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Abstract

Susceptibility of Asian megadeltas to climate change, including sea-level rise, is investigated using GIS. The Indus, Ganges-Brahmaputra-Meghna, Irrawaddy, Chao Phraya, Mekong, Red, Pearl, Changjiang, and Huanghe deltas began to form around 6000 years ago and have prograded since. The surface topography of active and abandoned delta plains is examined using digital terrain models derived from Shuttle Radar Topography Mission data and channel morphology is investigated using radar imagery. After delta plains are abandoned they become increasingly dominated by tidal processes. Population density is estimated using gridded world population data but highly variable local microtopography and uncertainty regarding future climate changes preclude detailed vulnerability analysis.

Keywords

Assessing, vulnerability, Asian, megadeltas, climate, change, using, GIS, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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ASSESSING THE VULNERABILITY OF ASIAN MEGADELTAS TO CLIMATE CHANGE USING GIS

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ABSTRACT: Susceptibility of Asian megadeltas to climate change, including sea-level rise, is investigated using GIS. The Indus, Ganges-Brahmaputra-Meghna, Irrawaddy, Chao Phraya, Mekong, Red, Pearl, Changjiang, and Huanghe deltas began to form around 6000 years ago and have prograded since. The surface topography of active and abandoned delta plains is examined using digital terrain models derived from Shuttle Radar Topography Mission data and channel morphology is investigated using radar imagery. After delta plains are abandoned they become increasingly dominated by tidal processes. Population density is estimated using gridded world population data but highly variable local microtopography and uncertainty regarding future climate changes preclude detailed vulnerability analysis.

KEYWORDS: GIS, DELTAS, TOPOGRAPHY, POPULATION, CLIMATE CHANGE

INTRODUCTION

Coasts appear to be particularly susceptible to impacts as a result of human-induced climate change. Amongst the most vulnerable coastlines are the low-lying plains associated with deltas and estuaries (McLean and Tysban, 2001; Nicholls et al., 2007). In order to better assess the relative vulnerability of different coastlines and provide quantitative information on the impacts, there have recently been a series of global vulnerability assessments (e.g. Hoozemans et al., 1993). For example, a global database of world coastlines has been developed as a part of the European Union DINAS-COAST project, integrating information on physical, ecological and socio-economic characteristics (Vafeidis et al., 2005). Although the project included a flexible, interactive assessment tool, termed DIVA, it is based on decomposition of the world's shoreline into a series of 1-dimensional coastal segments and does not therefore capture the multidimensional complexity of extensive low-lying areas such as deltas (David et al., 2008). This paper describes a standardised approach to describe the surface topography and population distribution for the 9 major Asian megadeltas using GIS.

PHYSICAL CHARACTERISTICS

Deltas occur at the mouths of large rivers where substantial sediment loads are brought to the coast. The Asian megadeltas are a series of extensive, productive and heavily populated delta plains at the mouths of the Indus, Ganges-Brahamputra-Meghna, Irrawaddy, Chao Phraya, Mekong, Red (Song Hong), Pearl (Zhujiang), Chiangjiang (Yangtze) and Huanghe (Yellow) Rivers (Figure 1). These rivers are fed by runoff, snowmelt and sediments from the uplifting Himalayan system and are influenced seasonally by the monsoon. In addition to intensive

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agriculture, aquaculture and silviculture, they are becoming rapidly urbanised and contain some of the world's largest, and most rapidly growing cities, many of them already megacities (cities of more than 8 million people).

