SUSPENDED SEDIMENT TRANSPORT IN THE GANGES-BRAHMAPUTRA RIVER SYSTEM, BANGLADESH

A Thesis

by

STEPHANIE KIMBERLY RICE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2007

Major Subject: Oceanography

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Approved by:

Co-Chairs of Committee,	Beth L. Mullenbach
	Wilford D. Gardner
Committee Members,	Mary Jo Richardson
Head of Department,	Robert R. Stickney

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ABSTRACT

Suspended Sediment Transport in the Ganges-Brahmaputra River System, Bangladesh.

(August 2007)

Stephanie Kimberly Rice, B.S., The University of Mississippi

Co-Chairs of Advisory Committee: Dr. Beth L. Mullenbach
Dr. Wilford D. Gardner

An examination of suspended sediment concentrations throughout the Ganges-Brahmaputra River System was conducted to assess the spatial variability of river sediment in the world's largest sediment dispersal system. During the high-discharge monsoon season, suspended sediment concentrations vary widely throughout different geomorphological classes of rivers (main river channels, tributaries, and distributaries). An analysis of the sediment loads in these classes indicates that 7% of the suspended load in the system is diverted from the Ganges and Ganges-Brahmaputra rivers into southern distributaries. Suspended sediment concentrations are also used to calculate annual suspended sediment loads of the main river channels. These calculations show that the Ganges carries 262 million tons/year and the Brahmaputra carries 387 million tons/year. These calculations are lower than published values because of either interannual variability and/or sampling artifacts and assumptions in the homogeneity of flow and sediment concentration. The conjoined Ganges-Brahmaputra River carries 530 million tons annually, or only 80% of the sum of the loads that the Ganges and Brahmaputra rivers carry upstream of the confluence. The remaining 20% of sediment is diverted from the main river by the distributaries and deposited along the main river channel during overbank flooding.

Suspended sediment concentration is also examined in the north-south oriented tidal channels on the Bay of Bengal to determine whether sediment is delivered to the channels by one of two pathways: (1) sediment is discharged into the Bay of Bengal by the main river channel, carried west by coastal currents, and advected northward into the channels by tidal currents or (2) diverted from the main river bed through the distributaries, migrating southward into the tidal channels. Suspended sediment concentration and salinity data are inconclusive in determining sediment source. Beryllium-7 radioisotope data indicate that newly transported sediment is present in the tidal channels and offshore despite values in the Ganges and Ganges-Brahmaputra rivers being below detection. Sampling artifacts are likely caused by the below detection readings in the Ganges and Ganges-Brahmaputra rivers. Newly transported sediment is observed in a distributary south of the Ganges River and indicates that sediment is actively being transported to the distributary region.

DEDICATION

This work is dedicated to Bangladesh and the scientists who go there to study her.

ACKNOWLEDGMENTS

I would like to thank my committee, Dr. Beth Mullenbach, Dr. Wilford Gardner, and Dr. Mary Jo Richardson, for working through tough circumstances to ensure that I was able to complete my degree and providing extraordinary guidance and support. I am grateful for the interest, patience, and attention you all showed for me and my project.

I would also like to thank the contributing members of the research team—Dr. Steven Goodbred, Jr., Dr. Sid Mitra, Kimberly Rogers, and Louie. Their camaraderie and insight while collecting data and writing my thesis has been immeasurable. I additionally thank S.R. Khan of the Bangladesh Geological Society for his coordination and assistance while traveling through Bangladesh.

I would also like to acknowledge the wonderful professors and students in the Texas A&M Department of Oceanography. Dr. Niall Slowey, Dr. Shari Yvon-Lewis, Daniel Murphy, Amy Wagner, Amy Eisin, Will Cain, and Ruth Mullins have contributed to the progress and development of my project on a daily basis by providing commentary and helpful suggestions.

I am also grateful for the support of my family—my mother, father, Rebecca, Daniel, and Debbie.

Finally, I would like to thank my boyfriend, Ryan Williams, for his unfailing devotion and support for the duration of graduate school. Despite great hurdles, we have been able to complete a momentous achievement with each other’s guidance and love.

This thesis was funded in part by a Geological Society of America Student Research Grant.

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CHAPTER I

INTRODUCTION

The Ganges-Brahmaputra River System (Fig. 1.1) carries the world's highest annual sediment load at one billion tons (Milliman and Meade, 1983; Milliman and Syvitski, 1992), and yet because of its remote location, research on sediment transport and accumulation in the delta has been limited (Barua et al., 1994; Goodbred and Kuehl, 1999). The rivers drain the Himalaya Mountains and flow through the Bengal Basin before debouching into the Bay of Bengal. Seasonal overbank flooding (Allison et al., 1998a) and high flood stages (Coleman, 1969) result from annual monsoons, which have a primary impact on river flow and sediment discharge; 80% of the annual water discharge and 95% of the annual sediment load is debouched during the four summer monsoon months (Goodbred, 2003).

The combination of the rivers' high sediment load, annual overbank flooding, and subsiding sub-aerial basin (Coleman, 1969), has created a 16 km thick fluvio-deltaic sediment layer in the Bengal Basin since the Paleogene (Allison, 1998a). Previous work has been conducted in the region to create annual sediment budgets. Approximately one third of the annual sediment load is deposited in the river flood-plain (Goodbred and Kuehl, 1998; Goodbred and Kuehl, 1999), 21% is deposited in the topset beds of the subaqueous delta (Michels et al., 2003), 20% contributes to subaqueous delta progradation in the foreset beds (Michels et al., 1998), and 25% is transported to the Swatch of No Ground Canyon which incises the sub-aqueous delta (Goodbred and Kuehl, 1999). An additional 1-2% of the annual sediment load contributes to the prograding subaerial delta (Allison, 1998b). In order to create a first order sediment budget, however, a reliable annual discharge must be accepted.

Several studies (Coleman, 1969; Holeman, 1968; Milliman and Meade, 1983)

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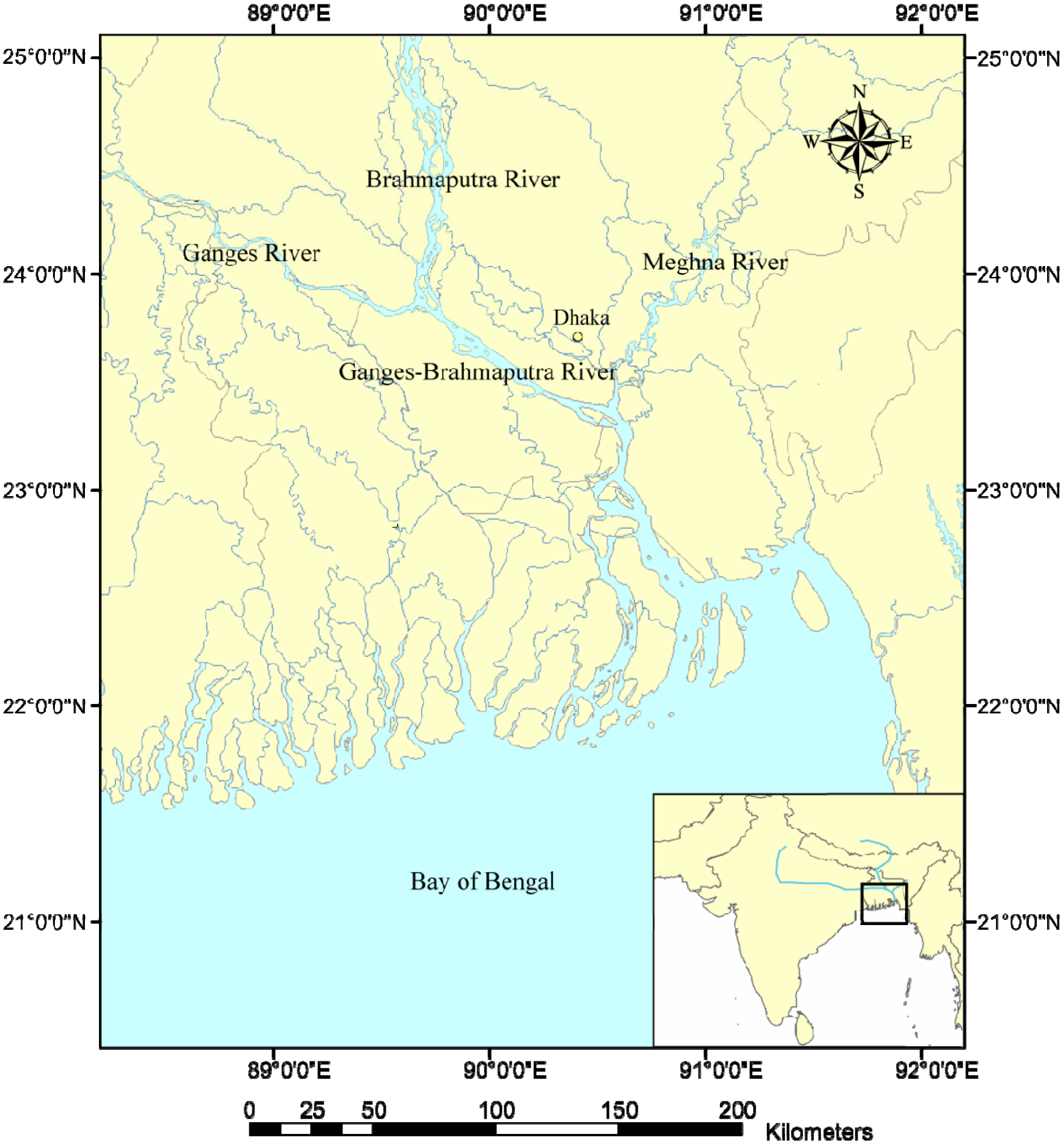

Figure 1.1. Main rivers of Bangladesh. The three prominent rivers of Bangladesh are shown, including their flow through their drainage basins. The Ganges-Brahmaputra River refers to the conjoined river south of the Ganges and Brahmaputra rivers' confluence.

have estimated the suspended sediment loads of the Ganges River (485-1600 million tons per year) and the Brahmaputra River (617-1157 million tons per year); however, these estimates are often based on data obtained from only one gauging station and the data vary depending on whether it was collected during the wet or dry season. The Ganges-Brahmaputra River System is also highly complex with tributaries and distributaries bifurcating the entire country of Bangladesh. Consequently it is difficult to compile comprehensive synchronous suspended sediment data. Although the suspended sediment load is known to vary over short time-scales (wet and dry seasons within one year), the spatial variation has not been studied.

The sediment loads of the two main rivers in the system are often calculated with data collected at one gauging station along each river; however, continually using these point locations could produce unrepresentative sediment estimates, as sediment could be diverted upstream and contributed downstream of the data collection site. Because no data exist about the amount of sediment that is missed in estimates calculated from the typical river gauging stations, it is unknown whether the discharge amounts in the wide-range of estimates are correct. By analyzing the river system by looking at classes of rivers, it will be examined whether existing sediment budgets are inadequately estimating the sediment loads of the rivers.

1.1 PROJECT SUMMARY

In this study, a system-wide analysis of river-transported suspended sediment is conducted to characterize the individual river's suspended sediment load (defined as the mass of sediment transported per unit of time) with the morphological features during high sediment discharge. Sampled rivers and channels are divided into geomorphological classes (main river channel, tributary, distributary, tidal channel) and the suspended sediment concentrations are used to assess the suspended load of each class. Sediment discharge estimates are calculated to determine each group's contribution to the suspended load of the entire river system.

To compare the suspended sediment loads of rivers by geomorphological classification, the river sampling sites are divided into groups according to their role in the drainage system. The classifications include main river channels, tributaries, distributaries, and tidal channels, as shown in Fig. 1.2. For the purpose of classification, the geomorphological classes will be defined as follows: “Main river channels” include samples taken from the three major rivers—the Ganges, Brahmaputra, and Meghna rivers. The classification “distributary” (shown in green in Fig. 1.2) includes all rivers where water flows from a main river channel into the Bay of Bengal. The classification “tributary” (shown in yellow in Fig. 1.2) includes all rivers which flow into a main river channel; the source of these rivers’ water is often a small watershed within the region. “Tidal channel” is the last classification (shown in pink in Fig. 1.2) and includes the lowest reaches of the river system, which will be analyzed separately. The boundary for the tidal channel region of the river system is defined as the limit of saline water intrusion in the area, which is documented at 100 km (Allison, 1998b).

It is hypothesized that the suspended sediment concentrations will vary dramatically throughout the entire river system, despite the overall load being high. If the suspended load of the rivers vary spatially throughout the system, this may help explain the discrepancy between estimates of the Ganges and Brahmaputra rivers’ annual sediment loads within the literature

Additionally, the sediment source in the lower delta plain of the river system has been studied, but remains unidentified. Two pathways exist for sediment to reach the tidal channels (Fig. 1.3): (1) delivery of sediment from distributaries that drain the northern Ganges River and discharge into the lower tidal channels, and (2) Ganges-Brahmaputra River sediment that has been discharged at the main river channel, carried west by coastal currents, and directed into the tidal channels by tidal currents. Previous work analyzing sediment accumulation in the tidal channels (Allison and Kepple, 2001) supports the hypothesis that sediment is discharged into the Bay of Bengal at the Ganges-Brahmaputra River mouth and carried to the tidal channels by coastal and tidal currents.

Figure 1.2. Map showing the geomorphological classes. Classes are determined for whether water flows from a drainage basin into a main river channel (tributaries) or from a main river channel into the Bay of Bengal (distributaries). The tidal channels class identifies channels in the southern region where saline water intrudes during the tidal cycle.

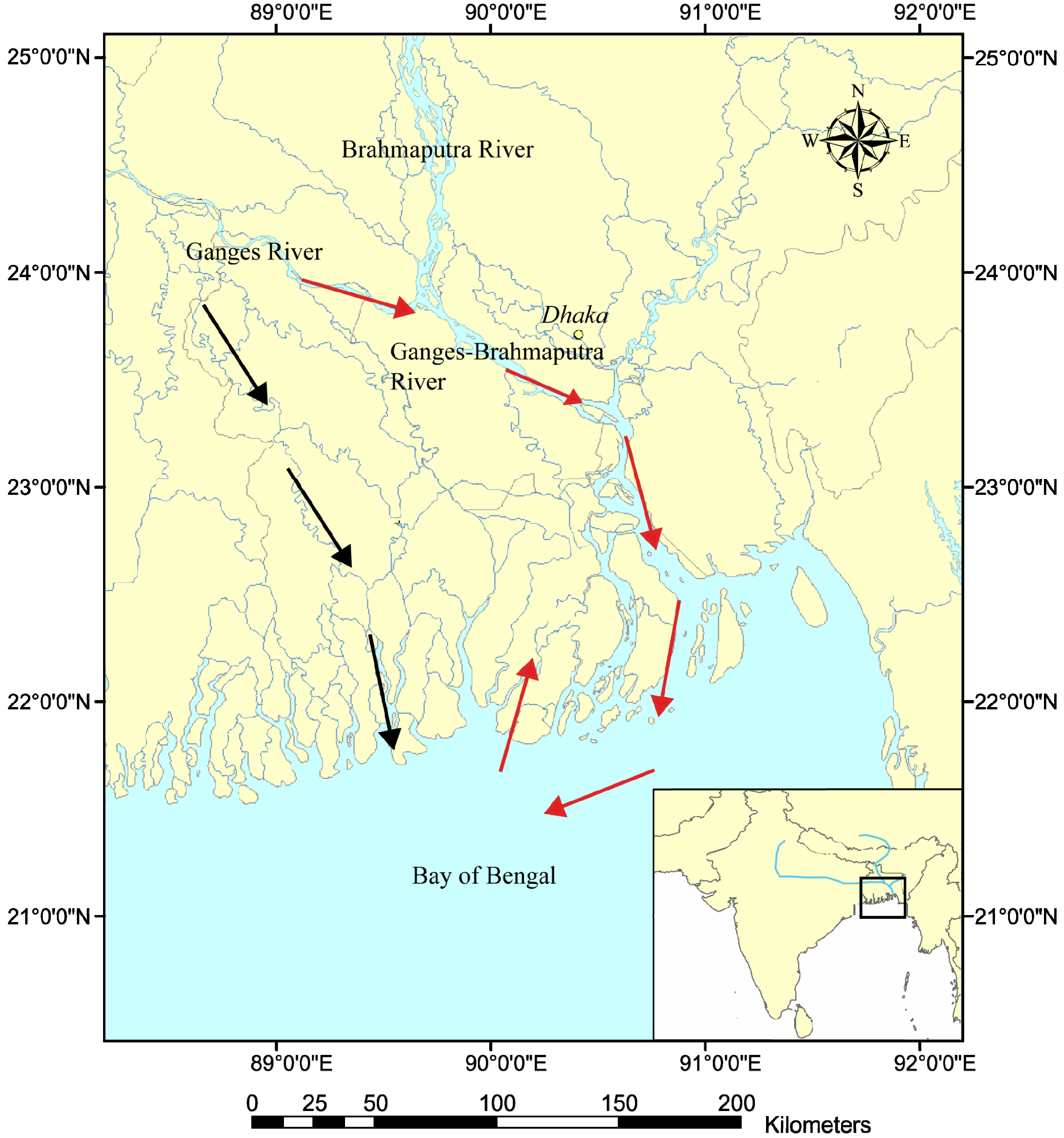

Figure 1.3. Possible transport pathways for sediment in the tidal channels. Sediment in the tidal channels is transported by one of two ways: (1) through the distributaries which branch from the main channel (black arrows) or (2) through the main river channel, and then discharged at the river mouth, carried west by coastal currents and advected into the tidal channels by tidal currents (red arrows).

In this study, suspended sediment in the tidal channels is used to support previous work on the source of sediment in the tidal channels. Sediment characteristics—suspended sediment concentrations and salinity—are used to analyze tidal channel conditions over one tidal cycle. Radioisotope data from the suspended sediment in the tidal channel are utilized to determine the source of sediment in the tidal channels. Beryllium-7 is a particle-reactive cosmogenic radioisotope that has a short half-life (53.3 days) and is assumed to settle through dry and wet deposition uniformly on land (Bettoli et al., 1995). The isotope is washed into rivers by precipitation and adheres to particles, creating a radioisotope clock of transport from the sediment source (Dibb and Rice, 1989). Based on the ^{7}Be half-life, its presence indicates sediments have been transported in the past three to four months.

It is hypothesized that the faster transport pathway is for sediment to remain in the main channel, be discharged at the river mouth, and carried west by coastal currents. Although this pathway may be a longer distance, it travels along this pathway more rapidly, and therefore has a shorter delivery time and higher ^{7}Be concentrations. Conversely, it is hypothesized that it takes more time to transport sediments from the main channel through the distributaries to the tidal channels. Although this route appears to be a shorter distance, the pathway is less direct as sediment must be transported through a complex series of branching and dividing channels. Additionally, river velocities are lower in the distributaries than in the main river channel.

If ^{7}Be is found in the tidal channels, it indicates recently transported sediment is present in the most southern area of the river system. This would indicate that the sediment has been transported within 4-5 half-lives, possibly through the faster pathway, along the main river channel and carried to the tidal channels by coastal and tidal currents. If ^{7}Be is not found in the tidal channel sediments, it indicates the sediment is older and may have been resuspended from the tidal channel floor or taken a longer route to the tidal channels, during which time the ^{7}Be has decayed below detection levels.

1.2 OBJECTIVES

This research examines sediment transport in the Ganges-Brahmaputra River System with the following specific objectives:

(1) *Relate the river sediment loads to the river's morphological classification.* Suspended sediment concentrations of individual rivers are compared within and between morphological classes. Details regarding individual river's sources and flow patterns are used to explain suspended sediment concentration patterns and anomalies within classes, as well as determine differences between morphological groups. The suspended sediment concentrations within river classes are used to calculate each class' percentage discharge of the suspended load of the entire system.

(2) *Identify the source of suspended sediment in the tidal-channels of the lower delta system.* Suspended sediment concentrations and ^{7}Be isotope data will be used to identify the source of sediment to the tidal channels. Tidal channel suspended sediment concentration and salinity will be compared to tide records for the sampling day to determine a graphical relation with the flood stage. Additionally, if radiometrically young sediment is found in the tidal channels, then the sediment source is hypothesized to be from the offshore sediment plume from the main river channel mouth, as this pathway provides the faster sediment transport route.

CHAPTER II

REGIONAL DESCRIPTION

2.1 BENGAL BASIN

The Bengal Basin is dramatically shaped by the uplifting Himalayan Mountains, which bound the region to the north. Formed by the mid-Oligocene collision between the Indian and Asian continental masses, the Himalayan and Indo-Burman Range (located to the east) began to uplift by the mid-Miocene (Curray et al., 1982). A subsiding region along the southern edge of the Himalayas became the repository for clastic material eroded from the steepening mountain range. This area became the present-day Bengal Basin, which continues to subside and collect large volumes of sediment from the Himalayan Mountains (Allison, 1998a; Goodbred and Kuehl, 1998).

As shown on figure 2.1, the Bengal Basin is bordered by the Precambrian Shillong Massif to the north, Indian Shield to the west, and Neogene Tripura Fold Belt to the east. A hinge line marked by high gravity and magnetic anomalies (Sengupta, 1966) divides the basin into two distinct regions: a stable shelf in the west/northwest provinces which contains a 1-8 km sequence of Permian to recent clastics (Iman and Shaw, 1985) and a subsiding foredeep in the south and east provinces which has continuing tectonic activity and has accumulated 16 km of Tertiary and Quaternary fluvial and deltaic sediment (Allison, 1998a). The foredeep can be divided into a number of sub-basins, including the Sylhet sub-basin in the northeast, which is subsiding at rates up to 2.1 cm/yr because of downthrusting under the Shillong Massif (Johnson and Alam, 1991). The Sylhet sub-basin floods extensively during monsoon season, however, the standing water is non-turbid because it is accumulated rainwater and not riverine overflow.

