Morphological Response of the Brahmaputra-Padma-Lower Meghna River System to the Assam Earthquake of 1950

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Abstract

The channels of the great rivers of Bangladesh are highly dynamic and their banklines change continuously, consuming large areas of floodplain and making thousands of people landless. As a result, bank erosion is a serious cause of poverty in Bangladesh. Severe bank retreat associated with net widening of the Jamuna, Padma and Lower Meghna Rivers during the last 50 years has greatly increased the suffering of the people. Changes in the width and planform patterns of these rivers indicate that they have not been operating in dynamic equilibrium. However, the causes of instability and planform metamorphosis remain contested. This is significant as identifying the causes of the observed channel adjustments would be of great interest not only to river scientists and engineers, but also to planners attempting better to manage the nation's natural and human resources.

In this context, the research reported in this thesis proposes a working hypothesis that morphological changes in the Jamuna-Padma-Lower Meghna system have occurred in response to disturbance of the fluvial system by the Assam earthquake of 1950. Contemporary documents report that landslides triggered by the earthquake generated about $4.5 * 10^{10}$ m^3 sediment, much of which entered the Brahmaputra River in Assam either directly or via its tributaries. It is proposed that the fine fraction of this sediment (silt and clay) travelled quickly through the system, without disturbing the morphology of the channels, before settling in the Meghna Estuary and Bay of Bengal. In contrast, it is hypothesised that the coarser fraction (sand) took half a century to progress through the system, moving as a wave of bed material load, with a celerity between 10 and 32 kmy^{-1}. Preliminary analyses of historical maps and satellite images, together with records of discharge, water level, sediment transport and cross-sectional form reveals a sequence of morphological changes in the Jamuna-Padma-Lower Meghna system with a downstream phase lag that is commensurate with the celerity of the coarse sediment wave.

A conceptual process-response model has been developed to elucidate the relationship between downstream propagation of the sand wave and morphological responses, based on models previously reported in the literature and the sequence of changes observed in the Jamuna River. The model has been validated using morphological responses observed in the Padma and Lower Meghna rivers, which appear to have acted as a downstream continuation of the Jamuna River. Based on the conceptual model, a scheme has also been developed to explain and predict planform responses to changes in sediment supply to a braided river. This scheme is shown to be consistent with earlier models, the responses to increased sediment supply in the great rivers of Bangladesh and those of some very large rivers in China.

Once fully validated, the conceptual model and the scheme may be used not only to explain the past behaviour of braided rivers, but also to predict the morphological responses of the large rivers of Bangladesh to future disturbance by, for example, climate change, seismic events or interventions in the fluvial system upstream in India. The capability to make such predictions would be immensely helpful in planning how to manage future channel instability and mitigate its socioeconomic impacts for the benefit of floodplain dwellers and the Nation.

Keywords:

Assam earthquake | Jamuna River | Lower Meghna River

Padma River | Planform | Process-response model

River morphology | Sediment supply

Chapter 1
Introduction

1.1 Setting the scene

The Bengal delta is the world's largest modern deltas comprising 100,000 km^2 of riverine, floodplain and deltaic plain environment (Goodbred *et al.*, 2003). The great rivers with their huge sediment loads, coming from the Himalayas, and tectonics interact in forming the delta. A great part of this delta lies within Bangladesh - an independent country that extends latitudinally between 20°34' and 26°33' North and longitudinally between 88°01' and 92°41' East (Rashid, 1991), making the land area of Bangladesh ~144,000 km^2. Most part of the country is formed by a low lying plain with a mild slope from the north to the south, where the country meets the Bay of Bengal (Elahi, 1991a).

At the time of the last census, in 2001, the population was just over 124 million, and the current growth rate is about 1.58 per cent per annum (Bangladesh Bureau of Statistics, 2003). The average population density is 843 persons per km^2, which makes Bangladesh one of the world's most crowded countries. Moreover, Bangladesh is one of the poorest countries of the world, as the *per capita* income is only US$ 445 (Economic Advisor's Wing, 2005). The country is still mostly rural, with only 19% of people living in urban settlements. Consequently, there are tremendous population pressures in the rural areas. The majority of the population are wholly dependent on small holdings for their livelihoods either as owner occupiers, tenants, sharecroppers, or as landless labourers. As the level of industrialisation of the country is low, there are limited opportunities for the rural-urban migrants. As a result, the majority of the people continue to rely on the rural land resources to support themselves (Elahi and Rogge, 1990). But the nature of these land resources is intimately related to the flood regimes of the rivers – both large and small. On average, monsoonal flooding inundates 20% of the area each year, while major floods submerge a much greater area of the nation.

For example, the mega-floods of 1988 and 1998 inundated 63% and 68% of the total area of Bangladesh, respectively (EGIS, 2002a). In addition, many towns and cities experience surface water flooding due to inadequate drainage systems, while the hill areas of eastern and northeastern Bangladesh experience frequent flash floods. It is then unsurprising that very large numbers of people living in both rural and urban areas become the victims of flooding annually. Moreover, river bank erosion is also a serious hazard that directly or indirectly causes the suffering of about one million people annually (Elahi and Rogge, 1990). These two hazards – flooding and river erosion – are major contributors to the process of impoverisation and marginalisation of rural peasantry.

The natural setting of Bangladesh between the Himalayas and the Bay of Bengal, together with the meteorological characteristics of the tropical monsoon are responsible for theprevalence of flooding and river bank erosion in Bangladesh (Elahi, 1991b). The major rivers, including the Ganges, Brahmaputra-Jamuna, Padma and Meghna and their numerous tributaries and distributaries make Bangladesh a 'land of rivers' (Figure 1.1). The catchment area of these rivers is about 1.65 million km^2 of which only 7.5% lies within the borders of Bangladesh (Sarker *et al.*, 2003). This catchment annually generates 120 million ha-m of run-off, only 10% of which is generated within Bangladesh. In addition to vast quantities of water, these rivers carry about 1.1 billion tons of sediment every year (EGIS, 2000; Sarker *et al.*, 2003).

The large discharges and heavy sediment loads carried by these rivers result in highly variable and dynamic channel morphologies characterised by rapid adjustments to the cross-sectional geometry, bankline positions and planform attributes (Coleman, 1969). A number of past studies have been carried out, particularly concerning morphological processes in the Jamuna since the late 1960s. These include the academic work of Coleman (1969), Bristow (1987), Richardson *et al.* (1996), Best and Ashworth (1997), Richardson and Thorne (2001), Islam *et al.* (1999), McLelland *et al.* (1999), Ashworth *et al.* (2000), and Islam and Chowdhury (2003) and consultancy studies carried out under the Jamuna Bridge Authority and the Flood Action Plan (FAP 1, FAP 4, FAP 9B, FAP 19 and FAP 24). On the basis of the studies several articles such as those by Klaassen and Vermeer (1988), Mosselman *et al.* (1995), Thorne *et al.* (1993), Thorne *et al.* (1995), Zhou and Chen (1998), Mosselman (2006) were presented in international conferences and published in journals and books. The general conclusion drawn in most of these studies is that, while the main rivers of Bangladesh exhibit short-term instability, they may be considered to be broadly in dynamic equilibrium. That is, their spatially and temporally averaged morphological features are meta-stable through time. It follows from this that the morphological changes that are observed may be explained on the basis of short-term departures from a form that is generally unchanging.

Observations by the Center for Environmental and Geographic Information Services (CEGIS), based on analyses of a 30-year time-series of satellite images, reveal that the Jamuna River during the 1970s and 1980s widened at a rate of approximately 160 my^{-1}. Widening has been continuing until now, although from the early 1990s the rate slackened to about 50 my^{-1} (EGIS, 2000, Sarker *et al.*, 2003). During the 1970s and 1980s, the behaviour of the Jamuna River was described as 'crazy' (Schmuck-Widman, 2001) and it eroded the floodplain at very high rates of 4,000 and 5,000 hay^{-1}, respectively, during these decades (CEGIS, 2007). More recently, the average annual erosion rates of the river have decreased, approaching 2,000 hay^{-1}, although this still represents a serious erosion hazard to the nation and, especially, those dwelling in the river's floodplain. In related studies based on long-term analysis of available map and satellite data, Sarker and Thorne (2006) showed that the rates of both widening and increasing braiding intensity in the Jamuna were also highest during 1980s, when the rate of annual erosion was at its peak.

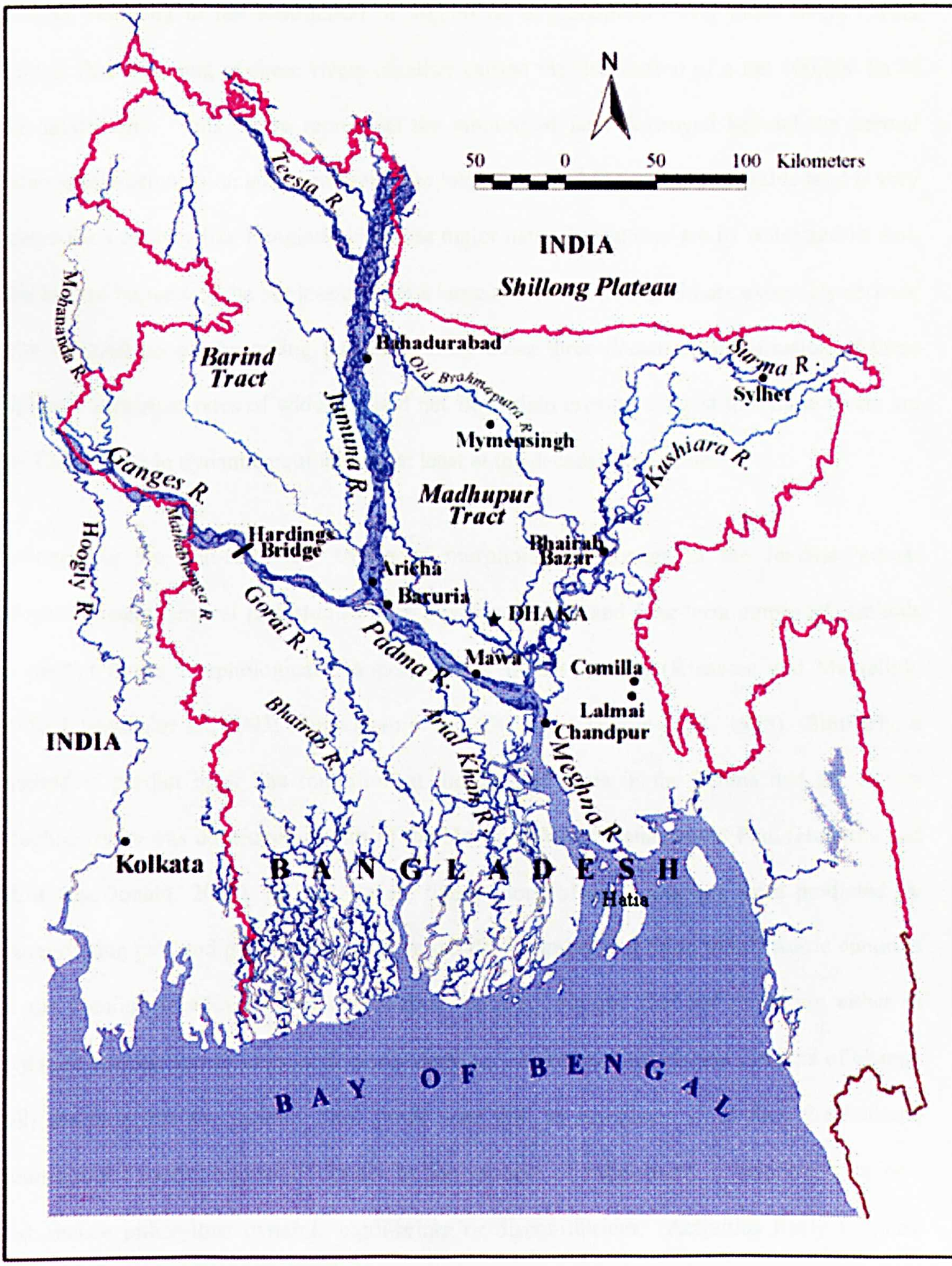


Figure 1.1: Map of Bangladesh showing the main river systems

Widening of the Jamuna River during the last three decades of the twentieth century destroyed a net area of 70,000 ha of floodplain land. During the late 1980s and 1990s, the Padma and Lower Meghna rivers widened at rates even higher than those exhibited by the

Jamuna, resulting in net destruction of 30,000 ha of floodplain along those rivers. This implies that widening of these rivers together caused the destruction of a net 100,000 ha of floodplain land. This figure represents the amount of land destroyed beyond the normal balance between erosion and accretion. The loss of such a huge amount of arable land is very severe for a country like Bangladesh, whose major natural resources are its water and its soil. The human impacts of the net loss of such a large amount of floodplain are extremely serious, with 800,000 people becoming landless during those three decades. Identification of these high and persistent rates of widening and net floodplain erosion suggest that these rivers are not functioning in dynamic equilibrium, at least at the decadal time-scale.

Recognising the non-stationary trends of morphological change in the Jamuna-Padma-Meghna system, several past studies have developed short and long-term empirical methods to predict future morphological changes, mainly in the Jamuna (Klaassen and Masselink, 1992; Klaassen *et al.*, 1993; Mosselman *et al.*, 1995; and Thorne *et al.*, 1995). Similarly, a method to predict bank line migration at the decadal scale in the Padma and the Lower Meghna rivers was developed as part of the National Water Management Plan (Halcrow and Mott MacDonald, 2000). In most cases, future morphological changes were predicted by extrapolating past and prevailing migration trends, assuming that these trends would continue in the coming decades. These approaches implicitly assume that the rivers are either in dynamic equilibrium or consistent disequilibrium, so that past trends and patterns of change will continue into the future. Such predictions will be inaccurate if, in fact, the Jamuna, Padma and Lower Meghna rivers are in the process of *adjustment* in response to a past disturbance rather than dynamic equilibrium or disequilibrium. Activities likely to cause adjustment of a river or river system include changes in the flow or sediment regimes or neo-tectonics that affect the channel slope or floodplain topography (Leopold and Maddock, 1953; Schumm, 1969; Schumm *et al.*, 2000; Chang, 1979; 1986; White *et al.*, 1982, Richards, 1982; Bettess and White, 1983; Bridge, 2003). The price of such adjustments in terms of the suffering of the people is quite high for Bangladesh.

The Jamuna River was a free-flowing river having almost no structural intervention before the mid-1990s. There were recurrent bank protection works to protect Sirajganj, a big commercial center situated at the right bank since the end of the 1950s. From the second half of the 1990s several bank protection works were implemented under the framework of the construction of the Jamuna Bridge project, Flood Action Plan (FAP), Right Bank Protection Project (RBPP) and Jamuna-Meghna River Erosion Mitigation Project (JMREMP) (Figure 1.2). These bank protection works, although small, contributed in reducing the rate of bank erosion along the Jamuna River since the mid 1990s.