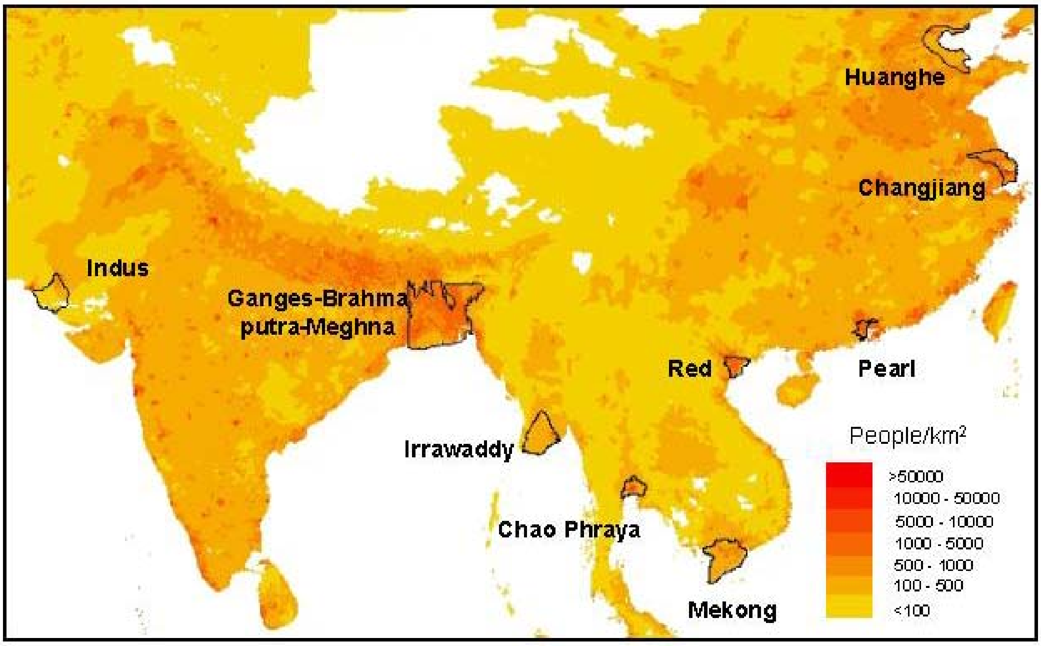

Figure 1. Gridded population density of Asia (based on CIESIN, GPW3 2000), showing concentration in river valleys and on megadeltas

Holocene delta evolution

The Holocene evolution of the extensive deltaic plains associated with Asian megadeltas provides the context within which to understand modern sedimentation patterns and deltaic processes and is fundamental to planning and sustainable development in these heavily populated areas. At the millennial scale, there has been a broadly similar history of development for each delta characterised by transgression during the final stages of postglacial sea-level rise up to around 6000 years ago, with deposition of intertidal or shallow marine sediments unconformably over an eroded Pleistocene alluvial surface (Tanabe et al., 2003a, b).

Each delta has followed an increasingly distinctive and individual evolutionary pathway during the past 5-6 millennia as a regressive sequence of sediments has prograded seaward (Woodroffe, 2000). Different deltas can be placed within a framework in relation to the physical processes that exert most influence on their development, river, wave and tide processes. River-domination can be inferred where there are prominent levées and evidence of channel meandering or avulsion, such as paleochannels. Wave-domination is characterised by shore-parallel sand ridges, often coalescing into beach-ridge plains. Tide-domination is indicated by exponentially tapering channels and complexly meandering, mangrove-lined tidal creeks (Woodroffe et al., 2006).

The millennial-scale evolution of these deltas has been subject to recent investigation and short-term sedimentary processes are understood at the microscale, but the behaviour of individual deltas at decade-to-century scale remains poorly understood by comparison. The large rivers are dynamic and adjust their course; the surface of the Holocene delta plains is often shaped by a cycle of distributary activity and there are numerous examples of river capture or avulsion. The most remarkable of these has been the Huanghe, which has switched its course completely in historical time. The Ganges-Brahmaputra-Meghna has undergone changes; there has been a major recent shift in the course of the Brahmaputra, resulting in the sequestration of sediment in the Sylhet basin and there is evidence of the progressive migration of the course of the Ganges eastward, with the abandonment of successive distributaries.

Dominant processes

Fluvial activity is focused on the active delta plain that is shaped by the river channel and comprises the floodplains that are subject to inundation when the river floods. Former distributaries in the abandoned delta plain carry much diminished flows and infill with sediment. Whereas subsidence is offset by accretion of new alluvial sediment in the active delta plain, the surface of the abandoned delta plain appears to become progressively lowered with supply of sediment unable to keep pace with regional subsidence. In contrast to the prominent delta lobes of the Mississippi, which become reworked by low-energy wave activity in the Gulf of Mexico, Asian megadeltas are subject to much greater wave or tidal energy. The Indus experiences considerably higher-energy waves, and the abandoned delta front of many of the deltas becomes increasingly dominated by tidal processes. For example, the Mekong delta underwent a transition from embayed estuary to lobate delta and the rate of seaward progradation slowed after 4000 years ago from 30-35 m/year to an average of around 11 m/year (Ta et al., 2002). The large tidal range in the Bay of Bengal means that the abandoned delta plain of the Ganges-Brahamputra-Meghna is tide-dominated, and behaves in a different way to the river-dominated active delta distributaries that carry large and highly variable discharges and substantial sediment loads.

