in comparison with human capacity to adapt, that costs would lie well into the future and could therefore be discounted perhaps amounting to only 1-2% of GDP, and that technological change might facilitate future economic savings. The concept of simple translation of the shoreline landwards as the sea rises, does not however capture the more complex changes that occur where variable topography is subject to diverse hydrodynamic processes.

By contrast, a companion paper by Brammer (1993) in the same volume expressed a contrary view, highlighting the geographical complexities of any detailed impact assessment. Based on considerable field experience, Brammer emphasised that the GBM delta plains are neither homogeneous nor static. Year to year variability and the occasional catastrophic changes are on a much greater scale than the gradual changes expected to result from a slowly rising sea level. In contrast to the view of shore-parallel retreat propounded by Broadus, Brammer implied that sedimentation within the mangrove-lined tidal channels of the Sundarbans might enable these to keep pace with sea-level rise, but that there might be greater implications for the population of the GBM system as a result of increased flood levels in mid delta. Altered flooding would have significant impacts on the resident population affecting the number of rice crops per year and rice yields, and necessitating heightening of house mounds and defences for roads and other communications.

The sensitivity of rice cultivation to flood conditions under scenarios of sea-level rise, and the consequences for the intensity and patterns of rice cultivation, is also a significant outcome of recent modelling by Wassman et al. (2004) in relation to the Mekong delta. Rice production will vary according to regional and local differences in depth and duration of seasonal flooding, soil moisture properties, salinity and irrigation practices. In contrast to an earlier study by Zeidler (1997) which considered that up to 20% of the rice producing area of Vietnam would be lost under sea-level rise, Wassman et al. (2004) used the Vietnam River System and Plains (VRSAP) model, a 2D finite difference hydraulic model, to simulate the changes in depth of wet season flooding under scenarios of sea-level rise. The modelling used observed hydrological parameters and the configurations and dimensions of channels as input, under scenarios of 20 and 45 cm higher sea level in the South China Sea. GIS-based interpolations of daily average water level were mapped in wet season months, to show spatial variations in the more extensive flooding and its impact on rice cultivation.

10.5.2 Coastal flooding and SRES climate and socio-economic scenarios

The extent to which coastal areas experience flooding in the future will be a function of changes in the natural systems as a result of climate change, but will also depend on a series of socio-economic factors, such as the ability and willingness of communities to invest in adaptation measures. This issue has been examined by Nicholls (2004), who considered the sensitivity of coasts around the world to climate and global mean sea-level rise using the HadCM3 model, driven by the Special Report on Emission Scenarios (SRES) emission scenarios (Nakićenović et al., 2000).

Based on 1990 population estimates, there appear to be about 200 million people around the world (4% of the total population) living beneath the 1 in 1000 year storm surge elevation, and 450 million people living beneath the 10 m contour (Small and Nicholls, 2003). Of these, on average about 10 million people per year experience coastal flooding due to storm surges (Nicholls, 2004). The average annual people flooded (also termed the people at risk) will increase in future as population increases, except where additional flood management and protection is undertaken. In the modelling, estimates of likely number of people flooded were calculated initially without sea-level rise, and then compared with conditions of higher sea level (Nicholls, 2004).

The SRES report supersedes the IS92 emission scenarios widely adopted by the IPCC to give an indication of ways in which the world's climate will be influenced by human adjustments. Four different pathways (A1, A2, B1, B2), termed storylines, have been outlined, being mutually consistent characterisations of how the world might develop, depending on environmental awareness and globalisation (Arnell et al., 2004). The A1 world is a global and economically-driven materialist/consumerist world, with increasing globalisation, rapid economic growth and technological innovation. The A2 world is economically-driven but much more localised, heterogenous with regional economic growth, but more diverse technological solutions and a gap between richer and poorer nations. The B1 world involves global co-operation, but has environmental policies and clean technologies rather than being entirely economically driven. The B2 world is environmentally conscious but more localised.

Population projections increase beyond the horizon of 2015 described above, and although global population continues to increase up to 2050 in all SRES cases, there is substantial divergence thereafter depending on scenario. The number of people flooded will increase as populations expand, but will depend on the exposed population, the surge regime including the magnitude of relative sea-level rise, and the adaptive capacity of the people, especially their ability to manage flooding. Under scenarios of high population growth, significant subsidence due to poor delta management, and limited economic growth, the number of people who might experience flooding could be very high, implying a regional catastrophe. Under scenarios of lower population growth, lower subsidence and higher economic growth (or access to other resources for adaptation) the flooding might be effectively managed.

Modelling was at a coarse national spatial scale, and does not consider the scale of individual deltas, yet alone the considerable spatial variability that either the topographic (SRTM) or population (GPW-3) datasets demonstrate within Asian megadeltas. Data were examined using 192 polygons that represent coastal countries in the early 1990s, subsequently aggregated to regional and global levels (Hoozemans et al., 1993). This highly aggregated scale imposes limitations on the interpretation of specific results. In the absence of global databases on flood protection levels, the standard of protection was estimated using national GDP per capita as a direct measure of adaptive capacity. The issue of protection standards is particularly problematic and assumes a range of protection scenarios from optimistic to pessimistic. Economic development serves to increase vulnerability through destruction of natural resources, such as the mangrove forests that might otherwise have acted as a first line of coastal defence against storm surges. Richer nations generally enjoy a higher level of protection through engineered structures such as embankments and other flood defences. This can be demonstrated with reference to China that already has 12,000 km of dykes constructed along its coast, which are reinforced and heightened periodically. Coastal provinces are generally prosperous, contributing a major component of Chinese GDP, and it has been calculated that the costs associated with these protection and adaptation measures to counter a rise in sea level of 65 and 100 cm correspond to only 0.008 and 0.017% of GDP respectively (Li et al., 2004).

In the context of the 1990s, it is apparent that a large proportion of the population at risk of flooding occurs in South Asia (4.3 million), and East Asia (2.9 million). Additional people will be flooded in future under each of the SRES scenarios as the populations described above expand through growth and in-migration. The most vulnerable socio-economic world is the A2, which has the largest population growth and the smallest increase in GDP per capita (Table 5). Without any rise in sea level, a further 18.4 million people worldwide, 12.4 million of them in South Asia, would on average be anticipated to experience flooding in any year (clearly in many individual years this would be exceeded). When sea-level rise is added to the modelling, an *additional* 13.4 million people in South Asia would be exposed to flooding (Table 5). It is important to note, however, that under alternative SRES scenarios the number of additional people at risk is considerably smaller. There are three implications of this generalised modelling: first, development pathway will have a more profound effect on susceptibility to flooding through the 21st century and beyond than the anticipated rate of sea-level rise; second, human-induced subsidence could greatly exacerbate the impacts of global sea-level rise due to climate change; and, third, these megadeltas make a disproportionate contribution globally to coastal vulnerability, with or without sea-level rise.

