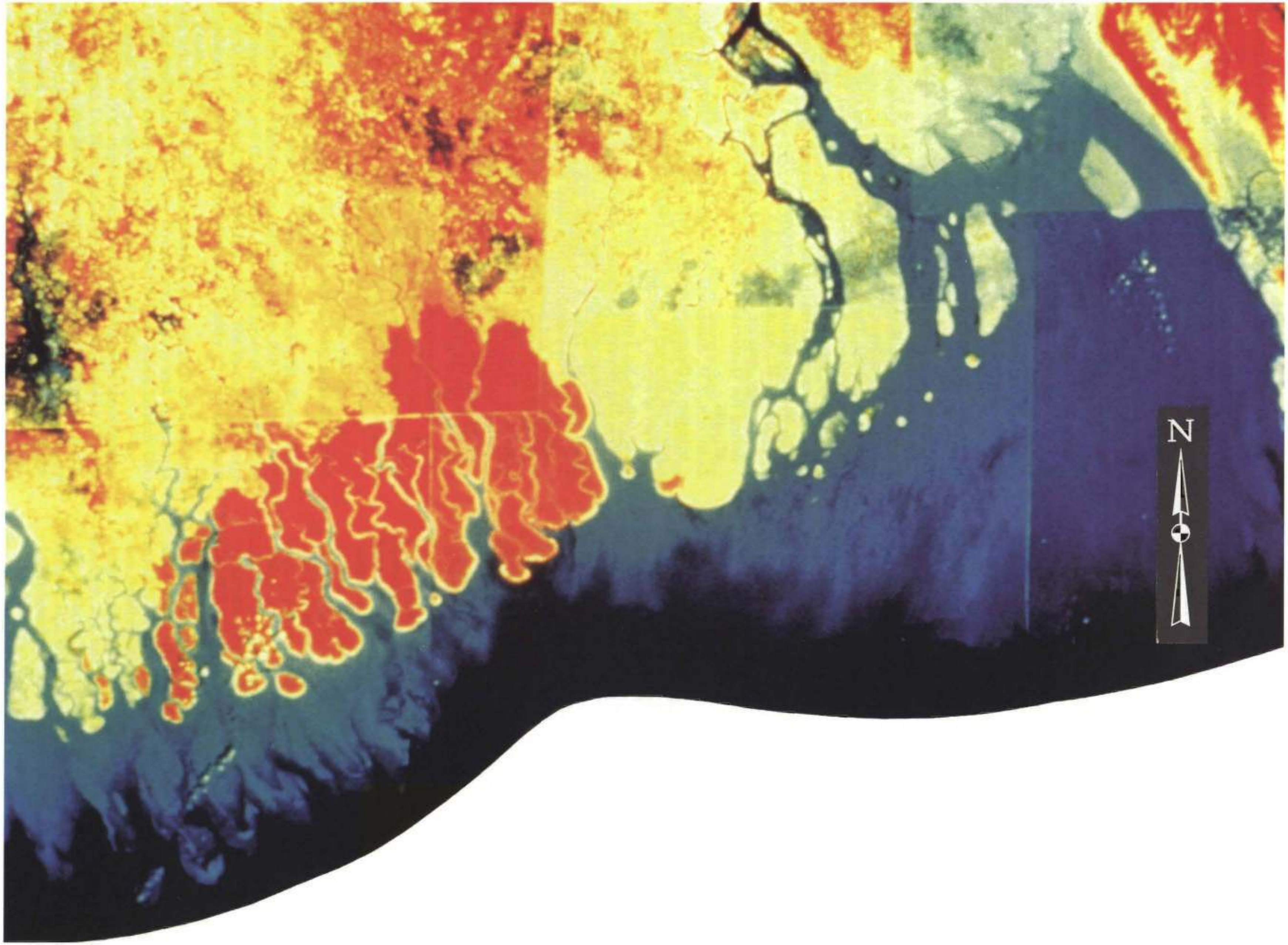

Plate 1. The Ganges-Brahmaputra delta was formed by the confluence of two great rivers, the Ganges and the Brahmaputra. Descending from the Himalaya plateau to a lowland upper delta plain, the rivers experience rapid lateral migration, which produces a patchwork of flood plains of various ages. Gathering runoff from a combined basin of over 1.7 million km^2, the high-gradient, braided Brahmaputra (right) and the meandering Ganges (left) each deliver sediment-laden water to a deltaic plain in the Bengal Basin.

Journal of Coastal Research | 14 | 3 | 826–836 | Royal Palm Beach, Florida | Summer 1998

Geologic Framework and Environmental Status of the Ganges-Brahmaputra Delta

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ABSTRACT

ALLISON, M.A., 1998. Geologic Framework and Environmantal Status of the Ganges-Brahmaputra Delta. *Journal of Coastal Research,* 14(3), 826–836. Royal Palm Beach (Florida), ISSN 0749-0208.

The enormous delta of the Ganges-Brahmaputra River in Bangladesh, and surrounding areas of India, is the lifeblood for one of the largest populations on Earth. Decending from the Himalayan plateau to a lowland upper delta plain, the rivers experience rapid lateral migration, producing a patchwork of flood plains of various ages. In the eastern lower (tidal) delta plain, the rivers enter the sea through the Meghna estuary, a 100-km-wide zone of multiple distributary channels and migrating islands. Coalescing subaqueous sand shoals in the river mouths form a delta front clinoform that is prograding seaward over the topset beds of a muddy subaqueous delta on the continental shelf. West of the river mouths, the lower delta plain is covered by a mangrove forest (Sunderbans), drained by a network of river distributary and secondary tidal channels and formed in an earlier phase of Holocene delta progradation. The Ganges-Brahmaputra delta is under increasing environmental pressure today in response to the needs of a rapidly growing and modernizing population.