The surface of the Bengal Basin is the vast alluvial plain formed by the Ganges-Brahmaputra Rivers. Encompassing nearly the entire country of Bangladesh and the adjacent Indian states of West Bengal, the plain is blanketed by Quaternary and Holocene alluvium (Coleman, 1969). The basin has very little relief, with a change in

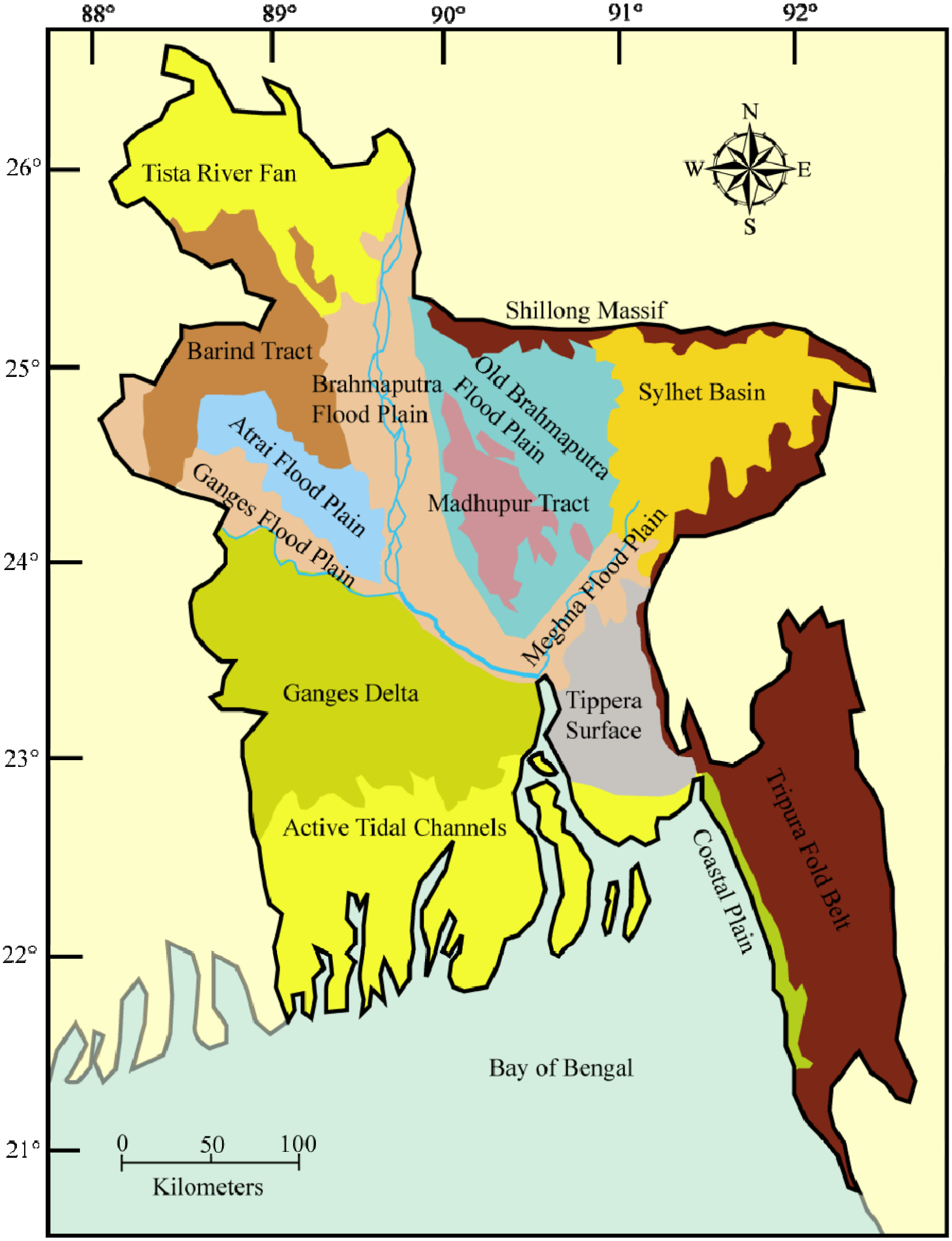

Figure 2.1 Basin province map of Bangladesh. Bangladesh is bordered to the north and east by mountains, from which the main rivers flow.

elevation from 90 m above sea level in the extreme northwest of Bangladesh near the Himalayan Mountains to a coastal plain of less than 3 m above sea level (Allison, 1998a). Despite this elevation change of 87 m, the majority of the country is composed of flat, deltaic deposits.

Two fault-bounded terraces, named the Barind and Madhupur tracts, outcrop in the west and central portions of the delta plain. Both are elevated between 3-15 m above the surrounding Holocene alluvium. Neither terrace floods during monsoon season, and the terraces' presence have a large effect on the Ganges and Brahmaputra rivers' varying channels.

The coastline of Bangladesh measures 654 km (Snead, 1985). The western coast is a flat low-lying intersection of distributaries of the Ganges-Brahmaputra River (Barua, 1991). This lower tidal delta plain extends inland as far as 100 km and is dissected by tidal channels oriented north to south, many of which are abandoned delta mouths of the migrating Ganges River (Allison, 1998b; Barua, 1991). The western coast region is mostly covered by the Sundarbans, the largest mangrove forest in the world at 5800 km^2 (Allison and Kepple, 2001; Saenger and Siddiqi, 1993).

The active delta plain is located in the central Bangladesh coastline, through which the majority of the Ganges-Brahmaputra is discharged. The active delta plain is primarily influenced by tides, and the saline intrusion of tidally-influenced water extends approximately 100 km inland (Allison and Kepple, 2001).

2.2 THE RIVERS

The Ganges and Brahmaputra rivers both originate in the Himalaya-Tibetan uplift. The steep, tectonic mountains provide a continuous amount of sediment for river transport. Seven of the world's ten largest fluvial sediment loads originate in the Himalaya-Tibetan uplift, with sediment loads ranging from 160 (Mekong River) to 540 (Brahmaputra River) million tons annually (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Published values for the estimated annual sediment loads of the two rivers vary throughout the literature, however, the Ganges carries between 485-1600 million tons per year and the Brahmaputra annually delivers 617-1157 million tons per year (Coleman, 1969; Holeman, 1968). It is widely undisputed, however, that the river system carries the highest world-wide annual load at over one billion annual tons (Milliman and Meade, 1983)

The Ganges River source is the Gangotri glacier in the Kumaun Himalayas at an elevation of 7000m (Sarin et al., 1989). The Ganges immediately flows over Miocene to Pleistocene-aged detrital rocks, such as coarsely-bedded sandstones, clays, and conglomerates, before reaching the central-lower Himalayas, which have three main zones: 1) outer belt of Upper Carboniferous aged dolomitic limestones, calcareous shales, and sandstones, with widespread replacement of gypsum for limestone; 2) inner sedimentary belt of limestones, overlain by shales and quartzites; 3) zone of igneous and metamorphic crystalline rocks composed of biotite-chlorite, Augen gneisses, and granites (Sarin et al., 1989). The Ganges is also fed by several lowland tributaries which drain Mesozoic and Tertiary mafic effusives and the Pre-Cambrian-Cambrian shield and contribute a different chemical and mineralogical signature (Huizing, 1971).

The Brahmaputra River originates from the Chamyungdung glacier at an elevation of 5200m in the Tibetan Himalayas (Sarin et al., 1989). The Brahmaputra flows westward along the northern slope of the Himalayas before turning south through Assam and flowing into the northern boundary of Bangladesh. The Brahmaputra flows over a variety of rock types including Precambrian metamorphics (high-grade schists, gneisses, quartzites, metamorphosed limestones), felsic intrusives, and Paleozoic-Mesozoic sandstones, shales, and limestones (Huizing, 1971).

The Meghna River is a third major tributary in the system, however, it flows west from the Tripura Fold Belt on the eastern boundary of Bangladesh, and its annual sediment contribution is considered to be insignificant. It is frequently omitted in scientific articles detailing the region, despite the fact that Bangladeshis identify the main estuary the Meghna Estuary.

Grain-size analyses on the river sediments indicate that the sediment is relatively coarse. Sediment that reaches the Bay of Bengal is dominated by silt and clay, with 15-

20% of the total discharge being fine to very fine sand (Thorne et al., 1993). An additional study shows that more than 76% of the bed sediments are within the fine to very fine sand class, and have a mean grain size between 2.5 Φ (177 μm) and 4 Φ (62.5 μm) (Datta and Subramanian, 1997). The grain size of bed sediments in the river also decreases gradually from the upper to lower reaches of the river system (Datta and Subramanian, 1997). The same study showed that the mean grain size for suspended sediments was approximately 6.5Φ (11.1 μm) (Datta and Subramanian, 1997). Fine-grained sediments are typically carried in the suspended load, however, during floodstages larger particles can be carried as the rivers' velocity and discharge increases. The suspended load of a river carries the majority of the sediment, while bedload transport accounts for approximately 10% of the suspended load (Lane and Borland, 1951).

2.3 RIVER DESCRIPTIONS

The three major rivers of Bangladesh—the Ganges, Brahmaputra, and Meghna rivers—are the major control over the topography, landforms, and human patterns of the entire country. The rivers are constantly evolving new paths and flood yearly, which dictates Bangladesh's landscape.

Upstream of the Ganges-Brahmaputra confluence, the Ganges River is primarily a meandering channel (Coleman, 1969). While in India, the Ganges bifurcates into two distributaries: the Hooghly River, which flows south through Calcutta into the Bay of Bengal, and the Ganga River which flows east into Bangladesh and is considered the continuation of the main Ganges channel (Islam et al., 1999). From source to sea, the Ganges flows approximately 2500 km and has a drainage basin of 980,000 km^2, of which only 34,188 km^2 lie within Bangladesh's borders (Islam et al., 1999).

The Brahmaputra River, locally known as the Jamuna River, is a braided river channel. From beginning to end, the river flows 2896 km—1600 km in Tibet, 900 km through eastern India, and 400 km through Bangladesh (Islam et al., 1999). The drainage basin is approximately 640,000 km^2, with 50,505 km^2 located inside Bangladeshi borders (Islam et al., 1999).

In comparison, the Mississippi River in North America has a drainage basin of 3,270,000 km^2, or 40% of the continental United States (Milliman and Meade, 1983). The Mississippi River's drainage basin is roughly twice the size of the combined Ganges-Brahmaputra River drainage basin; however, the Ganges-Brahmaputra River is ranked first in annual sediment discharge, and the Mississippi River ranks seventh (Milliman and Meade, 1983).

The Brahmaputra also has the highest downstream gradient of the three rivers, which is a result of it having occupied its present channel for only 200 years (Barua et al., 1994). As a braided stream, the river is characterized by many channels, shoals, and islands, which is one characteristic of a river with a high sediment load (Coleman, 1969). The Brahmaputra is 60-70 ft deep in most stretches, however, narrow points along the river can be as deep as 150 ft (Coleman, 1969).

The Brahmaputra has the highest sediment load of the three rivers, which is widely documented in sediment flux studies (Coleman, 1969; Holeman, 1968; Milliman and Meade, 1983). Galy and France Lenord (2001) compared the Himalayan erosion rates with the suspended sediment loads of the rivers, and determined that the eastern portion of the Himalayan Range is eroding faster than the western portion, which contributes to the Brahmaputra having a higher suspended load than the Ganges. The higher erosion in the eastern region is likely caused by higher precipitation in the eastern region (Fluteau et al., 1999; Galy and France-Lanord, 2001).

All three rivers flood extensively during the wet monsoon season. The Ganges and Brahmaputra rivers are heavily influenced by Himalayan snow melt in late spring, however, extremely high rainfall during the southwest monsoon season (occurring annually from June to September) is the main cause of annual flooding (Jakobsen et al., 2005). The Ganges River has the longer record of hydrologic observations, as gage records were begun in 1910 at Hardinge Bridge, shown in Fig. 2.2 (Coleman, 1969). As

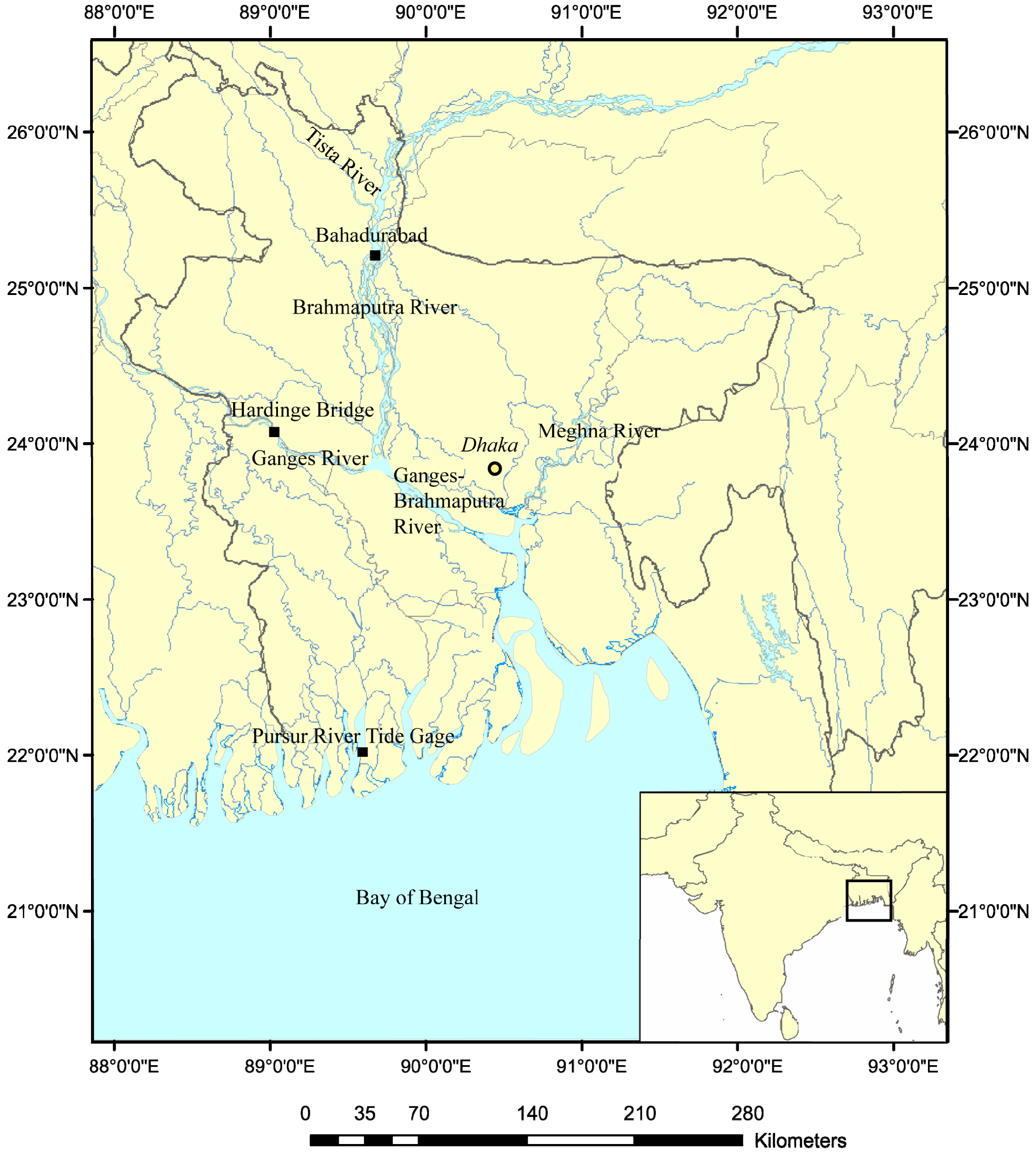

Figure 2.2. Locations of river and tide gage stations. Water gage records are collected at the Ganges and Brahmaputra rivers at Hardinge Bridge and Bahadurabad, respectively, by the Bangladesh Water Development Board. (Data from the Bangladesh Inland Water Transport Authority)

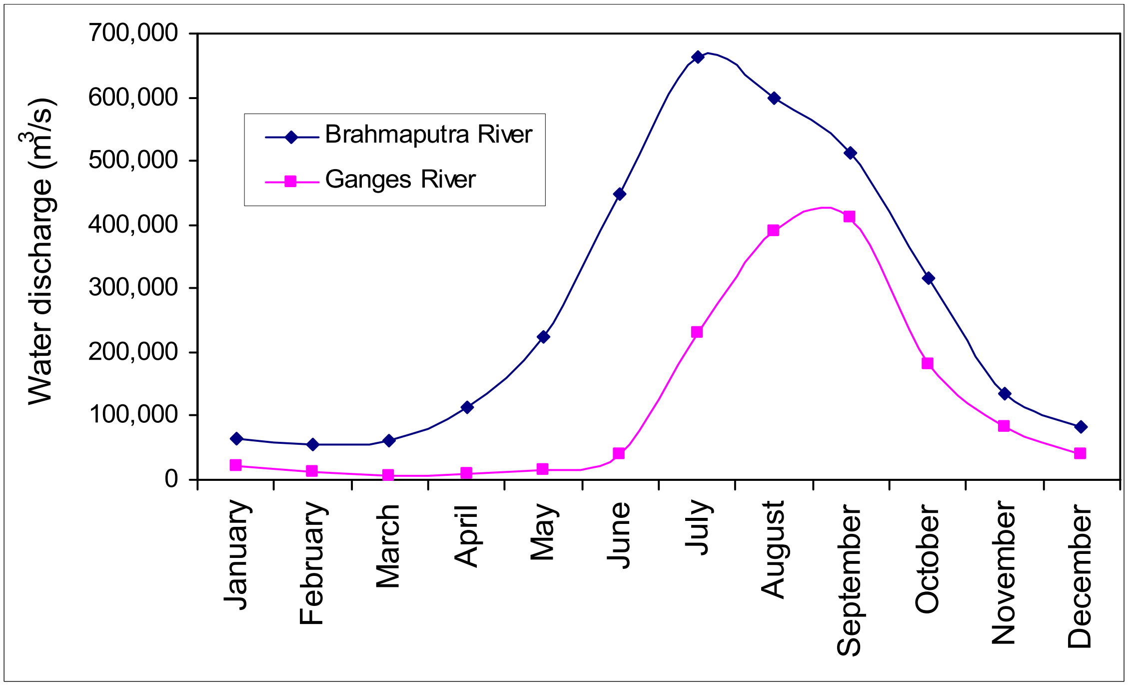

Figure 2.3. Flood hydrograph of the Ganges and Brahmaputra rivers. Monthly averages were averaged from 1990 to 2003. Data were collected at the river gage stations in Figure 2.2. (provided by the Bangladesh Water Development Board)

shown in Fig. 2.3, dry-season water discharge is approximately 5,000 m^3/s, while average maximum discharge is approximately 400,000 m^3/s (Coleman, 1969). The rising stage occurs rapidly over the monsoon season, when the discharge increases from the yearly base-level in June to the yearly maximum in August.

The Brahmaputra River's gage records were begun in 1949 in the town of Bahadurabad (shown in Fig. 2.2). While the dry-season water discharge is only slightly greater than the Ganges River (Fig. 2.3), average annual water discharge is higher (650,000 m^3/s compared to 400,000 m^3/s) because of higher precipitation in the eastern Himalayas than in the western Himalayas (Coleman, 1969; Fluteau et al., 1999).

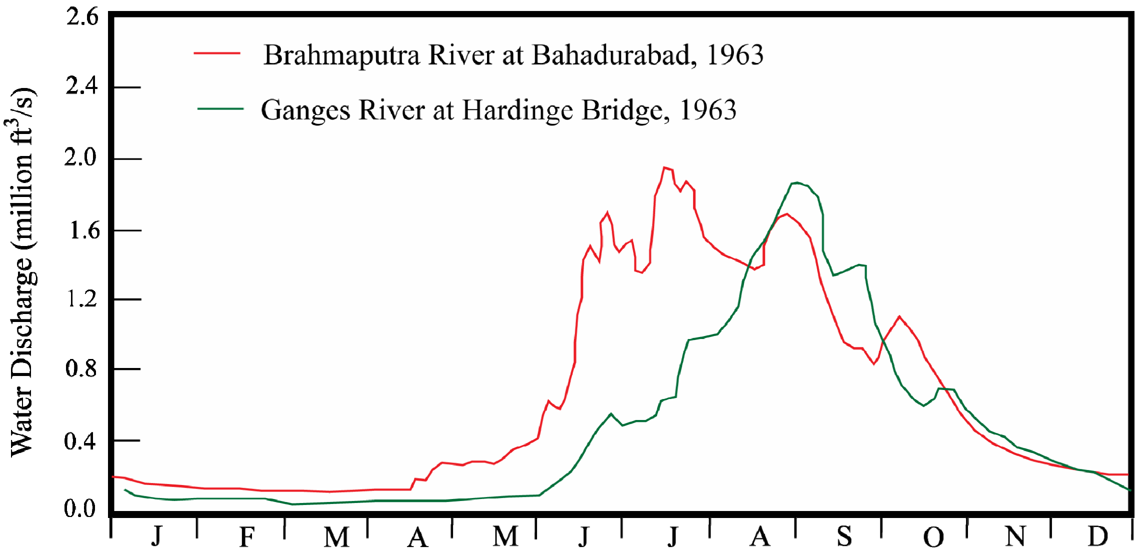

Figure 2.4. Flood hydrograph of the Ganges and Brahmaputra rivers for 1963. The flood hydrograph from 1963 is often used as a model annual hydrograph, as it clearly shows the three possible peaks of the Brahmaputra River water discharge. (modified from Coleman, 1969)

Annual flood hydrographs for the Brahmaputra can show two or three major flood peaks which typically occur over the summer monsoon season. As seen in Fig. 2.4, the 1963 monsoon season clearly showed three peaks in the Brahmaputra River's hydrograph; the two early peaks are caused by pulsated snow melt, while the last peak is caused by monsoon rainfall (Coleman, 1969). The first-peak occurred in mid-June and describes an extremely rapid increase in discharge; within a few days, the flow increased from 600,000 ft^3/s to 1,600,000 ft^3/s. The river level fell after this initial peak. The major flood peak followed in late July or early August, when the average maximum discharge reached 2,000,000 ft^3/s. A third peak occurred in early September—reaching 1,600,000 ft^3/s —and the river level remained elevated until the end of September or early October (Coleman, 1969).

The Meghna River drains the northeast fold belt of Bangladesh and is the smallest of the country's three main rivers. The Meghna is predominantly a meandering stream, however, portions of the river show braiding, particularly stretches where tributaries contribute high amounts of sediment. The average annual water discharge is 124,000 ft^3/s, although flood flow is on the order of 420,000 ft^3/s —roughly one fifth of the Ganges and Brahmaputra's individual flood discharge (Coleman, 1969).

Comparing the 1963 discharge hydrographs of the Ganges and Brahmaputra, it is apparent that two separate peaks in Brahmaputra flooding occurred before the only peak of the Ganges occurred. The average discharge hydrograph (Fig. 2.3) also shows that the earlier, larger peak in the Brahmaputra river's discharge occurs before the peak of the Ganges River. The timing of these flooding events influences the erosion and deposition of the river banks near the confluence. When the Brahmaputra is at high discharge stage (and the Ganges is not), scouring and erosion occurs north of the confluence. Later in the summer, when the Ganges and Brahmaputra have simultaneous high discharge, a backwater effect of Ganges current causes a considerable amount of deposition in the lower reaches of the Brahmaputra. During periods of low or late flooding on the Brahmaputra, the backwater effect causes increased deposition north of the confluence, which forms new sand bars and consequently widens the channel. Coleman (1969) states that these morphological features are a result of the Brahmaputra carrying a higher sediment load despite the two rivers having similar water levels. As a result of these backwater effects at the confluence, a significant portion of sediment carried by the Ganges and Brahmaputra rivers may be deposited within the Brahmaputra riverbed.