10.5.3. Impact of damming on sediment replenishment

Deltas are dynamic landforms maintained by a large supply of sediment. There are several potential storages that can be recognised on the sediment transport pathway from catchment source to receiving basin sink. Only recently have data become available to attempt to quantify the fractionation of the sediment between these storages across selected catchments. The availability of sediment in the headwaters for transmission downstream depends on rates of weathering, detachment and entrainment, and its transport depends on the competence of flow, with the potential for sequestration on the floodplains of the alluvial channel (see Chapter 4). Similarly that sediment which does make it to the apex of the delta can then be fractionated in various ways. Within the delta, distributaries may be active or abandoned and the proportions of the load that they carry can vary. The extent to which flow goes overbank is also important in that it constrains deposition on the delta plain surface. Monsoon flooding of the plains with sediment-laden waters may occur, but increasingly flood mitigation works are aimed to contain flow within the channel by levées, or artificial embankments. The sediment that reaches the delta front may be carried further seaward, and be lost to deep water, or where currents or wave action are strong, it can be reworked onto the abandoned part of the delta plain helping to maintain delta form. In the case of the Indus and GBM there is a fan in deep water, on which sediment has accumulated. On other deltas, such as the Huanghe, heavily-sediment laden, hyperpycnal flows carry turbid waters down the delta front (Wright et al., 1986). In the case of the Mekong mud is carried along the delta front and the muddy Camau Peninsula has built up by this longshore transport of mud in the wet season, with flow reversal and the upstream penetration of turbid waters in the dry season (Wolanski et al., 1998).

The pattern of sediment deposition also has considerable spatial variability to it, with sedimentation being more rapid in low-lying areas where water ponds as a result of flooding. Spatial variation in sedimentation has been demonstrated for the GBM system. Sandy river sediments, 3-20 m thick, dominate the upper delta plain. Tectonically-induced subsidence of around 1-4 mm a^{-1} in the Sylhet Basin (on the course of the former Brahmaputra River) has served to trap 70-80 Mt a^{-1} of sediment there. ^{210}Pb and ^{137}Cs dating of short cores indicates floodplain accretion of >10 mm a^{-1} in the modern braidbelt of the Brahmaputra River, sequestering >50 Mt a^{-1} of coarse sediments and 30 Mt a^{-1} of mud on the floodplains where accretion is 1-3 mm a^{-1} (Goodbred and Kuehl, 1998). Determining sedimentation rates over the subaerial lower delta plains is problematic, and it is spatially variable, with preferential fine-grained sediment deposition of up to 7-m thick in localised depressions called *bils*. Sedimentation rates of 1-2 mm a^{-1} in the southern delta plains have generally been balanced by high sediment supply from the Himalayan source. Riverine sediment supplied primarily by the Meghna leads to accretion in the river-dominated Meghna Delta plain of 5-16 km^2 a^{-1} (a process which has been successfully enhanced by engineering works and planting of mangrove forests). Some fraction of this sediment appears to be advected alongshore by westward flowing currents to the tide-dominated Ganges Tidal Plain, and within mangrove forests of the Sundarbans sedimentation rates of up to 11 mm a^{-1} have been recorded (Allison and Kepple, 2001). Nevertheless rapid subsidence, whether tectonic, flexural or through compaction and dewatering of sediments, leads to overall recession of this tide-dominated coast, with relict distributary shoals on the innermost shelf and erosion of the shoreline by 3-4 km since 1792 (Allison, 1998b). Around 30% of the sediment load of the rivers appears to be deposited on the subaqueous delta that has been prograding at 15-20 m a^{-1}.

Radiocarbon dating control on boreholes along the coast of several of the megadeltas has clarified the average rate at which deltas have been prograding over the past 2000 years. Over that period, the shoreline has migrated around 80 km at the mouth of the Huanghe, 100-150 km at the mouth of the Changjiang, 20-30 km at the mouth of the Red River, 30-40 km at the mouth of the Mekong, and 10-25 km at the mouth of the Chao Phraya. These are average rates, and even over this period human impact may have been occurring but is difficult to discriminate in terms of its effect on sediment dynamics. Rates may also vary as a result of natural factors. Many of the rivers of China continue to bring down such large volumes of sediment that, despite human impact and extensive land claim, they continue to prograde, and the coast is characterised by net wetland renewal (rates of 21 km^2 a^{-1} on Huanghe, 16 km^2 a^{-1} on Changjiang and 11 km^2 a^{-1} on Pearl) rather than net wetland loss (Li et al., 2004). Nevertheless, it is important to recognise that there is a threshold value of sediment input below which the system would cease to prograde and will start to retreat (see Chapter 4.2.4). For example it has been suggested that the Huanghe requires 245-300 Mt of sediment annually to maintain delta building, and if it receives less there will be net loss of wetland (Li et al., 2004). However, the current sediment discharge of the Huanghe is below this level due to operation of the Xiaolangdi Dam since 1999, resulting in coastal erosion for all the modern delta including its river mouth (Jiongxin, 2003).

In other cases the sediment load has clearly decreased (Syvitski et al., 2005); for example, the Kotri Barrage on the Indus River has substantially decreased flow and reduced sediment load (Milliman et al., 1984). The effect of dams is exacerbated by water extraction for irrigation and other use, and saltwater penetration up tidal channels and into agricultural land appears to be a consequence. Similarly the Farakka Barrage on the Ganges has decreased dry-season flow on the channel downstream, in an effort to maintain a navigable channel in the Hooghly ensuring access to Calcutta. Access to Haiphong is no longer available for big ships because of siltation of access channels. The Changjiang River has a load of around 5.3×10^8 t a^{-1} at the recently completed Three-Gorges Dam in its middle reaches (see Chapter 4.1). This dam will significantly reduce the supply of land-building sediment to the East China Sea, and there will be a need to recognise the effects of this and lags involved with movement of this sediment downstream in managing the coast. As a result of interference from numerous dams before operation of the Three-Gorges Dam, there has already been a decrease in the load that gets to the mouth of around 73%, and this has already resulted in a critical local loss of saltmarsh. Similar problems are encountered in the Red and Mekong river deltas; the sediment discharge of the Red River was reduced by 60-70% of the former level due to construction of the Hoa Binh Dam, and that of the Mekong already shows 10% reduction south of Laos due to dams in China, with plans for further dam construction.

Although accumulation of sediment in basins beyond the mouths of these large river systems does not record variations in sediment flux over the Quaternary (Métivier and Gaudemer, 1999), it is certainly clear that pathways and storages have changed significantly with sea-level fluctuations. Figure 7 illustrates this schematically. When sea level was lower during the last glaciation sediment appears to have been transported seawards and deposited on deep-water fans in the case of the Indus and GBM (Goodbred and Kuehl, 1999). During the late Holocene, under conditions of relatively stable sea level close to its present level, there has been progradation of delta plains with fractionation of sediment across the surface of those plains, along the delta front and offshore. Those parts of the abandoned delta which no longer receive sufficient additional sediment experience erosion, accelerated where the delta has been experiencing subsidence (see Chapter 4.2.4). In the case where the majority of sediment is sequestered behind dams, however, the supply of sediment to the coast is diminished and erosion and submergence become widespread. The example of the Nile is a case where chronic erosion has resulted from construction of a major dam (Milliman et al., 1989), but retreat of sections of coastline along other deltas around the world can also be attributed to dam construction and decrease of sediment supply.

10.5.4. The role of extreme events and related hazards

Climate change, and associated sea-level rise, will be gradual, and the incremental effects occur over many decades or longer. The Asian megadeltas are already subject to a series of extreme events and other hazards that have far-reaching impacts on delta populations and their livelihoods. Table 6 indicates several environmental hazards that are already of concern, and these impacts are likely to be exacerbated by environmental change.