ADDITIONAL INDEX WORDS: *Bangladesh, India, delta plain, Meghana estuary, Holocene.*

INTRODUCTION

The Ganges-Brahmaputra delta was formed by the confluence of two of the world's great rivers. With headwaters at elevations above 5000 m, the Ganges and Brahmaputra Rivers are the 2 largest of the 8 south Asian rivers (others are the Irrawaddy, Hungho, Mekong, Narmada, Indus, and Godavari) draining the Himalayas that number among the top 15 on earth in sediment discharge to the oceans (MILLIMAN and MEADE, 1983; MILLIMAN and SYVITSKI, 1992). Gathering runoff from a combined drainage basin of over 1.7 million km^2, the high-gradient, braided Brahmaputra and meandering Ganges each deliver sediment-laden water with distinct grain size and mineralogical character to a deltaic plain in the Bengal Basin (Figure 1). A sequence of up to 16 km of fluvio-deltaic sediments have filled this basin since the Paleogene (PAUL and LIAN, 1975). Regional tectonic uplift and subsidence are ongoing in the basin, making the Ganges-Brahmaputra subject to relatively rapid (10^2 yr) channel avulsions that have created a complex subaerial delta morphology. Virtually all of the nation of Bangladesh and surrounding areas of India are part of this fertile deltaic plain, which supports a population of approximately 200 million people in the 1990s. Although the delta has been extensively impacted by human activity for hundreds of years—British surveyor James Rennell observed earthen levees along the Ganges in 1764 (RENNELL, 1781)—the combination of river channel mobility and the persistence of traditional agricultural and rural settlement practices have retarded implementation of modern river control practices. Only since the 1960s has there been a significant impact on the delta from the construction of artificial levees, road embankments, and tributary dams.

The Ganges-Brahmaputra discharges into the Bay of Bengal along a delta front of 380 km. High-velocity tidal currents and frequent tropical cyclones in the Bay are major factors in shaping the subaerial delta front and in sediment delivery offshore. Sediment partitioning across the river-ocean interface has led to the formation of a subaqueous mud clinoform on the continental shelf adjacent to the river mouths. On the western edge of the delta, Swatch of No Ground submarine canyon incises the shelf to within 40 km of the shoreline. The submarine canyon is one of the few associated with major rivers that is an active conduit for sediment delivery to the deep sea, trapping sediment migrating westward along the subaqueous delta front. At the base of the submarine canyon is the world's largest submarine fan (Bengal Fan) which covers 3 million km^2 of seafloor (CURRAY *et al.,* 1982).

The objective of this paper is to provide a summary of the state of knowledge regarding the natural environment (e.g., geologic framework, ecology, physical processes) of the Ganges-Brahmaputra delta. A secondary objective is to identify some of the emerging issues that impact the natural environment of the region in response to a burgeoning population and the attendant socioeconomic growth.

PHYSICAL SETTING

The climate of the Ganges-Brahmaputra delta in Bangladesh is dominated by the monsoon cycle. Monsoon season,

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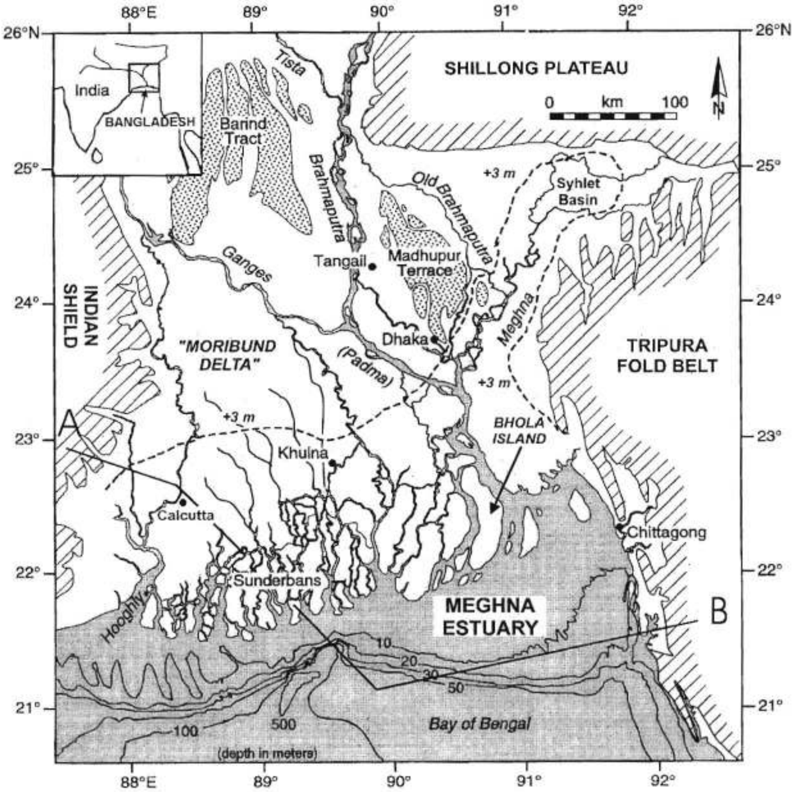

Figure 1. Map of the Ganges-Brahmaputra delta and adjacent areas of the Bengal shelf (modified from Kuehl *et al.*, 1997). Line A-B is the geologic cross-section in Figure 2.

which extends from late May to September, is the period when 80% of the rainfall occurs and winds blow from the Indian Ocean (*e.g.* southeast to southwest). Annual rainfall in the delta ranges from 125 cm in western Bangladesh to more than 300 cm in the river mouth region, and more than 500 cm in the extreme northeast bordering the Himalayan plateau (BRAMMER, 1996). Everywhere in the delta annual rainfall exceeds potential evapotranspiration rates. Mean daily temperature ranges from about 18°C in the dry season of continental winds (December–February) to 30°C prior to the onset of monsoon in April–May. Temperature extremes of 4°C and 43°C have been recorded in the region, with a narrower range along the coast (BRAMMER, 1996).