2.4 RIVERS' GEOMOPHOLOGICAL HISTORIES

Channel migration of the Ganges and Brahmaputra rivers and their numerous tributaries and distributaries has created a complex geomorphic history in the Bengal Basin. Instead of switching river paths solely to steepen river gradient to the Bay of Bengal, many other factors influence channel migration. Recent tectonic activity, annual monsoonal flooding, extreme river sediment loads, and human modification of levees and dams have contributed significantly to the varying river channels (Coleman, 1969).

The oldest Brahmaputra River sediments are found in the eastern region of Bangladesh. Geomorphic evidence indicates that the Brahmaputra occupied and abandoned at least three courses prior to the Old Brahmaputra River channel. Two hundred years ago, the Brahmaputra River flowed east around the Madhupur Tract, about 50-60 miles east of its current course, joining the Meghna River southeast of Dhaka. During this time, the Tista River (Fig. 2.2) carved the valley between the Madhupur and Barind tracts and served as a tributary of the Ganges, joining it downriver. Following a severe earthquake in 1782 and a severe flood in 1787, the Brahmaputra River gradually shifted paths over the next 30 years and established a new course through the river valley previously carved by the Tista River (Allison, 1998a; Morgan and McIntire, 1959). Since avulsing into its new channel, the river has expanded the valley from the original narrow course, to a braided stream valley averaging 8 miles wide. The valley expansion is documented on historic maps dating back to 1830. The Tista River now acts as a tributary to the Brahmaputra River, merging with the larger river 220 miles north of the Ganges-Brahmaputra River confluence. The Old Brahmaputra River still diverts water and sediment from the current river around the Madhupur Tract, however, it is remarkably less turbid than the current Brahmaputra River channel (Coleman, 1969).

While the Brahmaputra River is shifting course to the southwest, the Ganges River is currently migrating northwest. Prior to the 16th century, the Ganges River flowed into the Hooghly River near Calcutta, India, and discharged directly into the Bay of Bengal. Since then, the Ganges has steadily shifted eastward, occupying and abandoning several prominent courses during its migration (Coleman, 1969). Currently, the Ganges River has been migrating northwest for the past 250 years in response to tectonic uplift in the west which has raised areas as much as 6 m above present flood levels (Allison, 1998a). Many tidal channels found in the southwest mangrove forests of Bangladesh are abandoned Ganges River channels; known as the moribund delta, the area is crossed by numerous old, silted up distributaries which remain open to the Bay of Bengal (Allison, 1998a).

2.5 RIVER FLOODING

The annual monsoons of Southeast Asia control the oceanography and river hydrology of Bangladesh.

The annual monsoons are caused by differential heating of the ocean and land (Ramage, 1971). During the winter, the colder continent causes northeasterly atmospheric masses to bring weak precipitation to the Bay of Bengal (Fluteau et al., 1999). During the summer, warmer continents and cooler oceans create a low-pressure cell over the warm continent and a high-pressure cell over the cooler ocean. The differential heating, combined with the Coriolis Effect, causes the southwest monsoon to bring heavy precipitation to the Bengal Basin (Fluteau et al., 1999; Webster, 1987). The resulting monsoons are a dry monsoon from the northeast from September to May, and a wet monsoon from the southwest from June to September (Webster, 1987).

Flooding occurs yearly in Bangladesh as a result of increased rainfall during the summer monsoon and higher river levels (Jakobsen et al., 2005). Water flow of 2,000,000 ft^3/sec on the Ganges or Brahmaputra rivers or 300,000 ft^3/sec on the Meghna River are enough to cause the channels to overflow their banks (Coleman, 1969). Moderate floods occur approximately every four years, severe floods every seven, and catastrophic floods occurs every 30-50 years (Coleman, 1969). A flood's severity is determined by the amount of Bangladesh's land area submerged during the event; during the catastrophic flood of 1955, 38% of the country was inundated (Coleman, 1969). Typically, finer sediments are deposited on the adjacent floodplain during floods, and coarser material is deposited as crevasse splays adjacent to the river channel in the natural levees. The natural levees are therefore formed almost entirely of overlapping sediment deposits formed during flooding (Coleman, 1969). An additional study of the natural levees on the Brahmaputra River found that Cesium-137 accumulation rates are correlated with distance from the river and that accumulation rates decrease with distance (Allison et al., 1998b). Allison et. al (1998b) also determined that large amounts of river sediment are annually deposited in small areas in nearby plains during high flood events. This supports the hypothesis that a large portion of river-transported sediments are deposited landward of the river mouth during flood events in a high-load, tectonically active river system.

2.6 RIVER MOUTH

The subaerial and subaqueous deltas and fan of the Ganges-Brahmaputra River System provide an extraordinary opportunity to identify sediment transport and deposition in a large, relatively unstudied system. Before the Ganges-Brahmaputra River debouches into the Bay of Bengal, sediment is deposited and stored in the river's floodplain and subaerial delta. Once sediment is discharged from the mouth of the river, the particles accumulate on the Bengal Shelf in the river's subaqueous delta. A portion of the river load is channeled through the Swatch of No Ground Canyon (Fig. 2.5) to the Bengal Fan and the deep sea.

Original reports and studies announced that insignificant progradation of the delta had occurred over the last 200 years (Coleman, 1969; Fergusson, 1863; Morgan and McIntire, 1959). To explain the assumed lack of progradation—despite enormous amounts of sediment delivered to the delta annually—Morgan and McIntire (1959) proposed that sediments are trapped in a subsiding trough perpendicular to shore. Fergusson (1863) and Coleman (1969) reconciled the sediment dispersal issue by proposing that strong tidal currents keep the sediment in suspension so that they cannot settle and are by-passed to the Swatch of No Ground. Recent work has disproved these theories and shown that significant subaerial growth is indeed occurring. Allison (1998b) constructed a database referencing topographic changes between 19th century charts and modern maps. The database confirmed that the subaerial delta is prograding at an estimated annual rate of 7.0 km^2 (Allison, 1998b). The growth accounts for 1 to 2% of the overall river sediment budget.

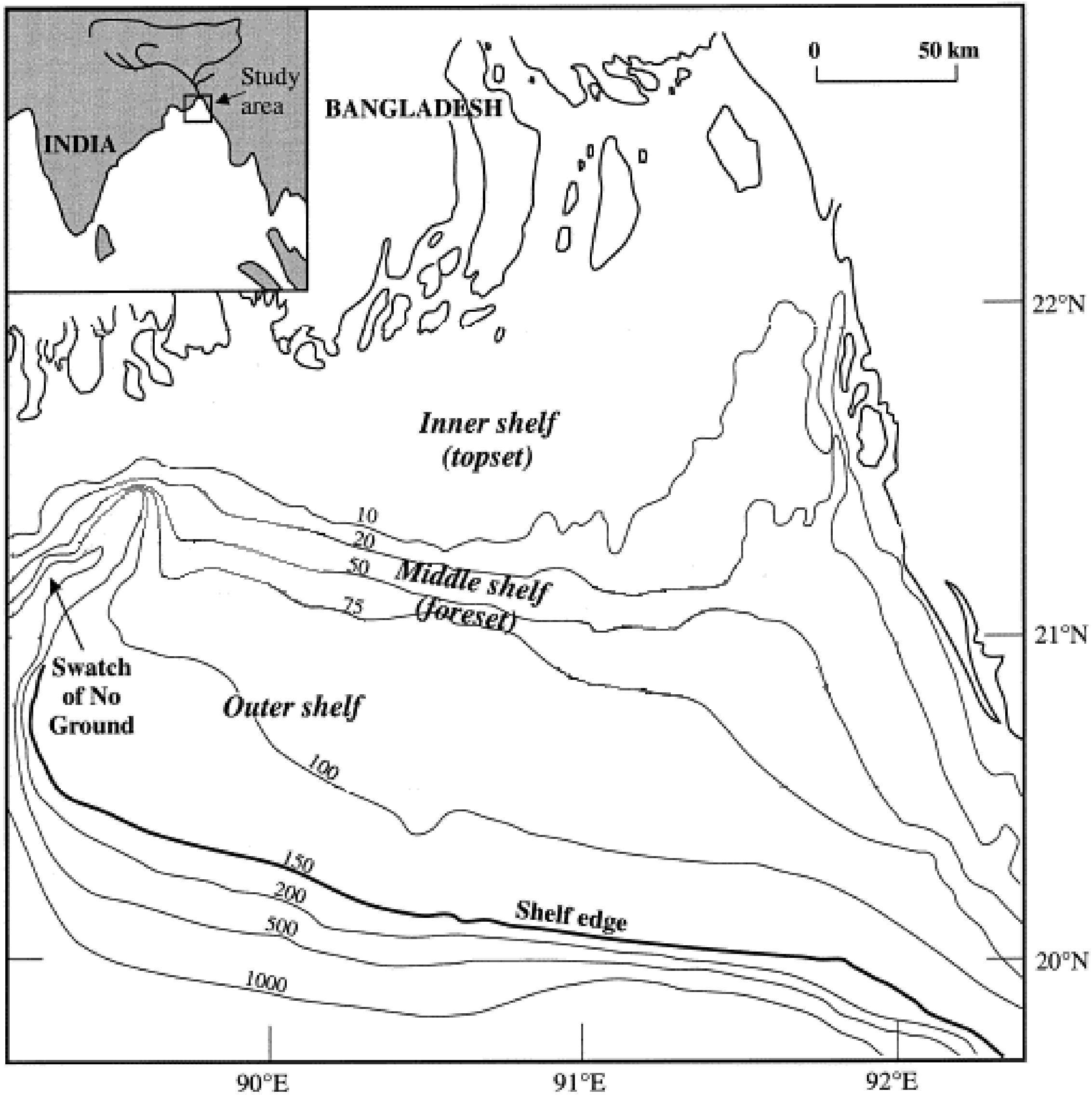

Fig. 2.5. Shelf bathymetry of the Northern Bay of Bengal. The topset, foreset, and outer shelf are subaqueous clinoform features. The Swatch of No Ground Canyon deeply incises the shelf (modified from Michels, 1998).

Further from shore, progradation is occurring in the subaqueous delta as well. Sediments on the inner shelf (landward of the 20 m isobath) are interlaminated silts and muds, probably recording neap-spring tide cycles; these sediments are considered ephemeral deposits and are probably eroded by the southwest (summer) monsoon (Kuehl et al., 1989; Segall and Kuehl, 1992). Sediments on the middle shelf are composed of alternating beds of silts and muds, probably deposited during high and low discharge seasons; coarse-grained intervals indicate multi-year depositions (Segall and Kuehl, 1992; Segall and Kuehl, 1994). The broad delta topset is comprised of a thick layer of sand and silt in less than 20 m water depth (Michels et al., 1998). Highest sedimentation rates occur in the center of the delta foreset beds, where about 10 cm of accumulation annually prograde the subaqueous delta front by about 15 m (Michels et al., 1998). Foreset beds consist of sand and silt layers interbedded with silty clay. Michels et al. (1998) contend that the sand and silt layers are tempestites, deposited by sediment flows triggered by tropical cyclones. The prograding submarine delta stores approximately 30% of the rivers' sediment load from the last 7000 years (Kuehl et al., 1997).

The Swatch of No Ground canyon acts as a sediment conduit to the Bengal Fan and deep sea. The canyon's head lies in about 38 m water depth and the canyon continues south for 160 km until is ends at the Bengal Fan at a depth of 1406 m (Curray et al., 2003). The canyon has an average gradient of 8.2 m/km. The canyon is the presumed location of the river mouth at the last glacial sea level low. There is a slight curve to The Swatch of No Ground, which may represent a westward migration of the river mouth during the last period of falling sea level (Curray et al., 2003).

Geomorphic features, such as sand bars and tidal channels bending in the direction of the shelf canyon, suggest that sediment is transported toward the Swatch of No Ground from the river mouth (Coleman, 1969; Fergusson, 1863). Sediment accumulation rates are highest at the canyon head, where they increase from 10 cm/yr on the topset to 50 cm/yr (Kuehl et al., 1989; Michels et al., 1998). The frequency of sand and silt layers (hypothesized to be storm-driven sediment layers) in the canyon matches the semi-annual frequency of tropical storms in the Bay of Bengal, suggesting that the net transport of sediment suspended during cyclones is westward toward the canyon from the river mouth and delta (Michels et al., 1998). An opposing opinion is that modern slides and turbidity currents are small and infrequent compared to canyon activity during lowered sea level (Curray et al., 2003). While some studies suggest that very little sediment enters the canyon today (Curray et al., 2003), the prevailing hypothesis is that the Swatch of No Ground acts as a conduit for sediment to reach the Bengal Fan and deep sea. A study of the mineralogy of sediment east and west of the canyon indicates that the Swatch of No Ground acts as a barrier of sediment transport to the Indian Shelf (Segall and Kuehl, 1992). Chlorite is enriched in Ganges-Brahmaputra River water and deposited along the Bengal Shelf, however, it is not present west of the canyon. The presence of chlorite on the Bengal Shelf indicates that the Ganges-Brahmaputra water and sediment is transported west by surface currents until it reaches the Swatch of No Ground. The canyon prevents chlorite-enriched sediment from reaching the western Indian Shelf (Segall and Kuehl, 1992).

The Bengal Fan is the final destination of sediment carried by the Ganges-Brahmaputra. The submarine fan is the largest in the world at a length of 3000 km, width of 1000 km, and maximum thickness of 16.5 km (Curray et al., 2003). Depths at the fan's apex and end are 1400 and 5000 m, respectively. Gradients range from 5.7 m/km at the uppermost fan, to less than 1 m/km on its lower reaches (Curray et al., 2003). The Ganges-Brahmaputra is the main supplier of sediment, although smaller rivers that debouche into the Bay of Bengal from India and Bangladesh make some contribution. First recognized as a submarine fan in 1953, the region was surveyed in 1971, when it was discovered that abandoned sediment channels were incorrectly labeled as turbidity current channels (Curray et al., 2003). Several inactive canyons and channels are present on the fan, however, only The Swatch of No Ground remains active today as a conduit of sediment to the Bengal Fan (Curray et al., 2003).

2.7 TIDAL CHANNELS

The lower delta plain is defined as the low-elevation, subaerial portion of a delta which is adjacent to the ocean and periodically subjected to saline flooding. In the Ganges-Brahmaputra Delta, the lower delta plain is located west of the active river mouth, and extends inland as far as 100 km as a series of north-south oriented channels (Allison and Kepple, 2001). These N-S channels are relict channels of the main Ganges-Brahmaputra River mouth, which formed as the river shifted eastward, (Allison, 1998b) and island accretions formed which have been joined to the mainland since the last maximum sea-level transgression (Allison et al., 2003). While the channels in the lower flood plain were formed by previous occupation of the main Ganges-Brahmaputra River, they still may be active as small distributaries which branch from the main river.

There are two possible sources of modern sediment supply to the lower delta plain west of the active river mouth: (1) delivery of sediment from distributaries that drain the northern Ganges River and discharge into the north-south tidal channels, and (2) Ganges-Brahmaputra River sediment that has been discharged from the main river channel, carried west by coastal currents, and directed into the tidal channels by tidal currents. Allison and Kepple (2001) determined that sediment accumulation rates in the lower delta have not changed over the last 2,500 years despite recent decreases in water and sediment flow through lower distributaries (resulting from upriver dams and dredging); this indicates that the sediment is not supplied by distributaries flowing to the lower delta channel, but is instead westward-transported main channel sediment moving inland through the lower delta channels. Significant amounts of sediment could be contributed to the tidal channels by distributaries which divert sediment from the main river channel, suggesting that this may be an active pathway for sediment transport. Additionally, ^{137}Cs sediment accumulation rates decrease upstream in the delta channels with increasing distance from the Bay of Bengal, suggesting that the sediment source is offshore (Allison and Kepple, 2001); if the sediment source were directly from the river, the accumulation rates would remain constant along the tidal channels or decrease from the river to the bay.

CHAPTER III

FIELD MEASUREMENTS AND SAMPLING

3.1 SAMPLE COLLECTION

Sampling was conducted during July and August 2006 during the southwest monsoon season throughout the Ganges-Brahmaputra River Delta in Bangladesh. The sampling team primarily resided in the capital city of Dhaka, and conducted three short expeditions into different regions of the country for sample collection.

The first of the three expeditions was a four day trip that covered the northwest and southwest regions of the country. The team traveled northwest from Dhaka, crossed the Brahmaputra River, and sampled the northwest tributaries. The next day, the group headed south, crossed the Ganges River, and sampled the southern distributaries. On the last day, the group traveled north and crossed the conjoined Ganges-Brahmaputra River by ferry on the return to Dhaka. Shown on Fig. 3.1, the rivers sampled on this trip were the Brahmaputra, Atrai, Ganges, Bhairabi, Rupsa, Madhumati, Arialkhan, and Ganges-Brahmaputra.

The second trip was a day trip from Dhaka into the northeast region of the country. The group traveled east from Dhaka and drove toward the Tripura Fold Belt on the eastern border of Bangladesh during this expedition and returned to Dhaka that evening. During this outing, the Meghna River and Abandoned Brahmaputra River were sampled (Fig. 3.1).

The last of the three sampling trips was a five day journey to the Bay of Bengal to sample the tidal channels. Travel to and from the coastal tidal channels took four days, and one day was spent sampling a selected tidal channel by boat (Fig. 3.1).

Rivers were selected to be sampled to provide a wide range of geographic locations and geomorphological characteristics. For accessibility, sampling sites were selected for proximity to the main roads which were traveled by the research team. In

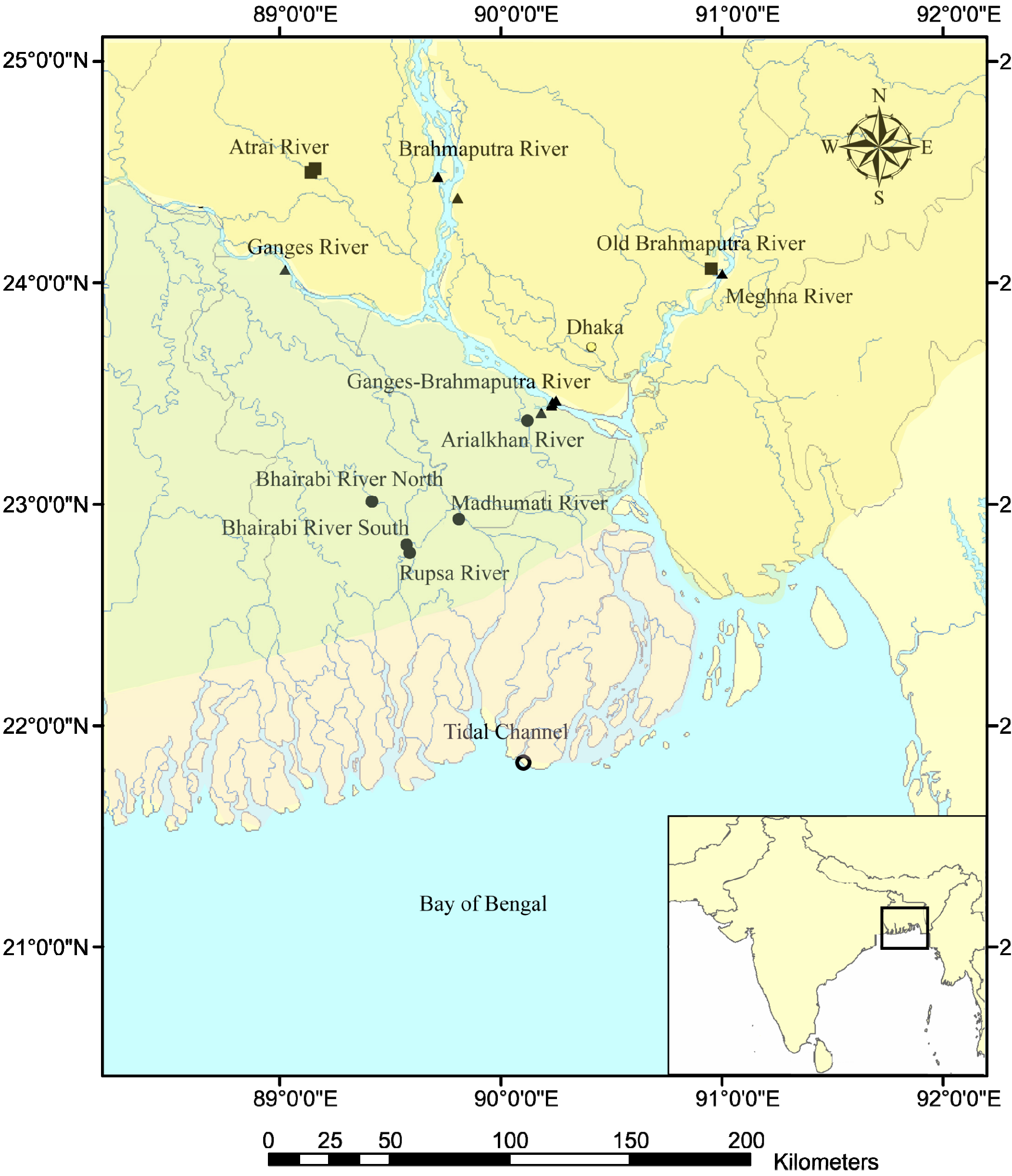

Figure 3.1. Map of sampling sites in Bangladesh. Main river channel sampling sites are denoted with a solid triangle; tributaries are marked with a solid square; distributaries are marked with a solid circle; the tidal channel is marked with an open circle. The tributary region is shaded yellow, the distributary region is shaded green, and the tidal channel region is shaded pink.

accordance with the objectives of this thesis, the sites were later classified into broad morphological groups for analysis.

Samples were collected using a sturdy metal bucket, which was thrown into the river and retrieved with an attached recycled jute rope. The surface samples were taken from river shore and were approximately one meter from river bank. The bucket was rinsed with river water several times prior to official water sample collection to ensure a clean, representative sample. At a small number of sites, samples were collected further from shore via an available dock or anchored boat. After bucket collection, water samples were swirled to prevent settling and immediately transferred to plastic storage bottles. Samples were stored for 2-4 days in the bottles until they were returned to a makeshift field laboratory in Dhaka for filtering.

In addition to collecting water samples at the river sites, observations were made regarding the river conditions. River flow was calculated by timing a floating object across a measured distance, or by pacing using a hand-held GPS unit. At each site, latitude and longitude, time of sampling, approximate river width, and bank conditions were recorded. When possible, river width was accurately measured using the car odometer while crossing the river over a bridge. Additionally, local Bangladeshis were interviewed for details about river depth and water flow.

During the last sampling expedition, tidal channel samples were collected by boat. The team rented a wooden fishing boat from a local fisherman and hired him to steer the vessel through the local tidal channel. As the group was visiting Kuakata on the Bay of Bengal coast, the tidal channel immediately located to the west of the city was selected as the representative tidal channel for sampling. Surface water samples were collected by the same metal bucket as was used in river sampling.

Water samples were collected from approximately the same location in the tidal channel at important phases in the tidal channel (i.e. maximum flood tide, maximum ebb tide). The boat also completed a small transect from shore into the Bay of Bengal and sampling was conducted every 10-15 minutes along the transect. At the end of the transect, the ship was approximately 4-5 km from the shoreline.