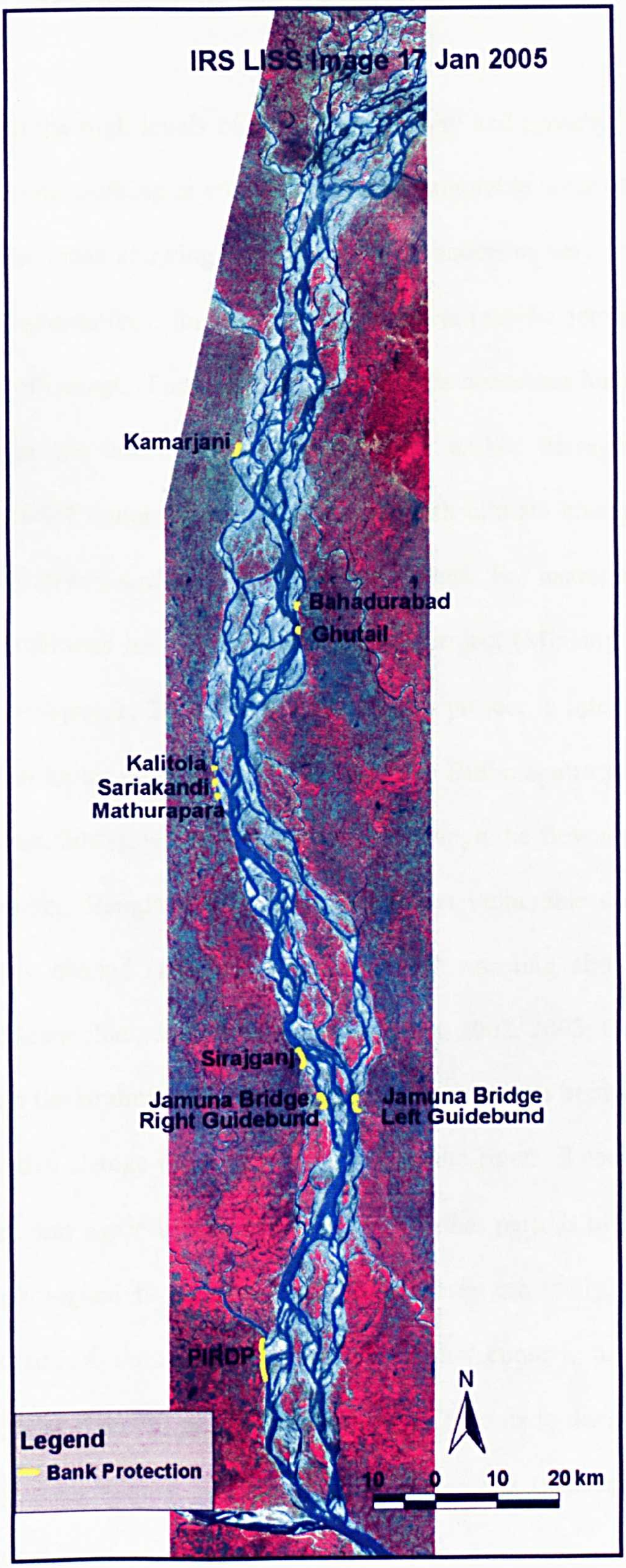


Figure 1.2: Satellite image of the Jamuna River showing the major structural interventions in the Jamuna River

1.2 Rationale of the Research

Due to the high levels of population density and poverty, it is impossible to prevent people living and working in erosion and flood vulnerable areas of floodplain. They continue to stay in these areas knowing the risks and consequences very well, because they do not have any better alternatives. In future, several drivers may be active in changing the river regime and trend of change. Future drivers may include conscious human interference in the river system through the construction of large dams and/or barrages, inter-basin transfers of water, unintended human impacts associated with climate change and relative sea level rise, and natural events such as a severe seismic event. For example, India is considering a very large and ambitious inter-basin water transfer project (Ministry of Water Resources, 2002; Gupta and Deshpande, 2004; ICID, 2006). The project is intended to divert 173 billion m^3 (17.3 million ha-m) of water annually from the Brahmaputra to the Ganges (Bandyopadhyay and Perveen, 2003), which would certainly change the flow and sediment regimes of both rivers. Moreover, Bangladesh is one of the most vulnerable countries on earth to the effects of climate change (Ahmed, 2006). Global warming and relative sea level rise will cause significant changes in flood regime (Mirza, 2002, 2003; Climate Change Cell, 2006). Finally, within the Brahmaputra basin, further seismic events are likely (Goodbred *et al.*, 2003), which may also change the sediment regime of the river. It seems likely, therefore, that these vast rivers may again be disturbed and that further periods of adjustment in fluvial processes and morphological forms due to multiple causes are likely, bringing more severe suffering to hundreds of thousands of people. In this context, understanding the response of these particular rivers to past disturbances may help us to develop predictive capacity and support early preparedness plans that could reduce the suffering of the people and minimize the national loses.

Any predictive capacity must be specific to the rivers in question, as, according to Schumm and Winkley (1994, p.1) – '*Alluvial rivers are singular; that is they are all the same* *landform, but each is different from others. The understanding, therefore, requires experience and the willingness to recognise the multiple variables that control the alluvial river morphology and behaviour*'. This implies that an understanding of the previous process-response behaviour in the fluvial system is highly relevant for predicting the future morphological adjustment of the Jamuna-Padma-Lower Meghna river system to disturbances that are yet to be determined but which are inevitable.

In view of the immense suffering to the hundreds of thousands of people and nationally significant loss of land and infrastructure caused by river instability during the last three decades, research was initiated on morphological changes (macro-scale) of the main rivers of Bangladesh through a studentship offered by the University of Nottingham and co-sponsored with CEGIS, with the aim of identifying the main causes and mechanisms of channel changes that occurred during the latter part of the twentieth and early part of the twenty first centuries.

1.3 Working Hypothesis

Morphological and process-responses in the Brahmaputra-Jamuna and downstream rivers may be due to the changes in discharge resulting from human interventions in the fluvial system such as deforestation, intensive agriculture, withdrawal of water, construction of dams, or natural causes such as changes in climate and the excessive melting of glaciers. The observed changes in the Brahmaputra-Jamuna River may also be due to the changes in sediment input or coarsening of bed materials resulted from deforestation in the Himalayas, intensive agriculture or seismic events like the 1950 Assam Earthquake. The changes might also be the result of neotectonic activity within Bangladesh. However, no evidence has been found to suggest an increase in flood magnitude or sediment concentration in the recent years due to deforestation in the Himalayas or extensive changes in land use (Hofer, 1998; Mirza et. al., 2001; Mirza, 2002). On the other hand, a number of indications may be found in the literature suggesting that the 1950 Assam earthquake affected the Brahmaputra-Jamuna-Padma-Lower Meghna system in various ways (Krug, 1957; Goswami, 1985; Brammer, 1995; Zhou and Chen, 1998; Verghese, 1999; Sarker, *et al.*, 2003; Goodbred *et al.* 2003; Sarma and Phukan, 2004; Sarma, 2005). For example, Brammer (1995) suggested that the observed widening in the upstream reach of the Jamuna River during the 1970s and 1980s was probably due to the effects of the 1950 Assam Earthquake. More recently, EGIS (2000) and Goodbred *et al.* (2003) attempted to relate observed morphological changes, such as the widening of the Jamuna River, to the propagation of coarse sediment generated by the 1950 Assam Earthquake. They suggested a possible process for propagating the huge amount of coarse sediment through the fluvial system, but did not provide any evidence to support their arguments. A number of articles in the literature also describe the morphological changes associated with the passage of a sediment wave (Nicholas *et al.*, 1995; Madej and Ozaki, 1996; Miller and Benda, 2000; Lisle *et al.*, 2001; Korup, 2004; Bartley and Rutherfurd, 2005). It has then been widely hypothesized that the earthquake in Assam in 1950 has been liable for the observed changes in the Jamuna River in the recent decades.

The event in question occurred in 1950, when a major earthquake occurred in the Indian part of the Brahmaputra. The earthquake delivered a huge amount of sediment to the Brahmaputra and its tributaries in the Assam valley, raising the riverbed at Dibrugarh (Figure 1.3) by about 3 m. The fine fraction of this huge sediment input passed quickly to the Bay of Bengal, but the coarser fraction, moving as bed material load, has taken decades to travel downstream as a moving sediment wave. Passage of the wave through the system generates a particular sequence of morphological adjustments through changes in bed elevation, width, braiding intensity and planform pattern. The same sequence of morphological responses to passage of the sediment wave would be observed in the Jamuna, Padma and Lower Meghna rivers, but the timing is lagged with increasing distance from Assam, reflecting downstream propagation of the sediment wave.

1.4 Assam earthquake

At just after 7:30 pm on August 15 1950, what was up to that time the strongest earthquake ever recorded occurred in the Indian State of Assam. The magnitude of the earthquake was 8.6 on the Richter scale. The epicentre was near the Chinese border at latitude 28.6^0 N, longitude 96.5^0 E, and the focus was 14 km below the earth's surface. About 52,000 sq. km of territory in Assam were seriously affected by the tremors and subsequent floods (Tillotson, 1951).

Kingdon-Ward (1951, p. 131) provides a vivid description of the earthquake, based on his direct observations of its effects from a vantage point on the left bank of Lohit River at approximately latitude 28.5^0 N, longitude 97^0 E, '*the first feeling of bewilderment – an incredulous astonishment that these solid-looking hills were in the grip of a force which shook them as a terrier shakes a rat – soon gave place to stark terror. ...The destruction extended to the very top of the main ranges – 15,000-16,000 ft. above sea-level. .... No wonder the mountain torrents begun to flow intermittently as the gorges became blocked, followed later by the breaking of the dam; whereupon a wall of water 20 ft. high would roar down the gulley, carrying everything before it and leaving a trail of evil-smelling gray mud.*'

The extent of the area affected by severe landslides was 15,550 km^2 and the estimated volume of landslide debris was about 45 billion m^3 (Verghese, 1999). Extensive landslides on the Himalayan slopes temporarily blocked the courses of the Dibang, Dihang and Subansiri rivers (Figure 1.3). Bursting of these dams, 3 to 4 days later, released huge amounts of water and sediment, causing devastating floods downstream (Goswami, 1985). Immediately following the earthquake, the riverbed was raised by 1.5 m at Dibrugarh (Figure 1.3) and in the months and years following the earthquake a vast amount of debris and sediment continued to pour into the Brahmaputra River. As a result, the bed of river at Dibrugarh had risen by more than 3 m by 1955, visibly altering the regime of the river (Krug, 1957, Verghese, 1999). Based on the rapid decline in the rate of aggradation during the mid-1950s, Krug (1957) concluded that the riverbed probably reached its maximum elevation in 1956.

Krug (1957) did not have any quantitative data on sediment loads in the Jamuna River, but he reported his suspicion that within a few years the effects of the earthquake would be observed in the downstream reaches and that a few decades would be required to pass the huge volume of sediment through the river system. Similarly, Verghese (1999) noted that fine sediment generated by the earthquake had been washed downstream rapidly, but coarser material had been transported slowly.

Working in the 1960s, Brammer (personal communication, 2000) learned from interviews with local inhabitants that an unusually large amount of sedimentation had occurred on the Jamuna floodplain around Dhaleswari during the monsoon flood of 1950. He also identified rapid accretion in the Meghna Estuary in the southern part of Noakhali District from aerial photographs taken in 1952. These observations provide evidence to support Verghese's (1999) statement concerning the rapidity with which fine sediment moved through the system. On the basis of a rise in peak water levels in the Jamuna River at Bahadurabad, detected in hydrological surveys conducted during the late 1960s, Brammer also suspected that this might be attributable to raising of the channel bed by the coarse sediment generated by the Assam Earthquake.

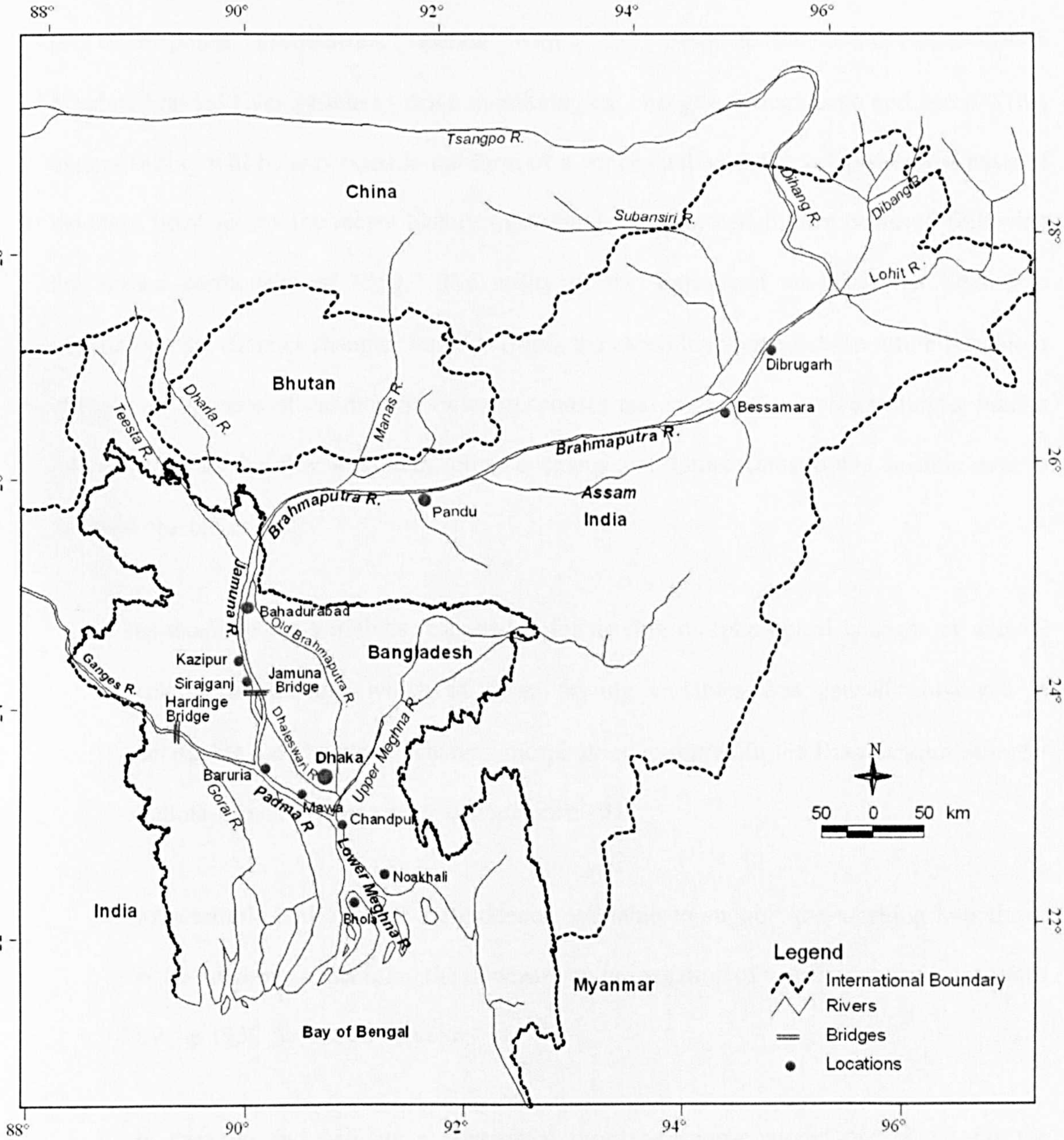


Figure 1.3: Brahmaputra, Jamuna, Padma and Lower Meghna river system

1.5 Objectives and scope of work

Compared to meandering rivers, braided rivers are more morphologically dynamic and complex, and much less is known about the geomorphological characteristics of this type of river (Schumm, 1977; Hooke, 1997; Thorne, 1997). Within this context, the aim of the research reported here is to achieve a new and improved understanding of how the dynamic process-response mechanisms operate within the Brahmaputra-Jamuna-Padma-Lower Meghna braided river system to drive morphological changes through time and space. This understanding will be expressed in the form of a conceptual model developed on the basis of evidence provided by the recent history of channel changes, which have occurred following the Assam earthquake of 1950. The utility of the conceptual model is not limited to explaining past channel changes, but also offers the capability to predict the future behaviour of the river in terms of the morphological responses that might be expected to further human interventions in the fluvial system, climate change, or future catastrophic seismic events. Specific objectives are:

1. to examine the variables responsible for driving morphological changes in alluvial rivers and identify which of these driving variables was causally involved in producing the changes in channel morphology observed in the Brahmaputra-Jamuna-Padma-Lower Meghna river system since 1950;

2. to assemble and analyse the evidence available to support the working hypothesis outlined above concerning the downstream propagation of a sediment wave generated by the 1950 Assam earthquake;

3. to develop and validate a conceptual process-response model that represents the relationships between changes in the driving variables and responses of the river system through changes to different morphological parameters; and

4. to compare the observed morphological responses and conceptual model of the Brahmaputra-Jamuna-Padma-Lower Meghna river system to the morphological behaviour of other large alluvial rivers elsewhere in the world.