Tidal currents are perhaps the strongest hydrodynamic influence on the subaerial delta front and subaqueous part of the Ganges-Brahmaputra delta. The tide is semidiurnal and approximately synchronous along the delta front. Interaction of the M_2 and S_2 major components produces a distinct daily inequality of successive tides (EYSINK, 1983). Mean tidal amplitude is approximately 2.8 m on the east side of the delta, decreasing to approximately 1.9 m on the west (BITWA, 1987). Deformation of the tide front entering the islands and channels of the Meghna estuary produces tidal amplitudes exceeding 4 m and tidal currents up to 300 cm/sec in the river mouth (BARUA, 1990). Differences in the channel aspect ratio (water depth : width) and tidal assymetry in the river mouth estuary leads to flood dominance in the eastern tidal channels and ebb dominance in the western (BARUA, 1990). Saline water penetrates as far upstream as the Padma confluence 100 km inland during the dry season, and tides are measurable up to the Ganges-Brahmaputra confluence. The inland limit of saline influence follows an irregular line west of the Meghna estuary seaward of the 3 m elevation contour (Figure 1) and depends on the size and separation of the 20+ distributary channels that dissect the Ganges-Brahmaputra delta front. An estimate of the vector sum tidal and non-tidal residual transport by BARUA *et al.* (1994) reveals generally southwestward water and sediment delivery on the subaqueous delta during the dry season. Their measurements show a strong influence of the Ganges-Brahmaputra outflow on the coastal circulation in August. Models of the freshwater plume during high discharge in June–September also show net advection toward the west of the Bay of Bengal circulation gyre (SHETYE *et al.*, 1996).

The northern Bay of Bengal has a moderate wave climate with average wave heights of less than 0.5 m and 3–4 second wave periods. During the monsoon season wave heights average 0.5–1.0 m, with occasional waves up to 2 m with corresponding periods of 6 seconds. Larger waves of up to 5 m have been observed during cyclones (NEI, 1978). Tropical cyclones can affect coastal areas of the delta in both the pre-monsoon (March–June) and post-monsoon (September–De-

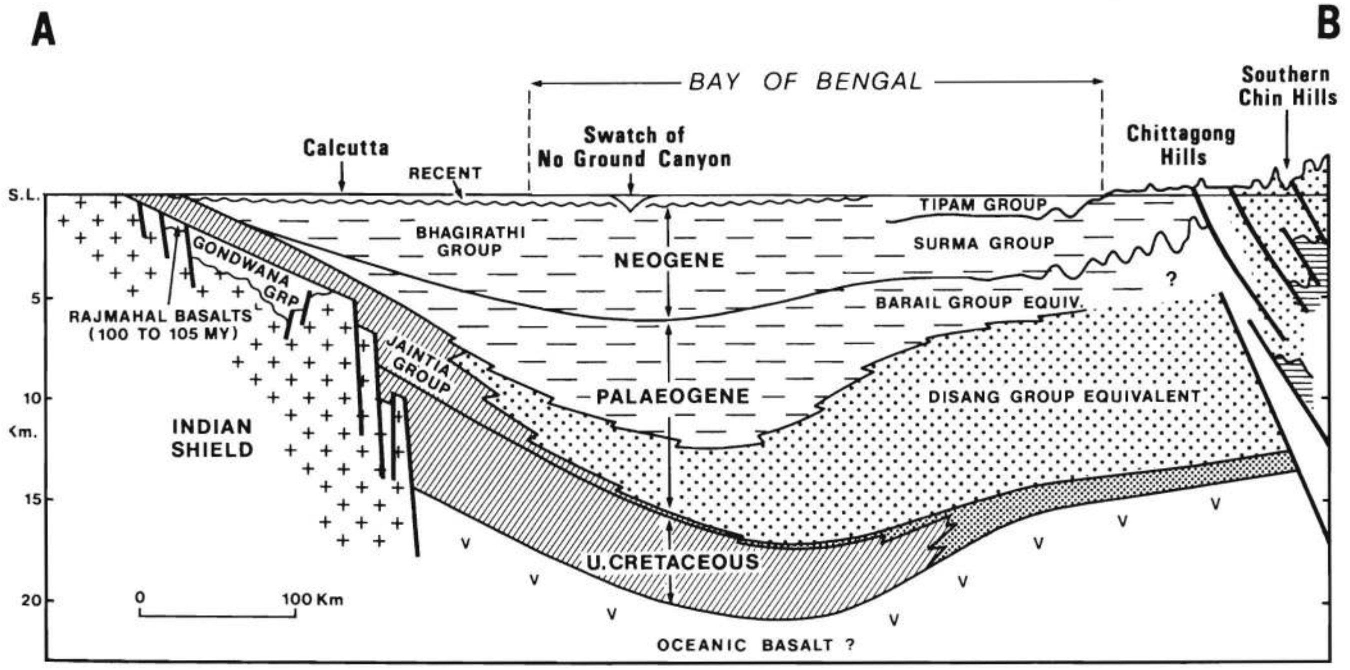

Figure 2. Regional cross-section of the Bengal Basin from line A-B in Figure 1 (from Imam and Shaw (1985).

cember) period (MURTY *et al.,* 1986). A total of 77 of these storms made landfall somewhere along the northern Bay of Bengal coast in the present century up to 1985. Owing to the low elevation of the Ganges-Brahmaputra deltaic plain, the resulting storm surges can penetrate as far as 100 km inland and have resulted in the death of an estimated 4.5 million persons in the period 1737–1985 (EMERY and AUBREY, 1989).