The separation of processes within a delta is most clearly seen on the plains of the Red River delta (Mathers and Zalasiewicz, 1999). The active floodplain flanking the main channel is river-dominated, a series of meander scroll plains flank the distributaries, and the location of formerly-active channels can be seen from the higher ground that has been formed by the deposition of levées. The southwest sector is wave-dominated, and contains a series of shore-parallel beach ridges. The eastern sector is tide-dominated; there are extensive tidal flats and tapering and meandering creek systems (Figure 2).

Delta plain morphology

The surface geomorphology of the 9 Asian megadeltas has been investigated using Shuttle Radar Topography Mission (SRTM) elevation data. This comprises single pass synthetic aperture radar (SAR) interferometry (C and X band) at 3 arc second resolution, corresponding to a cell size of around 90 m on the ground. The SRTM elevations are reported to the nearest metre, with the sea surface set to zero, and are available from the National Aeronautics and Space Administration (NASA - http://edcsns17.cr.usgs.gov/srtm/index.html).

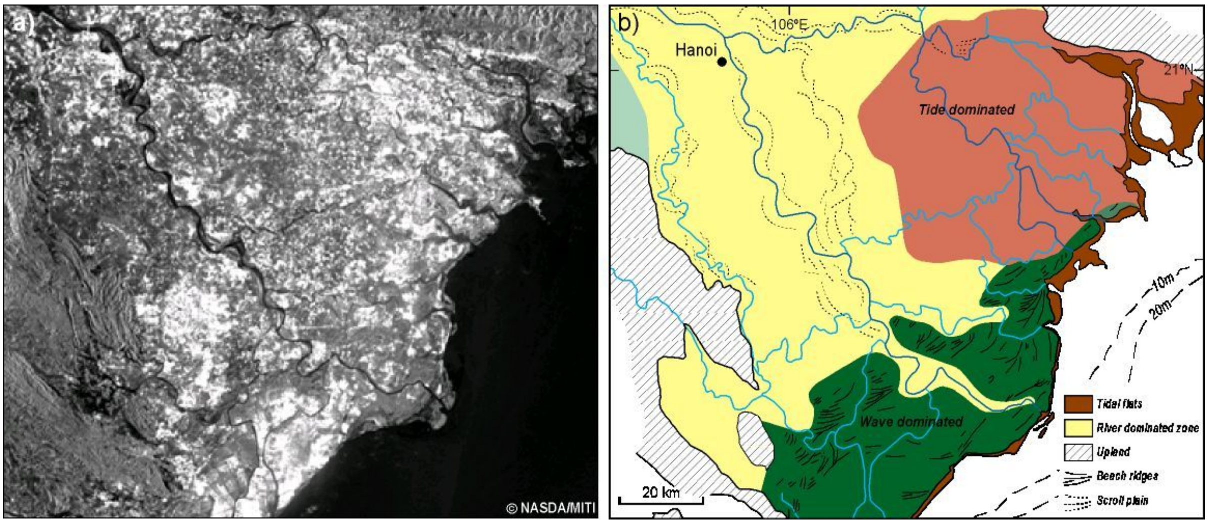

Figure 2. The Red River Delta; (a) JERS radar imagery of the delta showing the complexity of land-use, and (b) an interpretation of subaerial delta geomorphology that shows distinct sectors of the delta dominated by different processes (based on Mathers and Zalasiewicz, 1999)

The largest delta in the region is the combined Ganges-Brahmaputra-Meghna (GBM) delta, covering an area of more than 100,000 km^2 (Figure 3). The Meghna, to the east of this delta, is strongly river-dominated as the combined flow of several rivers (primarily the Ganges and Brahmaputra) reaches the Bay of Bengal. However, the western section of coastline is tide-dominated. Termed the Gangetic Tidal plain, and covered by the extensive mangrove forests of the Sundarbans, it contains a network of tapering tidal channels, and channel bank erosion and retreat of the coast are typical. It appears that, whereas the contributing rivers bring a large volume of sediment to the coast, it is the strong tidal currents associated with the large tidal range that re-suspend sediment and ensure that waters remain turbid.