The study area is very large. The length of the Brahmaptra-Jamuna River from Dibrugarh in Assam to the confluence with the Ganges River at Aricha is about 800 km. The combined flow of the Jamuna and Ganges then travels to the Bay of Bengal through the Padma and Lower Meghna rivers. The sediment wave travelled through the entire length of the Brahmaputra, Jamuna, Padma and Lower Meghna rivers from Dirbrugarh to the Bay of Bengal. Discharge, sediment load, slope and bed material size all vary between Dibrugarh to Aricha and dozens of tributaries join along both banks of the river. Information on the variation in river characteristics due to the influence of the tributaries is not available. This is especially true for the reach of the river within Assam. A little information (bed levels and flow areas mostly) on the Brahmaputra river within Assam has been provided by Goswami (1985), and that has been utilised to in this study. However, the capability to study the Brahmaputra River in Assam is very limited and so the study has focused on the river system in Bangladesh, where more information is available.

Information on the changes in bed level and flow area is also available for the Jamuna, Padma and Lower Meghna rivers in Bangladesh, but in addition changes in planform, width and braiding intensity of Jamuna, Padma and Lower Meghna are fairly well documented and are available through time-series satellite images. Also, historical maps provide an opportunity to study planform changes prior to the satellite era (that is pre-1973), based on 1953 aerial photographs (that is the period immediately after the 1950 Assam earthquake) and the Corona photographs of 1967. The availability of this longer record is potentially crucial as data revealing the interrelation between changes in hydro-morphology and planform could provide a better understanding of process-response in a large braided system.

The predictability of river behaviour is improved when the information on the past is combined with an accurate description of present and with reliable hydrological, hydraulic and sediment data (Schumm and Winkley, 1994). In this context, analysis of historical records of morphological change and relating them to changes in sediment load provides the key to enhancing our ability to predict the likely responses of the river system to future interventions, climate change or seismic events.

1.6 Approach

The entire Jamuna-Padma-Lower Meghna river system is very dynamic in nature, but among these rivers the Jamuna ranks first. It is a braided river with highly dynamic anabranch channels. Annual shifting of these channels ranges from few hundred metres to several kilometres. The rate of bank migration varies spatially, with local rates ranging from zero to several hundred metres, and in extreme cases exceeding one kilometre (Thorne *et al.* 1993).

Figure 1.4 illustrates patterns of bank migration and channel abandonment along the Jamuna River. Joining of two IRS, panchromatic images for 2001 and 2002 shows that the bank line at point 'A' migrated by about 500 m and the anabranch at point 'B' was abandoned within a single year. The point is that the temporal scale of these events is one year and yet the spatial scale of the morphological changes is several hundred metres. In fact, in the Jamuna River the rate of change may actually be much faster than the annual satellite images suggest. For example, a bathymetric survey conducted in the Jamuna River during the 1995 monsoon (Figure 1.5) showed a shifting of the thalweg by 300 m during a five day period. These two examples showed that it would be very difficult to develop an accurate picture of the whole river using the conventional method of surveys. For such a dynamic river, only satellite images can provide a snapshot of such a large reach of the river and a only a time-series of satellite images can reliably represent the history of planform changes in such a dynamic river.

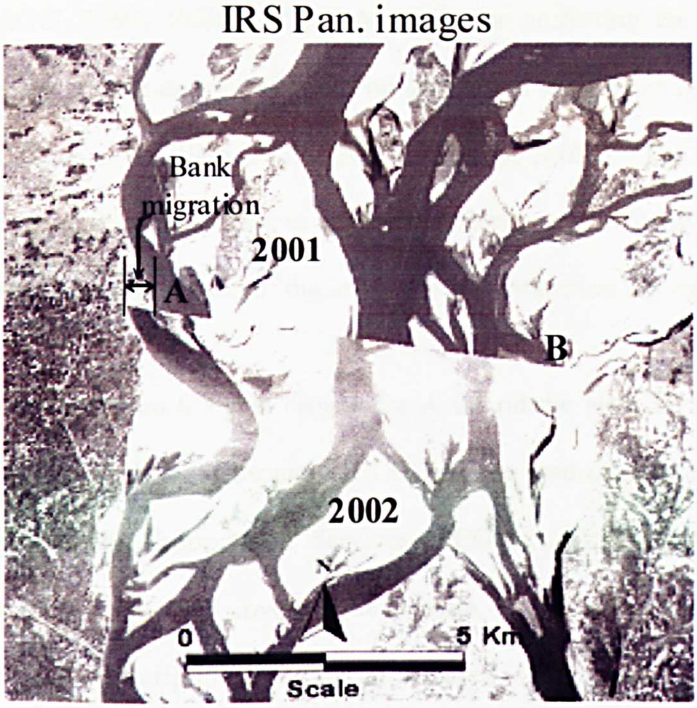


Figure 1.4: Juxtaposed images for 2001 and 2002, illustrating the scales of bank line migration and channel abandonment in the Jamuna River in a single year.

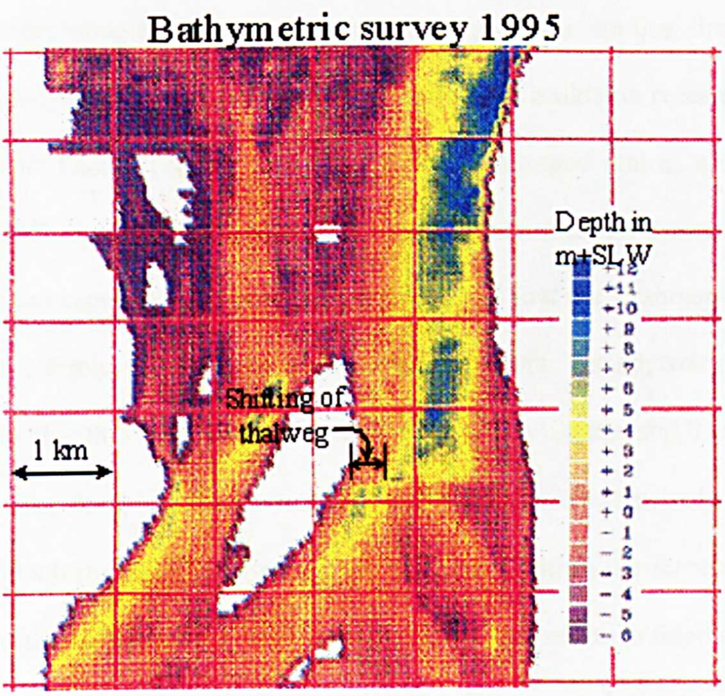


Figure 1.5: Bathymetric surveys showing the scale of morphological change due to shifting of thalweg over a 5-day period in the Jamuna River.

Several studies of morphological processes in the Jamuna River have made extensive use of satellite images (Bristow, 1987; Burger *et al.*, 1991; Thorne *et al.*, 1993; ISPAN, 1995a;

EGIS, 1997; EGIS, 2000). Methods for predicting the morphological changes and bank erosion were developed based on dry season satellite images (Klaassen and Masselink, 1992; Thorne *et al.*, 1995; EGIS, 2002b; CEGIS, 2005a). The temporal resolution of the satellite images selected in various studies was dependent on the dynamics of the river at that time and the spatial resolution of the images, which improves through time.

The Irrigation Support Project for Asia and the Near East (ISPAN) and Environmental GIS Project for Water Resources (EGIS) are the predecessors of the Center for Environmental and Geographic Information Services (CEGIS). This organisation has a time-series satellite images since 1973 covering the Jamuna, Padma and Lower Meghna images in its archive. A detailed description of the satellite images is presented in Chapter 4.

In this introductory chapter, a preliminary hypothesis has been presented to explain the morphological changes identified in previous studies through field monitoring and the analysis of maps and satellite images. This builds on research previously reported by Sarker and Thorne (2006). In summary, it is envisaged that as a sediment wave generated by the 1950 Assam earthquake passed downstream through the system, it changed the morphology (and especially the planform attributes) of first the Brahmaputra in Assam and, subsequently, the Jamuna, Padma and Lower Meghna rivers. The approach adopted in the research reported in this thesis builds on the work reported by Sarker and Thorne (2006). In this approach, a more complete time-series of satellite images is extensively used to document the sequential planform changes displayed by the rivers within the territory of Bangladesh. The left and right bank lines are used to define the width of the braided channel and are delineated based on the objective criteria developed by Hassan *et al.* (1997). Data are also extracted from the satellite image to measure the braiding intensity of the different geomorphic reaches of the rivers at various times, based on the braiding index of Howard *et al.* (1970). Together with the images, data on discharge, water level, sediment concentration, sediment size, and cross-sectional attributes (from hydrometric surveys) are used to describe morphological changes that have occurred since 1950 and which could be attributed to the propagation and progression of a sediment wave.

The recent and current behaviour of the river must, however, be considered within the context of the longer-term evolution of the fluvial system. In this respect, the characteristics of an alluvial river reflect its geologic history (Schumm and Winkley, 1994). In the case of the study rivers, deltaic development processes and active tectonics have governed the historical development of the river systems of the Bengal Basin (Goodbred and Kuehl, 2000a). Hence, a thorough review of the development and evolution of the rivers during the Quaternary, based on the available literature, was required to establish and characterise the prevailing long-term morphological trends and processes operating in the rivers within Bangladesh.

Further, the development of the preliminary hypothesis cannot take place in a vacuum, but should be informed by existing empirical and analytical models that have previously been developed to predict the response of alluvial rivers to disturbance including those of Lane (1955), Schumm (1969), Parker (1976), Chang (1979), White *et al.* (1982) and Jiongxin (1996). However, it would not be expected that the behaviour of a particular river would ever comply fully with any of the available models. Often empirical models were developed from the observations of a single river system or from rivers having a common type of environment (for example, Schumm, 1963; Burnet and Schumm, 1983; Jiongxin, 1996). Such models are unlikely to be transferrable to rivers of different types or in other geographical settings. Conceptual models may be more general and have been developed to inter-relate the different morphological parameters, in functional ways. Hence, in considering existing predictive methods, emphasis was placed on conceptual models which might be capable of explaining the sequence of process-responses and morphological changes observed in the Jamuna River. On this basis, according to the working hypothesis, changes in sediment load input to a geomorphic reach from upstream are taken to be the primary driver for the observed changes. However, in developing the initial hypothesis, it is examined whether changes in other independent variables, such as discharge regime and the calibre of sediment in transport and on the river bed contributed significantly to driving the process and morphological changes observed. Similarly, the roles of changes in key dependent variables such as channel slope, bed elevation, channel width and braiding intensity in conditioning morphological response are also considered. The conceptual model so developed for the Jamuna River is then tested and validated independently using information on the nature, sequence and timing of morphological responses in the Padma and Lower Meghna rivers.

This research was performed through part-time work in Bangladesh, interspersed with one or two short periods of full time study on campus in Nottingham each year for 6 years, as a part-time PhD funded jointly by the University of Nottingham (UoN) and CEGIS. The research was made possible thanks to the availability of satellite images within the CEGIS archive. These images were processed and geo-referenced by CEGIS and its predecessors EGIS and ISPAN. Hydro-morphological data including water levels, discharges, bed material sizes, sediment concentrations and cross-section surveys were mainly collected by Bangladesh Water Development Board (BWDB). Most of these data are available in National Water Resources Database (NWRD) of Water Resources Planning Organisation (WARPO). The database has been developed and is being maintained by CEGIS.

1.7 Structure of the thesis

This thesis documents the research carried out in developing and testing a conceptual model describing the morphological and process-responses of the Brahmaputra-Jamuna-Padma-Lower Meghna River system to the passage of a sediment wave generated by the 1950 Assam Earthquake.

Chapter 2 of the thesis provides the long-term context for the study by reporting the evolution of the rivers of the Bengal Basin during the Holocene. It also reports on development of the

Jamuna River in historical time, following its avulsion from a former course to the east of the Madhupur Tract to its present course to the west. The long, medium and short-term morphological evolution of the Jamuna, Padma and Lower Meghna rivers are also reviewed in this chapter.

A review of the literature pertaining to river form and process is presented in Chapter 3. An emphasis is placed on the different types models that have been developed to characterise and predict morphological responses to the human interference and/or natural disturbance of dynamic equilibrium in alluvial stream. Points of agreement and disagreement among the different models are identified and discussed. A scheme is developed to reconcile as many of the disagreements among the models as possible. This scheme attempts to explain the reasons for apparent contradictions between some of the models.

A time-series satellite images are the main source of the information on channel changes used in this research. However, use was also made of historical maps, Corona aerial photographs, cross-sectional surveys, discharge records, water level data, measured sediment loads and samples of bed material particle size distribution. The technical details of the satellite imagery and aerial photography, field techniques used in hydrographic surveying of the channels and description of the equipment used in sampling sediments are all presented in Chapter 4. This chapter also includes discussions on the reliability and accuracy of the data used in the analyses.

The methodologies employed in deriving various morphological parameters, such as delineating the bank lines, measuring the width and calculating the braiding intensity from the satellite images, are discussed in Chapter 5. The approaches used in checking the accuracy of the cross-section survey data and estimating the flow area below the bankfull elevation are also presented in this chapter. The chapter also provides the basis for specific gauge analysis and derivation of a sediment rating curve for the Jamuna River at Bahadurabad.

Chapter 6 deals with development of the conceptual model for describing and explaining the observed morphological changes with respect to the downstream passage of a sediment wave through the river system. The conceptual model is primarily based on existing theories and models of geomorphic process-response, coupled with interpretation of the observed changes in the morphology of the Jamuna River. The model is tested and validated using the observed morphological changes in the Padma and Lower Meghna rivers in the latter part of this chapter. An overview of propagation of the sediment wave and its effects of its downstream movement on the river system between Dibrugarh in India and the Bay of Bengal is also presented in Chapter 6.

Discussions of issues related to sediment transport, channel pattern and morphological response, and energy dissipation are addressed in Chapter 7. This chapter goes on to compare the conceptual model to previous process-response models, highlighting similarities and differences, and finally conclusions and recommendations are presented in Chapter 8.