BENGAL BASIN

Collision between the continental masses of India and Asia began in the mid-Oligocene; the onset of major uplift of the Himalayas and the Indo-Burman range to the east was underway by the mid-Miocene (CURRAY *et al.*, 1982). A subsiding region along the front of the mountain belts, the Himalayan foredeep, became the repository for large volumes of clastic sediments shed off the rising mountains. The Bengal Basin evolved out of this area bordered by the Precambrian Shillong Massif and Indian Shield to the north and west, and the Neogene Tripura Fold Belt to the east (Figure 1). A stable shelf on the west and northwest side of the Basin bordering the Indian Shield contains a sequence of 1–8 km of Permian-Recent clastics (IMAM and SHAW, 1985). To the south and east, tectonic activity continues in the Bengal foredeep centered below the present Ganges-Brahmaputra river mouths. Up to 16 km of Tertiary and Quaternary fluvio-deltaic sediments have accumulated in the foredeep (Figure 2). The two parts of the Basin are separated by a hinge zone marked by high gravity and magnetic anomalies (SENGUPTA, 1966).

The Bengal foredeep contains a number of sub-basins, structural troughs, and highs bounded by basement-controlled lineaments that exhibit regional uplift and subsidence (FAO, 1987). In the northeast, the Sylhet subbasin is subsiding at rates up to 2.1 cm/year because of down-thrusting under the Shillong Massif (JOHNSON and ALAM, 1991). During the monsoon season this area is subject to extensive rainwater (*i.e.* non-turbid) flooding. Although the overall effect of regional tectonic subsidence, intrabasin fault activity, and local compaction is not known, a sense of its magnitude and continuing nature is evident from observations of sinking buildings, buried forests, and active fault scarps in the delta plain (MORGAN and MCINTIRE, 1959; COATES *et al.*, 1988; COATES, 1990).

A vast flat alluvial plain, encompassing Bangladesh and parts of the adjacent Indian states of West Bengal, Assam, and Tripura, forms the surface of the Bengal Basin. The plain is covered almost entirely by Quaternary and Recent alluvium of the Ganges, Brahmaputra, and Meghna rivers with Tertiary sediments exposed on the northern edge and in the Tripura Fold Belt to the east (FAO, 1987). Overall relief is slight with a gradual seaward elevation drop from 90 m in the extreme northwest of Bangladesh to a coastal plain of less than 3 m south of 24° N latitude. In the northeast along the axis of the Sylhet subbasin, the 3 m elevation contour extends more than 150 km inland (Figure 1). Two fault-bounded terraces, the Barind and Madhupur (Figure 1), outcrop in the deltaic plain and are elevated 3–15 m above the Holocene alluvium. Both are composed of the Pleistocene Madhupur Clay, an older alluvial unit that has been uplifted and deeply dissected by streams (MORGAN and MCINTIRE, 1959). The presence of these raised terraces on the deltaic plain is a first-order control on the Ganges and Brahmaputra channel paths.

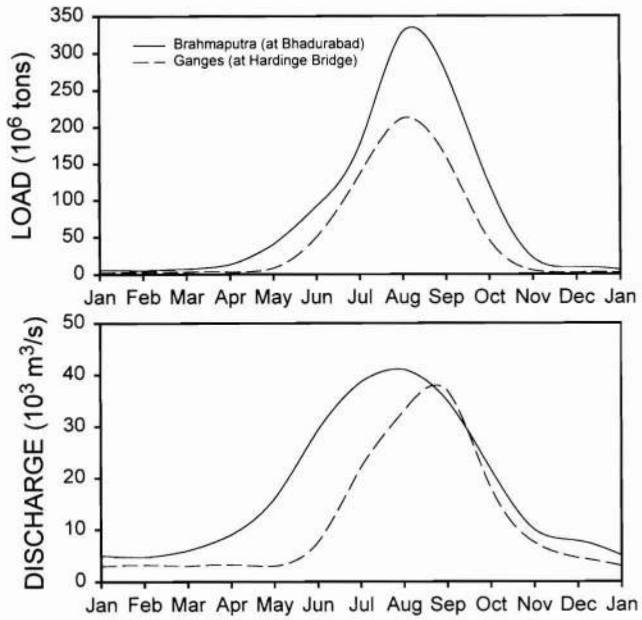

Figure 3. Water and suspended sediment discharge figures for the Brahmaputra and Ganges Rivers above the Padma confluence. Water discharge figures are 1969 to 1975 montly averages compiled by Emery and Aubrey (1989). Suspended sediment discharge rates for the Brahmaputra are 1958 to 1962 monthly averages; the Ganges are 1969 to 1970 monthly averages compiled by Barua, *et al.* (1994).

THE RIVERS

Approximately 85% of the surface runoff entering the fluvio-deltaic plain in Bangladesh is carried by three rivers: the Brahmaputra, Ganges, and Meghna. The Brahmaputra originates in Tibet and flows eastward along the northern slope of the Himalayas before turning south through Assam and merging with the Ganges 250 km inland of the Bay of Bengal. The Ganges rises west of the Brahmaputra along the Tibet-India border and flows 2200 km southeastward across India and Bangladesh. While the Brahmaputra catchment area is only half that of the Ganges (0.57 to 1.09 million km^2), its mean annual water discharge exceeds the Ganges (19,600 to 11,000 m^3/sec; FAO, 1987b) because of the tremendous monsoonal rainfall and snowmelt in the catchment. Both rivers have an enormous seasonal discharge range; in the Brahmaputra discharges have been measured from 2820 m^3/sec in mid-dry season (February–March) to an estimated 100,000 m^3/sec during the extreme flood of 1988 (EGIS, 1997). The Brahmaputra begins to rise a month before the Ganges in March–April in response to snowmelt in the Himalayas, reaching a peak discharge usually in late July–early August; the Ganges reaches its peak in late August–early September (Figure 3). Annual Ganges discharge figures have decreased since 1975 with the construction of the Farakka Barrage, which is designed to divert water into distributaries in eastern India to augment low dry season flows. The combined Ganges-Brahmaputra flow eastward for 120 km along the Padma reach where they meet the Meghna River. The Meghna drains the Shillong and Tripura hills in northeastern Bangladesh and contributes an additional mean annual water discharge of 2040 m^3/sec (COLEMAN, 1969).