Suspended sediment samples were also collected from the water column to be used to measure ^{7}Be activity data. Approximately 10 gallons of water from a sampled river was collected in a large carboy and allowed to settle for at least 24 hours. Once the sediment had settled, the remaining water was decanted from the container, and the sample was stored in a high-concentration slurry for radiometric analysis.

3.2 LABORATORY ANALYSIS

After arrival at the field laboratory, water samples were preserved on pre-weighed filters. Before use in the field, filters were placed in individual glassine envelopes, numbered, and dried in a dessicator for three days to ensure driness. Once dry, the filters were weighed to the nearest microgram on a Perkin Elmer AD-6 Autobalance. The filters were weighed twice: individually and in the glassine envelopes so that the entire unit could be weighed should sediment fall off the filter into the envelope after filtering.

Filtering was conducted in the field laboratory in Dhaka to measure sediment concentrations. Bottles were homogenized by shaking prior to filtering to ensure a well-mixed representative sample. To determine sediment concentration, a measured volume of the water sample was pumped through a pre-weighed filter. Because of the high sediment load, only a small volume of sample (usually between 10-30 mL) was needed before the filter clogged and severely increased the filtering time. Millipore 3.0 µm 25 mm cellulose filters were used. Four replicates of each sample were filtered. While wet, filters were stored in the glassine envelopes and allowed to dry.

After filters arrived in the United States, the same procedure was used to prepare the filters for weighing. The filters were dried for three days in the same desiccator and reweighed on the same balance.

Suspended sediment concentrations were calculated using the mass of sediment accumulated on the filter and the volume of water pumped through the filter. After return to the Texas A&M University, it was noted that sediment had fallen off approximately 10 filters into their envelopes. In these cases, the entire unit (filter and envelope) were weighed and compared the original measurement of filter and envelope.

After suspended sediment concentrations were calculated, it became apparent that these replicates produced imprecise calculations. The envelopes absorbed moisture quickly and produced inaccurate mass readings. Because the amount of moisture absorbed by the envelopes was unknown, the replicates which lost sediment to the envelopes were excluded from suspended sediment concentration calculations. As four replicates were usually filtered for each water sample, the exclusion of filters with lost sediment did not eliminate any sampling locations; the elimination of these filters only allowed fewer replicates to be included in the suspended sediment concentration averages.

Additionally, 20 mL of each water sample was saved in small vials. The small volume of sample saved was necessitated by restrictions on liquids carried on flights to the United States during August 2006. Upon return, the salinity of each sample was measured using a hand refractometer. The index of refraction was measured to four decimal places and converted to salinity using the empirical relation between index of refraction and salinity (Quan and Fry, 1995).

Salinities were measured for tidal channel samples. The salinities of all river samples were measured with the hand refractometer and found to have no measurable salinity.

Suspended sediment samples that were collected for radiometric analysis were measured for ^{7}Be activity. Beryllium-7 was measured by the Department of Geological Sciences at East Carolina University using a well-type germanium gamma detector. The suspended sediment samples ranged from 3-6 g dry weight and were analyzed on the detector for 24-48 hours. Activity measurements were made on beryllium's 477.6 KeV energy peak, which has an intensity of 10.4 % (i.e., gamma frequency per decay). Detector efficiency at 477.6 KeV is 0.1644 with minimum detectable activity (MDA) between 0.10-0.15 dpm/g.

CHAPTER IV

RESULTS

As hypothesized, suspended sediment concentrations vary widely throughout the entire river system. Four geomorphological classifications are determined for analysis of data: main river channels, distributaries, tributaries, and tidal channels. Sampling locations are shown in Fig. 3.1.

Main river channels (marked with a solid triangle in Fig. 3.1) include samples taken from the three major rivers—the Ganges, Brahmaputra, and Meghna rivers. The classification distributary (marked as a solid circle in Fig. 3.1) includes all rivers where water flows from a main river channel into the Bay of Bengal. The classification tributary (marked with a solid square in Fig. 3.1) includes all rivers which flow into a main river channel; the source of these rivers' water is often a small watershed within the region. The tidal channel (marked with an open circle in Fig. 3.1) is the last classification and includes the lowest reaches of the river system.

4.1 MAIN RIVER CHANNELS

Suspended sediment concentrations are predictably high for the majority of the main river channels (Fig. 4.1); however, values show significant variation within this geomorphological classification.

The Brahmaputra was sampled from both the east and west banks (Figs. 3.1 and 3.2). The river was 4.8 km wide as measured from the bridge spanning the Brahmaputra. The east bank was sampled from a grassy shore which was stabilized with non-native rocks. The west bank was sampled at a cut bank with a very strong river current. This west bank sampling site was protected with concrete bricks to stop the river from eroding away the river bank and nearby town. As listed in Table 4.1, the suspended sediment concentrations for the west and east banks (0.345 g/L and 0.465

g/L, respectively) are approximately equal. The flow at the east bank was measured to be 100 cm/s; a measurement was not available at the west bank, however, it was visually estimated to be considerably faster. While the suspended sediment concentrations on the two sides of this river are approximately equal, the value is lower for the west side, which had the stronger current.

The Ganges River was sampled on the west bank. The river width was measured from the nearby bridge and determined to be 2.1 km wide. The flow velocity was not measured as the site was sampled on a windy day which was increasing the surface flow velocity. The bank was lined with concrete bricks to prevent erosion. At 0.563 g/L, the Ganges' suspended sediment concentration is higher than the Brahmaputra's, even though the Brahmaputra is known to have a higher sediment load at other times (Galy and France-Lanord, 2001; Milliman and Meade, 1983).

Suspended sediment concentrations in the Meghna River vary considerably from the Ganges and Brahmaputra rivers because of the major difference in the sediment load of this smallest river. The Meghna River was sampled on the eastern bank. The sampling site was secured with non-native boulders to prevent erosion. As measured while crossing the river by bridge, the river width was approximately 1 km. A local worker stated that the river was approximately 14 m deep on the eastern side, and deeper than that on the western side. The river flow was measured by GPS to be 30 cm/s. At 0.010 g/L, the Meghna's suspended sediment concentration was the lowest of the three major rivers. This was consistent with field observations: the Meghna was not the typical muddy brown color, but instead had a greenish tint and was slightly translucent.

The Ganges-Brahmaputra River was also sampled downstream of its confluence (Fig. 4.2). The samples were collected while crossing the river by ferry. The ferry dock was situated on the south bank in a side channel of the river; a large, habited

Table 4.1. Suspended sediment concentrations of sampled rivers. The geomorphological classes and sampling locations are shown on Fig. 3.1.

River	Latitude	Longitude	concentration (g/L)	geomorphological class
Bhairabi River North	23.01230	89.41494	0.180	Distributary
Bhairabi River North	23.01176	89.41531	0.156	Distributary
Bhairabi River South	22.81617	89.57212	0.490	Distributary
Bhairabi River South	22.81617	89.57212	0.493	Distributary
Rupsa River East Shore	22.78000	89.58671	0.590	Distributary
Madhumati River	22.93251	89.80880	0.290	Distributary
Arialkhan River	23.37914	90.11842	0.823	Distributary
Ganges River	24.06081	89.02178	0.563	Main River Channel
Brahmaputra West Bank	24.47949	89.71310	0.345	Main River Channel
Brahmaputra East Bank	24.38390	89.80202	0.465	Main River Channel
Ganges-Brahmaputra, South bank, Ferry Dock	23.41391	90.18027	0.150	Main River Channel
Ganges-Brahmaputra, Main channel, south side	23.44696	90.22784	0.312	Main River Channel
Ganges-Brahmaputra, Main channel, center	23.45934	90.23093	0.531	Main River Channel
Ganges-Brahmaputra, Main channel, north side	23.46938	90.24728	0.326	Main River Channel
Meghna River	24.04215	90.99937	0.010	Main River Channel
Atrai River	24.51463	89.15895	0.101	Tributary
Atrai River	24.49912	89.13861	0.286	Tributary
Abandoned Brahmaputra channel	24.05740	90.96332	0.005	Tributary

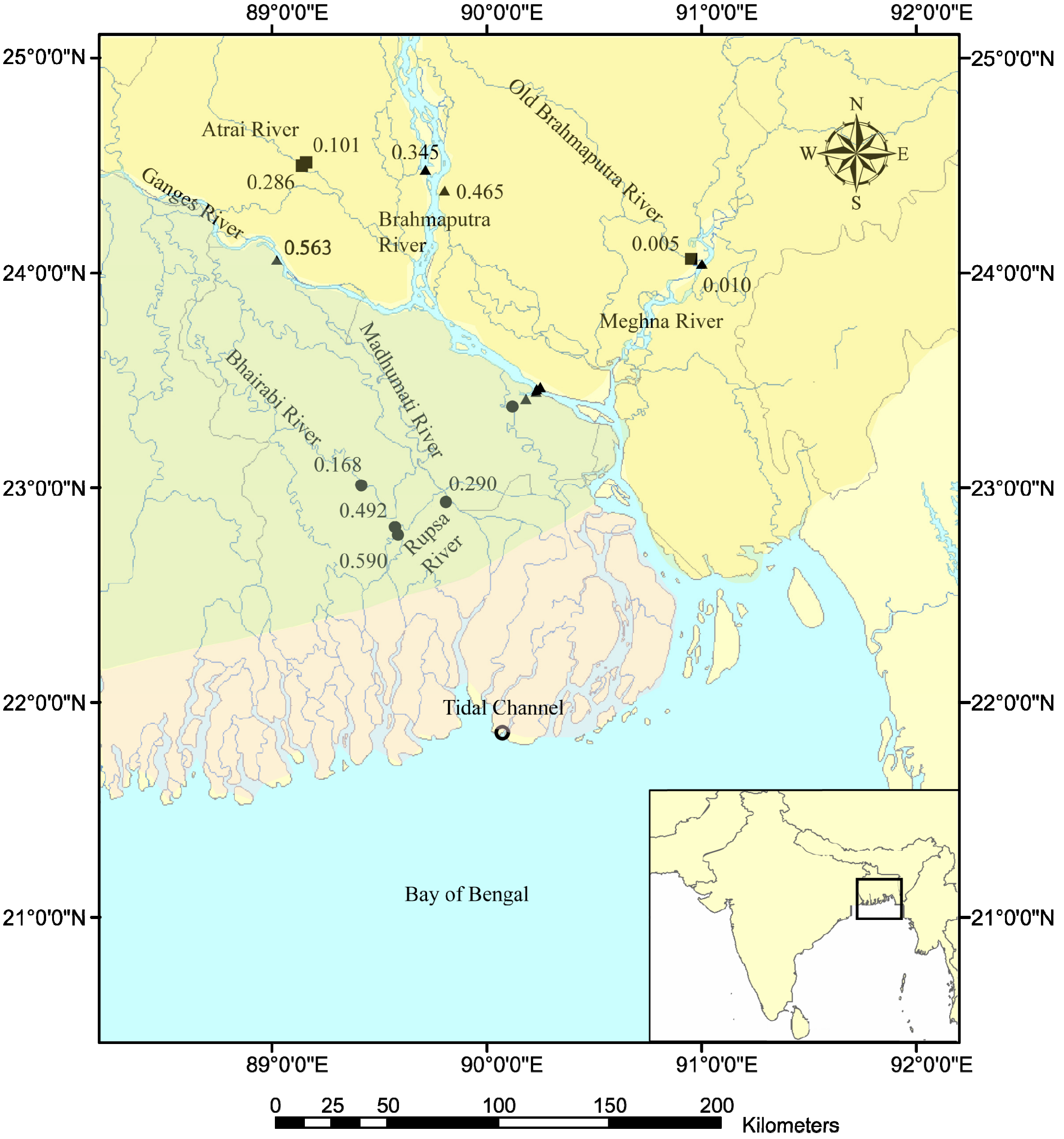

Figure 4.1. Suspended sediment concentration map. Suspended sediment concentrations of sampled locations are shown. At sites where multiple samples were collected (Atrai and Bhairabi rivers), the average suspended sediment concentration is shown. A close up of the Ganges-Brahmaputra River sites is shown in Figure 4.3.

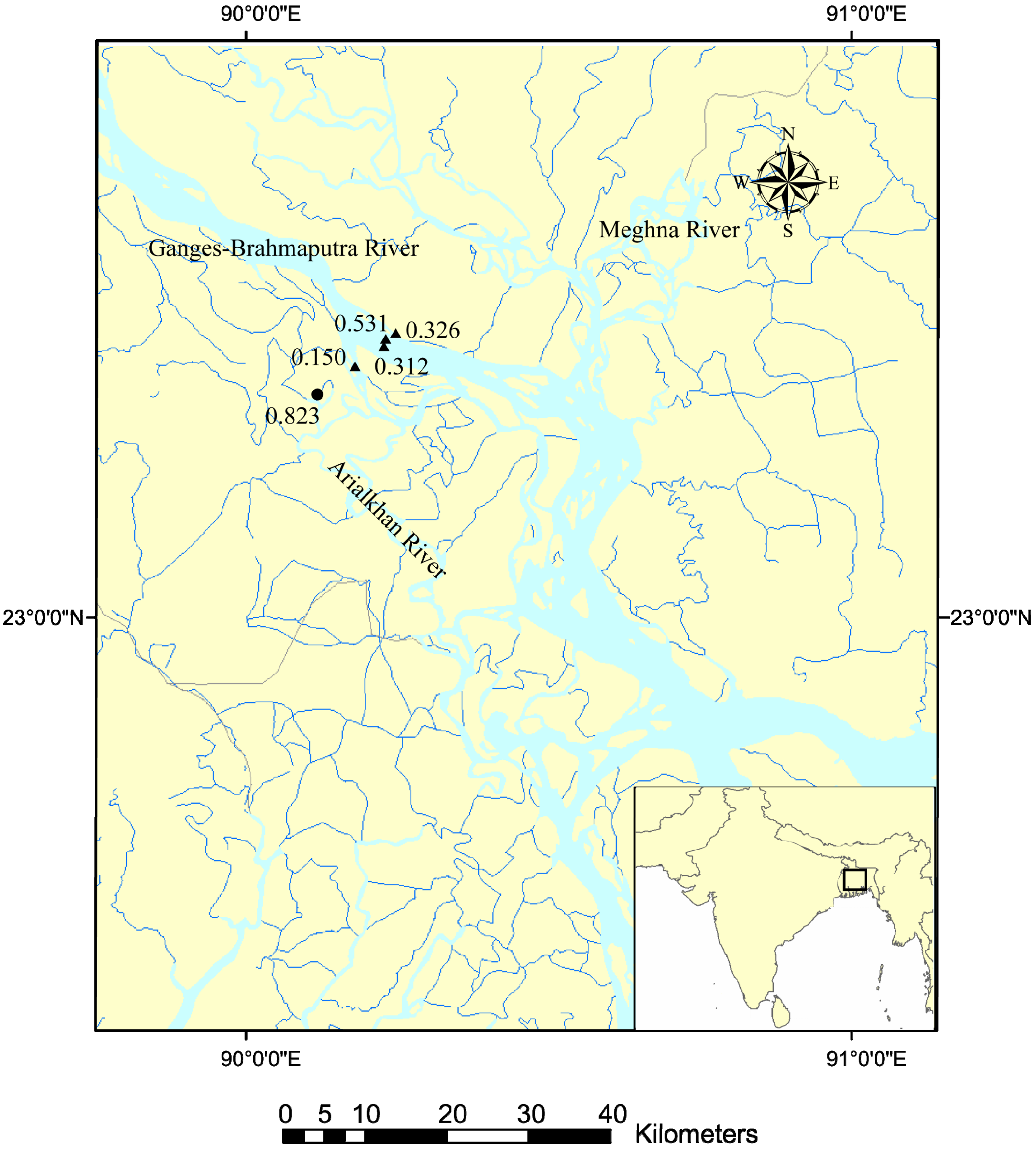

Figure 4.2. Suspended sediment concentration map of the Ganges-Brahmaputra main channel. Figure shows the suspended sediment concentrations of the Ganges-Brahmaputra River. The Arialkhan is also shown, and is classified as a distributary. The Meghna River joins the Ganges-Brahmaputra River southeast of the sampling location.

sand-bar divided the river into the main channel and the southern side channel. Samples were collected at the ferry dock in the southern channel, on the southern side of the main river channel, the center of the main channel, and on the northern side of the main channel. The four sampling points give a rough transect of suspended sediment concentrations across the conjoined Ganges-Brahmaputra River. The ferry dock sample had the lowest suspended sediment concentration in the transect, while the samples from the main river channel give a symmetric cross-section for suspended sediment concentrations with a maximum in the center.

4.2 TRIBUTARIES

The Atrai River drains a low-lying, possibly subsiding basin which is located north of the Ganges River and west of the Brahmaputra River. The Atrai flows southeast and is a tributary to the Brahmaputra River (Figs. 3.1 and 4.1). The river was sampled at two sites approximately 2.7 km apart. The first sampling site had a suspended sediment concentration of 0.101 g/L. At this location, the river was approximately 50 m wide with flooded fields surrounding. The river flowed along the main highway and the site was accessed by a small bridge and path to the river. The flow velocity was approximately 20 cm/s.

The second Atrai River sampling site had a higher suspended sediment concentration at 0.286 g/L. At approximately 100 m wide, the river was larger in this location. The river was bound on both sides by natural, sandy banks, and there were raised roads on both sides. The wind while sampling was blowing opposite of the river flow, making surface flow measurements unreliable.

The abandoned Brahmaputra River channel was sampled in the northeast region of Bangladesh (Figs. 3.1 and 4.1). The suspended sediment concentration of the abandoned Brahmaputra channel was the lowest sampled at 0.005 g/L. It had the highest level of visibility of any river sampled, including plants which were visible under water. The river was approximately 1 km wide, and sampling was performed from the middle of a bridge spanning the river. No sustained flow was identifiable and there was evidence that parts of the river included drowned fields and farm paddies.

4.3 DISTRIBUTARIES

As a large-scale river delta, the Ganges-Brahmaputra's intricate sediment dispersal occurs in the lower reaches of the river system as well. Suspended sediment concentrations in the rivers' distributaries vary considerably with tidal conditions.

The highest suspended sediment concentration within the distributary geomorphological classification occurred at the Arialkhan River, with a concentration of 0.823 g/L. The Arialkhan diverts water from the joined Ganges-Brahmaputra River south from the main river channel and flows through deltaic silts and sands before it reconnects with the main river south of the Meghna confluence. The river flows through agricultural fields and showed no evidence of tidal influence. The river was approximately 300 m wide at the sampling site and was flowing quickly at 100 cm/s (as measured using the GPS).

The remaining three distributaries were sampled further south where they received tidal influence, despite being 50 km further inland than the tidal saline intrusion limit at 100 km.

The Bhairabi River was sampled at two locations (Fig 3.1 and 4.1). At the north Bhairabi River sampling site, two samples were taken approximately 30 km apart. The suspended sediment concentrations are approximately equal at 0.180 g/L and 0.156 g/L, and shown as an average of 0.168 g/L in Figure 4.1. The samples were collected at approximately 11:00 AM during ebb tide. The river was flowing south at 100 cm/s as measured by the GPS. The sampling site showed evidence of recent tidal influence, including a high tide line marked on the river bank with bricks and recently deposited plant debris. The river was approximately 300 m wide. Local Bangladeshis said that the river is approximately 7 m deep and that the tidal range is approximately 2 m.

The Bhairabi River south location (Figs. 3.1 and 4.1) was sampled from a boat which was anchored at the end of a 20 m dock; the samples were collected approximately 20 m from the bank toward the middle of the river. At this location, the suspended sediment concentrations were higher at 0.490 g/L and 0.493 g/L, and shown on Fig. 4.1 as an average value of 0.492 g/L. The river was considerably wider at this location, approximately 1 km, however the flow was lower at 30 cm/s. The river water appeared to be flowing faster near the center of the river, although it was not possible to measure accurately. The river was sampled at 2:40 PM on the same day at the north Bhairabi River sampling site. The river was flowing north, showing tidal influence. It appeared to be high tide, as the river's banks were completely full and there was no evidence of a higher river level on the banks. The captain of the docked boat said that the river was approximately 9-12 m deep.

The Rupsa River (Figs. 3.1 and 4.1) was sampled the following morning at 9:30 AM. This sampling site had a suspended sediment concentration of 0.590 g/L. The sample was collected at low tide while the river was flowing south. Evidence that supported the river was at low tide included low water levels, exposed mud flats on the banks, and freshly eroded mud at higher levels on the shore. The sample was collected for the east bank of the river from a bamboo pier that jutted approximately 4 m into the river. The river was flowing at 70 cm/s as measured by the handheld GPS. Local Bangladeshis said that the river was approximately 1-2 m deep at low tide.

The last distributary sampled was the Madhumati River (Figs. 3.1 and 4.1). The Madhumati was sampled on the same day as the Rupsa River at 10:43 AM, however, it appeared to be high tide at this sampling location. The suspended sediment concentration was 0.290 g/L. The river was about 200 m wide, and flowing south at approximately 30-50 cm/s. The sample was collected from under a bridge, and the river banks were protected with concrete bricks. There was no evidence of recent flooding or erosion near the sampling site.

4.4 TIDAL CHANNELS

Tidal Channel data was collected from a small, private fishing vessel in a tidal channel west of the coastal town of Kuakata. The tidal channel was approximately 2 km wide and will be referred to as the "Kuakata Tidal Channel."

Samples were collected from approximately the same location in the Kuakata Tidal Channel to determine the variation of the suspended sediment concentration with the tidal cycle. Tidal data was collected in the Pursur River (Fig. 2.2), which is located approximately 55 km west of the sampled tidal channel at 21.7167° N, 89.5500° E. As shown in Fig. 4.3, on the sampling day, low tide occurred at 4:22 AM with a tide gage height of 0.91 m. The region was in flood tide until high tide occurred at 10:35 AM with a tide gage height of 3.47 m. Ebb tide occurred until low tide at 4:59 PM with a tide gage height of 0.91 m. The last high tide of the day occurred at 10:54 PM, with a tide gage height of 3.24 m.

Samples are identified with waypoint identification numbers (Fig. 4.4), however, there are no points 1 or 4. These locations were occupied, but not sampled due to limited supplies. The first sample (way point 2) was collected at 9:00 AM during the flood period as water flowed north from the Bay of Bengal into the channel. The suspended sediment concentration at waypoint 2 was 0.430 g/L (Fig. 4.5, Table 4.2). Also during flood tide, a sample was collected at 9:30 AM at the mouth of the channel (way point 3). This sample had a suspended sediment concentration of 0.784 g/L, indicating suspended sediment concentrations increase as flood tide progresses. Two samples were collected at approximately the same location in the tidal channel after the tide reversed to ebb tide: at 1:30 PM, way point 12 was collected and had a suspended sediment concentration of 0.324 g/L and at 2:10 PM, way point 13 was collected and had a suspended sediment concentration of 0.386 g/L.