Figure 3 shows the topography of the GBM with low-lying areas flanked by natural levées marking existing and former distributaries of the Ganges. These are important in channelling flow, are significant for human activities, and influence the extent and duration of flooding (Umitsu, 1985). These levées coalesce over much of the northern part of the delta resulting in considerably higher elevation. By contrast, the particularly low-lying, actively-subsiding Syhlet basin, which in places is only 2 m above sea level, is clear in the DTM extending northeastwards inland from the coast; this can be flooded by water that is up to 6 m deep in the wet season. Less than 4% of the flow of the Ganges feeds into the Sunderbans. The DTM indicates the former distributaries of the Ganges, such as the Hooghly and the Gorai. The location of delta deposition has been influenced by the progressive migration of the course of the Ganges eastward, and with the abandonment of successive distributaries. Loss of land in the order of 100 km^2 over the past 30 years has occurred along this coast, and islands such as Sagar Island have experienced retreat on the seaward side (Allison et al., 2003). This example from the Ganges-Brahmaputra-Meghna system demonstrates that deltas are dynamic, changes in their morphology are driven by sediment supply and accommodation space, which are in turn a function of the morphodynamics of the delta (Brammer, 1993).

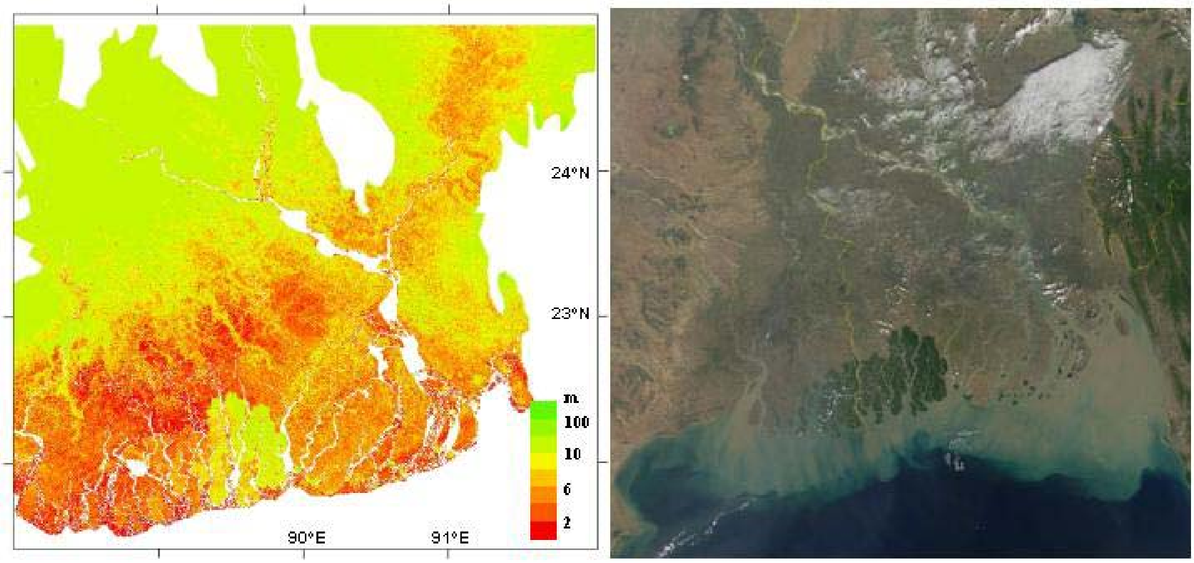

Figure 3. The delta of the Ganges-Brahmaputra-Meghna delta; (a) DTM determined from SRTM, and (b) MODIS image of delta