SARIN *et al.* (1989, 1990) examined major ion chemistry of the Ganges and Brahmaputra rivers and calculated dissolved fluxes to the oceans. Their data show an average concentration of dissolved components of 178 mg/l in the Ganges and 100 mg/l in the Brahmaputra. The figures are relatively high compared to other major rivers—the Amazon is about 5 to 50 mg/l (GIBBS, 1972)—and are a result of chemical denudation rates 2 to 3 times higher than the world average (36 tons km^{-2} yr; HU *et al.*, 1982). SARIN *et al.* (1989) attribute this to high relief and heavy rainfall in the catchment area. Ganges water carries more Na^+, HCO_3^- and Cl^- than Brahmaputra water as a result of high concentrations of soil salts in the lowland reach. Together, the dissolved flux of the Ganges-Brahmaputra (~130 million tons) accounts for about 3% of the annual global riverine source of dissolved ions to the oceans.

Estimates of the discharge rate for particulates in the rivers vary by a factor of two as a result of measurement differences and interannual river variability. At approximately 50 km above the confluence, the Brahmaputra has a mean annual sediment discharge of 387 to 650 million tons (FAO, 1987b; HOSSAIN, 1992) and the Ganges ranges from 196 to 480 million tons (CBJET, 1991; HOSSAIN, 1992). Data for the Meghna is more scattered but COLEMAN (1969) reports a maximum annual mean of 20 million tons. Combined sediment discharge of most estimates is about 1 billion tons annually, placing the Ganges-Brahmaputra in the top three in the world (*e.g.* Amazon, Huangho; MILLIMAN and SYVITSKI, 1992). Sediment discharge figures are made far upstream of the river mouth to avoid tidal influence. Recent examination of downstream sediment discharge trends by BARUA *et al.* (in press) suggest that at least 17% of this sediment never reaches the ocean and is likely deposited on the lowland flood plain by overbank flooding.

Most of the sediment transported by the Ganges-Brahmaputra (80%) is silt and fine sand with little clay supplied by the young catchment area (COLEMAN, 1969). Suspended sediment concentrations are about 190–1,400 mg/l in the Ganges and 220–1,600 mg/l in the Brahmaputra (BARUA, 1990). Bed material is coarser in the braided Brahmaputra channel with a median grain size of 0.22 mm, compared to 0.12 mm in the Ganges (BARUA *et al.*, in press). The sand fraction of the Ganges and Brahmaputra river load is 31 to 78% quartz, 15 to 30% alkali and plagioclase feldspars, 5 to 30% micas, and 2 to 9% heavy minerals (BRAMMER, 1996). Mica percentage is higher in Ganges material and makes up as much as 80% of the silt fraction. SARIN *et al.* (1989) examined the clay mineral composition and found major differences between the lowland Ganges and Brahmaputra and their upland tributaries, which they attributed to differences in the regional geology of the lowland reach. Lowland Ganges averages are 42% smectite, 43% illite, 7% kaolinite, and 8% chlorite; the Brahmaputra averages 5, 61, 18, and 16%, respectively. The enrichment of smectite in the Ganges has been attributed to the weathering of basaltic traps in India by lowland tribu-

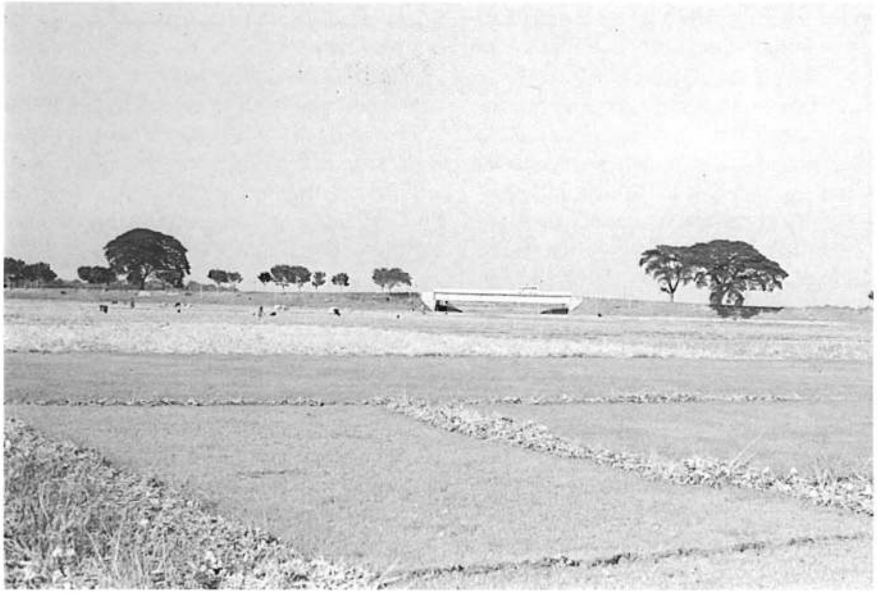

Figure 4. Characteristic lowland flood plain under cultivation near Tangail, Bangladesh. Farm plots are usually small (<200 m^2) and worked by human labor and draft animals. The viaduct on the road embankment in the background (bus on viaduct for scale) was the only feature in the area above water level in the 1988 flood.

taries such as the Chambak, Betwa, and Ken (SUBBA RAO, 1964; SARIN *et al.*, 1989).

GANGES-BRAHMAPUTRA DELTA

Lowland Flood Plain

Two main subaerial facies are formed by delta progradation: the saline-influenced lower delta plain, and the generally higher-elevation and freshwater upper delta plain. In the "Mississippi model" of delta evolution, the upper delta plain is a complex network of well and poorly drained swamps, freshwater marshes, and lakes. The heavily cultivated lowland flood plains of Bangladesh (Figure 4) are the equivalent in the Ganges-Brahmaputra delta. Entering this 3 to 20 m elevation plain, the Ganges, Brahmaputra, and Meghna rivers and their distributaries have left a Holocene alluvial stratigraphy that averages 40 m in thickness (UMITSU, 1987, 1993). Strata are composed of overbank and crevasse splay facies cut by coarse channel sequences.