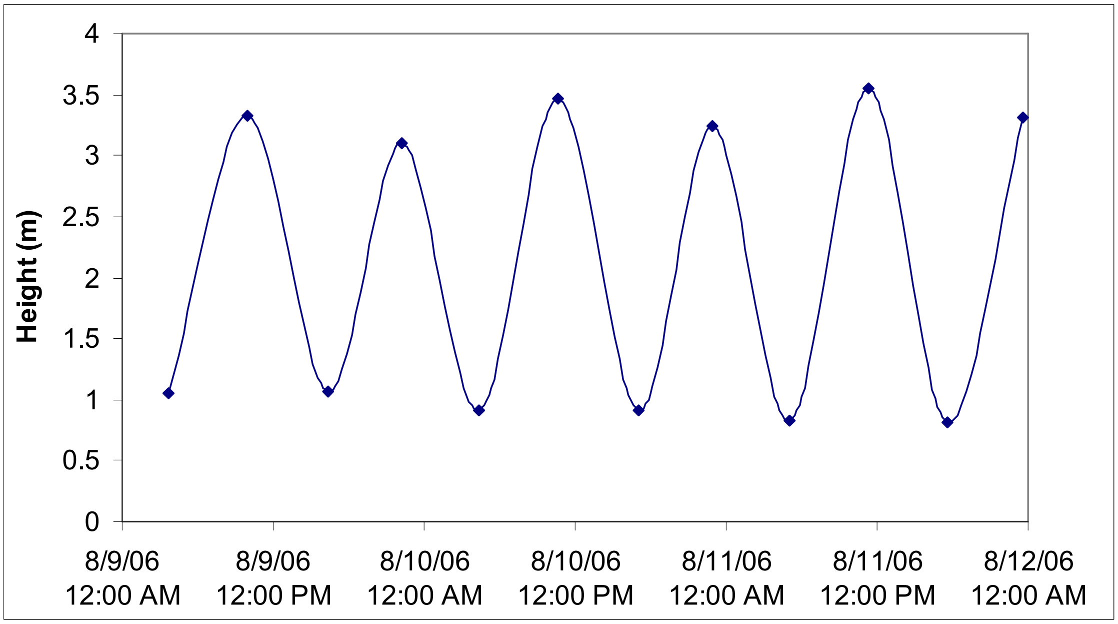

Figure 4.3. Pursur River Tide Gage Record. Figure details the high and low tides for the days proceeding, during, and following sampling in the Kuakata Tidal Channel. Figure 5.5 shows the tide gage data compared to the suspended sediment concentrations collected in the Kuakata Tidal Channel. (Data provided by the Bangladesh Inland Water Transport Authority).

Additionally, samples were collected on a transect into the Bay of Bengal (consisting of points 3, 5, 6, 7, and 8). Samples were collected at 15 minute intervals in the southeast transect. The transect ended approximately 4-5 km from shore and the surface flow in the Bay of Bengal was westward. At the furthest point from shore, a depth measurement was collected with an unweighted grab sampler. The water depth was approximately 5 m.

Samples from waypoints 9 and 10 were collected while returning to the tidal channel. Both were taken at the mouth of the channel during flood tide.

Two samples were collected from a mangrove inlet on the western side of the tidal channel. The inlet was approximately 10 m wide and was filled with fishing boats.

Waypoint 11a was collected during floodtide at 11:40 AM and had a suspended sediment concentration of 0.541 g/L. The tide reversed to ebb tide and water flow switched direction at approximately 12:30 PM. Waypoint 11b was collected while in the mangrove inlet at 12:32 PM and its suspended sediment concentration was 0.378 g/L.

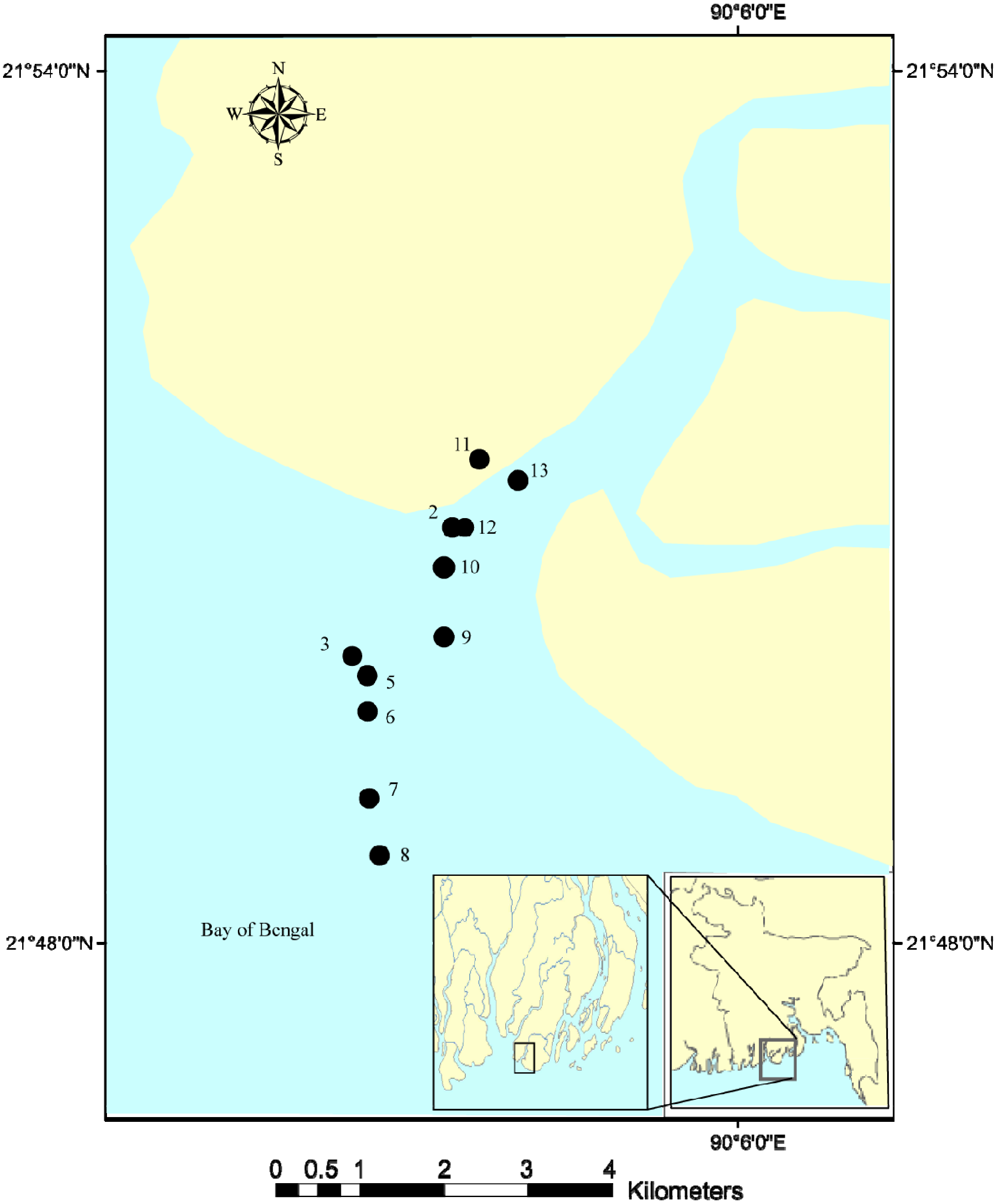

Figure 4.4. Tidal channel sampling locations. Samples at way points 3 through 8 were collected during a southeastward transect from shore; waypoint 11 was collected in a small mangrove inlet to the west of the tidal channel. Sites 1 and 4 were occupied briefly, but not sampled due to limited supplies.

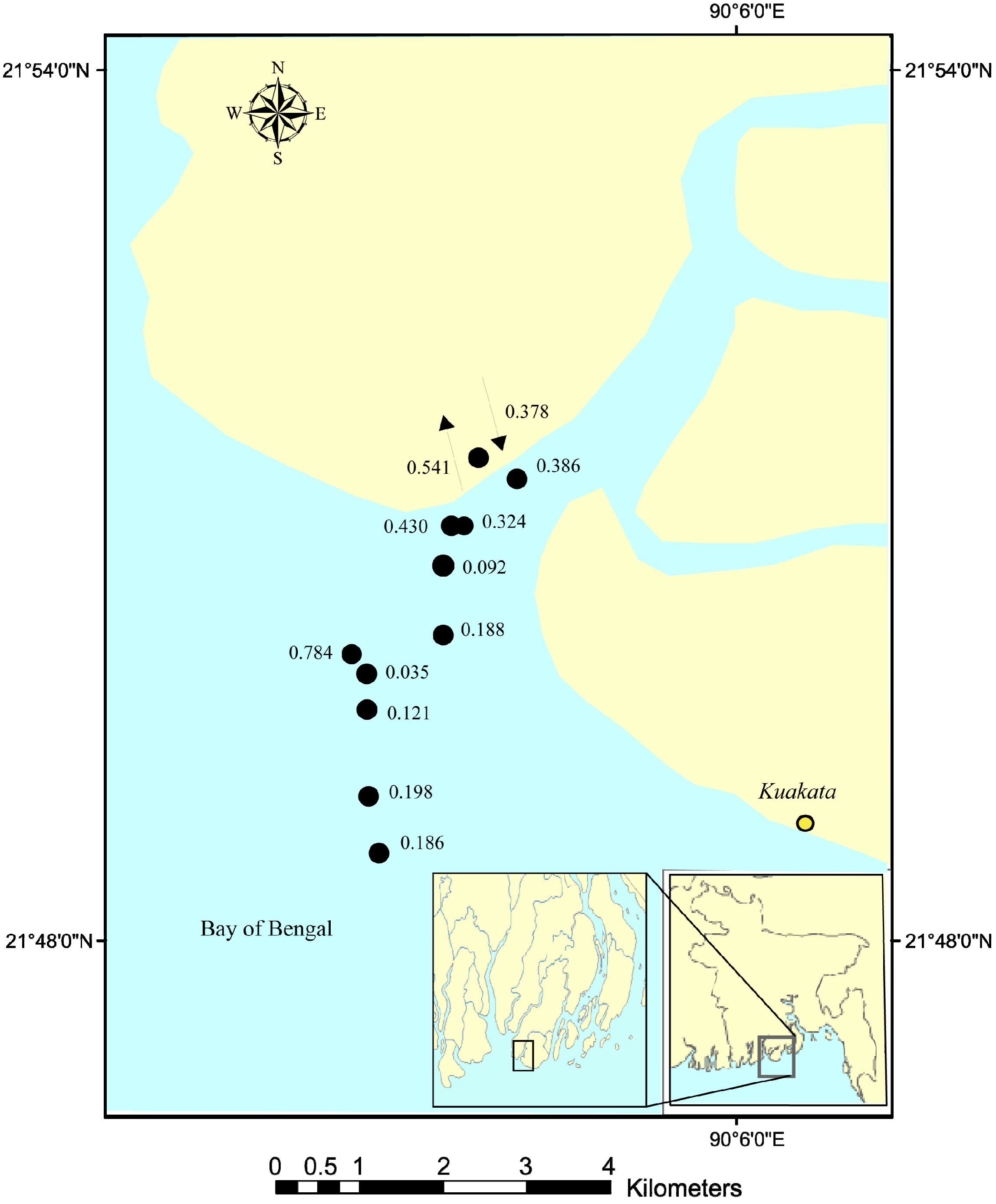

Figure 4.5. Suspended sediment concentrations of samples in the Kuakata Tidal Channel Suspended sediment concentrations are listed in g/L. Waypoint identifications of sampling locations are shown in Fig. 4.4.

Table 4.2. Suspended sediment concentrations of sampled points in the Kuakata Tidal Channel. Suspended sediment concentrations and salinities were measured from water filtered from the sample site. Tidal cycle stages were observed in the field and later confirmed using the Pursur River Tide Gage data.

Waypoint	Latitude	Longitude	Time	Tidal Cycle Stage	Suspended Sediment Concentration (g/L)	Salinity (PSU)
2	21.85935	90.07179	9:00 AM	flood	0.430	missing
3	21.83637	90.05802	9:30 AM	flood, transect	0.784	9.4
5	21.83661	90.05744	9:45 AM	flood, transect	0.035	12.8
6	21.82968	90.05817	10:00 AM	flood, transect	0.121	12.8
7	21.81571	90.05846	10:20 AM	flood, transect	0.198	13.3
8	21.80653	90.06010	10:30 AM	flood, transect	0.186	12.8
9	21.84171	90.07047	11:10 AM	flood	0.188	10.6
10	21.85291	90.07047	11:20 AM	flood	0.092	8.9
11a	21.87031	90.07616	11:40 AM	flood, mangrove inlet	0.541	9.4
11b	21.87031	90.07616	12:32 PM	ebb, mangrove inlet	0.378	7.8
12	21.85933	90.07382	1:30 PM	ebb	0.324	8.9
13	21.86690	90.08237	2:10 PM	ebb	0.386	7.8

CHAPTER V

DISCUSSION OF RESULTS

5.1 MAIN RIVER CHANNELS

At 0.563 g/L, the Ganges' measured suspended sediment concentration is higher than the Brahmaputra's, even though the Brahmaputra is known to have a higher sediment load in other studies (Galy and France-Lanord, 2001; Milliman and Meade, 1983). This discrepancy could be caused by the time difference between the flood stages of the two rivers. As seen in Fig. 2.3, the Brahmaputra River peaks in water flow and decreases slightly before the Ganges reaches its annual water discharge peak. Consequently, during late July when the rivers were sampled, the Ganges' flood stage is still increasing to its one annual peak in water discharge, while the Brahmaputra's water discharge is elevated from its dry season lows, but decreasing from its highest annual peak. Thusly, the Ganges' high suspended sediment concentration represents an increasing suspended load, while the Brahmaputra's lower suspended sediment concentration represents a decreasing suspended load.

Remote sensing data indicates that the Ganges' suspended sediment concentration is annually higher than the Brahmaputra's during the high discharge monsoon season, although the Brahmaputra has a higher suspended sediment concentration during low discharge (Islam et al., 2001). Remote sensing data can only interpret the surface layer, however, and cannot represent the higher, coarser bedload of the Brahmaputra River.

The sampling method of collecting suspended sediment concentrations at the surface also likely under represents the Brahmaputra River more than the Ganges River. Known to have coarser sediment than the Ganges, the Brahmaputra may carry more of its sediment in the middle and bottom portion of its channel (Coleman, 1969).

An analysis of the suspended load of a river can be determined by using the Rouse parameter $p = w/(Ku_*)$, where w = settling velocity of sediment, K = von

Karman's constant, and u* = shear velocity (Vanoni, 1946). The profile of suspended sediment concentration with depth is dependant on the Rouse parameter. As depth increases, the amount of sediment transported in the suspended load decreases, while the Rouse Parameter remains constant. Consequently, as depth increases, less sediment is carried in suspension.

Although the necessary parameters were not measured in order to draw the concentration profile with depth for the two rivers, it is hypothesized that they would resemble Fig. 5.1. The Ganges River is hypothesized to have a higher concentration at

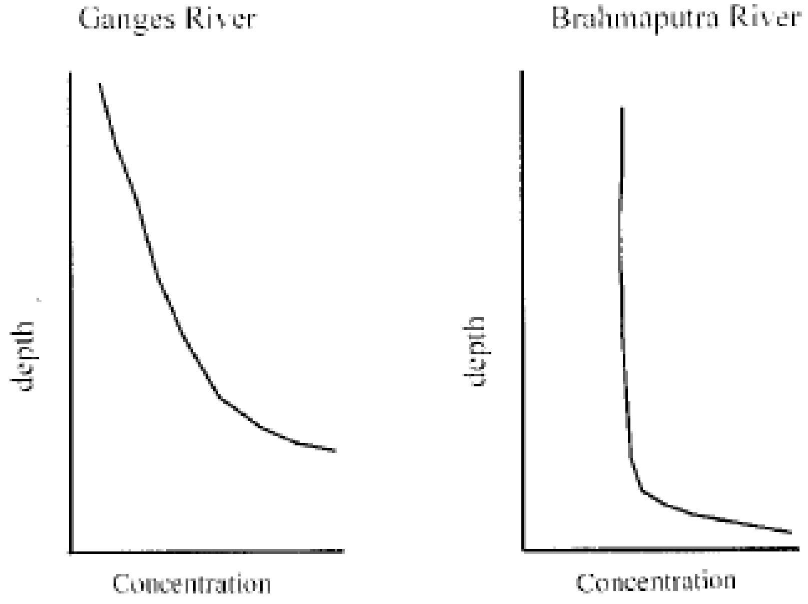

Figure 5.1. Estimated suspended sediment concentration profile with depth for the Ganges and Brahmaputra rivers. Parameters were not measured to draw exact concentration profiles, however, the figure depicts estimated profiles. The Rouse parameter (p) is equal to w/(K u*) where w = settling velocity of sediment, K = von Karman's constant, and u* = shear velocity.

the surface because the sediment grain size that the river carries is finer (smaller w). The Brahmaputra River is hypothesized to have a lower concentration at the surface because the sediment is more coarse-grained. Because the Brahmaputra River is a braided stream, with a high, coarse sediment load, it is hypothesized that concentration remains constant with depth, and then quickly decreases at the channel bottom. The Brahmaputra River is predicted to have lower suspended sediment concentrations, and higher concentrations in the bed load. The Ganges River is hypothesized to carry more sediment in suspension with depth because of the finer sediment load.

If this assumption is true, then the sampling method of collecting water surface samples from the river edge underestimates the Brahmaputra River load more than the Ganges River. Because the Brahmaputra River is hypothesized to carry more sediment in the bedload than the suspended load, then more of the river's sediment is underrepresented by sampling at the surface. Consequently, annual load calculations for the Brahmaputra will be underestimated.

The Meghna River has a predictably low suspended sediment concentration because of its different source. The northeast region of Bangladesh is subsiding at rates up to 2.1 cm/yr as the basin downthrusts under the Shillong Massif to the north (Johnson and Alam, 1991). Consequently, this subsiding basin collects large volumes of non-turbid rainwater during the southwest monsoon (Allison, 1998a). In addition to draining this rainwater, the Meghna has tributaries which have source waters in the Tripura Fold Belt of the northeast. Less erosion occurs in the Tripura Fold Belt than the Himalayan Mountains because of lower elevations and a lack of glaciers which enhance erosion. Rivers draining the fold belt, are therefore likely to contribute less sediment to the Meghna River than the amount of sediment that rivers draining the Himalayan Range contribute to the Ganges and Brahmaputra rivers. Because of these source differences, it is estimated that the Meghna carries only one fifth of the sediment that either the Ganges or Brahmaputra carries (Coleman, 1969). Consequently, it is often omitted in studies of the entire river system.

The Ganges-Brahmaputra River transect also demonstrates the variation in suspended sediment within a river channel. While the river is presumably well-mixed, the sediment concentration varies dramatically across the river as the flow varies. In a straight river section, maximum flow velocity occurs in a river channel where water has the least amount of frictional drag caused by contact between the water and channel bed. As this transect shows, the highest suspended sediment concentration occurs in the middle of the channel where the maximum flow would be. The suspended sediment concentrations in the lower flow regions on the sides of the channel are lower and relatively equal, indicating that sediment may have fallen out of suspension as flow decreased. The variation in suspended sediment concentrations across the Ganges-Brahmaputra River transect presents the inherent problem of this river sampling method. Most water samples were collected from the shore in the area of low velocity in a straight river stretch. These suspended sediment concentrations are most likely under representing the actual suspended load in the river. Conversely, if samples were taken from an area of maximum flow velocity, for example the inside of a curve at the cut bank, then the suspended sediment concentration could be at a maximum value. In the case of the Ganges-Brahmaputra River transect performed from the ferry, suspended sediment concentrations extrapolated for the entire river taken from the sides of the main river channel—or from the southern side channel where the ferry dock was located—would severely underestimate the suspended load of the river.

The suspended sediment concentrations in the Ganges-Brahmaputra River also indicate the difficulty in determining river properties. The suspended sediment concentration downstream of the confluence is not simply an average value of the concentration in the two rivers that join (Table 4.1; the suspended sediment concentration in the Ganges-Brahmaputra (0.531 g/L) is not the average of the concentration in the Ganges (0.563 g/L) and Brahmaputra (0.465 g/L and 0.345 g/L)). One must add the volume times the concentration of each river and divide by the sum of the river volumes to estimate the final suspended sediment concentration. Additionally, the rivers do not mix immediately at the confluence. Remote sensing data indicates that the water and suspended sediment of the two rivers can be seen as separate units for several kilometers downstream of the confluence (Islam et al., 2001).

5.2 TRIBUTARIES

The Atrai River is a northwest tributary of the Brahmaputra River which merges with the main river north of its confluence with the Ganges River. The Atrai River drains paludal, or marshy, deposits which are located between the two main rivers (Kurshid et al., 1990). This was observed in the field as the river flowed through flooded farms and rice paddies. However, as shown on Fig. 2.1, there are three geologic regimes that northwest tributaries of the Ganges and Brahmaputra rivers flow through in Bangladesh: paludal deposits, the uplifted Barind clay, and alluvial deposits from the Tista River Fan (Khurshid Alam et al., 1990). The uplifted Barind Terrace and the Tista River have higher elevations than the paludal deposits, and more capacity for erosion. While the Atrai River drains the paludal deposits in the northwest region, it is not representative of the sediment flux for the entire region. The Tista River drains the Himalayan Range and originally eroded the channel that the Brahmaputra River recently avulsed. Consequently, the Tista River is hypothesized to have a higher suspended load than the smaller Atrai River. While using the suspended sediment concentrations of the Atrai River can give some insight into the suspended load of the northwest tributaries, using the Atrai River to estimate the sediment contribution of the northwest tributaries to the Brahmaputra River will be an underestimate.

Conversely, the Abandoned Brahmaputra channel is located in the northeast region of Bangladesh and had a low suspended sediment concentration. This relict marks the previous, more eastward channel of the Brahmaputra River which was occupied in the 1700’s before a severe earthquake triggered a 30-year channel avulsion to its current location. Today, a small amount of river water is diverted from the main Brahmaputra River near Bangladesh’s northern border; the river flows east around the Pleistocene-uplifted Madhupur Terrace before joining the Meghna River. The abandoned Brahmaputra River therefore acts as a distributary of the Brahmaputra River and a tributary of the Meghna River. The abandoned Brahmaputra River is classified as a tributary in this project because it flows through monsoon-flooded, low-lying reaches of northeast Bangladesh before reaching the Meghna River. Its water source is more predominantly monsoon rains and flow from the Tripura Fold Belt which also feed the Meghna River than the Himalayan highland water which feeds the Brahmaputra River. Consequently, the suspended sediment concentration is lower than that in the Brahmaputra.