Chapter 2

Evolution and Geomorphologic Development of the Jamuna, Padma and Lower Meghna Rivers

2.1 Introduction to the Jamuna, Padma and Lower Meghna Rivers

The course of the Brahmaputra River from the international border between Bangladesh and India to the confluence with the Ganges at Aricha is referred to in Bangladesh as the Jamuna River and this convention is adopted throughout the thesis. The Brahmaputra originates at the snout of a glacier in the Kailas Range of the Himalayas, in south-western Tibet (Figure 2.1). The river rises at elevation of about 5300 m (Goswami, 1998) and then flows 1100 km eastward across the Tibetan Plateau as Tsangpo River, before turning south to cross the east-west trending ranges of the Himalayas. The ranges crossed include the Greater Himalaya (average elevation 6000 m), Middle Himalayas (average elevation 3000-5000 m) and the Sub-Himalayas (average elevation 1000-2000 m). The river breaks through these ranges via a series of deep, narrow gorges before entering the Vale of Assam in India. After travelling 700 km in a south-westerly direction in the Assam valley, the river turns south again to enter Bangladesh.

Within Bangladesh, the length of the Jamuna River between the border and its confluence with the Ganges at Aricha is approximately 220 km (Figure 1.1). Downstream of this confluence, the combined flow is named the Padma River. This river flows southeast for about 100 km before its confluence with the Meghna River. The name of the combined flow is the Lower Meghna River, which flows south to enter the Bay of Bengal. Some key characteristics of the Jamuna, Padma and Lower Meghna Rivers are listed in Table 2.1.

Table: 2.1. Key characteristics of the Jamuna, Padma and Lower Meghna Rivers (Sarker *et al.*, 2003)

Parameters	Rivers		
	Jamuna	Padma	Lower Meghna
Drainage area (10^3 km^2)	573	1,573	1,650
Average annual rainfall (mm)	1,900	1,450	1,600
Average annual discharge (m^{3}s^{-1})	20,200	30,000	34,600
Average slope (-)	7.5 x 10^{-3}	5 x 10^{-3}	5 x 10^{-3}
Median bed material size (mm)	0.20	0.12	0.09

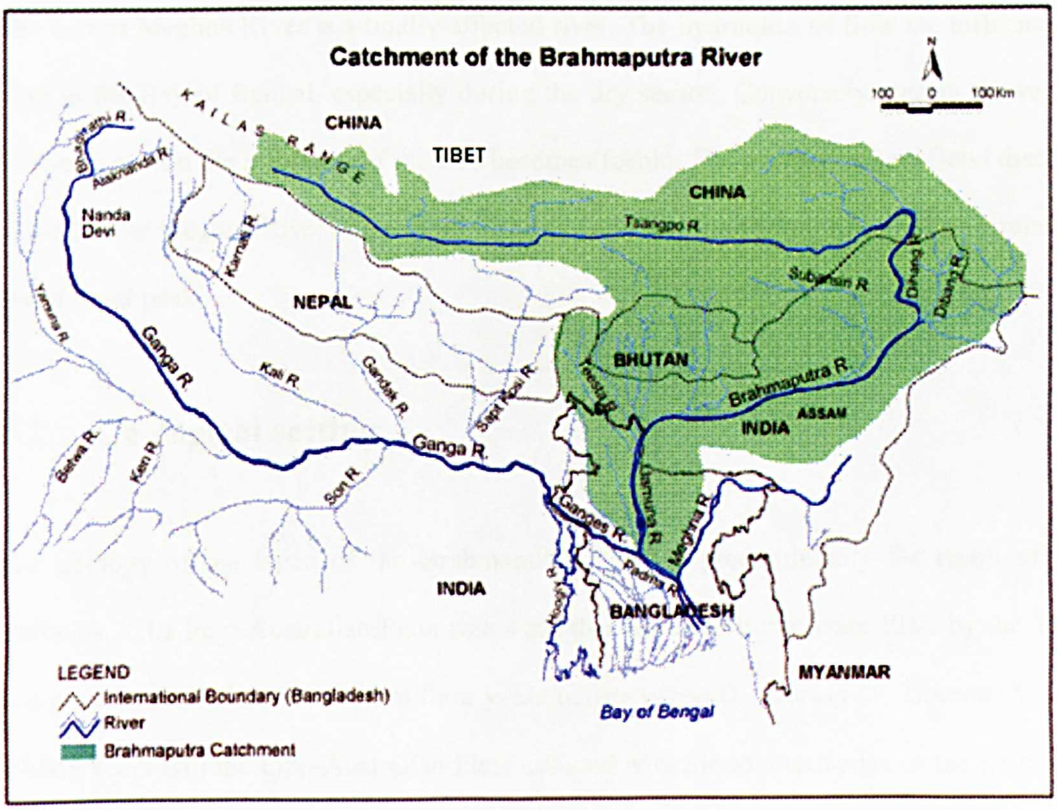


Figure 2.1: Catchment of the Brahmaputra River

The Jamuna is one of the largest rivers in the world ranking fifth in terms of discharge and eleventh in terms of drainage area (Thorne *et al.,* 1993). The annual hydrograph of the river is characterised by low flows in winter, between January and March, and high flows in summer, between July and September. The summer high flow season occurs due to a combination of snowmelt runoff from the Himalayas and monsoon rainfall in India and Bangladesh. The average annual flood is 70,000 m^3s^{-1} while the average low flow is 4,250 m^3s^{-1}, which yields a ratio of high to low flow that is greater than 16.

The average annual flood discharge of the Padma River is about 90,000 m^3s^{-1}, and the river ranks third in the world in terms of average discharge (Schumm and Winkley, 1994). Runoff in the Padma is derived by the snowmelt from the Himalayas and monsoon rainfall entering from the Jamuna plus additional monsoon runoff from the Ganges. Generally, the flood peak in the Jamuna River occurs in July while that in the Ganges is later (occurring in the late August or early September), resulting in a relatively prolonged flood peak in the Padma.

The Lower Meghna River is a tidally affected river. The hydraulics of flow are influenced by tides in the Bay of Bengal, especially during the dry season. Conversely, during the summer monsoon season the influence of the tide becomes feeble. The average annual flood discharge in the Lower Meghna River is about 97,000 m^3s^{-1} and like the Padma River, it has a relatively broad flood peak.

2.2 Geological setting

The geology of the basin of the Brahmaputra River is predominantly the result of plate tectonics. The Indo-Australian Plate was separated from the Euro-Asian Plate by the Tethys Sea prior to the Palaeocene (65 million years before present). During the Eocene (54 to 38 million years BP) the Indo-Australian Plate collided with the southern edge of the Euro-Asian Plate (Rashid, 1991). Since then, the Indo-Australian Plate has advanced northwards about 2000 km, passing beneath the Euro-Asian Plate, uplifting it and crumpling its southern edge to form the Tibetan Plateau and the Himalayas, respectively (Rashid, 1991).

The Indian Plate is subducted along the line of Himalayas, but at the eastern boundary the plates rub past each other along transform faults (Figure 2.2). During the Oligocene Epoch (38 to 26 million years BP), the north-eastern part of the Indian Plate in the vicinity of the junction of the subduction zone and the eastern transform fault, fractured and sank below the sea-level to form the Bengal Basin. The northern part of this basin was then gradually filled up by sediments carried by surface waters draining into it (Figure 2.3).

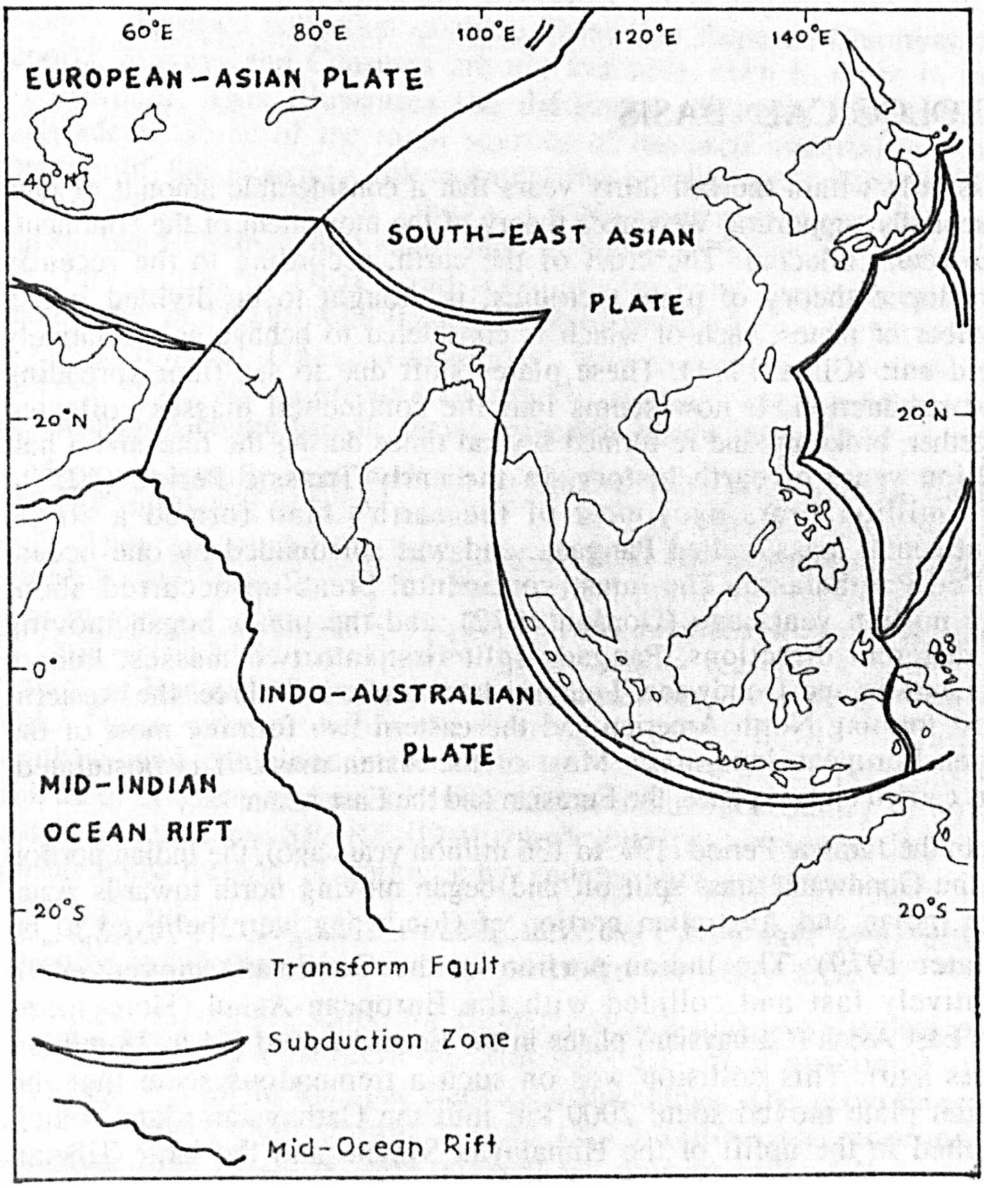


Figure 2.2: Tectonic map of the Indo-Australian and Euro-Asian Plates (Rashid, 1991)

The Pre-Cambrian rock beneath the northern part of the Bengal Basin is tilted from the northwest to southeast along a hinge line that developed during the Eocene. The hinge line divides the basin into two zones (Alam *et al.*, 1990). The sedimentary fill in the northwest is relatively thin, with a minimum thickness of 350 m, as the basement rock is close to the land surface (Khan, 1991). In contrast, the sediment fill in the southeast of the hinge line is extremely thick, reaching a maximum of about 18 km at Barisal.

The Bengal Basin is bounded by the Rajmahal Hills to the west, the Himalayas to the north and the Tippera Hills and Chittagong Hills to the east (Figure 2.3). Within the basin, the Shillong Hills occupy an area close to the Bangladesh-Indian border in the northeast corner. The Shillong Hills are formed by the uplifted Shillong Block, which is separated from the subsiding Sylhet basin to the south by the Dauki fault (Figure 2.3).

The Bengal basin has been filled by sediments derived from erosion of the highland boundaries on all three landward sides. However, the main source of the sediment has been the Himalayas due to their alpine nature, which features very high elevations, steep slopes and young rocks that are vulnerable to physical weathering and erosion. For millions of years sediments eroded from the Himalaya have been carried to the basin by the rivers Ganges and Brahmaputra, two very large rivers which rise in the Himalayas. The Ganges has not always drained from the Himalayas to the Bengal Basin however, as it only broke through the eastern margin of the Rajmahal Hills to enter the basin during the Pleistocene (Bhuiya, 1993). Since the Pleistocene the Ganges has, together with the Brahmaputra, delivered enormous quantities of sediment to the Bengal Basin. These sediments have formed the world's largest river delta with an area of about 100,000 km^2 and a sub-aquatic fan extending 3,000 km south into the Bay of Bengal (Goodbred *et al.*, 2003)

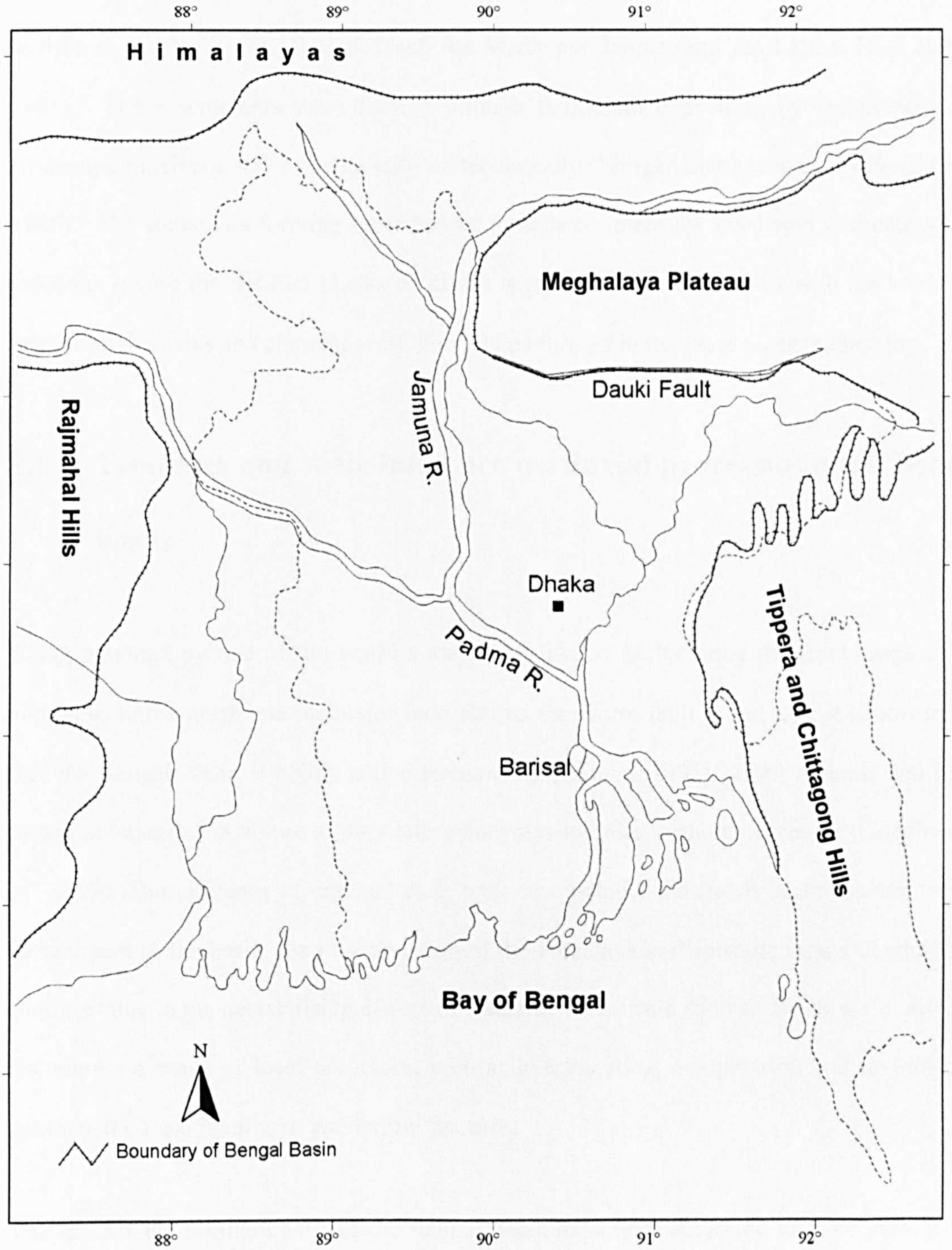


Figure 2.3: Boundaries of the Bengal Basin (Rashid, 1991)

About 90% of the land area of Bangladesh is formed in recently deposited, alluvial and deltaic sediments. The surficial topography of the fan within Bangladesh is very subdued. The highest elevation is only 90 m above sea-level (a.s.l.) in the northwest corner of the country, with 75% of Bangladesh lying below 29 m a.s.l. and 50% below 12.5 m (Halcrow *et al.*, 1993). The remaining 10% of Bangladesh is formed by raised blocks of older, Pleistocene sediments making up the Barind Tract, the Madhupur Jungle, and the Lalmai Hills (Khan, 1991). These sediments were formed through floodplain deposition by the Ganges and Brahmaputra Rivers, before being uplifted tectonically (Morgan and McIntire, 1959; Monsur, 1995). The sediments forming these blocks have been intensely weathered and extensively oxidized, giving the uplifted blocks relatively rugged relief that contrasts with the low relief of the deltaic plains and contemporary floodplains formed in the more recent sediments.