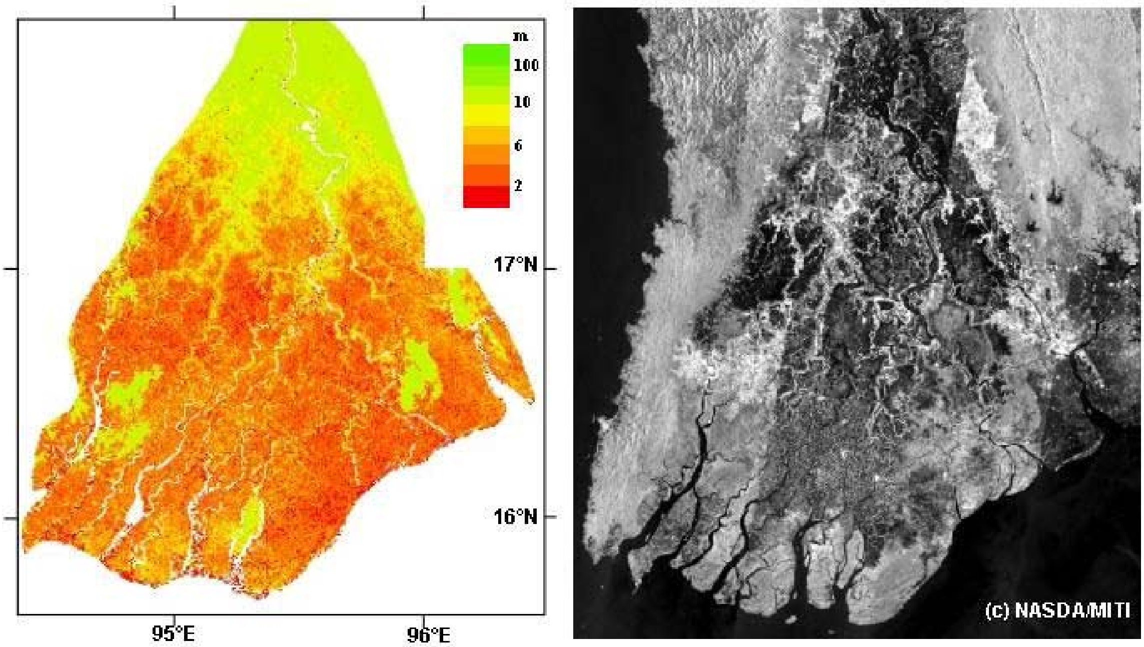

Figure 4. The delta of the Irrawaddy River, Myanmar; (a) Digital terrain model (DTM) derived from Shuttle Radar Topography Mission (SRTM) data; (b) JERS radar imagery, showing the tide-dominated 'Mouths of the Irrawaddy'

Figure 4 shows the topography of the Irrawaddy delta determined from SRTM and the morphology of the delta as seen by JERS radar imagery. Whereas the river has been structurally constrained between the Araken mountains and the Shan plateau, the delta has switched between distributaries. River-dominated channels are characteristically braided, or marked by meander scroll plains. The western portion of the coastline comprises a series of tide-dominated channels, the ‘mouths of the Irrawaddy’. These show negative exponential changes in width along their course, and mangrove-lined tidal creeks. Whereas deposition may occur at the active locus of river supply of sediment, erosion is likely to be the main process in the tide-dominated parts of the abandoned delta plain.