Coastal erosion is already a prominent feature of many delta shorelines; in places it may be a natural component of the abandoned phases of delta development, but in other situations it has been accelerated by human agency. Those cities directly on the coast may be subject to erosion of the shoreline. Many of the megadeltas are prone to damage from cyclones, both through wind damage and through the associated surge and other weather-related hazards. Flooding remains a problem in many of the low-lying areas, and in other cases reduction of freshwater flows have led to saltwater penetration and acid sulphate soil development on the plains. Each of these hazards may already threaten population centres on the Asian megadeltas, almost all are likely to be exacerbated by global climate change and the continued human development of the catchment and delta plains.

Seawater intrusion has already been observed along almost all of the deltas, with particularly pronounced intrusion where freshwater flows have been reduced. Dry season saltwater penetrates further up distributaries on many megadeltas as river flows decrease (through natural diversion or human interference) and this will be enhanced if flows are reduced by further damming (Wolanski et al., 1998). Typhoons play a major role and there have been large death tolls from the associated storm surges. The coast of China has been hit by 390 storm surges over the period 1949-1986, more than 300,000 were killed in 1931, and flooding continues to result in human tragedies each year (Chen and Stanley, 1998). Whereas storms in east Asia are accompanied by surges of typically 1-2 m, a maximum of 3m has been experienced along the Vietnam coast (Thanh et al., 2004), and the worst in southern China was a surge that reached 5.94 m in Guangdong province (Li et al., 2004). Embankments provide protection up until their design height (generally built for 1 in 50 to 1 in 100 years storm), but they also reduce the capacity of the waterbody to hold large floods, promoting sediment deposition in the channel at slack water and further reducing channel capacity. Flooding levels can also be accentuated by heavy rain. Surges associated with such storms in the Bay of Bengal over the past 200 years have resulted in a death toll in the GBM system that probably exceeds 1.3 million people, including losses of more than 500,000 in 1970 and 100,000 in 1991 (Nicholls et al., 1995; Ali, 1996). Extreme events impact many other coasts; for example, Typhoon

Linda hit Vietnam and Thailand in 1997, and a super cyclone caused widespread flooding and an estimated 10,000 deaths in Orissa in eastern India in 1999.

Land claim has been important and is still practiced in China, where placing rocks to retain muddy water at high tide encourages sedimentation and claims further land. Such coastal engineering practices have a long history and can be traced back to protection works in the Tang Dynasty around 1000 years ago. These reclamations are assisted because the large sediment supply means that build-out is of the order of 20-40 m a^{-1}. Channels have sluices on them to prevent inundation under surges. Ground subsidence has been known in Shanghai since 1921, but has been reduced since restrictions on extraction of groundwater strictly enforced over period 1966 onwards. The city centre has subsided 2.63 m over the period 1921-1965; whereas and Tianjin subsided 2.7 m over the period 1959-1993 (Li et al., 2004). Erosion, where it is occurring on the coast of China is mainly due to reduced river supply of sediment, although some is due to sand mining, and only 10% can be attributed by these authors to sea-level rise

10.6 KNOWLEDGE GAPS AND RESEARCH DIRECTIONS

This chapter has concentrated on the natural processes that shape megadeltas at a range of scales, and advocates integration of the study of physical processes with data on socio-economic factors, in an effort to develop a more integrated approach to planning and management of the very populous megadeltas in the Asia-Pacific region. Figure 8 indicates that there is a range of natural and socio-economic processes operating at different spatial scales; our understanding of most of these is incomplete.

10.6.1 Natural processes

Geological investigations of Holocene (and longer-term) development of megadeltas provide insights into the directions and rates of processes and set the context within which to better manage deltaic processes so that resident populations can maximise the opportunities and minimise the hazards of their location. The delta plains that exist today represent particularly extensive near-horizontal coastal plains, most of which have been deposited during the mid and late Holocene. The former shoreline at the maximum transgression provides a useful boundary by which to define the delta extent. Whereas the long-term evolution of deltas can be reconstructed based on stratigraphy and radiocarbon dating, and the physics of fluid dynamics and sedimentary processes are understood at the microscale, the behaviour of individual deltas at decade-to-century scale remains poorly known, and the response to intrinsic thresholds with significance at planning and management timescales, such as distributary switching, is less reliably understood (Figure 6). There needs to be a greater focus on the extent to which sediment budgets of different components of a delta are influenced by different physical factors, particularly whether river, wave or tide processes dominate. For example, the abandoned delta plain of most Asian megadeltas is tide-dominated, and behaves in a different way to the river-dominated active delta distributaries that may receive substantial sediment loads.

A geological perspective, as developed in this chapter, need not imply that engineering projects on major deltas should not proceed, but, as stressed by Milliman et al. (1989), it could guide how projects are undertaken. All actions in these deltas are likely to have implications for the distribution and pathways of sediment. Ongoing research will be needed to establish not only what these impacts are, but also to examine the natural archive of sedimentological data within cores, and to determine comparative rates of sedimentation under past, present and future environmental conditions. In many cases it will be necessary for geoscientists to work with other specialists and to extend their consideration from sediment to other factors such as nutrients (see Chapter 4).

There has been increasing recognition that, in contrast to traditional engineering philosophies of 'controlling nature', it may be more effective and efficient to develop management that works more with nature (sometimes called 'natural systems engineering'), and to incorporate natural, or slightly modified, patterns of sediment movement to reduce the impacts of human activities (eg. Nicholls et al., 1995). There will be need for increased awareness of the sedimentological implications of actions in the future. In Asian megadeltas nutrient depletion may follow loss of sediment sources, and eutrophication associated with large populations remains a risk. Geochemical consequences of delta evolution have not received the attention they deserve; for example, proliferation of acid sulphate soils occurs once surface waters are excluded, by irrigation or drainage, and high levels of arsenic can occur in sediments as found in parts of the delta plains of the GBM and Red River systems.

Knowledge of the elevation of the land surface of these low-lying plains is a prerequisite for their better management. Traditional surveying has proved difficult across the intermittently flooded delta plains and survey control, against which sedimentation or subsidence rates might be assessed, has been problematic. New technologies offer sophisticated options to establish the subtleties of terrain variation. For example, the gross topography of Asian megadeltas can be compared, as in Figure 3, using digital terrain models based on shuttle imagery (SRTM). Remote sensing, such as the JERS and MODIS imagery, offers synoptic overviews of these poorly accessible areas, and airborne remote sensing techniques, such as laser (LiDAR) surveying can form the basis for terrain models at unprecedented resolution.

However, integrated geoscientific assessments of future delta evolution need to consider a range of natural processes, including subsidence, compaction, sediment supply, sea-level change and changes in tidal amplitude, which show both temporal and spatial variability within each delta (Figure 8). Delta environments are generally treated as passive, but they are dynamic, as emphasised by Brammer (1993). On many deltas, channels can be expected to change their position, and banks to erode. Changes in flow through the distributaries of each delta will respond to both environmental changes and to man-made interventions. For example, saline intrusion in the Ganges tidal plain has been aggravated by damming of former Ganges distributaries and abstraction of water. There is a clear need for better morphodynamic models of distributary processes, such as hydrodynamics, and sedimentation (see Chapter 4.4.2).