Further work on the abandoned Brahmaputra channel could look into the sediment load of this channel when it diverges from the main Brahmaputra Channel. The suspended sediment concentration is predicted to be high where this channel diverts from the main channel, however, significant settling must occur once the river reaches the flooded potion of the northeast plains. Future work could look at the settling and accumulation of sediment in the northern parts of this channel and compare the sediment dynamics at the river's northern and southern reaches.

5.3 DISTRIBUTARIES

The distributary samples collected from the southwest region of Bangladesh reveal the extraordinary tidal influence within the Ganges-Brahmaputra River System. Evidence of recent changes in water levels—including fresh erosion higher than the current bank levels, plant debris lines, and wet, muddy deposits along the banks—presumably from tides, was observed at nearly all of the sampling sites. The most important observation, however, is the reversal in river flow at the southern Bhairabi River site. Even at approximately 150 km from the coastline, the tidal forces are strong enough to reverse river flow.

The two Bhairabi River sampling locations differed considerably in suspended sediment concentration, despite being only 30 km from each other. Part of the difference could result from the lower concentration samples at the northern sampling site being taken from the river bank (from where almost all the samples were collected) and the higher concentration samples from the southern sampling site being collected from a docked boat approximately 20 m from the bank. The suspended sediment concentration should increase toward the center of a straight channel. However, there are several possible reasons for the variation. The higher concentration samples were taken from a wider stretch of the river, where sediment capacity and water volume would be higher. The higher concentration sample was also collected downstream of the Bhairabi River's convergence with a distributary branch of the Madhumati River, which may have had a higher concentration.

Additionally, the variation in suspended sediment concentration between the two sampling locations on the Bhairabi River may be influenced by tides. The higher concentration sample was collected at approximately high tide while the river was flowing north. Highest suspended sediment concentrations occur during periods of decelerating flow velocity during tidal cycles (Dyer, 1986). The samples from the Bhairabi River occurred at approximately high tide during decelerating flow velocity (Table 4.1, Fig. 4.1). The varying flow velocity through the tidal cycle could resuspend sediment from the river bottom and increase suspended sediment concentrations.

The suspended sediment concentration in samples collected at the Rupsa River were high at 0.590 g/L. Collected at low-tide, while the water was flowing south, the sample was collected near the middle of the river from the bamboo pier. The high suspended sediment concentration at the Rupsa River could occur for several reasons. Foremost, the Rupsa River is located downstream of the Bhairabi River sampling sites and therefore receives the suspended sediment load of the Bhairabi River, as well as another unnamed distributary from the Madhumati River. If the sample was collected during a period of decelerating flow velocity, the suspended sediment concentration could be higher due to resuspended particles.

The Madhumati River was sampled during high tide while the river was flowing south. At 0.290 g/L, the suspended sediment concentration is not as high as the Rupsa River or southern Bhairabi River sample. However, this sample was collected downstream of two distributaries which divert water from the Madhumati west to the Bhairabi and Rupsa rivers. Suspended sediment concentration can therefore not be estimated by distance from the river’s point of divergence from the main river channel. As seen in these data, tidal influences and diverging distributaries influence the suspended load in the river.

Lastly, the Arialkhan River had the highest suspended sediment concentration of any of the rivers sampled, including main river channels. The high concentration is evidence that the Arialkhan diverts a significant amount of sediment from the conjoined Ganges-Brahmaputra River. The suspended sediment concentration could increase in the Arialkhan River if high amounts of sediment are diverted into a river with a lower water flux. The large suspended load of sediment diverted from the Ganges-Brahmaputra River to the Arialkhan helps to explain why the suspended sediment concentration of the conjoined Ganges-Brahmaputra River is lower than the individual rivers upriver of their convergence. This suggests that significant amounts of sediment are being diverted from the main river channels by distributaries.

5.4 SEDIMENT BUDGET CALCULATIONS

The sediment load is calculated for the geomorphological classifications to determine the groups’ roles in the overall distribution of sediment. River maps were studied to determine the number of significant tributaries and distributaries that join and branch from the two main rivers. Significant tributaries and distributaries are defined as greater than 200 m wide during wet monsoon season. Suspended sediment concentrations in a given geomorphological classification are averaged to determine a general value to be used for each class. Rivers classified in the tributary class that flow from the Brahmaputra River to the Meghna River are separated from the tributary classification and defined as distributaries from the Brahmaputra River.

Fig. 5.2 illustrates the river measurements needed to calculate the sediment load of a river. The collected suspended sediment concentration (g/L) was used to estimate an average suspended sediment concentration for a geomophological class and multiplied by the river flow (m/s) to determine the mean sediment flux of the river (g/m^{2}s). The flux was then multiplied by the cross-sectional area (m^2) of the river to determine the instantaneous suspended sediment load (g/s) of the river (Dyer, 1986).

For sampling locations where width was not measured, river widths were estimated from published maps (Kurshid et al., 1990). Depths were determined by interviews with local Bangladeshis and from published values (Coleman, 1969). As suspended sediment concentrations and flow velocity measurements below the surface were not possible, calculations were made assuming suspended sediment concentration and velocity were constant with depth. Although sediment concentrations increase with depth, the limited data set prohibits further extrapolation.

Several assumptions were necessary to calculate the loads because of the limited

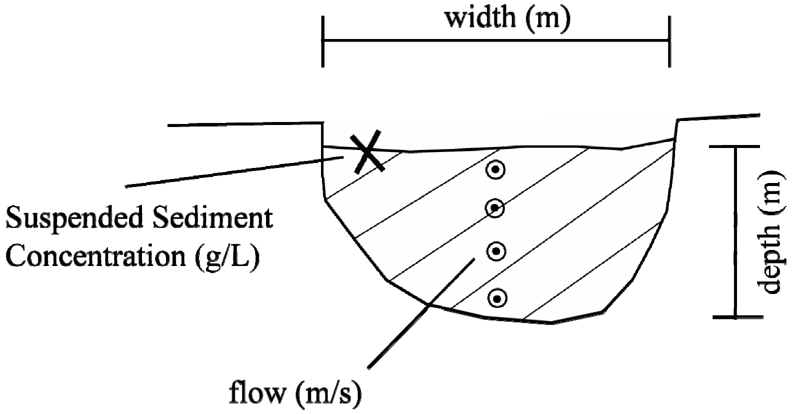

Figure 5.2. Schematic cross-section of river measurements used in calculating river suspended sediment loads. For a first approximation of suspended sediment load, suspended sediment concentration is assumed to be homogenous and flow velocity is assumed to be constant with depth. Width and depth were measured at the sampling site or determined from maps.

data set. Because only surface concentrations were determined, the mass flux only estimates the suspended load of the rivers. It is estimated that the bedload flux for the Ganges-Brahmaputra is only 10% of the suspended load flux, although the actual bedload flux remains undocumented (Galy and France-Lanord, 2001; Lane and Borland, 1951; Milliman and Syvitski, 1992). Additionally, the surface concentrations were measured from the sides of the rivers, where friction with the sides of the river slows the flow velocity and may decrease the sediment concentration. Consequently, these values are likely low estimates of the suspended load. Thirdly, it is unknown whether these point measurements are representative of recent rainfall events or if they demonstrate trends for the entire monsoon season. It is unknown whether sediment estimates created with samples collected at other times during the monsoon season could produce different results. The rivers were assumed to be parabolic in shape. Despite these limits in assumptions, these data present the spatial differences in the suspended sediment load of the river system with minimized time variation.

Listed in Table 5.1, the load is the estimated instantaneous suspended sediment load carried by the river or total sediment carried by river grouping

A sediment budget flow chart is created in Fig. 5.3 to illustrate the sediment loads of rivers that drain from and into the main river channels. Drainage basins are shown with the sediment loads calculated in Table 5.1. The tributary region is divided into drainage basins where water and sediment flow into the Brahmaputra (drain into the Brahmaputra (as listed in Table 5.1); bright orange), into the Ganges (drain into the Ganges (as listed in Table 5.1); light orange), and tributaries to the Meghna which flow from the Brahmaputra (drain the Brahmaputra (as listed in Table 5.1); blue). The distributary region is divided into drainage basins where water flows from the Ganges (drain the Ganges (as listed in Table 5.1); dark green) and from the Ganges-Brahmaputra (drain the Ganges-Brahmaputra (as listed in Table 5.1); bright green).

Table 5.1. Suspended sediment load estimates for geomorphological classifications. The number of rivers which drain into or from the rivers was determine using regional maps. The 6 distributaries which drain the Brahmaputra are included in the tributary classification on Fig.1.2 as they flow east from the Brahmaputra River into the Meghna River. The single [or one] river which drains the Ganges-Brahmaputra River is the Arialkhan River.

	width (m)	depth (m)	concentration (g/L)	Flow (m/s)	**Instantaneous load (g/s)**
Main River Channels					
Ganges	2100	20	0.563	1.0	**2.36×10^7**
Brahmaputra	4800	18	0.405	1.0	**3.50×10^7**
Meghna	1000	5	0.010	0.3	**1.50×10^4**
Ganges-Brahmaputra	7500	20	0.319	1.0	**4.79×10^7**
Tributaries					
7 drain into Brahmaputra	100	5	0.286	0.2	**2.00×10^5**
3 drain into Ganges	100	5	0.286	0.2	**8.58×10^4**
Distributaries					
6 drain the Ganges	300	7	0.349	0.7	**3.08×10^6**
6 drain the Brahmaputra	300	5	0.005	0.3	**1.35×10^4**
1 drains the Ganges-Brahmaputra	300	5	0.823	1.0	**1.23×10^6**

The sediment loads are shown in Fig. 5.4 as the percent of the total sediment load of the entire system carried by rivers in each drainage basin. The total sediment load is assumed to be the sum of the sediment loads of the Ganges River and Brahmaputra River. Approximately 80% of the suspended sediment from the Ganges and Brahmaputra rivers remains in the suspended load in the main river channel downstream of the confluence (Fig. 5.4). Approximately 7% of the suspended load of

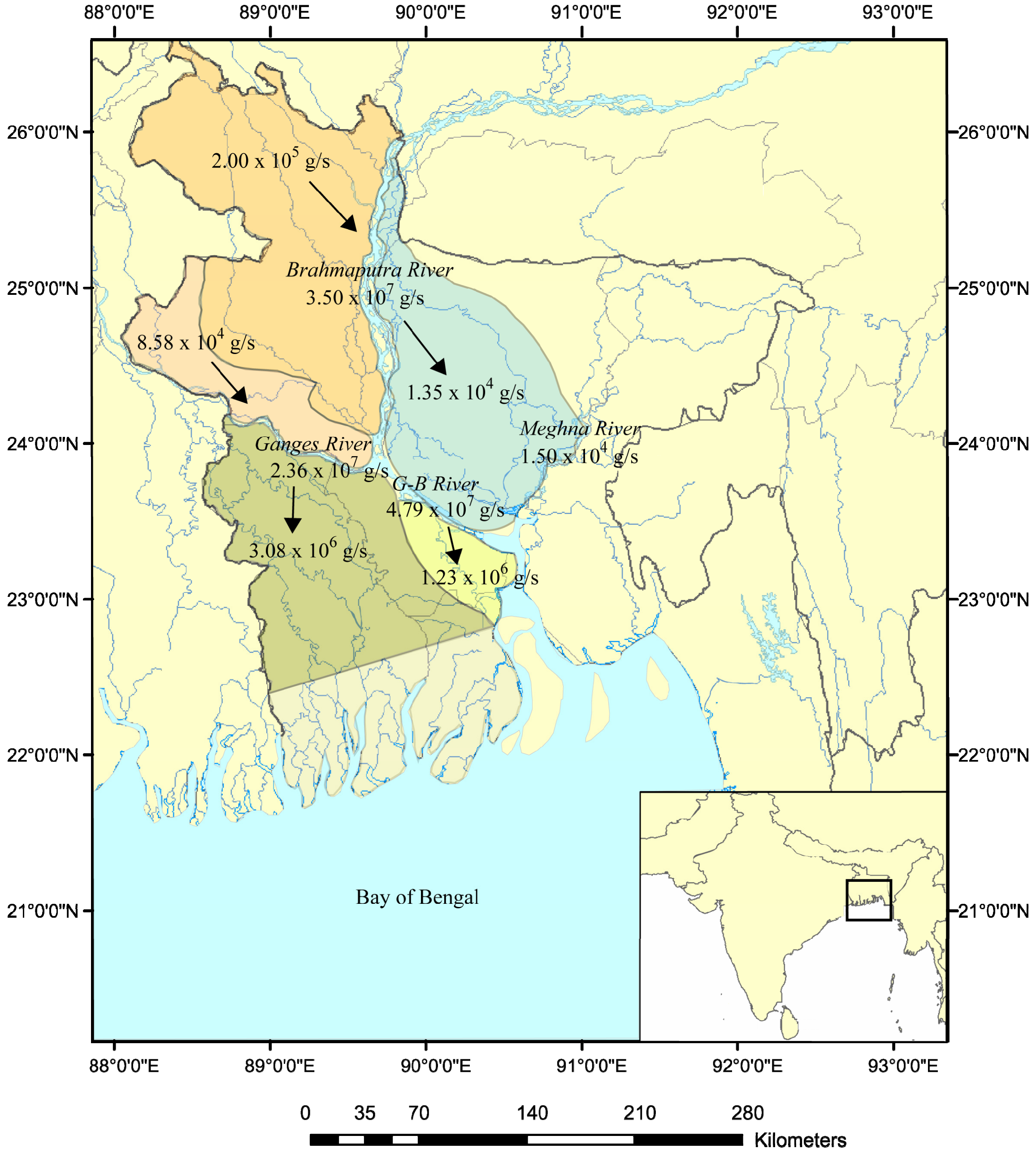

Figure 5.3. Suspended sediment load estimates for main rivers and distributary/ tributary drainage basins. The drainage basin for rivers draining into the Brahmaputra are bright orange, rivers draining into the Ganges are light orange, from the Brahmaputra are blue, from the Ganges are dark green, and from the Ganges-Brahmaputra are light green.

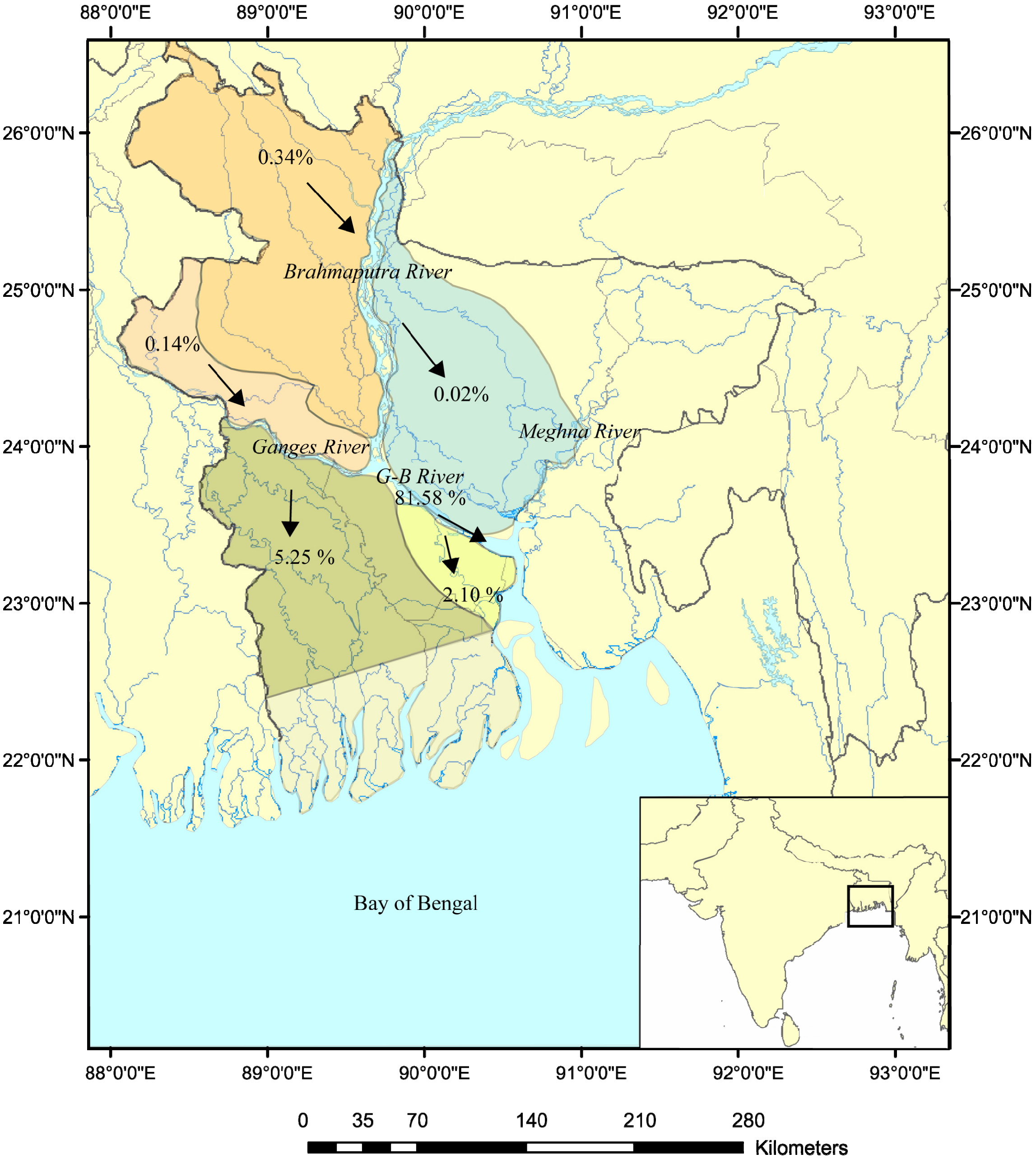

Figure 5.4. Suspended sediment flow chart of the Ganges-Brahmaputra River System. Percentage values are calculated with the total suspended load in the system as the sum of the Ganges and Brahmaputra rivers' individual loads. Approximately 82% of the sediment from the two individual rivers continues in the Ganges-Brahmaputra main river channel.

the river system is diverted from the main channel by 6 distributaries that drain the Ganges River and one that drains the Ganges-Brahmaputra River.

With 7% of the 20% discharge deficit—as identified with these calculations—accounted for, the pathway of 13% of the suspended load is unidentified. It has been shown that suspended sediment concentrations rapidly increase at the Ganges and Brahmaputra rivers' confluence, and decrease again downstream (Islam et al., 2001). The rapid increase in suspended sediment concentration may result from mixing turbulence resuspending bottom sediment. Part of the sediment deficit between up and down river of the confluence may be a result of changing flow dynamics as the rivers merge.

A large portion of the missing sediment between the individual Ganges and Brahmaputra rivers and the conjoined Ganges-Brahmaputra River is probably deposited during overbank flooding. As the rivers constantly evolve and overflow, considerable sediment is deposited along the natural levees (Allison, 1998b). Sediment that is not accounted for between the individual rivers and the combined river has most likely been deposited near the river banks during high flow.

Consequently, the highly complex nature of the sediment dispersal throughout the river system does not allow sediment load calculations to be determined from a single point along each river. The sediment load is changed by distributary and tributary contributions and diversions, as well as overbank flooding which occurs seasonally along the entire river. Furthermore, suspended load estimates cannot be calculated by a point measurement at the Ganges-Brahmaputra river mouth as sediment has been diverted and deposited throughout the river system. To determine a comprehensive sediment load estimate, suspended sediment concentrations must be measured throughout the system to accurately determine the true sediment load of the entire river.

The instantaneous suspended sediment loads during the monsoon season are used to estimate the annual suspended sediment load for the system. The instantaneous loads are used to determine the total load for the four month monsoon season (assuming the same sediment load for the entire duration). The annual suspended sediment loads are calculated with the assumption that 95% of the sediment load is carried during the four months of the monsoon season (Goodbred, 2003).

The annual suspended sediment loads from the literature and this study are listed in Tables 5.2 and 5.3 and shown graphically in Fig. 5.5.

Compared to published values, the annual suspended sediment loads calculated in this thesis are lower. The loads may be lower because of the inter-annual variability or because of the original assumption that suspended sediment concentration and velocity are constant with depth. The measured suspended sediment concentrations were sampled from the sides of rivers, where friction decreases the flow velocity and capacity to carry suspended sediment. Consequently, these values underestimate the suspended sediment load.

Additionally, the suspended sediment concentrations for the entire classes were determined from only a few sampling points. It is assumed that these points are representative of the entire region, however, there could be variations between geologic units and local rainfall.

The calculated annual suspended sediment loads in this thesis agree with the published literature that the Brahmaputra River carries more sediment, despite the Ganges River having a higher suspended sediment concentration during sampling. Because the volume transport of the Brahmaputra River is greater (width of 4.8 km compared to 2.1 km in the Ganges, and similar depths), it carries a larger suspended load. The Brahmaputra likely carries a higher bedload as well, as it has coarser material which is more often carried along the river bottom.

Table 5.2. Calculations of annual suspended sediment loads. The instantaneous load measured here is assumed to persist for four months to calculate the total monsoon season load. The monsoon season load is assumed to be 95% of the total discharge to calculate the annual load.

	Instantaneous Load (g/s)	Monsoon Season Load (tons/Monsoon Season)	**Annual Load (tons/yr)**
Main River Channels			
Ganges	2.36×10^7	2.49×10^8	**2.62×10^8**
Brahmaputra	3.50×10^7	3.68×10^8	**3.87×10^8**
Meghna	1.50×10^4	1.58×10^5	**1.66×10^5**
Ganges-Brahmaputra	4.79×10^7	5.03×10^8	**5.30×10^8**
Tributaries			
7 drain into Brahmaputra	2.00×10^5	2.11×10^6	**2.22×10^6**
3 drain into Ganges	8.58×10^4	9.03×10^5	**9.50×10^5**
Distributaries			
6 drain the Ganges	3.08×10^6	3.24×10^7	**3.41×10^7**
6 drain the Brahmaputra	1.35×10^4	1.42×10^5	**1.49×10^5**
1 drains the Ganges-Brahmaputra	1.23×10^6	1.30×10^7	**1.37×10^7**

Table 5.3. Comparison of suspended sediment loads from published studies. Annual load calculations in this thesis are lower than published values because of stated assumptions about the sampling method and calculation method.