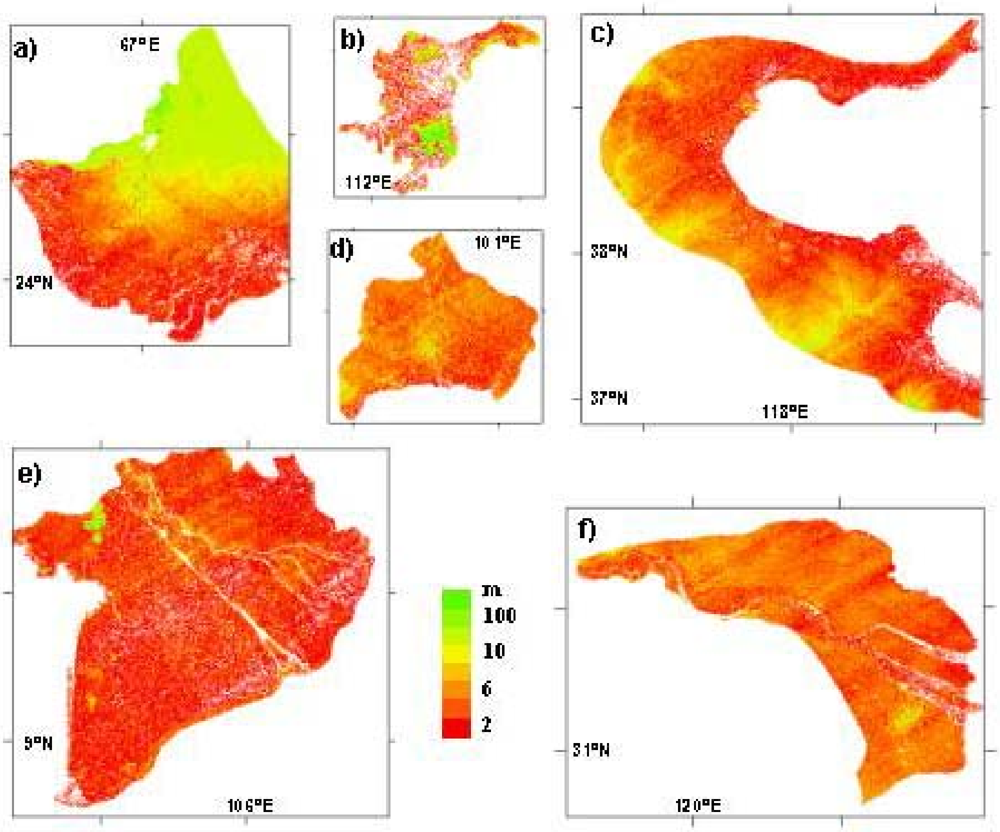

Figure 5. DTM of a) Indus, b) Pearl, c) Huanghe, d) Chao Phraya, e) Mekong, and f) Changjiang deltas based on Shuttle Radar Topography Mission (SRTM) data (after Woodroffe et al.,. 2006)

Figure 5 presents the SRTM-derived DTM for the other Asian megadeltas. The Indus is characterised by an active delta plain that is river-dominated, and abandoned delta plains that are tide-dominated and covered by extensive mangrove forests. The delta shows a progressive increase in elevation inland, composed of several abandoned delta lobes to the east of the modern river course. The Chao Phraya has formed the extensive low-lying central plain of Thailand. SRTM data indicate that the Mekong is especially low-lying, with more than 70% of the delta plain less than 4 m above sea level. More than 50% of the plains of the Pearl, Changjiang and Huanghe deltas are also below 4 m above sea level. The abandoned former Huanghe mouth in Jiangsu is below 4 m above sea level over more than 80% of its area and is subject to rapid coastal erosion (Li et al., 2004).

Although the megadeltas are low-lying, projected rates of sea-level rise are only gradual and inundation of most of the area of the delta plains does not appear imminent. However, vulnerability of these deltas to flooding is determined not just by elevation, but by wet season river flood levels over the active floodplain, and the upper levels reached by the tide in the tide-dominated abandoned delta plain. Sea-level rise and its effect on the Vietnamese

Mekong Delta has been modelled in terms of water elevation in the flood season, and the implications for rice production have been examined (Wassmann et al., 2004).

VARIABILITY OF SOCIO-ECONOMIC FACTORS ACROSS DELTAS

The natural dynamic behaviour of Asian megadeltas is subject to alteration by human influence including indirect effects and direct impacts. Land-use change in the catchment has been one of the most significant indirect influences. In the case of the Huanghe, land-use change in the loess plateau has meant substantially increased sediment loads in the river (Saito et al., 2001). By contrast the construction of dams on rivers has resulted in the reduction of sediment loads through retention of sediment in dams (Ericson et al., 2006). For example, the Indus is now extensively dammed and sediment supply to the coast has been reduced to low levels (Syvitski et al., 2005).

Delta Populations

Figure 1 shows gridded population densities for Asia based on the updated and expanded GPW-3 (beta version), produced by the Center for International Earth Science Information Network (CIESIN - http://sedac.ciesin.columbia.edu/gpw), adjusted to UN estimates of country total populations. It is clear that people are disproportionately concentrated within the river valleys and on the Asian megadeltas (Small and Nicholls, 2003). The populations of the megadeltas have been calculated using ArcGIS raster calculator with the delta margins defined by the maximum Holocene shoreline (Table 1). The gridded population datasets are based on census returns distributed within administrative units, using a mass-conserving algorithm for 1990, 1995 and 2000, and an estimated population for 2015 using country-specific growth rates. Data are gridded using 2.5 arc minute cells (4.6 km at equator). Spatial uncertainties in population distributions are generally larger than boundary uncertainties.

The population of the GBM delta is the largest; almost the entire nation of Bangladesh occurs on the delta, although those higher areas such as the Barind and Madhupur tracts have been excluded, but West Bengal (India) has been included. The population of the Changjiang delta consists of nearly 26 million. 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.