Channel morphology of the Ganges-Brahmaputra was examined in detail by COLEMAN (1969). The Brahmaputra in Bangladesh, known as the Jamuna reach below the Old Brahmaputra offtake (Figure 1), is a braided channel characterized by multiple thalwegs, numerous mid channel bars exposed at low flow (*e.g.* chars), and vegetated islands. Channel aggradation and char formation result from sediment loads that exceed the carrying capacity of the wide and shallow channel. The channel belt is subject to rapid lateral migration (up to 800 m/yr) and frequent, overlapping crevasses that build up a broad (100 to 1000 m wide) natural levee of silty sand on the channel margins. Other stretches of the channel belt are relatively stable "node points," one such area 40 km above the Ganges confluence is the site of the Jamuna Bridge, slated for completion in 1998–1999. The Jamuna Bridge will provide the first road link to the isolated northwest of Bangladesh. The Ganges in Bangladesh exhibits characteristics of a meandering river with a few braided reaches. Since 1780, the river has occupied and abandoned several large meander loops 70 km above the confluence at Hardinge Bridge (COLEMAN, 1969). Constructed early in the century, Hardinge Bridge remains the only road connection across the Ganges in Bangladesh.

Historical records indicate the Ganges-Brahmaputra is subject to periodic major avulsions in the lowland flood plain. Major Rennell's survey maps from the 1760's show the Brahmaputra flowing down a channel now known as the Old Brahmaputra (Figure 1) east of the Madhupur Tract, and joining the Meghna southeast of Dhaka. Avulsion into the present Jamuna channel west of the Madhupur Tract seems to have occurred gradually over a 30 yr period following a severe earthquake in 1782 and a major flood in 1787 (BRAMMER, 1996). Geomorphic evidence from aerial photos suggests the Brahmaputra successively occupied and abandoned at least three other channel belts to the northeast of the Old Brahmaputra course prior to that time (COLEMAN, 1969). The Ganges has been migrating toward the northwest in the last 250 years, perhaps in response to tectonic uplift in the west which has raised areas as much as 6 m above present flood levels (BRAMMER, 1996). Known as the moribund delta, this area south of the Ganges is crossed by a number of old, silted up distributaries (*e.g.* Hoogley, Gorai, Arial Khan) that remain connected to the Bay of Bengal. The Padma reach is also actively migrating; in the 1966 flood near Faridpur, the channel moved northward by 1.5 km, excavating a 30 m deep channel (ISPAN, 1989). In Rennell's time, the Ganges and Brahmaputra had separate discharge points, with the Ganges flowing south of the present Padma course and entering the Bay of Bengal west of Bhola Island (Figure 2).

The upper delta plain of the Ganges-Brahmaputra has been divided into 17–20 distinct flood plains (ALAM et al. 1990). The quantity and characteristics of sediment received in these flood plains varies considerably with flooding characteristics of individual rivers, flood plain elevation, the presence of offtakes, local subsidence induced by groundwater withdrawal and sediment compaction, tectonic uplift and subsidence, and the presence of artificial embankments (ALLISON *et al.*, 1998). Flooding occurs during the monsoon season with average floods inundating about 20% of Bangladesh, while the extreme flood of 1988 inundated 46% (ISPAN, 1989). Much of the inundation, which in normal years can exceed 3 m in low-lying areas, is rainwater (*e.g.* non-turbid) flooding. Heavy rainfall in the delta in May-September coincides with high river levels caused by delivery of large volumes of water from upper catchment areas. High river levels elevate the water table and block drainage of rainwater. Turbid flooding is limited to areas proximal to river channels and is delivered to the flood plain by overbank flow and through secondary channel offtakes from the main channel.

ALLISON *et al.* (1998) presented the first quantitative sediment accumulation rates in the lowland flood plain utilizing ^{137}Cs geochronology. Their study of the east bank of the Jamuna flood plain (about 7% of the total lowland flood plain) showed strong correlation with distance from the main river channel and from secondary distributaries. Rates decreased from about 4 cm/yr adjacent to the natural levees to mm/yr in the distal flood plain. Satellite images suggest distal areas only experience turbid water inundation during extreme (1988-type) floods. GIS extrapolation of site data indicates an average of 23 million tons of Jamuna sediment is deposited annually in the region; supporting the BARUA *et al.* (in press) discharge study of downstream sediment discharge patterns that showed the lowland flood plains are a significant storage area for modern riverine sediment. A report on flood plain sedimentation by ISPAN (1993) demonstrated that soil type is closely allied to relative sediment accumulation rate. Older flood plains receiving limited riverine sediment today, such as along the Old Brahmaputra, for instance, have thick (>75 cm), organic-rich soils with original alluvial stratification destroyed by biological mixing. Soils are less well-developed and lower in organic content in "younger" flood plain areas proximal to the river. Duration and depth of annual flooding also has an effect on flood plain soil development (ISPAN, 1993).

Grain size in the flood plain is dominantly in the silt range, with an overall decrease in mean grain size away from the channel (COLEMAN, 1969; ALLISON *et al.*, 1998). Surface soils in inactive areas such as the Old Brahmaputra flood plain can be enriched in clay-sized material due to elevation-controlled sediment redistribution (BRAMMER, 1996). Permanently flooded water bodies (*e.g.* bils) can be observed in low-lying distal flood plains, and probably form by tectonic and compaction-induced subsidence.

The lowland flood plain of Bangladesh is one of the most densely populated regions on Earth, with the majority of the population living by subsistence farming. Per capita income averages about $150 per year. Bangladesh has 11.6 people per hectare of arable land compared to 1.3 in the United States (ISPAN, 1989). At present estimates of population growth indicate that figure will increase to 38.5 by the time the population reaches a stationary level in about 100 years (ISPAN, 1989). Introduction of modern high-yield rice hybrids, groundwater irrigation in the dry season, crop rotation, and food banking in recent years have averted widespread famine—the catastrophic famine of 1971 was the result of disruption of agriculture by the Independence War in Bangladesh—but these advances have had environmental costs. Large-scale groundwater withdrawal for land irrigation and drinking water, for instance, is likely to accelerate land subsidence, and recently has been identified as a source of widespread arsenic poisoning in Bangladesh, likely from Ar leached from aquifer sediments (K. ALAM, pers. comm.).