The trajectory of regional climate change through the 21st century and beyond is uncertain (Figure 8), but modest increases in temperature, precipitation and sea level seem likely in much of the Asia-Pacific region. Change in the future is assured, but it will be a considerable challenge to determine which components, or how much, of the observed future changes can be attributed to natural climate variability and how much to human influence. The nature of the impact of future sea-level rise remains uncertain, but appears to involve increased potential for loss of property, flood risk and loss of life, as well as other stresses such as the realisation of acid sulphate soil development following flood control. Too often potential sea-level rise impacts are viewed as linear; linear assessments are based primarily on simplistic assumptions ignoring the complexity and variability of landscape dynamics. However, significant non-linear effects can be expected in response to threshold levels, such as embankment and dyke heights, as well as the elevations of natural levées. This has been tragically demonstrated in the wake of Hurricane Katrina and its impact on New Orleans in August and September 2005. Although it is possible to continue to build up flood defences to counter gradual sea-level rise or regional subsidence, the impact when an event does breach the defences, may be substantially more catastrophic. Cities such as Shanghai and Bangkok, already known to have undergone subsidence and protected by flood defences, will become still more vulnerable in the future.

10.6.2. Societal response

Spatial variability in natural processes, such as geomorphology, hydrology and salinity patterns, provides the physical framework over which is draped considerable spatial variability in human use of the landscape, including settlement, communications and land use and tenure (Figure 8). The GBM system is by far the largest and contains a population of well over 100 million people, and the most rapidly expanding megacity (Dhaka). Other deltas have millions of people, and are also experiencing rapid urbanisation with several more cities either already megacities or likely to become so during the first half of the 21st century. Each of these factors varies at spatial and temporal scales that differ within and between deltas. Combining natural resource and socio-economic datasets, such as DEM and population datasets (as in Figure 4) is a powerful method to examine exposure to risk, but it must be remembered that natural and anthropogenic processes operate at differing scales, and rarely is information available at the optimal scale for detailed vulnerability assessment.

The topography of the Asian megadeltas is summarised in Figure 3, using SRTM DTMs. This shows the broad pattern of natural landscape variation but each comprises a more locally variable mosaic of landforms than is captured by the space-based global overview data. Similarly, the distribution of people, estimated from gridded population statistics, also involves spatial clustering at scales that are not fully amenable to analysis at the scale of global data. Thus, while the combination of the two datasets gives broad generalisations of the enormous numbers of people already at risk of flooding, more detailed vulnerability assessments will need to be based on data that can be appropriately synthesised across scales (Figure 8). The Asian megadeltas are already subject to considerable spatial variability in both physical and human landscapes, and this complexity will be compounded, and the impacts generally exacerbated, as a result of changing climate.

Low-lying areas appear most vulnerable to inundation, but their susceptibility is a function of whatever protective measures are instigated to reduce risk. Any consideration of sensitivity to these impacts is highly dependent on socio-economic scenarios and the different possible development pathways. There is no question that much of coastal Bangladesh is very vulnerable; much already experiences a range of stresses, and sea-level rise is likely to be an additional stress on an already heavily impacted coast. This is also true of the other megadeltas; the natural processes within these deltas are now inextricably linked with human use of resources. Rice production has gone from subsistence, to self-sufficiency and in many areas rice is now exported, based on judicious cropping of rice in relation to flood levels. Choice in adoption of several possible productive activities across the delta plains in addition to agriculture (eg. forestry, fish production, prawn farming, or salt production) increases the potential adaptive capacity of communities. Research on multiple land use across megadeltas is in its infancy. For example, changes to flooding conditions as a result of change in precipitation or sea-level can be modelled, as shown by Wassmann et al. (2004) for the Mekong Delta, but implications for rice production or adoption of alternative land-use options have yet to be explored in detail. Detailed modelling of this kind provides insights into impacts of a higher sea level, but does not include a series of additional impacts, such as the significant observed effects of increase of dry season tide levels and saline intrusion, which may also affect rice productivity. Nor does the modelling include the effects of extreme events such as storm surges, or the geomorphological changes in channel morphology that may result from changed processes.

More research is needed into the roles of extreme events in these systems. Nevertheless, whereas weather-related hazards, such as those listed in Table 6, exert occasional acute impact on deltaic coasts, it seems inescapable that human activities are often a chronic stress on the system. Synergistic effects between several stresses will often increase the vulnerability of the low-lying delta plains generating impacts that are sometimes quite unexpected. Finding the appropriate balance between flood control and sediment delivery remains a challenge for Asian megadeltas, in common with large deltas in developed countries such as the Mississippi. As Asian societies become increasingly prosperous, adaptation becomes more affordable; for the poorest societies, such as those in Bangladesh, there remains low adaptive capacity, and it is highly uncertain how development will modify this situation (eg. Nicholls, 2004).

Human activities also involve many negative effects, including changes to supply of sediment, water and nutrients, as well as loss of habitats and spread of pollutants. There is a need for more research into the ecological footprint of megacities and urban agglomerations on the environment, as well as an understanding of their role in globalisation, as discussed in Chapter 7. With improving living standards, there is likely to be increased demand for flood protection, and less tolerance of flood damage. It is clear that susceptibility to flooding is very sensitive to the extent of flood management and in this respect socio-economic factors often over-ride climatic factors. Water management has a long and proud history in these deltas but damming of the upstream rivers poses a major threat, with reduced sediment and nutrient supply, as well as altered water conditions. This is also usually associated with increased saline intrusion, which can be a dramatic impact in itself.

Sedimentation in one sector of the delta may offset subsidence, but both processes occur at rates that equal or exceed present rates of sea-level change. Human use of these deltaic environments, for whatever purposes, whether urbanisation, agriculture or subsistence, will have economically significant impacts if the balance between sediment demand and supply is upset, even without further accentuation through global climate changes. By encouraging long-term perspectives on delta utilisation it may be possible to undertake sustainable development that will minimise future vulnerability. Given that all the Asian megadeltas are so sensitive to a range of natural and human-induced drivers of change, an integrated assessment approach is fundamental to understanding delta vulnerability to climate and other change.

The complexity of delta systems with the multitude of interacting natural and socio-economic factors suggests that we need to build on the earlier study of Milliman et al. (1989) and begin to consider all the factors that will shape future delta evolution. This indicates the need to collect much more data on these megadeltas, and to undertake multidisciplinary studies. Vulnerability analyses need to be focused on detailed local factors such as topography and integration with flood levels, land use, and other relevant factors. Existing population data rarely adequately represent the extent of urbanisation and the rapid growth of megacities and urban agglomerations in the megadeltas, and their ecological footprint needs to be examined (see Chapter 7). Such assessments are challenging from a number of perspectives, but are essential if scientific understanding is to be translated into useful guidance for coastal management.

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developed with fractionation of sediment between the subaerial delta, the delta front and the prodelta. In the 20th/21st centuries human retention of sediment in upstream dams has been, or is likely to be, a major driver of delta change.

Figure 8. Schematic representation of spatial variability in the natural processes and human usage of megadeltas. Different physical processes are manifest at different spatial scales, and socio-economic processes also operate at different scales.

Table 1. Principal characteristics of the large rivers of Asia including estimated pre-disturbance and present suspended sediment load.