2.3 Tectonics and their influence on fluvial processes in the Bengal basin

Being bounded by one of the world's major subduction faults along the front range of the Himalaya to the north and the major Indo-Burma transform fault to the east, it is no surprise that the Bengal Basin is highly active tectonically (Bhuiya, 1993). Both regional and basin tectonics have and continue to play important roles in delta forming processes (Goodbred *et al.*, 2003). The influence of regional scale tectonics includes the steady and abundant supply of sediment to the basin due to denudation of the Himalaya and episodic inputs of additional sediment due to the destabilising effects of catastrophic seismic events. Basin-scale tectonics encompass a range of local processes, such as overthursting, compression and faulting that generate the local landforms and terrain features.

The eastern and northern parts of the Bengal Basin have been subjected to more seismic and tectonic activity than the southern and western parts (Morgan and McIntire, 1959). Prominent basin-scale terrain features include the Chittagong Hills, built by the Indo-Burman fold belt, which invades from the east, and the overthurst block of the Shillong Massif to the north. It was overthrusting of the Shillong Massif that caused uplifting of the Barind Tract, the Madhupur Jungle and Comilla Terraces together with related subsidence that formed the Sylhet basin. The topography generated by these tectonics has divided the northern part of the Bengal Basin into distinct sub-basins and has been indirectly responsible for directing and periodically changing the courses of its major rivers.

There is hard evidence that earthquakes and related seismic activities have had direct impacts on river courses and delta building processes. For example, the severe earthquake of 1762 caused a vertical displacement of the Madhupur Jungle that is believed to have contributed to an avulsion of the Brahmaputra River from its former course through the Sylhet Basin (to the east of the Madhupur Jungle) to its present course as the Jamuna, about 60 km to the west sometime near the end of the 18th century (Fergusson, 1863)

Fergusson (1863) first suggested the presence of a '*zone of weakness*' due to a major fault at depth between the Barind and Madhupur Pleistocene terraces, aligned approximately along the present course of the Jamuna River. Morgan and McIntire (1959) expanded on this belief to explain past changes in the courses of the main rivers as being largely the result of the contemporaneous tectonics (Figure 2.4) and proposed that uplifting of Madhupur and Tippera blocks is coupled with the subsidence of the Sylhet Basin and the zone of weakness between the uplifting Barind and Madhupur Terraces. According to this theory, abandonment by the Brahmaputra River of its course to the east of Madhupur in favour of its present course, avulsion of the Teesta River to join the Brahmaputra and systematic shifting of the mouths of the Ganges from the west to east may all be explained as responses to the shorter distance to the sea and, hence, steeper gradient offered by a course along the '*zone of weakness*'.

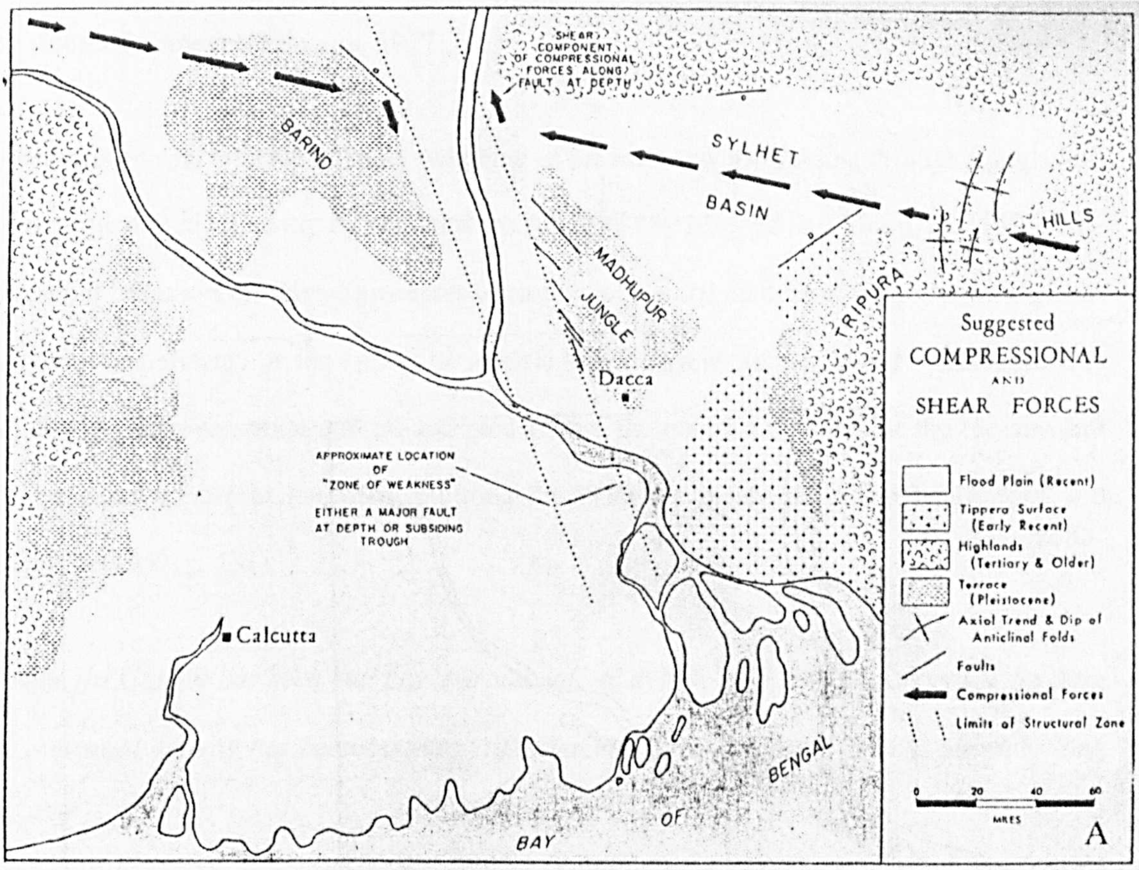


Figure 2.4: Structural forces affecting the Bengal Basin (Morgan and McIntire, 1959)

However, Goodbred *et al.* (2003) indicated that when the Brahmaputra River changed its course in the late 19th century it was not the first time that it had occupied the 'zone of weakness' and they suggest that its course may shift again in the future, including the possibility of the river reverting to its former course through the Sylhet Basin. This might occur because on-going subsidence of the Sylhet Basin that is no longer matched by the deposition of large quantities of Himalayan-derived sediments delivered by the Brahmaputra may lead to lowering of the surface elevation of the land to produce a steeper path to the seas, which could trigger re-occupation of the old course of the Brahmaputra River, to the east of the Madhupur block. According to this explanation of course shifting, reconnection of the heavy load of sediment carried by the Brahmaputra with the Sylhet Basin would more than compensate for land lowering by subsidence, leading to aggradation and, eventually, another shift to the alternative course west of the Madhupur when the gradient again became more favourable. This could be characterised as a type of 'geomorphic threshold' behaviour driven by slope adjustments (Schumm, 1977).

It remains unclear whether channel switching of the major rivers draining through Bangladesh is controlled predominantly by tectonics (as suggested by Morgan and McIntyre, 1959) or by threshold behaviour in fluvial processes operating within the context of longer-term, regional tectonics complicated by the impact of specific seismic events (as explained by Goodbred *et al.* 2003). However, what can be accepted is that the contrasting roles of the Ganges and Brahmaputra Rivers in long-term building the delta are nicely expressed by Morgan and McIntire (1959, p. 131);

"*while the Ganges has been building a broad, lateral deltaic mass, the Brahmaputra, because of structural activity has been building a thicker mass of sediment in structurally subsiding basins*".

2.4 Recent Evolution of the Bengal Basin and its river system

Williams (1919) first described recent changes in the course of the Ganges and their inter-relationship with the evolution of the Ganges Delta. He concluded that about 500 years ago the Ganges was flowing along what is now the course of the Hoogly River, with the Bhairab River being one of several large left-bank distributaries of the Ganges. Accordingly, the western part of the delta was being actively built by the Ganges, while the middle area of the delta was nourished by the sediment carried along the Bhairab River. At that time, the Ganges did not confluence with the Brahmaputra, which flowed almost due south along the '*zone of weakness*' between Madhupur and Barind Tracts, to reach the Bay at a point to the east of the outfall of the Bhairab, but to the west of the present mouth of the Lower Meghna. This was prior to switching of the Brahmaputra to a course east of the Madhupur block. At this time, the Kosi, Mahananda and Teesta Rivers were right bank tributaries of the

Brahmaputra. Thus, the middle and eastern parts of the delta were being built sediments delivered by the Brahmaputra.

According to Williams (1919), sometime just less than 500 years ago, the Ganges abandoned its course along the line of the Hoogly and shifted eastwards, leaving the Mathabhanga as a right bank distributary, and adopting a course close to that of the Gorai River. At this time the Brahmaputra shifted to the east of the Madhupur and the Kosi, Teesta and Mahananda Rivers became left bank tributaries of the Ganges. Later still, the Ganges shifted further eastwards again to flow along the line of the present Arial Khan River, leaving the Gorai as a right bank distributary. After the Brahmaputra switched back to its former course along the '*zone of weakness*' towards the end of the 18^{th} century, the Ganges again shifted eastwards to confluence with the Brahmaputra at Aricha. The combined flow formed the Padma River, which was sufficiently strong to break through a narrow band of older, erosion-resistant Chandina clay at Mawa and confluence with the Meghna River to form the present day Lower Meghna.

While Fergusson (1863) and Williams (1919) may be credited with formulating credible accounts of long-term and recent shifting of the main rivers draining through Bangladesh, the timings they suggest are very approximate and are unrelated to known changes in conditions bounding the terrestrial component of the delta, such as seas level change. To address this short coming, Umitsu (1993) analysed data from several boreholes in the Ganges delta and the surrounding area. Radiocarbon dates were determined for a number of samples and the results used to develop palaeo-geographic maps of the delta. Umitsu (1993) related changes in the courses of the Ganges and the Brahmaputra to rising sea level since its lowest stand during the last glacial maximum. While the sequence of shifting of the Ganges and Brahmaputra Rivers suggested by Umitsu (1993) is somewhat similar to that described by Williams (1919), the timing is quite different. Umitsu's time-scale is similar to that of Goodbred and Kuehl (2000a) (Figure 2.5) in envisaging that it took several thousand years for the Ganges to shift from the west to its present location.

More recently, a comprehensive account of the development of the Ganges/Brahmaputra delta from the late Quaternary and extending through the Holocene was presented by Goodbred and Kuehl (1998, 2000a and 2000b). Their account is based on further borehole data they collected themselves, as well as that from Umitsu (1993) and other sources. Based on the compiled data, they presented palaeo-geographic maps of the development of the Ganges-Brahmaputra delta. They conclude that changes to the courses of the Ganges and Brahmaputra were a consequence of the delta building process, which was itself driven by abundant sediment input from erosion of the Himalaya, conditioned by sustained sea-level rise that began during the Late Quaternary, and modified internally by regional tectonics within the Bengal Basin. The palaeo-geographic maps of Goodbred and Kuehl (2000a) are more detailed than those of Umitsu (1993) and represent the most up to date account of how the configuration of the major rivers has evolved to its current pattern. Hence, a summary description of the development of the delta based on Goodbred and Kuehl's contribution is presented below.

At the time of the lowest stand, about 18,000 years BP, sea-level was more than 100 m below its present elevation. The climate was drier than today and river flow regimes would have been flashier, with reduced sediment supplies from the Himalayas upstream. The Ganges and Brahmaputra Rivers responded to the falling base level and lower sediment supply by degradation to form incised, alluvial valleys that dissected the lateritic, Pleistocene deposits (Figure 2.5). By 11,000 years BP, the climate had become more humid and discharges in the rivers were greater than at present. As a result, sediment inputs to the basin increased markedly, being as much as 2.5 times greater than contemporary values. The rivers responded to the increased sediment inputs by infilling the incised valleys, adjusting the long-stream slopes of their channels through aggradation to match sediment transport capacity to the elevated sediment inputs. At this time, sea-level had begun to rise, but only slowly, so that conditions were ideal for the delta building process. In this context, it is interesting to note that onset of the period of rapid building of the Ganges Delta precedes the mean time for rapid delta building by other rivers globally by 2,000 to 3,000 years, probably reflecting the unparalleled inputs of sediment to the Bengal Basin from the Himalayas. The rate of sea-level rise then accelerated, reaching its maximum (> 10 mmy^{-1}) about 11,000 to 10,000 years BP. While such a rapidly rising base level would not favour delta formation, this continued in Bengal Basin, possibly due to the on-going high sediment yield from upstream.

At 9,000 years BP, the Brahmaputra was flowing to the west of the Madhupur block, while the Ganges was close to the present course of the Hoogly River. At this time, sediment deposited by the Brahmaputra was building the delta rather than compensating for subsidence in the adjacent Sylhet Basin, which was sinking as a result. Despite the relative fall in elevation, the Sylhet Basin remained cut-off from the sea by the narrow, aggraded corridor of the Meghna River which was itself higher than the sea-level.