Increasing use of earthen and hardened artificial levees along river and distributary channels may have far-reaching consequences. Since the 1960's, a significant percentange of arable land in the flood plains has been walled off from river flooding by these embankments, and indirectly by the construction of raised roads. Virtually the entire west bank of the Jamuna, for example, is protected by a 5–6 meter high levee today. Bangladeshi culture has evolved many ingenious methods over hundreds of years, including raised villages, to cope with the effects of monsoonal floods. In other river deltas, the denial of river water and sediment has resulted in decreased soil fertility and the deleterious effects of reliance on chemical fertilizers, as well as land subsidence that increases saline intrusion and the damage caused by storm surges. Continued aggradation of high-load rivers, such as the Ganges-Brahmaputra, raises bed level, creating an expensive and potentially dangerous situation. Embankments will also influence many of the beneficial effects of the monsoon, including the wet season fishery, which contributes over 70% of the Bangladeshi animal protein intake, and which is the second largest export after jute, itself a flood-dependent crop (ISPAN, 1989). Fish stocks have declined in the main Ganges channel in recent years as a result of flood control and land use practices (NATARJAN, 1989). Political tension has also arisen because all of the river's upland tributaries lie outside Bangladesh and water supply to the delta plain is impacted by the tributary dams and water diversion projects intended for the benefit of other nations.

Lower Delta Plain

It is convenient to consider the lower (tidal) delta plain as two distinct regions, the Meghna estuary in eastern Bangladesh, which is the focus of modern Ganges-Brahmaputra discharge, and the Sunderbans mangrove forest in western Bangladesh and adjacent India (Figure 1). While the Holocene evolution of this region remains poorly understood, all available evidence indicates that maximum sea level transgression occurred at about 6,500 BP when the shoreline was 100 to 300 km inland of the present shoreline (VISHNU-MITTRE and GUPTA, 1970; BRAMMER and BRINKMAN, 1977; UMITSU, 1987; BANARJEE and SEN, 1988; UMITSU, 1993). The

Figure 5. Characteristic mangrove forest in the Sunderbans. Note the mangrove pneumatophores protruding above the sediment surface.

paleo-shoreline follows approximately the present 3 m elevation contour (Figure 1). Shoreline progradation and basin infilling by the Ganges, Brahmaputra, and Meghna rivers subsequent to this time accounts for ~30,000 km^2 of growth, comprising 30% of the modern delta plain.

As the focus of freshwater discharge and tidal energy, the Meghna estuary region is extremely dynamic, composed of migrating channels and islands of <2 m above sea level. West of about 90.5° E longitude, away from the active river discharge, islands have coalesced to form peninsulas separated by tidal channels. The islands and peninsulas are densely settled and cultivated. Sediments are sandy silts that below the cultivated horizon exhibit mm-scale tidal interlaminations of silt and micaceous fine sand (BRAMMER, 1996). In a comparative study of historical charts from the 18th to early 20th centuries with satellite imagery, ALLISON (1998) demonstrated that the Meghna estuary region is undergoing net land accretion at an average rate of 7.0 km^2/yr since 1792 south of 22.9° N latitude (4.4 km^2/yr since 1840). A comprehensive analysis of LANDSAT imagery by MARTIN and HART (1997) gave a figure of 16.4 km^2/yr south of 23.1°N for 1973–1996, with significant interannual variation: the 1973–4 to 1979 period was marked by net erosion of 70 km^2/yr. Over the last 200 yrs the Meghna estuary has evolved by seaward accretion of the islands and their subaqueous shoal extensions by up to 50 km, and gradual welding of the landward end to the mainland to form peninsulas (ALLISON, 1998). The river mouth has also stepped eastward during this time by silting up and abandoning channels. A digitate peninsula morphology is present across the entire 380 km delta front shoreline, suggesting areas to the west of the Meghna estuary were formed in an older phase(s) of this process.

The eastern lower delta plain and adjacent coastal areas along the Chittagong coast have a population of over 20 million persons who make their living primarily by agriculture, fishing, and, increasingly, by shellfish aquiculture. Living near sea level, this population is extremely vulnerable to rising sea levels and to storm surges associated with tropical cyclones: the cyclones of 1970 and 1991 each killed 300,000–400,000 persons. The government of Bangladesh is addressing this issue by constructing a network of raised emergency shelters and by building earthen coastal embankments (*e.g.* polders). While scattered polders built by local landlords (Zamindars) have existed since at least the 17th century, beginning in 1965–1966 with the Coastal Embankment Project (CEP), the government has extended and improved the polder system in the eastern half of the lower delta plain and inland of the Sunderbans. The project and its successors had the twin goals of protection from cyclonic surges and reclamation of tidal wetlands for cultivation. Experimental cross-dams spanning small channels in the Meghna estuary and designed to stimulate land accretion were also tested in 1957 and 1964 by the Land Reclamation Poject (EYSINK, 1983). Within ten years of the inception of the CEP, problems with land flooding began as sluice gates in the polders were silted up by bed aggradation of adjoining channels. Over one million persons had been affected by 1997 with an estimated 114,000 hectares of year-round flooding (S. AMIN, pers. comm.). This problem is likely exacerbated by land subsidence induced by polder cutoff of tidal sediment supply to these areas.