The gridded population data are only an approximation of the spatial distribution of people within the deltas; the spatial resolution of census data poses a fundamental limitation on calculating population in the near-coastal zone. Extrapolations of populations based on GPW2015 are also available. Figure 6 shows the gridded estimates for the Red River delta, determined assuming continuation of recent geometric demographic patterns of growth between 1990 and 2000 censuses, adjusted at national level to UN 2015 population projections. Urbanisation is the most significant contributor to growth; rural populations are generally distributed 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 that can be seen in the SRTM-derived DTM of the Red River delta.

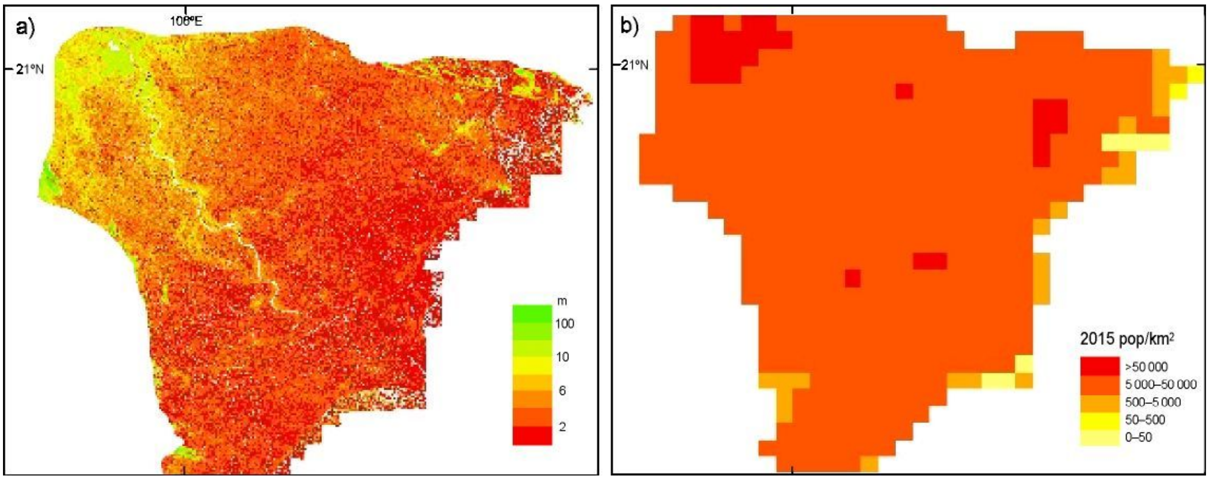

Figure 6. The Red River Delta; (a) DTM derived from SRTM; (d) gridded population density for 2015 using estimates of population increase (based on GPW3, CIESIN)

The population data are not at sufficient resolution for detailed hazard analysis, or local vulnerability assessment. Such vulnerability analyses should be focused on detailed local topography and integration with other variables such as flood levels, land use, and other relevant factors. The population data does not adequately represent urbanisation and growing rural-urban imbalance with growth of enormous cities in the megadeltas.

Flooding and flood management

Natural levées are frequently built up as a component of flood control, decreasing the frequency with which the plains are overtopped but increasing the magnitude of flood when overtopping does occur. Such activities have ramifications for the supply of sediment and nutrients to the delta plain surface. Drainage and irrigation works impact the movement of water, but have more subtle effects on sediment and sediment geochemistry. A widespread problem is the acidification of potential acid sulphate soils with oxidation of pyrite.

There has been a long history of interference with water in the deltas, from flood mitigation and groundwater extraction to irrigation and channelisation. The natural systems which underlie the Asian megadeltas have been increasingly influenced by human alterations, and the incorporation of human factors into a systems approach remains challenging (Milliman et al., 1989; Syvitski and Saito, 2007). The spatial variability of elevation and hydrodynamics within a delta implies that management of deltaic environments needs to be based on an understanding of the geomorphological dynamics of each system. Widespread land-use change to agriculture, silviculture and aquaculture in the rural areas, and more recent urbanisation can lead to irreversible effects, such as compaction, subsidence and acid sulphate soil development. There is a need to understand these processes more completely and to reinforce the resilience of the natural systems.

GIS provides a geoscientific framework within which to assess the balance of natural processes, including subsidence, compaction, sediment supply, sea-level change and changes in tidal amplitude. An integrated assessment framework needs to be based on an appreciation of the role of sediment delivery and sequestration within suites of landforms and the socio-economic factors such as population and land use, emphasising spatial variability and the interconnectedness of the components of a delta.