Megadelta	**Catch-ment area[1] km^2 x 10^3**	**Mean annual dis-charge[1] m^3 s^{-1}**	**Mean annual discharge[2] m^3 s^{-1}**	**Mean annual sediment[3] load t x 10^6**	**Pre-human sediment discharge[2] kg s^{-1}**	**Post-human sediment discharge[2] kg s^{-1}**	**Max tidal range m**	**Mean wave height m**	**Trapping efficiency[2]**	**Regulation by dams[1] %**
Indus	1082	6564	3333	385	9593	3686	~3	~2	0.54	13
GBM	1667	22102	40025	1402	40534	46287	>4	~1.2	0.02	8
Irrawaddy	414	11953	20501	260	16331	8239	~3	~1	0.00	1
Chao Phraya	179	961	987	11	452	256	~2	~0.2	0.26	76
Mekong	806	15900	15029	150	2551	2531	~4	~0.9	0.17	3
Red	171	3900	2487	130	1039	4119	~4	~0.7	0.00	3
Pearl	409	10700	8732	69	1547	1427	~3	~0.7	0.35	31
Changjiang	1722	29460	29583	480	109444	49504	>4	~1	0.67	12
Huanghe	945	1990	1438	1080	3237	931	1.2	~1	0.97	51

[1] Data from Nilsson et al. (2005)

[2] Data from Syvitski et al. (2005)

[3] Data from Métivier and Gaudemer (1999)

Table 2. Relative elevation of megadelta plains as derived from Shuttle Radar Topography Mission (SRTM) 3-arc DEM. Percentages are for cell distribution within 0-20 m range.

Megadelta	**<2m**	**2-4m**	**4-6m**	**6-8m**	**8-10m**	**>10m**
Indus	21.0	23.2	13.7	11.0	8.9	22.2
GBM (N of 23ºN)	0.3	2.6	8.7	15.1	16.4	56.9
GBM (S of 23ºN)	9.2	25.2	27.2	17.0	10.8	10.6
Irrawaddy	4.0	28.1	29.1	13.3	8.2	17.3
Chao Phraya	12.4	35.8	33.8	13.1	3.5	1.4
Mekong	45.3	35.7	13.6	4.0	1.1	0.3
Song Hong (Red)	24.8	37.8	20.7	9.0	4.3	3.4
Pearl	37.5	21.9	13.1	7.9	5.2	14.4
Changjiang	13.7	42.8	33.4	7.81	1.5	0.8
Huanghe	24.1	31.3	24.2	13.7	4.9	1.8
[Jiangsu]	53.8	29.3	10.1	3.8	1.8	1.2

Table 3. Estimates of population within the Holocene deltaic plains of megadeltas, based upon GPW_3, 2.5 arc minute gridded population of the world (CIESIN) for 2000 and 2015.

Megadelta	**Area km^2**	**Population 2000**	**Population 2015**	**Increase (%)**
Indus	19800	3058500	4425100	+45
GBM	115600	129931100	166217000	+28
Irrawaddy	31500	10591700	12163600	+15
Chao Phraya	11600	11485600	16487900	+44
Mekong	37900	15754200	19039800	+21
Song Hong (Red)	9900	13293900	16063400	+21
Pearl	5900	9846400	27166900	+176
Changjiang	15600	25945700	33147500	+28
Huanghe	25100	14060400	16614100	+18
[Jiangsu]	30300	19930700	14978400	-25

Note. Area of delta plain has been determined from gridded population cell count, and is only approximate as it does not take into account areas that are covered by water, including major distributaries.

Table 4. Actual and emerging megacities associated with Asian megadeltas; their growing populations (1975, 2000 and 2015 projected: after UN/DESA, 2002).

Large city	**Megadelta**	**Relative location**	**Population (millions)**		
			1975	2000	2015
Karachi	Indus	Delta margin	4.0	10.0	16.2
Calcutta	GBM	Delta margin	7.9	13.1	16.7
Dhaka	GBM	Mid-delta terrace	2.2	12.5	22.8
Rangoon	Irrawaddy	Delta margin	1.8	4.4	6.3
Bangkok	Chao Phraya	Mid delta	3.8	7.4	9.8
Ho Chi Minh City	Mekong	Delta margin	2.8	4.6	6.3
Hanoi	Red	Delta apex	1.9	3.8	5.2
Guanzhou	Pearl	Mid delta	3.1	3.9	4.2
Shanghai	Changjiang	Mid delta	11.4	12.9	13.6
Tianjin	Huanghe	Delta margin	6.2	9.2	10.3

Table 5. Regional incidence of flooding (millions of people per year) as modelled for the 2080s in terms of the HadCM3 SRES scenarios under lagged evolving protection (low subsidence and low population growth scenario), with the impact of a rise in sea level (in italics) in terms of additional people flooded. Sea-level rise varies from 22-34 cm, in response to SRES drivers (after Nicholls, 2004, Table 14).

Region	1990	2080							
		A1	+*SLR*	A2	+*SLR*	B1	+*SLR*	B2	+*SLR*
South Asia	4.3	0.1	*0.6*	12.4	*13.6*	0.1	*0.2*	1.0	*1.3*
Southeast Asia	1.9	0.1	*0.5*	3.6	*0.4*	1.1	*0.1*	0.2	*0.1*
East Asia	2.9	0.0	*0.0*	0.8	*0.1*	0.0	*0.0*	0.1	*0.0*
Global total	10.3	0.4	*6.6*	18.4	*28.3*	1.4	*1.4*	3.0	*15.6*

Table 6. Summary of major hazards presently experienced on Asian megadeltas.

Megdelta	**Erosion**	**Cyclone**	**River floods**	**Storm surge**	**Saline intrusion**	**Subsidence**	**Dam**	**Acid soil**	**As**
Indus	X	X	?	?	X	?	XX		
GBM	X	XX	XX	XX	X	X	X		XX
Irrawaddy	X	X	XX	?	XX	?	X		
Chao Phraya	XX					XX	X		
Mekong	?	X	XX	X	XX	?	X	XX	
Red	X	X		X		XX	X	X	X
Pearl	?	X	X	X		X	X	X	
Changjiang	X	X	XX	X		XX	X		
Huanghe	X		X			X	X		

Note. Acid soil refers to identified acid sulphate conditions; As refers to arsenic contamination of shallow wells.