Sundarbans National Park and adjacent areas in India are the largest mangrove forest on Earth (Figure 5). Total area of the forest today is approximately 5,993 km^2, of which 29% is tidal channels. At the advent of British rule in the 18th century, the forest was double its present extent, but Zamindars were allowed to reclaim much of the northern area (AHMED, 1968). The Sunderbans was first declared a reserved forest in 1875 as a refuge for the Bengal Tiger (*Pan-*

thera tigris) and other endangered species. Over 60% of the forest is composed of two mangrove species, Sundri (*Heritiera fomes*) and Gewa (*Excoecaria agallocha*), with a decrease in species diversity in the more saline southern region (ISLAM and KHAN, 1988). Sediments in the forest are relatively organic-poor (*e.g.* non peaty) clayey to sandy silts exhibiting mm-scale tidal lamination below the biologically mixed horizon. The forest floor exhibits a microtopography of elevations from 0.9 to 2.1 m above mean sea level (KATEBI and HABIB, 1989). Although the entire region is affected by tides, saline penetration varies seasonally, reaching a maximum of 100 km inland during the dry season. It is unknown to what extent sediment is supplied to the Sunderbans either from Ganges distributaries or from the marine side, although SEGALL and KUEHL (1992) report high smectite clay concentrations at the mouth of these distributaries that they attribute to a Ganges origin.

The Sunderbans is a managed forest where an estimated 350,000 people earn a livelihood as wood cutters, fisherman, and honey gatherers through a system of auctions and licences (JALAL, 1989). The most serious environmental threat to the forest today is increased saline intrusion. In the 1930's, sporadic mortality of Sundri trees was noted by a process known as "top-dying" (KHAN *et al.,* 1990). By 1970, timber loss was estimated at 1.44 million m^3 and harvesting of Sundri was halted for a time (SHAFI, 1982). Although the ultimate cause of top-dying of Sundri is a fungal cankar (*Botryoshaeria ribis*), it is associated with increased soil salinity (CHAFFEY *et al.,* 1985) related to siltation of the Ganges distributaries that provide freshwater runoff to the Sunderbans. To what extent this process is natural, caused by shifting of the Ganges discharge eastward, or has been accelerated by dry season water withdrawal upstream at the Farrakka Barrage, remains a subject of debate. ALLISON (1998) documents net erosion of the Sunderbans shoreline, increasing to the west, where 3 to 4 km of retreat have occurred since 1840. The alongshore difference in erosion rates suggest the western Sunderbans is sediment-starved, either by eastward migration of the river mouths or by decreased Ganges sediment delivery via the local distributaries. Whatever the case, shoreline erosion and saline intrusion may also be compounded by regional subsidence (tectonic and compaction) process.

Continental Shelf

The Bengal continental shelf seaward of the Ganges-Brahmaputra delta plain is an important fishery for Bangladesh, with the bulk of this fish and shrimp resource (75%) exploited by small-scale, non-mechanized operations that involve some 200,000 persons (JALAL, 1989). Petroleum exploration is in an embryonic stage on the Bengal shelf at present compared with other deltas of the world, but is a potential economic boon of the future to Bangladesh and India.

The subaqueous component of the Ganges-Brahmaputra delta resembles other large river systems entering an energetic continental shelf environment. KUEHL *et al.* (1989) first identified a mud clinoform on the Bengal shelf, similar to those previously discovered on the continental shelf adjacent to the Amazon (NITTROUER *et al.*, 1986), Huangho (ALEXANDER *et al.*, 1991) and Fly (HARRIS *et al.*, 1993). Topset beds in less than 30 m water depth dip gently (0.036°) and diverge offshore (KUEHL *et al.*, 1997). Surface sediments are sandy silts (2–6 phi mean diameter) that landward of the 15 m isobath are tidally laminated (KUEHL *et al.,* 1989; SEGALL and KUEHL, 1994). Discontinuous ephemeral mud layers 2 to 3 m thick overlie the coarser-grained surface; SEGALL and KUEHL (1992) suggest these muds may buildup during successive high discharge periods for the 3 to 5 years on average between cyclones. Historical charts show that a lobate apron has formed from the coalescence of island shoal extensions off the Meghna estuary mouth in 8 to 15 m water depths (ALLISON, 1998). Progradation of a coarse-grained subaerial delta front clinoform over the subaqueous mud clinoform is a characteristic that is absent in the clay-rich Amazon and Fly systems.

On the middle shelf (30–60 m), more steeply dipping (0.19°) foreset beds form the thickest (40–60 m) part of the subaqueous delta (KUEHL *et al.*, 1997). Rapid sediment accumulation (up to 9 cm/yr; KUEHL et al., 1989) of fine to medium silts (mean grain size 7–8.5 phi) is characteristic of the foreset region. Further offshore (>60 m), the modern sediment wedge thins seaward into gently dipping (0.022°) bottomset muds over an erosional surface that is likely the Pleistocene lowstand surface (KUEHL *et al.*, 1997). Evidence of growth faults, slumps, and mass wasting near the head of Swatch of No Ground submarine canyon, which incises the shelf to about the 20 m isobath, suggest that the canyon is intercepting deltaic sediment transported alongshore to the west, funnelling a fraction of this material to the deep sea (KUEHL *et al.*, 1997). Studies of clay mineralogy on the Bangladesh and Indian shelves indicate that the canyon acts as a barrier to the transport of Ganges-Brahmaputra sediment to the Indian shelf (SEGALL and KUEHL, 1992).

CONCLUSION

In the new millenium, the Ganges-Brahmaptra delta faces a number of environmental issues stemming from habitat modification and rapid population growth. Among these are rising sea level and saline intrusion, water rights, inland and offshore fish stocks, flood control, soil fertility, water-borne pollutants, and river channel migration. A number of poorly understood geological processes need to be better studied to allow informed decision-making on these environmental issues. Among these are:

(1) The quantities and processes of river sediment supply to the lowland flood plain, lower delta plain, and marine endmember.

(2) The character of river sediment supply to the lowland flood plains and its contribution to soil fertility.

(3) The regional pattern and rates of tectonic and sediment compaction-induced subsidence and uplift in the delta plain.

(4) The Holocene evolution of the delta plain-subaqueous delta since maximum sea level transgression at 6,500 yBP.

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