By 7,000 years BP the rate of sea-level rise had slowed and the Brahmaputra River had avulsed to the east of the Madhupur block to supply a large amount of sediment to the over-deepened Sylhet Basin. The resulting rate of infilling was very rapid (> 20 mmy^{-1}), leading to the accumulation of an inland delta and robbing the middle delta of its previously abundant sediment supply. The Ganges, meanwhile, had migrated further east to bring sediment to the western part of the delta, where the maximum rate of marine transgression occurred. Transgression in the eastern delta still continued however, albeit at a slower rate because delta growth was limited due to deposition of some sediment in the Sylhet Basin. During this period, the delta forming process changed from being primarily aggradational to being mainly progradational, leading to formation of the sub-aqueous delta.

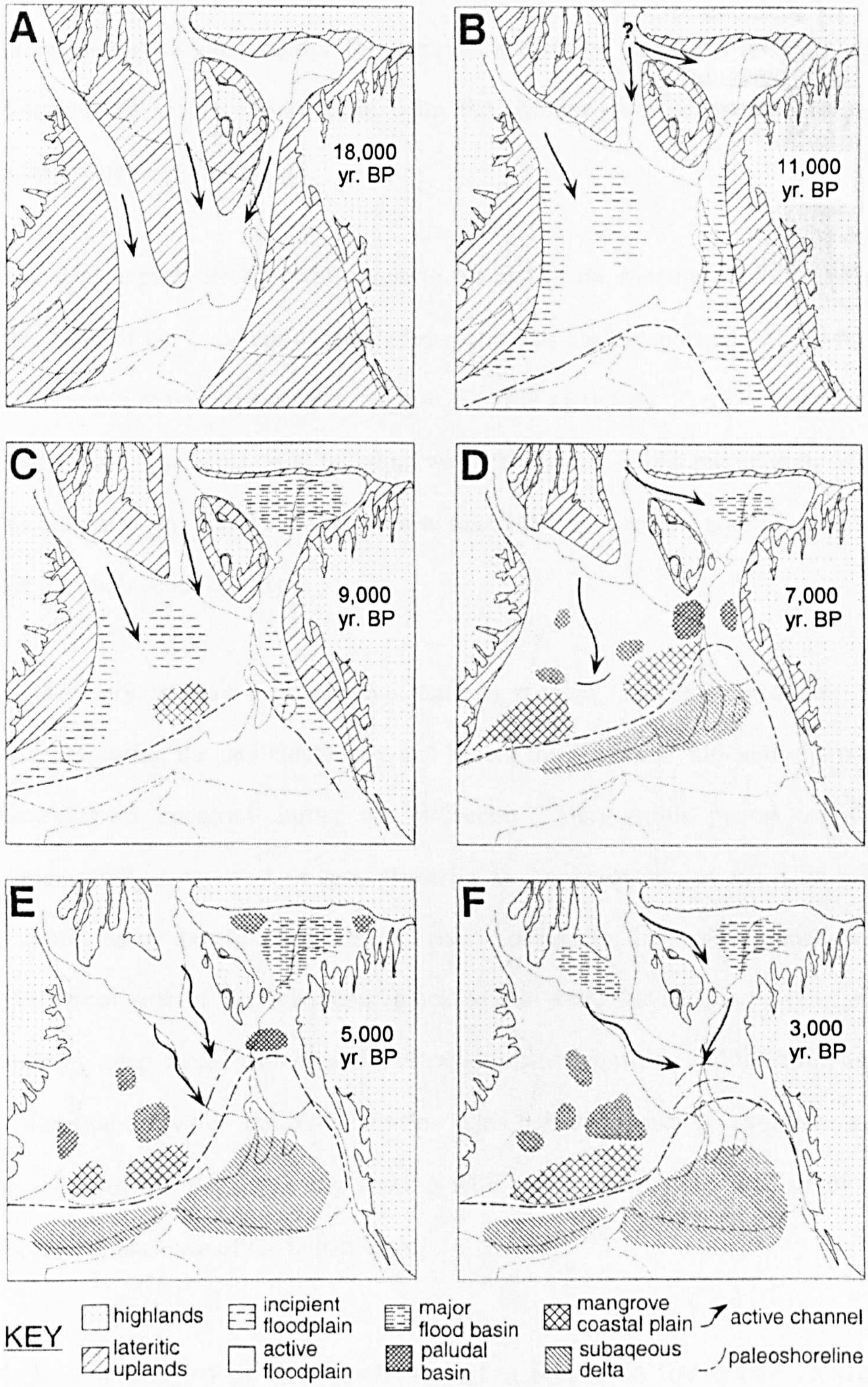


Figure 2.5: Palaeo-geographic map of Ganges-Brahmaputra Delta (Goodbred and Kuehl, 2000a).

The next switches in the courses of the major rivers occurred at about 5,000 years BP. The Brahmaputra River moved to the west of the Madhupur and the Ganges shifted to further east again. This allowed the rivers to meet for the first time during the Holocene. Here the account given by Goodbred and Kuehl is close to that of Williams (1919), although the timescale differs significantly. Delta growth at this time was (as is currently the case) mainly concentrated in the eastern delta, with the western delta becoming moribund due to its abandonment by the Ganges.

The Brahmaputra River shifted again to the east of the Madhupur block around 3,000 years BP. Most of the sediment of the Brahmaputra was again deposited to infill the Sylhet basin, with only a remnant passing through to the Bay of Bengal. The Ganges once again shifted further east. The situation at this time was very similar to that recorded by Major Rennell in his map of 1776, which may be taken to faithfully represent the configuration of the rivers in the late eighteenth century.

In summary, it may be concluded that the modern Ganges/Brahmaputra delta began to develop during the late Quaternary and before the Holocene, although the major part of its development occurred during the Holocene. During this period the Ganges shifted incrementally from west to east, primarily as a consequence of the delta building process conditioned by the effects of sea level rise. Conversely, the Brahmaputra switched back and forth from east of the Madhupur block to the west, featuring periods of extensive delta building interspersed with episodes of rapid inland deposition and fan building as a result of sedimentation within the Sylhet Basin. This behaviour may be explained as the result of coupling of the delta building process with sea-level rise, as modified by the effects of tectonic subsidence of the Sylhet basin

2.5 Avulsion of the Brahmaputra River to form the Jamuna River

Sometime between 1776 and 1830, the course of the Brahmaputra River shifted from the east of Madhupur block to the west, and river in its new course took the name Jamuna. The term 'avulsion' may be used to describe this shift as the change in channel alignment was achieved by a abandonment of one course and adoption of a new one some distance away rather than by progressive shifting (Bristow, 1999). There is no agreement among the scientists concerning exactly when, how and why the avulsion occurred (Morgan and McIntire, 1959; Coleman, 1969, Monsur, 1995; and Bristow 1999). In this context, use of this term should not then be taken to indicate that the shift occurred during a single event or even within a few years. For example, in 1916, Hirst suggested that the avulsion took place gradually over a sixty year period (Morgan and McIntire, 1959). What is known is that shifting did not begin in earnest earlier than 1776 because Major Rennell's map of that date clearly shows the Brahmaputra flowing east of the Madhupur, along the present course of the Old Brahmaputra River. It is also clear that shifting of the main course had been accomplished by 1830, as Colonel Wilcox's map of that date indicates that the main flow had been diverted to form the Jamuna, to the west of the Madhupur block (Figure 2.6).

Regarding how the shift occurred, writing in 1810, Buchanan Hamilton noted that the Brahmaputra was at that time 'threatening to shift westwards along the course of Konni (or Jennai) River' (Fergusson, 1863) and for many years the common opinion was that this threat was realised in the late 18th century when, 'the Brahmaputra started to divert the flow through the Jennai River' (Morgan and McIntire, 1959; Coleman, 1969; and Monsur, 1995). However, this opinion has recently been challenged (Bristow, 1999) on the basis that both on Rennell's map of 1776 and modern maps, the Jennai River is located to the east of the town of Dewanganj while, following its avulsion, the Brahmaputra occupied a channel west of Dewanganj.

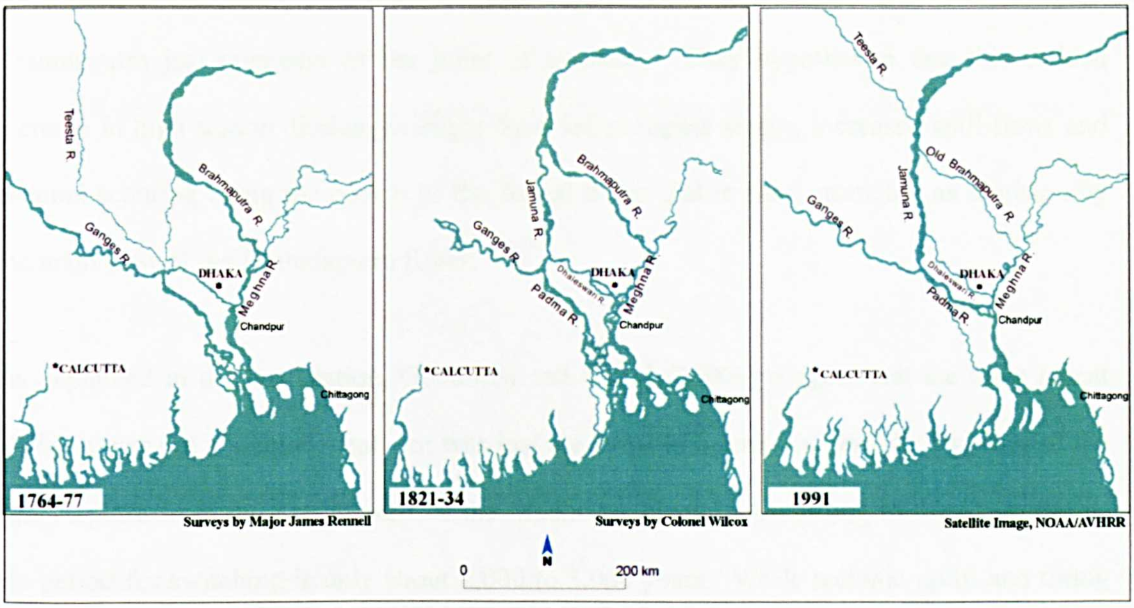


Figure 2.6: Development of the main rivers in Bangladesh over time

There are also different opinions on the cause of the avulsion, including tectonic influence, tributary switching, and the occurrence of a very large flood (Bristow, 1999). For many years scientists believed that tectonics were the main cause of switching the Brahmaputra from the east of Madhupur to the west, with Fergusson (1863) being one of the first to attribute the avulsion specifically to uplift of Madhupur block. In 1916, Hirst advanced an explanation based on the hypothesis that the avulsion was triggered by ground sinking along the present course of the Jamuna together with compensatory uplift of the Barind and Madhupur blocks (Morgan and McIntire, 1959). Coleman (1969) suggested that geologic events such as earthquakes, which caused faulting and tilting of the Madhupur block, were liable for the avulsion. He also mentioned that the present course of Jamuna River is one of the former courses of the Teesta River, implicating tributary shifting as a supplementary cause of the avulsion. More recently, the map of sediment deposition thickness during the Holocene produced by Goodbred and Kuehl (2000b), which shows a narrow subsiding strip along the present course of the Jamuna River, supports Hirst's concept.

Morgan and McIntire (1959) concluded that the avulsion occurred gradually in response partly to tectonic tilting of the Madhupur block and partly due to the addition of the flow from the Teesta River due to its sudden avulsion from west to east, to confluence with the Brahmaputra just upstream of the point of avulsion. They hypothesise that this sudden increase in high season discharges might have led to higher stages, increased spill flows and channel scouring along the course of the Jennai River that in time promoted an avulsion by the main flow of the Brahmaputra River.

As explained in the last section, Goodbred and Kuehl (2000a) suggest that the most recent avulsion was not a unique event, but was just the latest in a series of periodic switches of the Brahmaputra from the east to west of the Madhupur block. According to their hypothesis, the period for switching is only about 2,000 to 3,000 years. While tectonic uplift and tilting of the Madhupur block and associated subsidence in the Sylhet Basin and along the 'zone of weakness' between the Madhupur and Barind Tracts is the underlying cause of switching, different events may act as triggers for particular avulsion events. Specifically, trigger events might include earthquakes, tributary diversions, and major floods (Makaske, 2001). To these might be added the crossing of geomorphic thresholds intrinsic to the fluvial system (Schumm, 1977) associated with channel slope adjustments driven by sediment accumulation that is alternately centred in the Sylhet Basin and the trough between the Madhupur and Barind Tracts.

2.6 Morphological development of the Jamuna River

The morphological development of the modern Jamuna River began in the late 18th and early 19th when significant flows switched from the course of the Old Brahmaputra. In order to identify and understand the process-response mechanisms responsible for the morphological development of the river, its morphodynamics must be considered over time-scales ranging from longer-term evolution (over several decades to two hundred years), through medium-term adjustment (over a several years to a few decades) to short-term change (over a flood season to a few years).

The longer-term morphological development of the Jamuna since its creation by avulsion of the Brahmaputra River has been described by Coleman (1969), ISPAN (1995a) and EGIS (1997). These accounts are all based on analysis of historical maps, aerial photographs and satellite images to establish trends and patterns in the migration of the banks and/or centreline of the river and changes in the planform characteristics. Using maps from 1830 to 1963, Coleman (1969) showed that during the last 130 years the river had developed an alluvial valley 210 km long and 13 km wide. Coleman concluded that, in doing so, the Jamuna has reworked and broadened the former course of the Teesta River. Palaeo-geographic maps developed by Goodbred and Kuehl (2000a), support the first part of Coleman's account, but suggest that the Jamuna is reworking its own previous course (Figure 2.5), which was abandoned a few thousand years ago at the time of the last periodic switch in course. Comparing the valley margin and the map of 1963, Coleman (1969) further concluded that the river has been migrating westward since 1830 due to ongoing (i.e. neotectonic) uplift of the Madhupur block and the development of a transverse slope in the Jamuna floodplain. However, Thorne at el. (1993) put forward a different opinion. They suggested that widening, coupled with bank migration at the outer margins of concave bends in the Jamuna braid-belt (in a manner similar to bend growth and progression in a meandering stream), is mainly liable for lateral shifting. They note that, as there are two concave bends in the braid-belt along the west (right descending) bank but only one along the east (left descending) bank, migration is greater at the west bank, and this would be expected to result in net westward migration of the channel.

Movement of the bank lines of the Jamuna River during the last 200 years was comprehensively studied by FAP 19 (Flood Action Plan, project 19) in Dhaka and the results published in ISPAN (1995a). They obtained original copies of the maps of 1830, 1914 and 1953 and fitted them to a common Bangladesh Transverse Mercator (BTM) projection by comparing villages and other recognizable features with those on recent maps. The maps of

1914 and 1953 were easily matched to the BTM projection, although a shift of several degrees of longitude was necessary for the Wilcox map owing to mis-location of the city of Calcutta, which was used as a datum in the original map. Once the maps had been re-projected, their accuracy was checked and found to be reasonable (ISPAN, 1995a). The banklines on the maps were then digitised to indicate the position, width and planform pattern of the Jamuna in 1830, 1914 and 1953. Next, bankline maps of the Jamuna River were derived from georeferenced and orthocorrected satellite images for a variety of dates between 1973 and 1992. All the bank lines were then plotted on a common map with a referenced bank line of 1992 (Figure 2.7).