Megdelta chapter Figures

Fig. 1

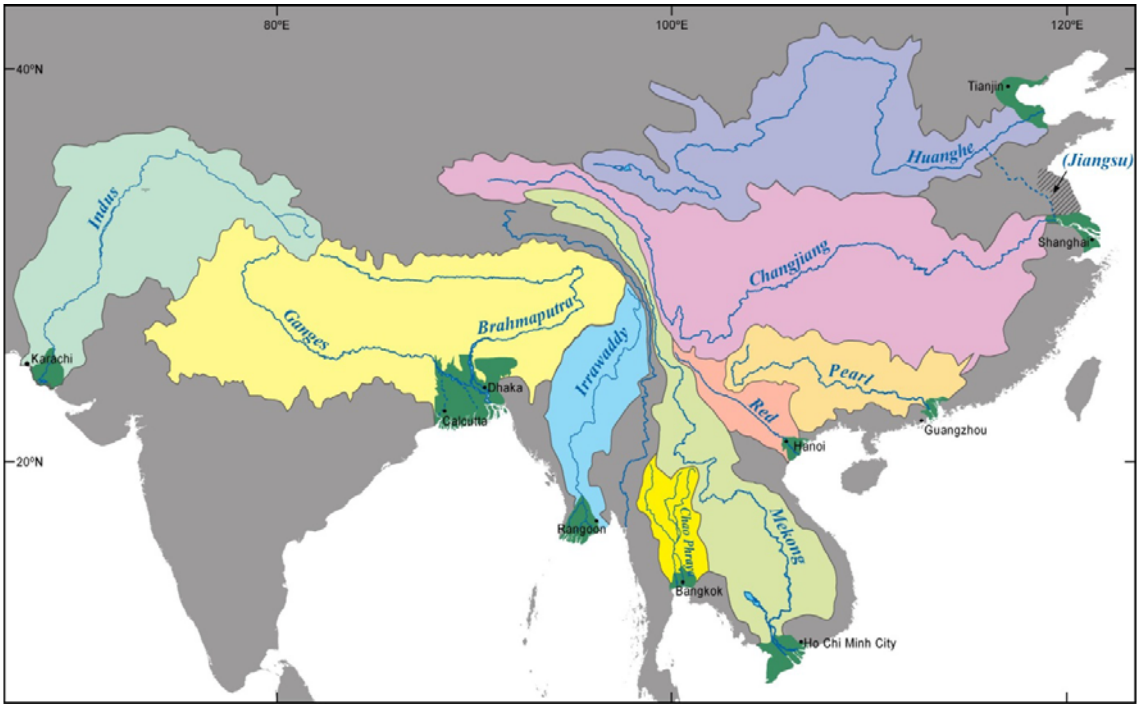


Fig. 2

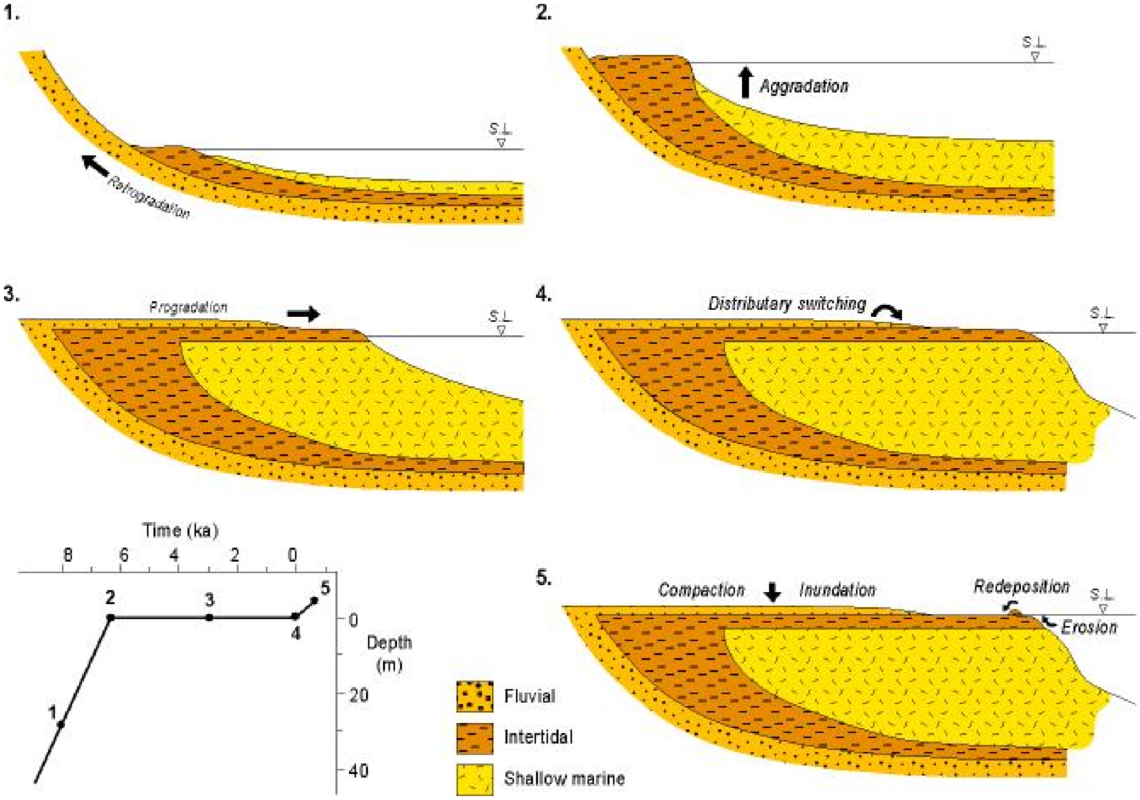


Fig. 3

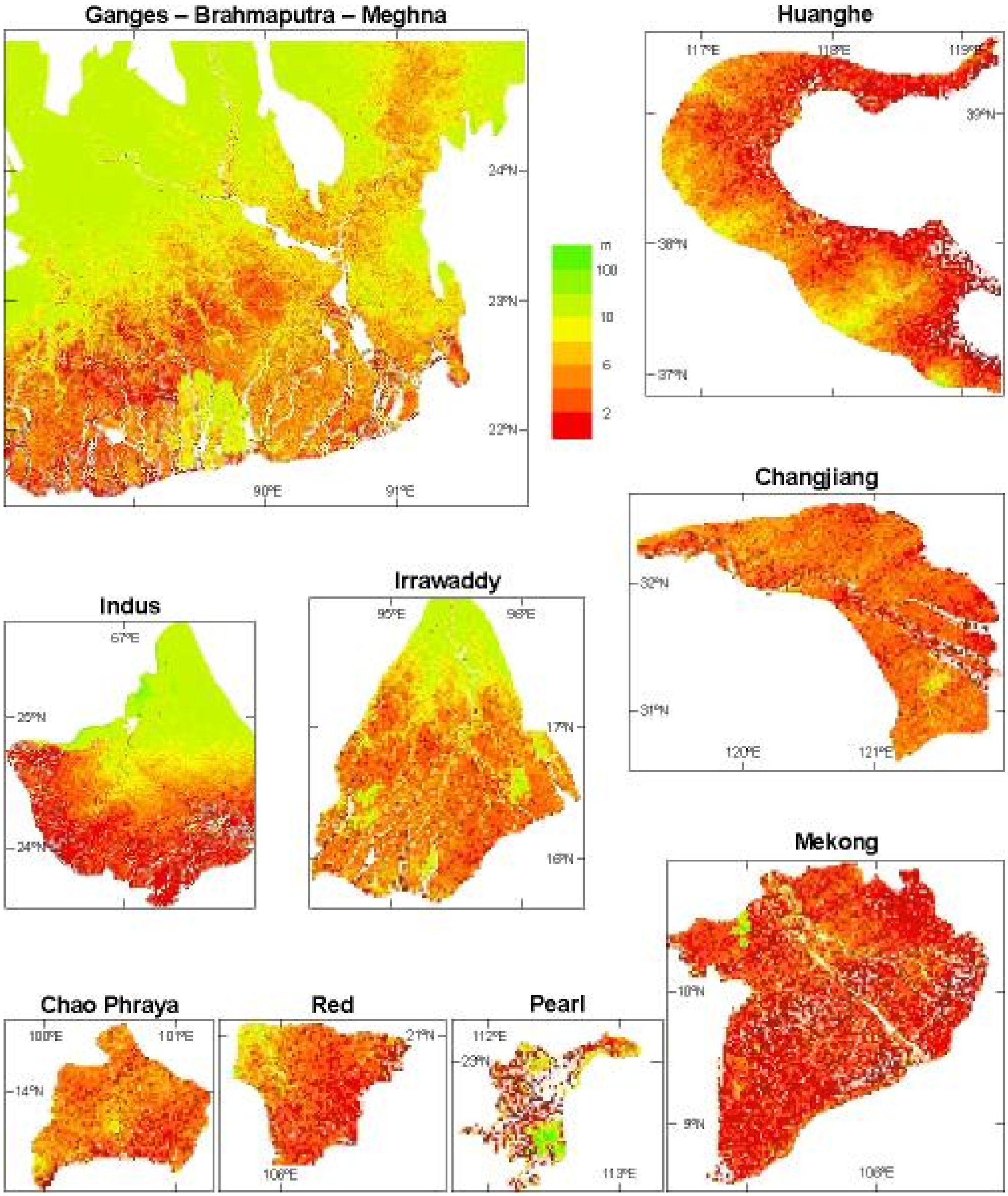

Ganges – Brahmaputra – Meghna
24°N
23°N
22°N
90°E
91°E
m
100
10
6
2
Huanghe
117°E
118°E
119°E
39°N
38°N
37°N
Changjiang
32°N
31°N
120°E
121°E
Indus
67°E
25°N
24°N
Irrawaddy
95°E
96°E
17°N
16°N
Mekong
10°N
9°N
106°E
Chao Phraya
100°E
101°E
14°N
Red
21°N
106°E
Pearl
112°E
23°N
113°E

Fig. 4