Erosion is a part of the natural dynamics of some sectors of the delta, becoming progressively accentuated as the delta has built seaward during the late Holocene. It is an essential phase of a delta cycle, when subsidence or compaction exceeds the rate of supply of new sediment, or when it is accentuated by human dewatering through groundwater extraction. Abandonment of a delta lobe is followed by self-cannibalisation. The contrasting dominance of different physical processes along the front of the delta results in differing trends of coastal erosion or deposition.

Inundation of low-lying areas is already a problem around the world's shorelines, with on average around 10 million people experiencing flooding per year. Megadeltas are subject to a series of hazards, such as cyclones and storm surges, and extreme events of this kind have resulted in massive death tolls, particularly along the shores of the Bay of Bengal (Ali, 1996). Although the number of people at risk might be expected to increase as a result of future sea-level rise, the principal factor influencing future flood vulnerability appears to be the socio-economic pathway that is followed, including population growth rates and the economic constraints on the extent of flood protection (Nicholls, 2004).

DISCUSSION

Despite the fact that deltas represent some of the largest sedimentary deposits in the world, the shorelines of many of the world's deltas, and those of Asian megadeltas in particular, are highly variable and in many places are already undergoing erosion. Geomorphological variability across delta plains means that different parts of a delta are likely to respond differently to global climate change, with erosion accentuated in those parts of a delta already subsiding and no longer receiving fresh sediment inputs.

This natural geomorphological variability is further complicated by variability in human settlement and land use. Water extraction and water/flood management has been spatially variable across deltas, ranging from levée enhancement to installation and maintenance of dikes and canals. A corollary of water control has been a rerouting of sediment pathways, and human modification of natural patterns of sedimentation and erosion (Thanh et al., 2004). Further use of groundwater, and the subtle adjustments of ground level as a consequence, appear to have exacerbated problems such as compaction associated with the natural dynamics of deltas. Subsidence as a result of groundwater extraction is a serious problem, especially for Bangkok (Phienwej and Nutalaya, 2005). Wise sustainable management of these systems requires more attention to sediment pathways and consideration of the consequences of elevation change.

Long-term sustainability of these populated deltas is frequently affected by large-scale engineering projects with impacts that often outweigh those likely to be associated with global warming and sea-level rise (Syvitski and Saito, 2007). The rate of relative eustatic sea-level rise is often exceeded by the rate of isostatic-controlled subsidence and of similar magnitude to natural sediment compaction. Accelerated compaction may result from petroleum and groundwater extraction, exacerbated by reduction in sediment delivery due to trapping behind dams and the construction and enhancement of levées (Syvitski and Saito, 2007).

Table 1. Principal characteristics and population estimates of the Asian megadeltas

Megadelta	Catch-ment area km^2 x 10^3	Mean annual dis-charge $m^3 s^{-1}$	Population 2000 (GPW3) millions	Population 2015 (GPW3) millions	Pre-human sediment discharge $kg\ s^{-1}$	Post-human sediment discharge $kg\ s^{-1}$
Indus	1082	6564	3.1	4.4	9593	3686
G-B-M	1667	22102	129.9	166.2	40534	46287
Irrawaddy	414	11953	10.6	12.1	16331	8239
Chao Phraya	179	961	11.5	16.4	452	256
Mekong	806	15900	15.7	19.0	2551	2531
Red (Hong)	171	3900	13.3	16.1	1039	4119
Pearl	409	10700	9.8	27.1	1547	1427
Changjiang	1722	29460	25.9	33.1	109444	49504
Huanghe	945	1990	14.0	16.6	3237	931

CONCLUSION

GIS provides a valuable tool for assessment of the impacts of climate change. Whereas the topographic variability of delta plains is partially captured at the scale of the SRTM radar altimetry, for many of the deltas the socio-economic data is not available at a suitable scale. Still more problematic is the nature of probable impacts as a result of climate change. Although sea-level rise has received much attention, rates of sea-level rise have been revised downward in successive IPCC assessments, and it is becoming clear that other aspects of climate change, such as rainfall and runoff change may play an equally important role. In the case of these deltas the extent of human influence has been overwhelming. Anthropogenic impacts on river flow and sediment delivery have had, and seem likely to continue to have, just as far-reaching impacts as those related to climate change.

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