The ISPAN (1995a) report reveals that in 1830 the Jamuna River had a meandering planform and followed a course that was for most of its length to the east of the line of the present east (left descending) bank. In 1914 the planform remained meandering, but the river had shifted noticeably westward and the average width of the channel (5.55 km) was somewhat narrower than that displayed in 1830 (6.24 km) (Table 2.2). Between 1914 and 1953 the river continued its westward migration while widening significantly and metamorphosising its planform from meandering to braiding. By 1973, the average width of the river had reduced slightly, but rapid westward migration had continued. Between 1973 and 1992 the rate of increase of the average width accelerated to a very high level (Figure 2.8), although the rate of westward migration slowed right down.

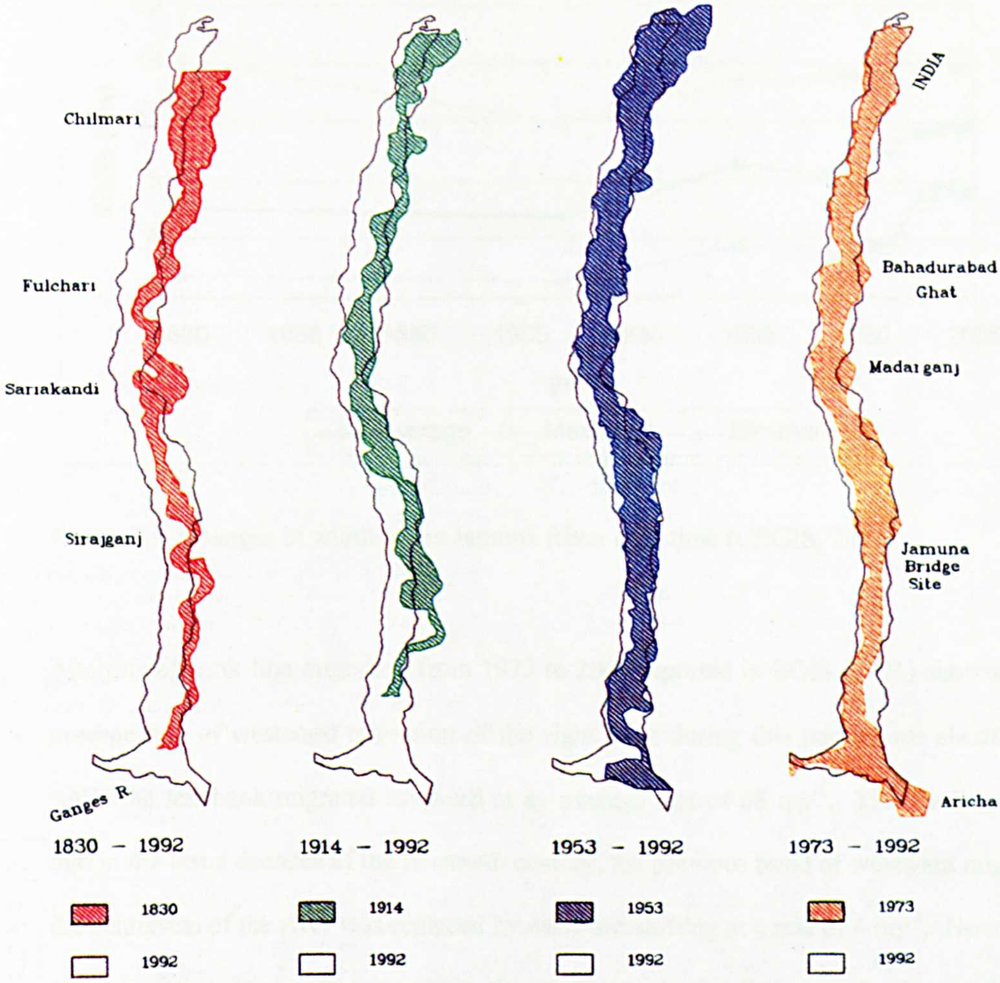


Figure 2.7: Historical bank line changes of the Jamuna River (EGIS, 1997)

The average westward migration rate of the centreline of the Jamuna River between 1830 and 1992 was 28 my^{-1}, while the rate of the migration of the west bank was about 50 my^{-1} (ISPAN, 1995a). The difference in the two rates reflects the impacts of processes of westward migration and channel widening, which operated simultaneously during much of this period.

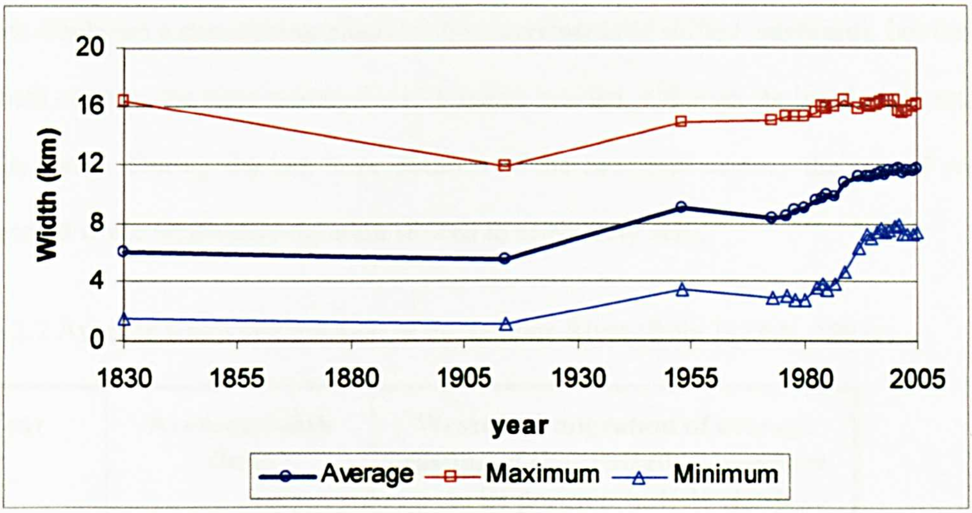


Figure 2.8: Changes in width of the Jamuna River over time (CEGIS, 2007)

Analysis of bank line migration from 1973 to 2000 reported in EGIS (2001) showed that the average rate of westward migration of the right bank during this period was about 60 my^{-1}, while the left bank migrated eastward at an average rate of 68 my^{-1}. This finding indicates that in the last 3 decades of the twentieth century, the previous trend of westward migration of the centreline of the river was replaced by eastward shifting at a rate of 4 my^{-1}. However, this rate of eastward migration is within the error margin for the analysis, due to the coarse resolution of the satellite images (either 80 x 80 m or 30 x 30 m pixels) and uncertainties associated with geo-correction of the images. However, it can be concluded that during the last 30 years, the rate of westward migration of the centreline of the Jamuna River has slowed and may now be close to zero. This conclusion, based on planform analysis, is supported by the results of an analysis of cross-sectional data from the Jamuna River collected between the mid-1960s and the mid-1980s (Burger *et al.*, 1991), which showed no evidence for a westward migration trend of the river.

In summary, based on these sources and analyses, it may be concluded that longer-term evolution of the Jamuna since 1830 has progressed through westward migration, widening and planform metamorphosis following creation of the river by avulsion. Initially, the

Jamuna displayed a meandering planform that incrementally shifted westwards, but during the twentieth century the river widened and became braided, although its braid plain retained a sinuous form. During the last three decades of the twentieth century the rate of widening accelerated while westward migration slowed to effectively zero.

Table 2.2 Average width and position of the Jamuna River (from ISPAN, 1995a)

Year	Average width (km)	Westward migration of average easting of the centreline, compare to its position in 1830 (km)
1830	6.24	--
1914	5.55	1.9
1953	9.05	3.6
1973	8.08	4.5
1992	10.61	4.6

Medium-term morphological adjustments

Morphological adjustments in the medium-term occur through bankline shifting, planform alteration and changes in the bed and cross-sectional forms of the channel at the decadal scale. These adjustments have been previously been described by Coleman (1969), CBJET (1991), Thorne *et al.* (1993), EGIS (1997), Zhou and Chen (1998) and Sarker and Thorne (2006).

In an important and often quoted paper, Coleman (1969) studied the banklines derived from maps made in 1944, 1952 and 1963. He overlaid the banklines derived from successive maps to reveal patterns of bankline migration during the intervening periods. Coleman found marked reach-scale variability in the trends of medium-term channel adjustment. There were three patterns of bank line migration. In some reaches both banks migrated outwards leading to widening. In other reaches outward migration of one bank was compensated for by inward migration of the opposite bank, to drive lateral migration. In other reaches, inward migration of both banks led to channel narrowing.

In terms of overall adjustment, Coleman found that between 1944 and 1952 the river widened at a very high rate of 178 my^{-1} while between 1952 and 1963 the average width actually decreased slightly, at a rate of 8 my^{-1}. However, these average trends for the entire length of the Jamuna obscure contrasting patterns of reach-scale adjustments. For example, between 1944 and 1952 the river simultaneously narrowed at a rate of 850 my^{-1} in some reaches while widening at a rate of 790 my^{-1} in others.

From the analysis of contemporary cross-sections, Coleman (1969) concluded that the morphology of the Jamuna varied significantly in space as well as time with respect to trends of medium-term adjustment. Writing in the late 1960s, he concluded that the river was wider and shallower, with a fully developed, braided planform upstream of Sirajganj, but narrower and deeper downstream, with a planform that displayed elements of both meandering and braided channel planforms. As differences in bed sediment sizes and water surface slopes during formative flood events observed in the two reaches were insignificant, Coleman (1969) suggested that the presence of cohesive, erosive resistant bank materials along the downstream reach might be responsible for its narrower width.

Subsequent investigation of bank material properties reported by Thorne *et al.* (1993) failed to find marked differences in the characteristics and erodibility of the bank materials throughout the length of the Jamuna. This finding, together with the increase of width and conversion to a more braided planform that developed in the Jamuna River downstream of Sirajganj in the years following Coleman's paper, indicate that the contrasting planforms he observed were a actually a transitional state and occurred as part of longer-term evolution of the channel morphology. Obviously, Coleman could not have known this in the late 1960s.

Thorne *et al.* (1993) also investigated whether another of Coleman's hypotheses was supported by detailed planform information that became available after 1973 from satellite images. Coleman (1969) proposed that the braided planform of the river could be divided into relatively long, divided reaches with a major anabranch at each bank and large, long-lived islands at the channel centreline (Coleman termed these island reaches), separated by short, relatively narrow reaches where the major left and right bank anabranches converged and sometimes crossed over (which he termed nodes). Thorne *et al.* (1993) examined the planform pattern of the Jamuna, concentrating on downstream changes in channel width, the position and orientation of the major anabranches, and the presence or absence of large islands (called chars in Bangladesh). Thorne *et al.* (1993) identified seven island reaches and nine nodal reaches between the Teesta confluence in the north and the confluence with the Ganges at Aricha in the south. The average length of the island reaches was found to be about 30 km, while nodal reaches (crossings) were indeed shorter, being about 10 km long. Thorne *et al.* (1993) went on to analyse more recent trends of bankline shifting based on digitised banklines from the map of 1953 and a number of satellite images with dates between 1973 and 1989. They measured the lateral movement of the east and west banks at 500 m intervals along the length of the Jamuna.

Thorne *et al.* (1993) found that banklines had migrated westward between 1953 and 1989. However, the average rate of westward migration of the west (right descending) bank was 90 my^{-1}, while the equivalent figure for the east (left descending) bank was only about 7 my^{-1}, producing an average widening rate of about 83 my^{-1}. The spatial distributions of widening and westward migration were also shown to be related to the island-node pattern, with retreat of the west (right) bank being about 3 times higher in island reaches than in nodal reaches. Along the east (left) bank differences in bank retreat rate between the island and nodal reaches were smaller.

Thorne *et al.* (1993) further examined the planform morphology of the Jamuna to explore the dimensions and morphodynamic roles played by second order channels and bars found within the primary channel and scaled on the dimensions of the main, east and west bank anabranches. They established that second order bars in the Jamuna are 3 to 6 km long and are spaced at about 6 to 8 km intervals along the major anabranches. They concluded that flow deflection and division by these second order bars was responsible for the erosion of embayments in the floodplain, each on average about 7 km long, that were mostly responsible for retreat of the banklines, especially along the west (right) bank. This observation suggested that it was the initiation, growth and downstream migration of second order bars that was the main driver of bank erosion, which is consistent with the explanation of braiding mechanics proposed by Leopold and Wolman (1957).

Building on earlier work, the next comprehensive study of morphology and medium-term adjustment of the Jamuna was performed by EGIS (1997). EGIS used 13 dry season satellite images from 1973 to 1996, with spatial resolutions varying from 80m to 30m providing the basis for the study. In an improvement of the work by Thorne *et al.* (1993), these images were orthocorrected, fully georeferenced and coregistered. The maximum root mean square error for the coarse resolution (80m x 80m) images was 96 m and for fine resolution (30m x 30m) 45 m. In a further improvement, strict criteria were developed to define the banklines and eliminate subjectivity in delineating the river banks on the satellite images (EGIS, 1997; Hassan *et al.* 1997).

The EGIS (1997) study divided the 204 km length of the Jamuna River from the confluence of the Dharla River to Aricha into eight reaches (Figure 2.9). The bases of the division were:

i. channel alignment,

ii. stability,

iii. trend and direction of migration,

iv. presence of an off-take or confluence.

The length of the reaches varied from 16 to 35 km. Trends and the downstream distribution of bankline migration, changes of width and braiding intensity were analysed on the basis of these reaches.

The results revealed that between 1973 and 1996 both banks migrated outwards. That is, the right bank migrated westward and left bank eastward. The spatially-averaged rate of westward migration of the right bank was 64 my^{-1}, while eastward migration of the left bank occurred at a rate of 70 my^{-1}. There were marked, reach-scale variations in average bank migration rates. The range of variation along the right bank was 25 to 120 my^{-1}. Along the left bank, variation in the migration rate is highly erratic and varied between -14 and 187 my^{-1}. These findings for the first time cast doubt on the contention that the Jamuna River was still migrating westward in the 1990s, although at the time it was concluded that this was probably a temporary, short-term reversal in the longer-term trend for westward migration.

The migration rate of the banks indicated that bank erosion was the dominant process and widening the predominant morphological adjustment between 1973 and 1996. The area of floodplain eroded during this 23 year period was 73,550 ha, while accretion created only 10,630 ha of new floodplain. The average widening rate was 134 my^{-1}. EGIS (1997) found that the rate of widening varied along the river, ranging from 16 to 218 my^{-1}. Generally, the rate was higher in narrower reaches than it was in wider reaches. For example, the width of a wide reach (Reach 3) was 11 km in 1973 and the rate of widening was only 16 my^{-1}. In contrast, the width of a narrow reach (Reach 8) was 6.5 km in 1973 but the average rate of widening was 218 km. This finding contrasted with the finding of Thorne *et al.* (1993) that widening was greater in wide (island) reaches than in narrow (nodal) reaches. The reason for these contrasting findings probably stems from the fact that the two studies considered different periods. Thorne *et al.* (1993) considered the period 1953 to 1989, during which, on average, the river narrowed by 0.75 km between 1953 to 1973 and subsequently widened by 2.4 km between 1973 and 1989 (Figure 2.8). The EGIS (1997) study covers a period of persistent widening at an unprecedentedly high rate. The contrasting behaviour of the river in terms of the rates and spatial distributions of bankline migration and widening hint that the processes responsible may have been different and suggest that a new form of morphological adjustment may have begun in the 1980s, perhaps in response to a new and unprecedented driver of morphological change.