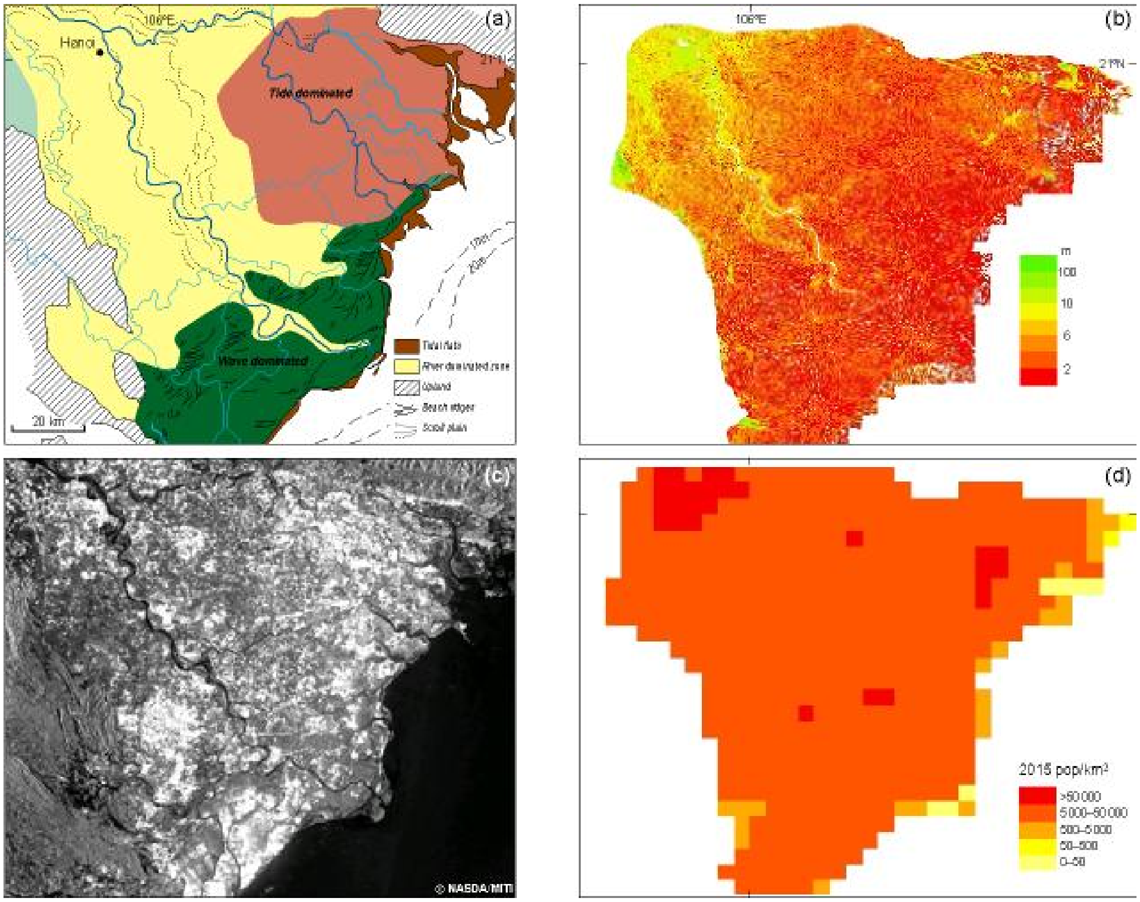

(a)
106°E
Hanoi
21°N
Tide dominated
Wave dominated
10m
20m
20 km
Tidal flats
River dominated zone
Upland
Beach ridges
Scroll plain
(b)
106°E
21°N
m
100
10
6
2
(c)
© NASDA/MITI
(d)
2015 pop/km²
>50 000
5 000–50 000
500–5 000
50–500
0–50

Fig. 5

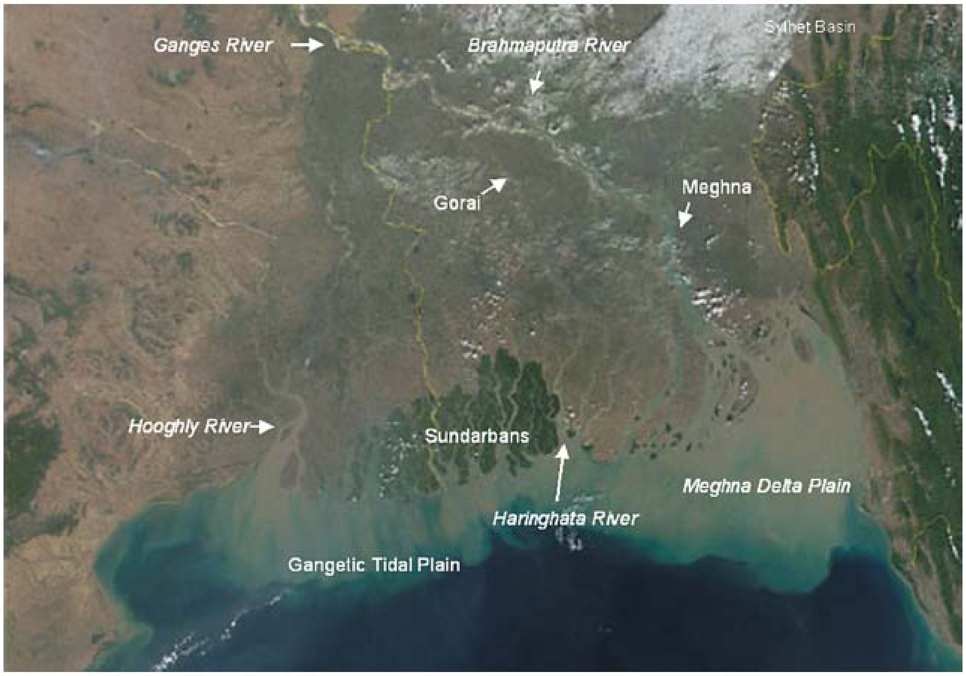

Ganges River
Brahmaputra River
Sylhet Basin
Gorai
Meghna
Hooghly River
Sundarbans
Haringhata River
Meghna Delta Plain
Gangetic Tidal Plain