	Ganges (tons/yr)	Brahmaputra (tons/yr)
Holeman, 1968	1600×10^6	800×10^6
Coleman, 1969	485×10^6	617×10^6
Milliman and Meade, 1983	680×10^6	1157×10^6
this thesis	262×10^6	387×10^6

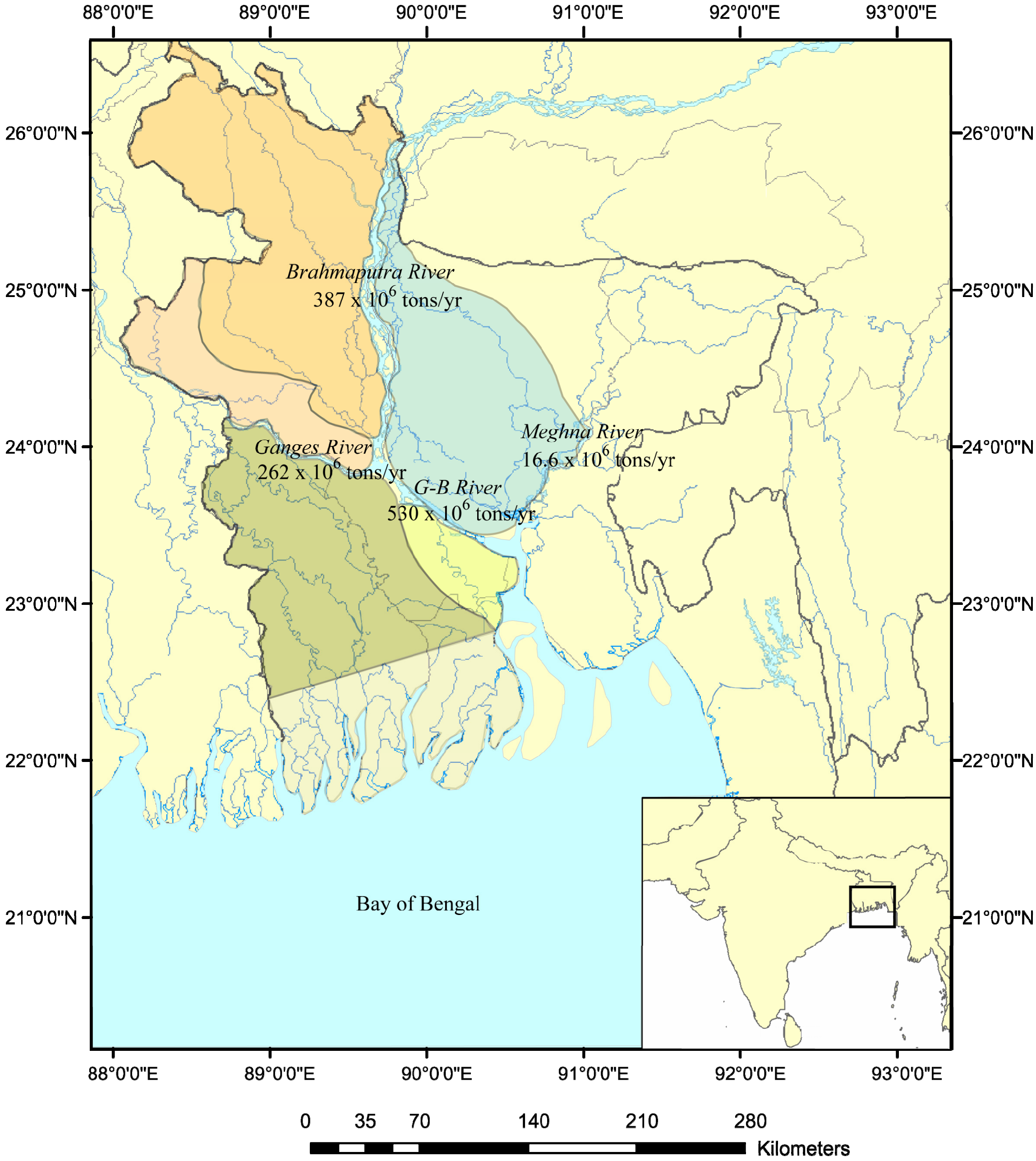

Figure 5.5. Calculated annual sediment loads for the main river channels
The Ganges-Brahmaputra River carries a lower load than the sum of the individual loads of the Ganges and Brahmaputra rivers (shown in percentages in Figure 5.4). The Meghna River carries a comparatively insignificant suspended sediment load.

5.5 TIDAL CHANNELS

Suspended sediment concentration in the Kuakata Tidal Channel is used to determine if the sediment source can be determined for the tidal channel region. Suspended sediment, salinity, and ^{7}Be activities are used to assess sediment source.

As shown in Fig. 5.6, suspended sediment concentrations from the Kuakata Tidal Channel are compared with the tidal cycle of the nearest tide gage, the Pursur River Tide Gage(Fig. 2.2), to determine if suspended sediment concentrations vary with the tidal cycle. The suspended sediment concentration follows the same trend as the tidal variation, however there is a time difference between the tidal stages of the sampled tidal channel and the tide gage. The suspended sediment concentration peaked before the Pursur Tide Gage, located to the west, measured the occurrence of high tide. This time difference, however, is not consistent with the lag between suspended sediment concentration and water level at the tide gage during ebb tide. The lag time is approximately one hour before the tide gage for high tide, and roughly 3.5 hours before low tide. This time difference indicates that suspended sediment concentration in the tidal channel began to increase even before low tide occurred.

This time lag between sediment concentration and tidal flow has been linked to flow velocity and observed in various estuaries (Dyer, 1986). In the Ganges-Brahmaputra River mouth (Fig. 5.7), it has been shown that suspended sediment concentrations are highest during decelerating flow (Barua, 1990). In Fig. 5.7, during the accelerating flow of the ebb period, from 1 to 3 hours, the suspended sediment concentration is lower than during the decelerating flow of the ebb period from 3 to 7 hours (Barua, 1990). Maximum ebb current velocities occur before low tide, causing a switch from periods of accelerating current velocity to periods of decelerating current velocity (Postma, 1961). Sediment entrainment is not solely a function of current velocity, and is instead influenced by turbulent kinetic energy and Reynolds stresses (Gordon, 1975). It has been shown that for a given flow velocity, bed movement and the rate of entrainment increase during the phases of a tide when the current is decelerating

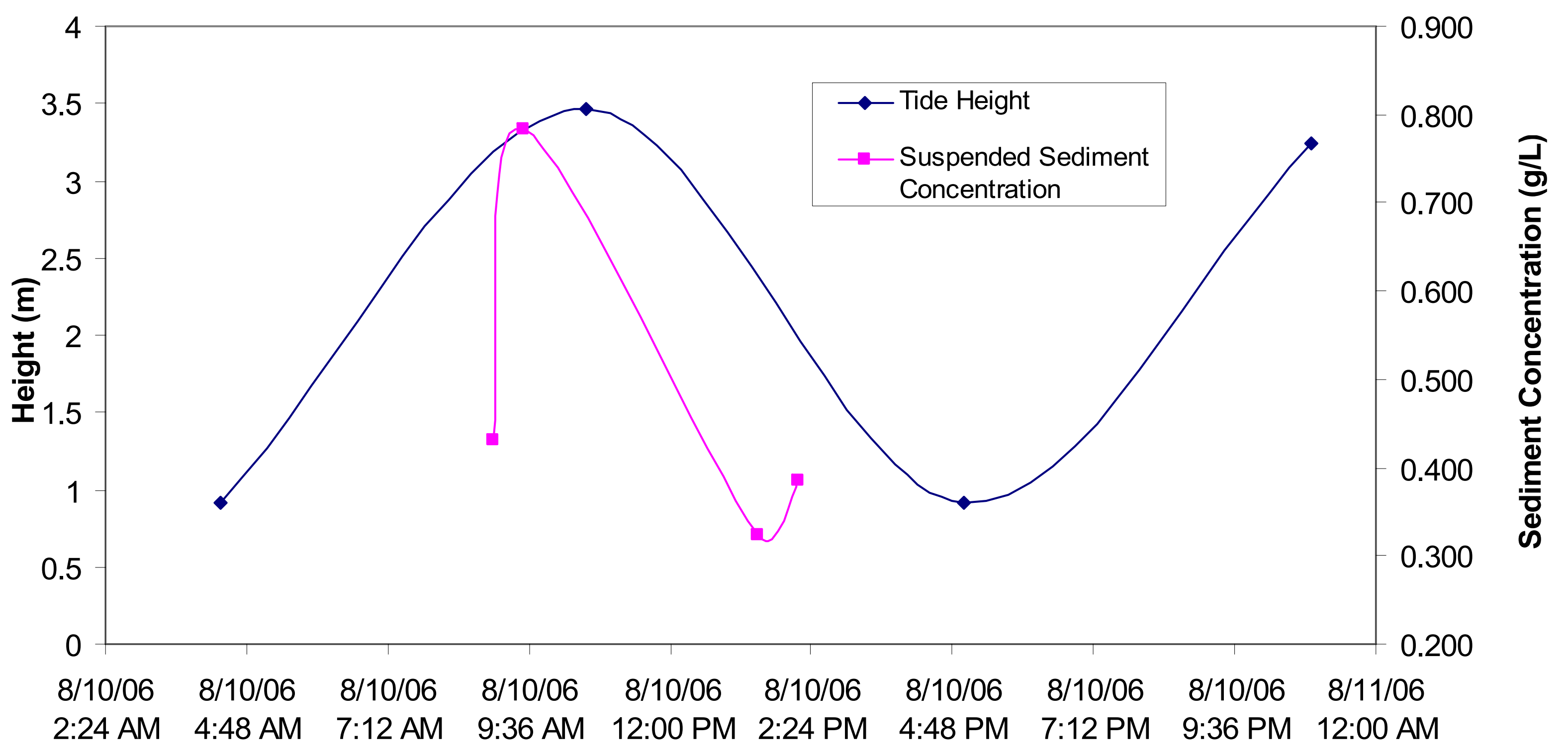

Figure 5.6. Pursur River Tide Gage height and tidal channel suspended sediment concentrations over one tidal cycle.

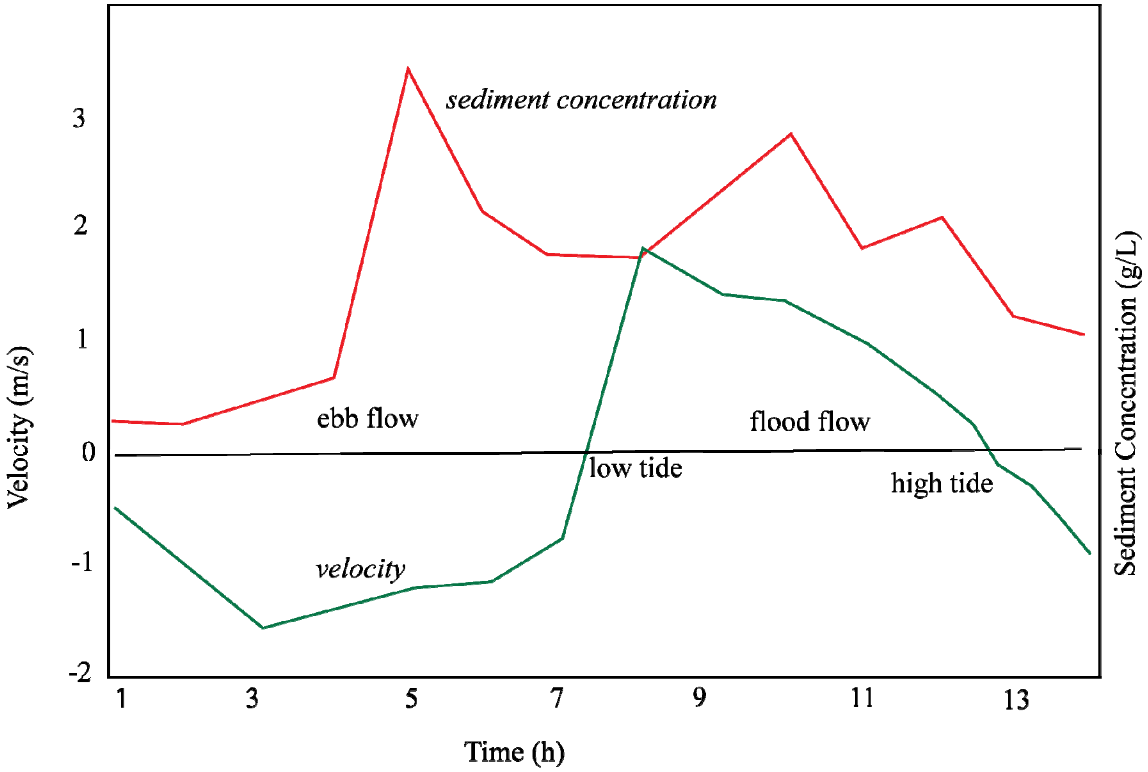

Figure 5.7. Suspended sediment concentration response to flow velocity over one tidal cycle (modified from (Barua, 1990). The sediment concentration profile is shown in red and the velocity profile is shown in green. Sediment concentration peaks during decelerating velocity of ebb flow and again during decelerating velocity of flood flow.

(Gordon, 1975). Consequently, decelerating tidal phases transport more sediment than accelerating phases. This relationship is attributed to the higher Reynolds stresses during the decelerating flow (Dyer, 1986).

Measurements for Fig. 5.7 were taken at the Ganges-Brahmaputra River mouth, where sediment is delivered from upriver. In this location, the suspended sediment concentration has a higher peak during ebb flow, when water flows from the channel into the Bay of Bengal. The smaller suspended sediment concentration peak occurs during flood flow when sediment is delivered to the channel from the Bay of Bengal. If this same pattern occurs in the Kuakata Tidal Channel, it could suggest that sediment in the tidal channels is supplied from the direct upriver sources.

Although flow velocity was not measured while collecting the Kuakata Tidal Channel samples for this thesis, it is hypothesized that the decelerating ebb flow caused the increase in suspended sediment concentration preceding low tide in Fig. 5.6. However, samples were not taken over a full tidal cycle, so it is unknown whether the suspended sediment peak during decelerating flow of the flood tide would be larger or smaller. If the suspended sediment peak during flood tide is larger than the peak during ebb tide, then sediment is likely provided from the Bay of Bengal and delivered to the tidal channels from the sediment plume. If the suspended sediment peak is higher during ebb tide, then sediment is likely delivered directly from upriver sources.

In addition to suspended sediment concentrations, salinities were examined in the Kuakata Tidal Channel. Listed in Table 4.2, salinities were low through all stages of the tidal cycle. A comparison of salinity and the tidal cycle showed no correlation. Salinities decrease from the Bay of Bengal into the Kuakata Tidal Channel (Fig. 5.8).

The salinity at the mouth of the tidal channel during flood tide (waypoint 3; salinity 9.4 PSU) was higher than the salinity in the channel during ebb tide (waypoints 12 and 13; salinities 8.9 PSU and 7.8 PSU, respectively). This is expected as flood tide brings saline Bay of Bengal surface water into the tidal channel, and ebb tide supplies fresh water from upriver into the tidal channel. A decrease in salinity was also observed between waypoints 11a and 11b (salinities 9.4PSU and 7.8 PSU, respectively) when the tides reversed from flood to ebb.

Salinities of samples collected during the transect into the Bay of Bengal (waypoints 3 through 8) were higher than those collected in the tidal channel, however, they are still relatively low for an ocean body (all are below 14 PSU). These low surface salinities are caused by dilution from the high river output of freshwater. Salinities have been shown to vary throughout the entire Bay of Bengal during the wet monsoon

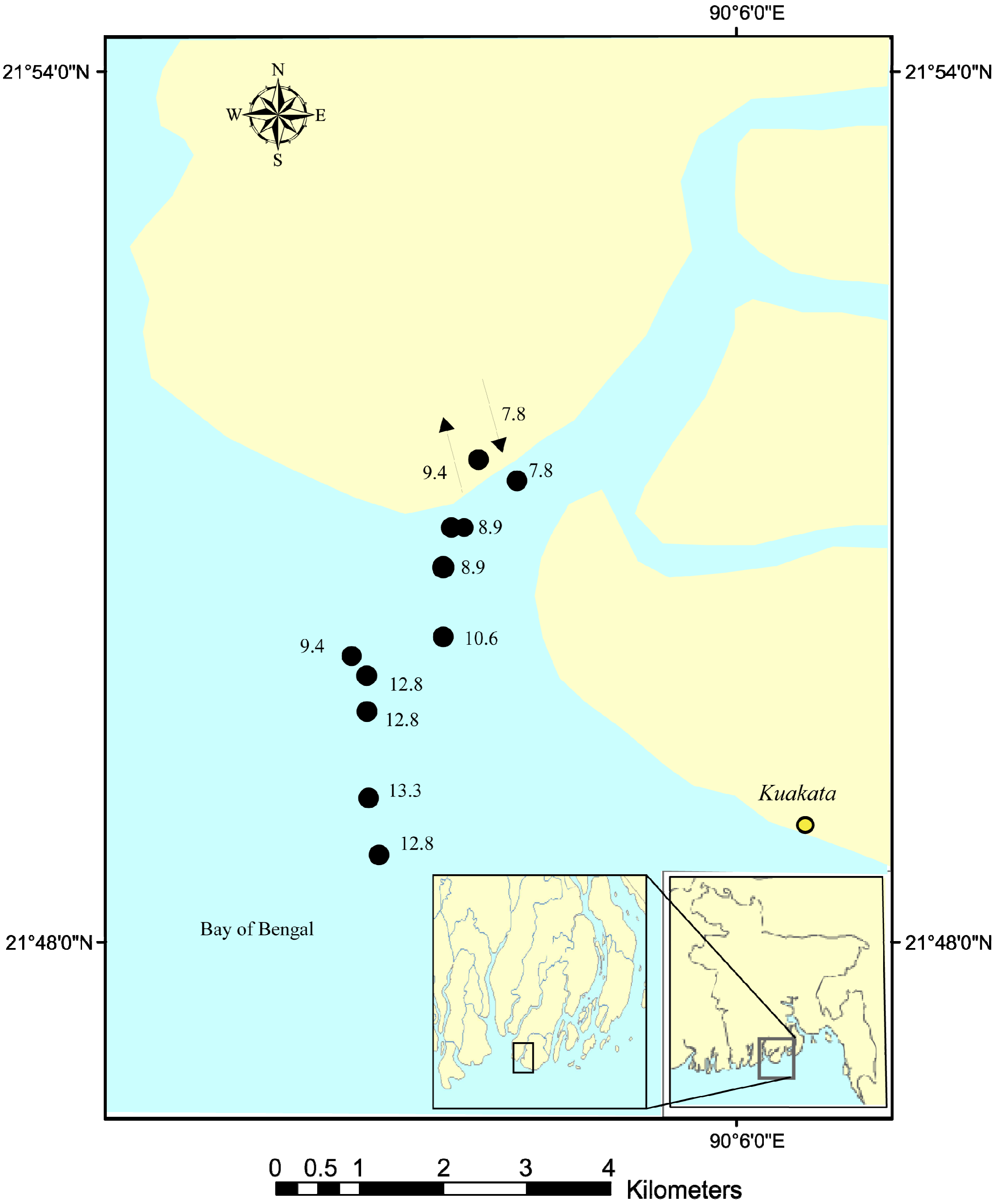

Figure 5.8. Surface salinities of water samples from the Kuakata Tidal Channel. Samples were collected over flood and ebb tide and generally decrease from the Bay of Bengal into the Kuakata Tidal Channel.

season, with values typically less than 20 PSU in the coastal zone (Varkey et al., 1996). The fresh water output leads to a highly stratified surface layer characterized by warm (29.0° C) and low saline (29.0-32.8 PSU) waters (Gopalakrishna et al., 2002). The salinities measured during the present study are lower than those characteristic of the freshwater plume because of closer proximity to shore.

Salinities of the samples are compared to the suspended sediment concentrations in Fig. 5.9. Although the correlation is weak, sediment concentration decreases with increasing salinity, as evidenced by the negative slope between sediment concentration and salinity. Suspended matter flocculates inorganically at chloride concentrations between 0-3 PSU, and further increases in chlorinity do not cause significantly more flocculation, as seen in settling rates in laboratory experiments (Meade, 1972). The decrease in concentration in the tidal channel is probably not due to flocculation as the salinities are larger than the 0-3 PSU which would cause significant flocculation.

Beryllium-7 (half life = 53.3 days) activity data is useful for determining short-term sediment transport. A product of cosmic-ray spallation of nitrogen and oxygen, Beryllium-7 quickly adheres to small particles in the atmosphere. It is flushed from the atmosphere by precipitation, solubized by acidic rainwater, and quickly scavenged by fine particles in terrestrial and marine environments (Olsen et al., 1986). It has been shown that in an estuarine environment, ^{7}Be activities decrease with distance from the fluvial, upriver source in estuaries (Dibb and Rice, 1989). In the estuaries of large rivers, fluvial inputs of ^{7}Be are significantly greater than direct atmospheric inputs to the lower estuary (Corbett et al., 2004).

Activities for sampling locations are shown in Fig. 5.10. Detectable activities in the Brahmaputra River (1.37 dpm/g and 0.73 dpm/g) indicate sediment has been transported to the river within three to four months.

The activity in the Ganges River was below detection, indicating that sediment has taken longer to be transported through the river. Activity was also below detection in the Ganges-Brahmaputra River downstream of the confluence. The below detection

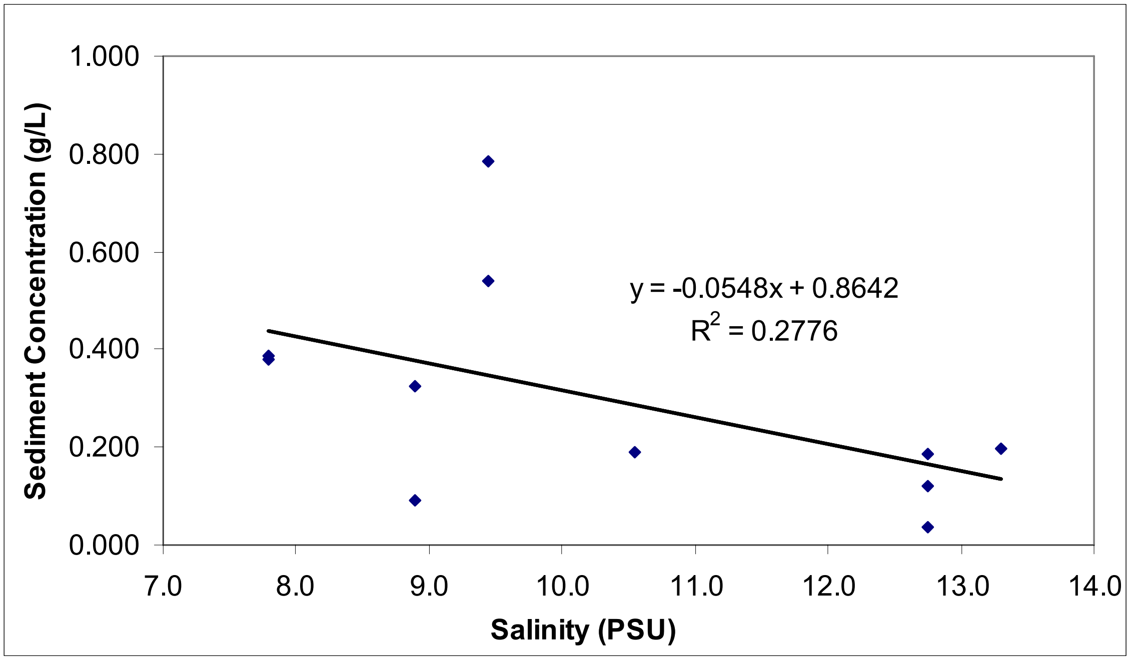

Figure 5.9. Suspended sediment concentration vs. salinity of tidal channel samples in the Kuakata Tidal Channel. Suspended sediment concentrations decrease with depth. The small correlation coefficient indicates a weak correlation.

reading of the sediment in these two locations, suggests that sediment takes longer than 3 to 4 months to travel through the Ganges drainage basin and river channel, rendering ^{7}Be signatures too low to be detected at the sampling location. However, ^{7}Be activities in the Kuakata Tidal Channel and offshore show that recently transported sediment is suspended in the tidal channels. The presence of newly-transported sediment in the Bay of Bengal and tidal channels indicates that sediment does reach the lowest reaches of the river system before 4-5 half-lives have occurred.