Fig. 6

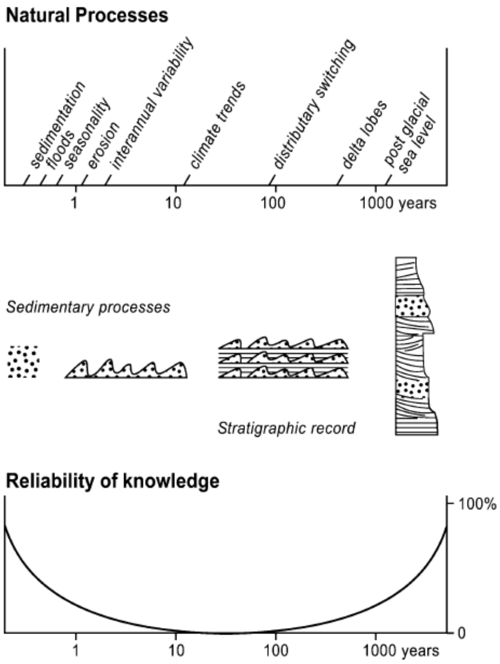

Natural Processes
sedimentation
floods
seasonality
erosion
interannual variability
climate trends
distributary switching
delta lobes
post glacial sea level
1
10
100
1000 years
Sedimentary processes
Stratigraphic record
Reliability of knowledge
100%
0
1
10
100
1000 years

Fig. 7

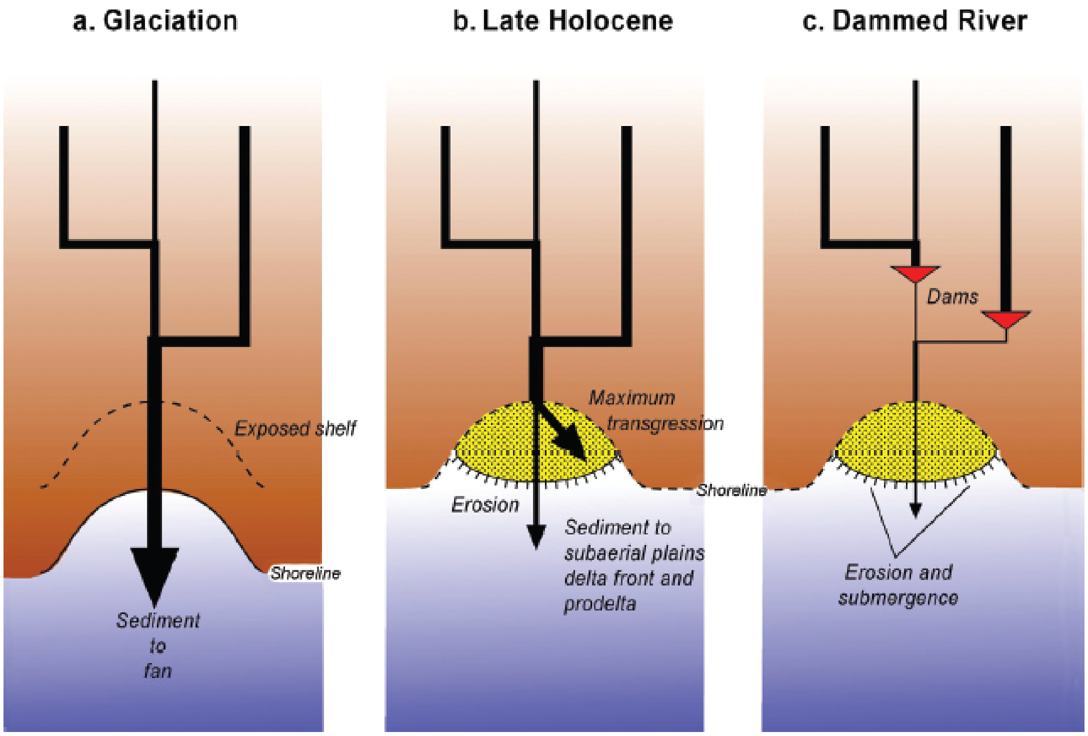
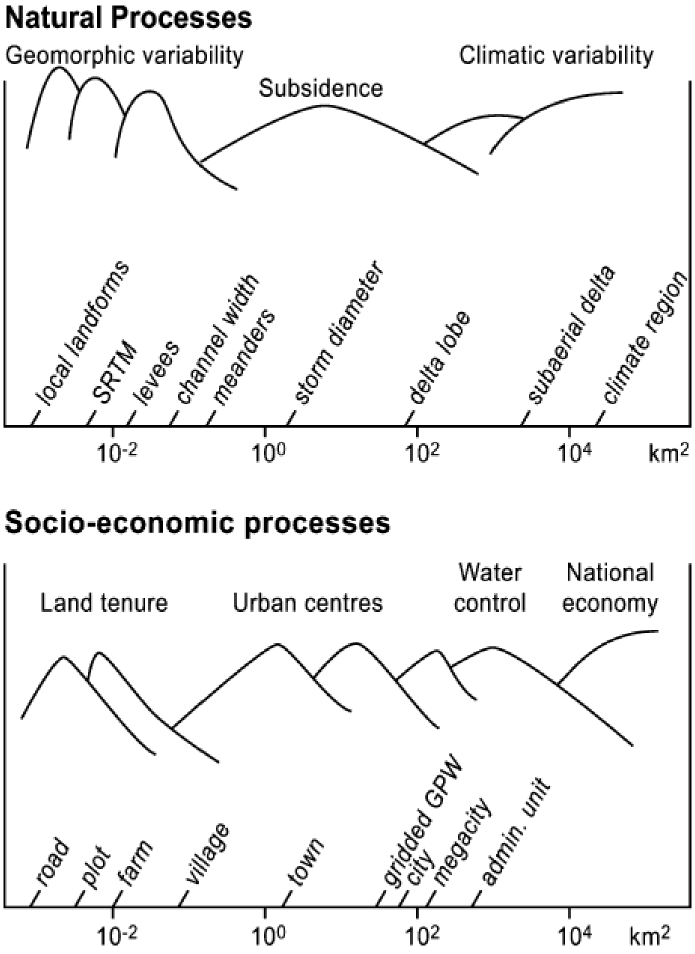

a. Glaciation
Exposed shelf
Shoreline
Sediment to fan
b. Late Holocene
Maximum transgression
Shoreline
Erosion
Sediment to subaerial plains delta front and prodelta
c. Dammed River
Dams
Erosion and submergence

Fig. 8


Natural Processes
Geomorphic variability
Subsidence
Climatic variability
local landforms
SRTM
levees
channel width
meanders
storm diameter
delta lobe
subaerial delta
climate region
10-2
100
102
104
km2
Socio-economic processes
Land tenure
Urban centres
Water control
National economy
road
plot
farm
village
town
gridded GPW
city
megacity
admin. unit
10-2
100
102
104
km2