Because there are two possible pathways for sediment to reach the lower tidal channels—diversion through the distributaries or coastal transport from the main river channel mouth—this recently transported sediment must be transported through the Ganges or Ganges-Brahmaputra rivers. The presence of active ^{7}Be sediment in the

Kuakata Tidal Channel and in the Bhairabi River (Fig. 5.10) dictates that radiometrically young sediment must be present upstream. Recordable activities in the Brahmaputra River indicate that the recently-transported sediment is present upstream of the two rivers' confluence. However, because the distributaries that divert sediment to the Bhairabi River branch from the Ganges River north of the confluence, the presence of ^{7}Be activities in the Bhairabi River dictate that there must be radiometrically young sediment in the Ganges River. The ^{7}Be signature could also not be delivered to the Bhairabi River from a tributary with a different source, because all rivers in the distributary region flow south from the Ganges River. Additionally, if the ^{7}Be activities in the Kuakata Tidal Channel and offshore come from the main river channel sediment plume, then there must be ^{7}Be activities upstream in the main Ganges-Brahmaputra River channel. This evidence suggests that the below detection ^{7}Be activity values in the Ganges and Ganges-Brahmaputra rivers have a sampling artifact which prevents the reading of a reliable ^{7}Be signature.

The Ganges River was sampled on a windy, stormy day. The increased waves possibly resuspended older bottom sediment into the water column. If older sediment was mixed with the newly-transported suspended sediment, then dilution of the ^{7}Be signature would occur. The river conditions might have also eroded older bank sediment into the river. As the sample was collected from the river bank, older, eroded sediment could have been inadvertently collected. The wind and waves most likely contributed to the collection of the unrepresentative sample.

The Ganges-Brahmaputra River downstream of the confluence was collected from a ferry boat. The propellers could have resuspended older bottom sediment, which would dilute the ^{7}Be signature. Additionally, the unstable banks of the river could have eroded into the water column, further diluting the radiometric signature. There is likely a residual sampling artifact in the collection method that contributed to the below detection readings in both the Ganges and Ganges-Brahmaputra rivers.

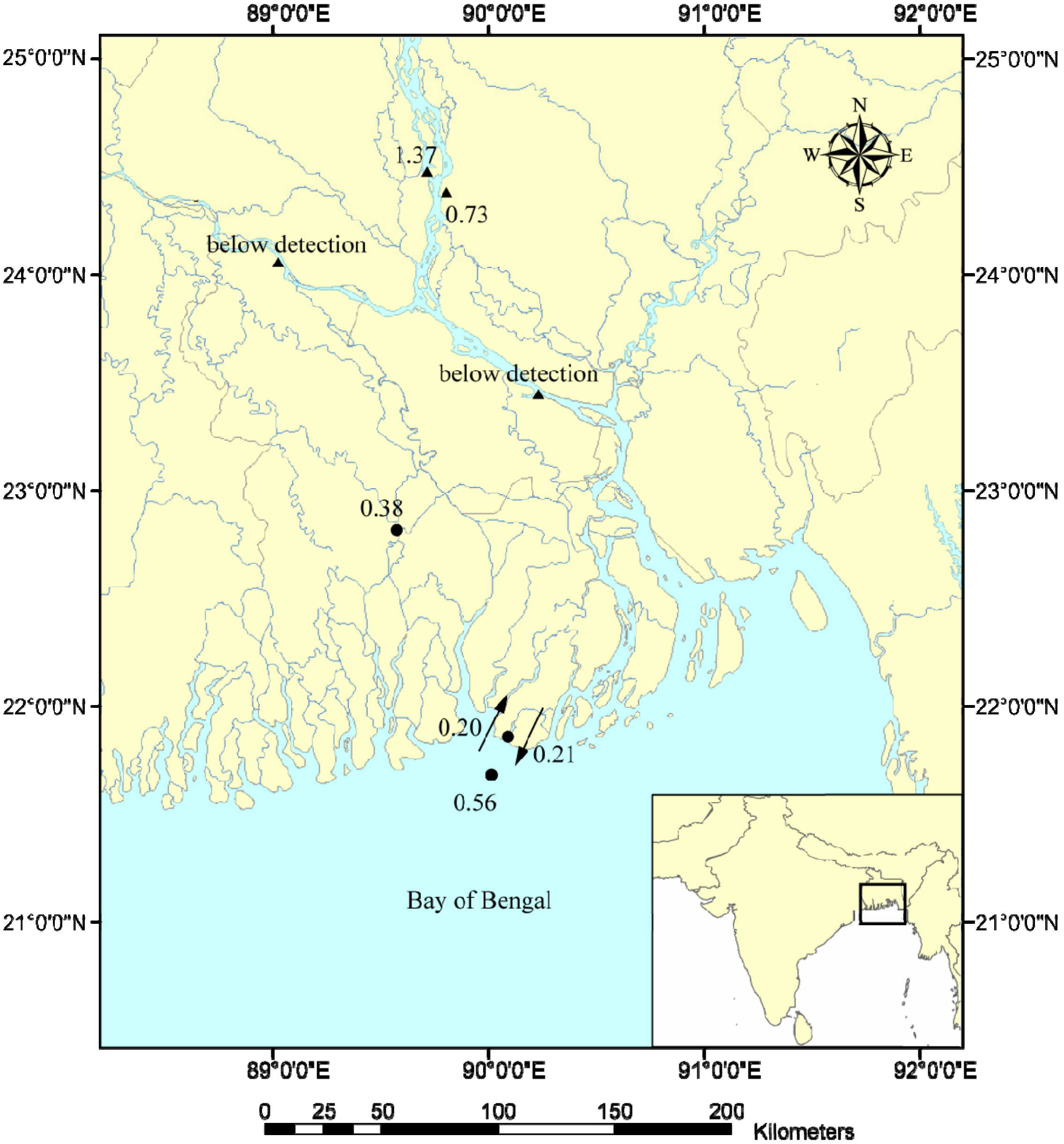

Figure 5.10. Beryllium-7 activity values for suspended sediment in the water column of select sampled rivers. Values are reported in dpm/g. The ^{7}Be data is inconclusive for identifying sediment source in the tidal channels. The below detections reading of Sediment from the Ganges and Ganges-Brahmaputra rivers is likely a sampling artifact error as radiometrically young sediment is found in the tidal channels.

The ^{7}Be activities of sediment collected in the Kuakata Tidal Channel are inconclusive for determining sediment source. The activities are roughly equal during flood and ebb tide (0.20 dpm/g and 0.21 dpm/g, respectively), eliminating using the ^{7}Be ages to determine the source. The activity measured ~5 km offshore is higher at 0.56 dpm/g. Because activity decreases as ^{7}Be ages, the higher value offshore than in the tidal channels may indicate that sediment is sourced to the tidal channels from the Bay of Bengal. However, it is documented that the sediment plume from the main river mouth extends into the Bay of Bengal and is transported west by coastal currents (Segall and Kuehl, 1992; Barua et al., 1994). The presence of radiometrically young sediment offshore does not conclusively indicate the sediment in the tidal channels comes from the main sediment plume, it merely indicates that sediment is transported through the entire system within 3-4 months. The lower activities in the Kuakata Tidal Channel could also be ^{7}Be activities which have been diluted by resuspended bed sediment. Suspended sediment concentrations increase due to resuspension during decelerating velocities of ebb and flood flow (Fig. 5.7). The older, resuspended sediment from the channel bottom could dilute the ^{7}Be activities of suspended sediment from the main river mouth.

The ^{7}Be activity measured in the Bhairabi River (0.38 dpm/g) is higher than that measured downstream in the tidal channel. This young ^{7}Be signature in the central tidal plains is not likely contributed by tidal currents. The Bhairabi River location is located too far from the Bay of Bengal (150 km) for sediment to be contributed from the downriver source. Although there are tidally-influenced flow reversals in the Bhairabi River, there was not measurable salinity. Consequently, the radiometrically young sediment in this river is unlikely contributed from the sediment plume in the Bay of Bengal.

This radiometrically young sediment in the Bhairabi River is more likely diverted from the Ganges River upstream. The sediment budget created in this project indicates that roughly 7% of the suspended sediment from the main river channel is diverted into the distributaries of the southern tidal plain. While the below detection value obtained by samples collected in the Ganges River does not support this hypothesis, the sampling problems mentioned previously suggest this pathway may still be valid. Because the ^{7}Be activities obtained from the Ganges and Ganges-Brahmaputra rivers may be susceptible to sampling error, they are not fully accepted, and therefore do not rule out this pathway. The ^{7}Be signature in the Bhairabi River is not likely a result of local sediment input to the distributary from its drainage basin because the small atmospheric input to a lower estuary is small compared to the fluvial input of the system (Corbett et al., 2004). The ^{7}Be signature is representative of radiometrically young sediment transported to the distributary from the main river channel.

The presence of radiometrically active ^{7}Be concentration at the Bhairabi River site, however, indicates that sediment is actively being contributed to the lower distributaries in the Ganges-Brahmaputra System. The unit is composed of a 16 km fluvio-deltaic sediment layer which has accumulated since the Paleogene, however, it was assumed that new sediment was not actively being contributed as the Ganges river migrates eastward (Allison, 1998a). Sediment load calculations in this study indicate that approximately 7% of the sediment load in the system is being contributed to these lower channels, bringing radiometrically young sediment with a recent ^{7}Be signature to the distributary rivers.

CHAPTER VI

CONCLUSIONS

Suspended sediment concentrations in the Ganges-Brahmaputra River System vary dramatically spatially during the high discharge, monsoon season. Suspended sediment concentrations can be analyzed within different geomorphological classes to determine patterns and explanations of the variation. Additionally, the suspended sediment concentrations can be used to determine annual sediment load estimates for the region.

An analysis of the geomophological classes' contribution to the annual sediment loads indicates that up to 7% of the total sediment load could be excluded in current sediment budget calculations because of its diversion into the distributary region of the river system. Suspended sediment load estimates are calculated to be 262 million tons per year on the Ganges, and 387 million tons carried annually on the Brahmaputra River. These estimates are lower than previously published studies, due to interannual variability or to sampling artifacts and assumptions that underestimated the true suspended load of the rivers. However, the data show that approximately 80% of the sediment carried by the Ganges and Brahmaputra rivers individually remains in the main Ganges-Brahmaputra River channel south of the rivers' confluence. The remaining 20% of sediment is diverted from the main river by the distributaries and deposited along the main river channel during overbank flooding.

Suspended sediment concentrations are analyzed to determine the source of sediment in the lower tidal channels of the Ganges Brahmaputra River. Samples were not collected over an entire tidal cycle, however, it is hypothesized that the suspended sediment concentration peaks over the tidal cycle suggesting resuspended sediment as a source to the tidal channels.

Beryllium-7 activity data were analyzed to investigate suspended sediment source in the tidal channels. The ^{7}Be data were below detection in both the Ganges and Ganges-Brahmaputra rivers, indicating the sediment is older than 3-4 months. This is inconsistent, however, with the radiometrically young sediment that was found downstream in the tidal channels and in the inner distributary region. The below detection readings in the Ganges and Ganges-Brahmaputra rivers is therefore assumed to be a sampling artifact, and the data are inconclusive.

The radiometrically young sample found in the Bhairabi River in the distributary region, however, indicates that newly-transported sediment is actively being transported to the inner portion of the distributary region. Often assumed to be deficient in new sediment as the Ganges River migrates east, the distributary region is found to be actively receiving newly-transported sediment diverted from the main rivers upstream.

REFERENCES

Allison, M.A., 1998a. Geologic framework and environmental status of the Ganges-Brahmaputra Delta. Journal of Coastal Research. 14(3), 826-836.

Allison, M.A., 1998b. Historical changes in the Ganges-Brahmaputra Delta. Journal of Coastal Research. 14 (4), 1269-1275.

Allison, M.A. and Kepple, E.B., 2001. Modern sediment supply to the lower delta plain of the Ganges-Brahmaputra River in Bangladesh. Geo-Marine Letters. 21, 66-74.

Allison, M.A., Khan, S.R., Goodbred, S.L., Jr. and Kuehl, S.A., 2003. Stratigraphic evolution of the late Holocene Ganges-Brahmaputra Lower Delta Plain. Sedimentary Geology. 155, 317-342.

Allison, M.A., Kuehl, S.A., Martin, T.C. and Hassan, A., 1998. Importance of flood-plain sedimentation for river sediment budgets and terrigenous input to the oceans: insights from the Brahmaputra-Jamuna River. Geology. 26 (2), 175-178.

Bangladesh Inland Water Transport Authority. http://www.mobilegeographics.com:81/locations/5180.html?y=2006&m=8&d=10. Accessed on 2/1/07.

Bangladesh Water Development Board. http://www.bwdb.gov.bd/. Accessed on 6/1/07.

Barua, D.K., 1990. Suspended sediment movement in the estuary of the Ganges-Brahmaputra-Meghna River System. Marine Geology. 91, 243-253.

Barua, D.K., 1991. The coastline of Bangladesh--an overview of processes and forms. Proceedings of the 7th Symposium of Coastal Ocean Management, American Society of Civil Engineers, New York. 2284-2301.

Barua, D.K., Kuehl, S.A., Miller, R.L. and Moore, W.S., 1994. Suspended sediment distribution and residual transport in the coastal ocean off the Ganges-Brahmaputra River mouth. Marine Geology. 120, 41-61.

Bettoli, M.G., Cantelli, L., Degetto, S., Tositti, L., Tubertini, O. and Valcher, S., 1995. Preliminary investigations on ^{7}Be as a tracer in the study of environmental processes. Journal of Radioanalytical and Nuclear Chemistry. 190 (1), 137-147.

Coleman, J.A., 1969. Brahmaputra River: channel processes and sedimentation. Sedimentary Geology. 3, 129-239.

Corbett, D.R., McKee, B., Duncan, D., 2004. An evaluation of mobile mud dynamics in the Mississippi River deltaic region. Marine Geology. 209, 91-112.

Curray, J.R., Emmel, F.J. and Moore, D.G., 2003. The Bengal Fan: morphology, geometry, stratigraphy, history and processes. Marine and Petroleum Geology. 19, 1191-1223.

Curray, J.R., Emmel, F.J., Moore, D.G. and Raitt, R.W., 1982. Structure, tectonics and geological history of the northern Indian Ocean. In: A.E. Nairn and F.G. Stehli (Eds), The Ocean Basins and Margins. Plenum, New York, pp. 129-239.

Datta, D.K. and Subramanian, V., 1997. Texture and mineralogy of sediments from the Ganges-Brahmaputra-Meghna River System in the Bengal Basin, Bangladesh and their environmental implications. Environmental Geology. 30 (3/4), 181-188.

Dibb, J.E. and Rice, D.L., 1989. Temporal and spatial distribution of Beryllium-7 in the sediments of the Chesapeake Bay. Estuarine, Coastal and Shelf Science. 28, 395-406.

Dyer, K.R., 1986. Coastal and estuarine sediment dynamics. Wiley, Chichester, UK, 342 pp.

Fergusson, J., 1863. On recent changes in the delta of the Ganges. Journal of the Geological Society of London. 19, 322-354.

Fluteau, F., Ramstein, G. and Besse, J., 1999. Simulating the evolution of the Asian and African monsoons during the past 30 million years using an atmospheric general circulation model. Journal of Geophysical Research. 104, 11,995-12,018.

Galy, A. and France-Lanord, C., 2001. Higher erosion rates in the Himalaya: geochemical constraints on riverine fluxes. Geology. 29 (1), 23-26.

Goodbred, S.L., Jr., 2003. Response of the Ganges dispersal System to climate change: a source-to-sink view since the last interstade. Sedimentary Geology. 162, 83-104.

Goodbred, S.L., Jr. and Kuehl, S.A., 1998. Floodplain processes in the Bengal Basin and the storage of Ganges-Brahmaputra River sediment: an accretion study using ^{137}Cs and ^{210}Pb geochronology. Sedimentary Geology. 121, 239-258.

Goodbred, S.L., Jr. and Kuehl, S.A., 1999. Holocene and modern sediment budgets for the Ganges-Brahmaputra River System: evidence for highstand dispersal to flood-plain, shelf, and deep-sea depocenters. Geology. 27 (6), 559-562.

Gopalakrishna, V.V., Murty, V.S.N., Sengupta, D., Shenoy, S. and Araligidad, N., 2002. Upper ocean stratification and circulation in the northern Bay of Bengal during southwest monsoon of 1991. Continental Shelf Research. 22, 791-802.

Gordon, C.M., 1975. Sediment entrainment and suspension in a turbulent tidal flow. Marine Geology. 18, M57-M64.

Holeman, J.N., 1968. Sediment yield of major rivers of the world. Water Resources Research. 4 (4), 737-1968.

Huizing, H.G.J., 1971. A reconnaissance study of the mineralogy of sand fractions from East Pakistan sediment and soils. Geoderma. 6, 109-133.

Iman, M.B. and Shaw, H.F., 1985. The diagenesis of Neogene clastic sediments from the Bengal Basin, Bangladesh. Journal of Sedimentary Petrology. 55, 665-671.

Islam, M.R., Begum, S.F., Yamaguchi, Y. and Ogawa, K., 1999. The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation. Hydrological Processes. 13, 2907-2923.

Islam, M.R., Yamaguchi, Y. and Ogawa, K., 2001. Suspended sediment in the Ganges and Brahmaputra rivers in Bangladesh: observation from the TM and AVHRR data. Hydrological Processes. 15, 493-509.

Jakobsen, F., Hoque, A.K.M.Z., Paudyal, G.N. and Bhuiyan, M.S., 2005. Evaluation of the short-term processes forcing the monsoon river floods in Bangladesh. Water International. 30 (3), 389-399.

Johnson, S.Y. and Alam, A.M.N., 1991. Sedimentation and tectonics of the Sylhet trough, Bangladesh. Geological Society of America Bulletin. 103, 1513-1527.

Khurshid Alam, M., Shahidul Hasan, A.K.M., Khan, M.R. and Whitney, J.W., 1990. Geological map of Bangladesh. Geological Survey of Bangladesh, Dhaka, Bangladesh, scale 1:1,000,000.

Kuehl, S.A., Hariu, T.M. and Moore, W.S., 1989. Shelf sedimentation off the Ganges-Brahmaputra River System: evidence for sediment bypassing to the Bengal Fan. Geology. 17, 1132-1135.

Kuehl, S.A., Levy, B.M., Moore, W.S. and Allison, M.A., 1997. Subaqueous delta of the Ganges-Brahmaputra River System. Marine Geology. 144, 81-96.

Lane, E.W. and Borland, W.M., 1951. Estimating bed load. American Geophysical Union Transactions. 32, 121-123.

Meade, R.H., 1972. Transport and deposition of sediments in estuaries. The Geological Society of America, Memoir. 133, 91-120.

Michels, K.H., Kudrass, H.R., Hubscher, C., Suckow, A. and Wiedicke, M., 1998. The submarine delta of the Ganges-Brahmaputra: cyclone-dominated sedimentation patterns. Marine Geology. 149, 133-154.

Michels, K.H., Suckow, A., Breitzke, M., Kudrass, H.R. and Kottke, B., 2003. Sediment transport in the shelf canyon "Swatch of No Ground" (Bay of Bengal). Deep-Sea Research II. 50, 1003-1022.

Milliman, J.D. and Meade, R.H., 1983. World-wide delivery of sediment to the oceans. Geology. 91, 1-21.

Milliman, J.D. and Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology. 100, 525-544.

Morgan, J.P. and McIntire, W.G., 1959. Quaternary geology of the Bengal Basin, East Pakistan and India. Geological Society of America Bulletin. 70, 319-342.

Olsen, C.R., Larsen, I.L., Lowry, P.D., Cutshall, N.H., 1986. Geochemistry and deposition of ^{7}Be in river-estuarine and coastal waters. Journal of Geophysical Research. 91, 91-112.

Postma, H., 1961. Suspended matter and secchi disk visibility in coastal waters. Netherlands Journal of Sea Research. 1, 359-390.

Quan, X. and Fry, E.S., 1995. Empirical equation for the index of refraction of seawater. Applied Optics. 34 (18), 3477-3480.

Ramage, C.S., 1971. Monsoon Meteorology. Academic, New York, 296 pp.

Saenger, P. and Siddiqi, N.A., 1993. Land from the sea-the mangrove afforestation progam of Bangladesh Ocean & Coastal Management. 20 (1), 23-39.

Sarin, M.M., Krishnaswami, S., Dilli, K., Somayajulu, B.L.K. and Moore, W.S., 1989. Major ion chemistry of the Ganga-Brahmaputra River System: weathering processes and fluxes to the Bay of Bengal. Geochemica et Cosmochimica Acta. 53, 997-1009.

Segall, M.P. and Kuehl, S.A., 1992. Sedimentary processes on the Bengal continental shelf as revealed by clay-sized mineralogy. Continental Shelf Research. 12 (4), 517-541.

Segall, M.P. and Kuehl, S.A., 1994. Sedimentary structures on the Bengal Shelf: a multi-scale approach to sedimentary fabric interpretation. Sedimentary Geology. 93, 165-180.

Sengupta, S., 1966. Geological and geophysical studies in the western part of the Bengal Basin, India. American Association of Petroleum Geologists Bulletin. 50, 1001-1017.

Snead, R.E., 1985. Bangladesh. In: E.C.F. Bird and M.L. Schwartz (Editors), The World's Coastline. Van Nostrand Reinhold, New York. 1071pp.

Thorne, C.R., Russell, A.P.G. and Alam, M.K., 1993. Planform pattern and channel evolution of the Brahmaputra River, Bangladesh. In: J.L. Best and C.S. Bristow (Eds), Braided Rivers. Geological Society of London Special Publication, London. pp. 157-276.

Vanoni, V.A., 1946. Transportation of suspended sediment by water. Transactions of the American Society of Civil Engineers. 111, 67-102.

Varkey, M.J., Murty, V.S.N. and Suryanarayana, A., 1996. Physical oceanography of the Bay of Bengal and Andaman Sea oceanography and marine biology. An Annual Review. 34, 1-70.

Webster, P.J., 1987. The elementary monsoon. In: J.S. Fein and P.L. Stephens (Editors), Monsoons. Wiley-Interscience, New York, pp. 3-32.

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