EGIS (1997) also established that the braiding intensity of the river has been changing over time. The braiding index defined by Howard *et al.* (1970) was adopted to provide an objective measure of braiding intensity that could be extracted from satellite images of the Jamuna. The average braiding index for the Jamuna as a whole was about 4.5 in the 1970s, rising to 5.5 to 6 in the 1990s. Reach-scale analysis revealed contrasting trends of change between the upstream and downstream reaches of the river. Generally, the braiding intensity in the downstream reaches decreased in the early 1980s before later increasing. This sequence of variation did not feature in the upstream reaches, however, Sarker and Thorne (2006) extended the braiding analysis up to 2000. They divided the Jamuna River into just two reaches of approximately equal length, up and downstream of Sariakandi (Figure 2.7). They found that braiding intensity in the upper reach increased from 1973 onwards to peak in the early 1990s, before declining. In contrast, the braiding intensity of the lower reach decreased from 1973 to its minimum in the early 1980s, before subsequently increasing to reach its maximum in the mid-1990s.

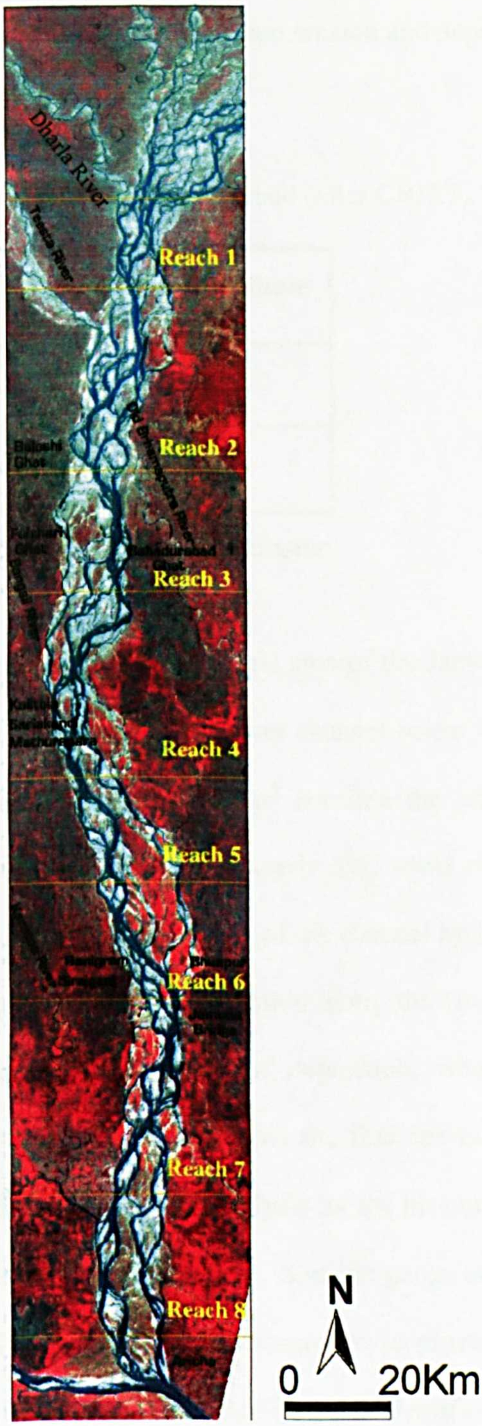


Figure 2.9: Satellite image of the Jamuna River 2001 showing eight reaches as defined by EGIS (1997)

The existence of monumented cross-sections that have been resurveyed annually since they were established by the Bangladesh Water Development Board (BWDB) in 1966 potentially represents a useful record of medium-term morphological change. Cross-sections cover the entire length of the Jamuna, have a fixed alignment and are spaced about 6.4 km apart. CBJET (1991) used this resource to investigate erosion and deposition at the channel bed over a period of 23 years (Table 2.3).

Table 2.3 Erosion and deposition at the riverbed (after CBJET, 1991)

Period	**Total change in volume (10^9 m^3)**
1965/6 – 1980/1	-0.278
1980/1 – 1988/9	+0.502

'+' represents deposition and '-' represents erosion

CBJET found that the average cross-sectional area of the Jamuna to be about 30,000 m^2 and thus the total volume of the 200 km long river channel below bankfull elevation is $6x10^9$ m^3. It follows that net erosion of $0.278x10^9$ m^3 between the mid-1960s and the early 1980s represents enlargement of the channel by nearly 5%, while net deposition of $0.502*10^9$ m^3 during the 1980s would indicate a shrinking of the channel by just over 8%. CBJET analysed the distribution of aggradation and degradation along the river for different periods. They also reported the existence of a wave of deposition, which appeared to be travelling downstream along the river. To help validate the findings of their cross-sectional analysis, CBJET also performed a specific gauge analysis for the mean annual discharge (20,000 m^3s^{-1}) at a number of water level gauging stations. Specific gauge analysis establishes a time trend in the stage associated with a specific discharge and so provides an indirect measure of bed level changes at the selected location. CBJET (1991) identified a rising trend in effective bed level at the main BWDB gauging station at Bahadurabad, during the early 1970s followed by a falling trend in the late 1970s. At other locations, the changes of bed level were insignificant.

While any data is valuable, it must be mentioned in connection with the BWDB cross-sections that uncertainties concerning the reliability of the surveyed data are very high. The accuracy of the surveyed cross-sections was investigated as part of FAP 1 (Halcrow *et al.*, 1994) and FAP 24 (Delft Hydraulics and DHI, 1996a & b). According to the independently obtained findings of these two investigations, the accuracy of the cross-sectional surveys is not encouraging. In fact, after checking the horizontal and vertical controls on the surveyed cross-sections, Delft Hydraulics and DHI (1996a) selected just a few indicative sections and survey dates for use in their morphological analysis, retaining only those data whose accuracy was (according to their assessment) reasonable. It may, therefore, be concluded that uncertainty in the reliability of the cross-sectional data effectively nullifies the CBJET's assessments of erosion or accretion.

A specific gauge analysis of flows at Bahadurabad was performed by Sarker and Thorne (2006) for the period 1960 to 2000. Their analysis revealed that stage elevations for both low and high specific discharges began rising during the late 1960s and reached their maxima in mid-1970s, indicating a clear aggradational trend at Bahadurabad of the Jamuna River. Stages then began to fall for a range of different discharges, dropping by up to a metre during the 1980s, and clearly indicating a trend of bed degradation.

Compilation and comparison of the results of various investigations of medium-term morphological adjustments in the Jamuna River reveal agreement on some points and disagreement on others. What can be concluded at this stage is that a series of significant adjustments have in fact taken place in the river during the last fifty years, that the spatial distributions of changes to channel width, position and elevation at the reach-scale are complex, and that temporal trends in the rates and directions of channel change are non-linear. In this context, contrasts between the types and timing of adjustments up and downstream of Sariakandi hint at the possibility that adjustments propagated downstream through some form of dynamic, downstream process-response, perhaps in response to disturbance to the fluvial system that was centred further upstream in the Brahmaputra River and which occurred at an earlier date.

Coleman (1969), Bristow (1987), Klaassen and Masselink (1992), Thorne *et al.* (1993), Richardson *et al.* (1996), Delft Hydraulics/DHI (1996c), McLelland *et al.* (1999) and Ashworth *et al.* (2000) have each presented accounts of characteristic, short-term morphological changes exhibited by the Jamuna and the processes responsible for those changes. Typically, short-term channel changes result from bar accretion, bank erosion, anabranch shifting, and erosion or deposition at the riverbed. Each of these processes is described briefly in the remainder of this section.

Braided channels are characterised by mid-channel bars. Formation and evolution processes of mid-channel bars in the Jamuna River are studied by Ashworth *et al.* (2000). The bar forms downstream of a regiom of flow convergence. Initial growth of the bar core occurred due to the amalgamation of dunes that are always present in the Jamuna River (Ashworth *et al.*, 2000). Bar-top aggradation continues through both dune superimposition and amalgamation of smaller dunes in the shallower flow on the bar-top. The bar widens through lateral accretion produced by the dune migration onto the margins of the bar during the low flow. As the bar aggraded and widened, the reach of the river maintains the same cross-sectional area through bed and bank erosion of the anabranches.

McLelland *et al.* (1999) studied the flow structure and suspended bed material transport around a mid-channel bar of the Jamuna River. They did not find any evidence for helical flow cells in the anabranches around the bar at any flow stage and it contradicts the findings of the study carried out by Richardson *et al.* (1996) on the Jamuna River. According to McLelland *et al.* (1999), the high width-depth ratio, small planform curvature and high turbulence due to the presence of large dunes minimizes the opportunity of generation of helical flow. High sediment concentration and the divergence of flow downstream of flow convergence are the main causes of initial formation of bar core. Transport of suspended bed material from the bar head changes progressively during the development of the bar. The bar widening is associated with high suspended-sediment concentrations adjacent to the bar margin. Extension of the bar accompanies increased suspended sediment transport over the bar top.

Extensive investigations of erosion processes and failure mechanisms responsible for bank retreat have established that multiple factors are involved. These include near-bank flow velocity, the balance between sediment supply and removal at the toe, the geometry and bed topography of the local and approaching channel, bank hydrology, bank material properties and vegetation. Of these factors, vegetation does not have a noticeable influence on bank erosion in the Jamuna River due to the huge scale of the stream (Klaassen and Masselink, 1992). Generally, vegetation has a significant influence on the bank erosion mostly in smaller rivers (Lawler *et al.*, 1997).

In the Jamuna, the primary process of bank erosion is toe scouring by the near-bank flow, followed by bank failure under gravity (Thorne *et al.*, 1993). Consequently, the velocity of the near-bank flow in the anabranch adjacent to the bankline is the most important factor in determining the rate of bank retreat (Mosselman, 1992). The temporal distribution of near-bank velocities is highly stage dependent, with velocities being highest and bank scour potential greatest during the summer monsoon runoff season. The spatial distribution of high near-bank velocities is determined mainly by the planform pattern and cross-sectional geometry of the anabranch(es) approaching and adjacent to the bankline. In the Jamuna, like many other rivers, bank retreat is characteristically associated with the outer margins of bends where secondary currents carry high velocity flow close to the concave bank. Secondary currents are found at all flow stages in the bends in meandering rivers (Markham & Thorne, 1992) and direct measurements made in the anabranches on either side of a growing second order bar near Bahadurabad (Richardson *et al.*,1996) indicate that strong secondary currents also lead to bank attack and toe scour in both the meandering and braided anabranches of the Jamuna.

In light of similarities in the flow patterns responsible for severe bank and toe scour in the Jamuna with those observed in meandering rivers, it is not surprising that approaches similar to those used to characterise bank retreat at meander bends have also been developed for the Jamuna. For example, Klaassen and Masselink (1992) expressed the relative bank erosion rate (erosion rate over width of the channel) displayed by anabranches in the braided channel as a function of relative curvature (radius of curvature of the channel bend divided by the width of the channel) in a manner similar to that developed for single-thread meandering streams by Hickin and Nanson (1984). They found that local rates of bank erosion in flanking anabranch channels of the Jamuna River usually vary from 0 to 500 my^{-1}, but in exceptional cases may exceed 1,000 my^{-1}. As a result, short-term morphological changes caused by localised bank retreat in the bends of flanking anabranches along the outer margins of the Jamuna braid belt annually erode 2,000 to 4,000 ha of the floodplain (CEGIS, 2005b).

The life-span of the embayments in the floodplain created by localised bank retreat at anabranch bends largely depends on the rate of bank erosion (Thorne *et al.*, 1995). If the rate of erosion is very high, for example more than 350 my^{-1}, the embayment quickly deepens, leading to its abandonment (through a chute-type cut-off or anabranch avulsion) when the ratio of embayment length to depth falls below a value of about 3. Under these circumstances, the expected life span according to Thorne *et al.* is less than three years. However, if the erosion rate is slow, for example 25 to 50 my^{-1}, the expected life-span of such a meander embayment can be as long as 10 years.

In a single-thread, meandering river, bank erosion at the outer bank of bends is often matched by accretion at the opposite bank. However, in braided rivers bank erosion or accretion may occur along both banks simultaneously (Coleman, 1969). In the Jamuna, simultaneous erosion or accretion of both banks may be identified when the first order channel is considered, the first order channel being defined as the entire river, extending across the full width of the braided planform (Bristow, 1987). The first-order channel comprises of two or more second order channels, which in turn have smaller third-order channels within them.

According to Bristow (1987), the second order channels of the Jamuna River behave like meandering rivers, migrating through erosion of the outer banks at bends that is matched by accretion at the inner margin.

The banks of the Jamuna River are formed in weakly cohesive, silty-sand with only a few clay layers and the composition of the bank material is remarkably uniform throughout the length of the Jamuna River (Thorne *et al.*, 1993). The banks are generally composed of ~60% sand and ~40% silt. Such is the extent of bank erosion that the contribution of the sand supplied by bank erosion makes up about a quarter of the total sand load in the river. However, due to the massive load of silt coming from upstream, the silt yield from bank erosion constitutes only 5% of the total wash load of the river (Thorne *et al.*, 1993). The nature of the bank materials means that bank stability is also adversely influenced by high levels of ground water and, especially seepage during draw down on a flood recession. This is important in triggering mass failures by slumping that contribute significantly to rapid bank retreat along the Jamuna River (Coleman, 1969; Thorne *et al.* 1993).

Most researchers, including all those mentioned thus far, have defined bank erosion as the process responsible for retreat of the outer banklines of the first order, braided channel. Hence, this process is limited to outward shifting of the left and right bank anabranches flanking the mainland floodplain. By this definition, erosion of sand bars and islands (local named *chars*) that lie within the first order channel is not considered to constitute bank erosion. However, the anabranches are conditionally unstable due to variations in the fluxes of water and sediment that enter them from bifurcations upstream and so they continually shift their positions and alter their planforms over timescales of weeks, months or a few years. These short-term changes are then inherent to anabranch instability and evolution, and they are generally achieved by three processes acting singly or combination: lateral migration, avulsion and flow switching (Coleman, 1969 and Bristow, 1987).

Lateral shifting of anabranches occurs along the length of the channel through processes similar to those that operate in single-thread rivers. Individual anabranches develop semi-independently of one another through meandering, braiding and planform metamorphosis. Examination of the positions and patterns displayed by anabranches from one dry season (low stage) to the next using satellite images reveals though that shifts tend to be more rapid and more erratic than would be expected for a single-thread river with similar dimensions and morphological attributes. Coleman (1969) noted that the lateral shifting is mostly accomplished during the rising and falling stages of the monsoon flood (Figure 2.10) and that shifting was rarely unidirectional. For example, while a typical average annual shift of a major anabranch was found to about 600 m, this was the net outcome of a number of movements back and forth with a magnitude of up to 1200 m.

Anabranch avulsions within the braid-belt occur mainly due to cut-off of tightly curved sub-channels (Klaassen and Zanten, 1989). With respect to flanking anabranches that erode embayments into the floodplain, Thorne *et al.* (1993) observed that this was the process that usually limited both the life-span of an embayment and the degree to which it penetrated into the mainland floodplain. Klaassen and Masselink (1992) conducted an empirical analysis to establish a 'cut-off ratio' with which to predict the probability of abandonment of a given anabranch and sub-channel bend or embayment in the Jamuna River (Figure 2.11). They suggested that about 90% of are likely to be abandoned by a cut-off when the value of cut-off ratio falls below 1.5. However, when EGIS (2002a) extended the analysis to many more bends and a longer period of coverage, they found a somewhat higher limit than that proposed by Klaassen and Masselink (1992).

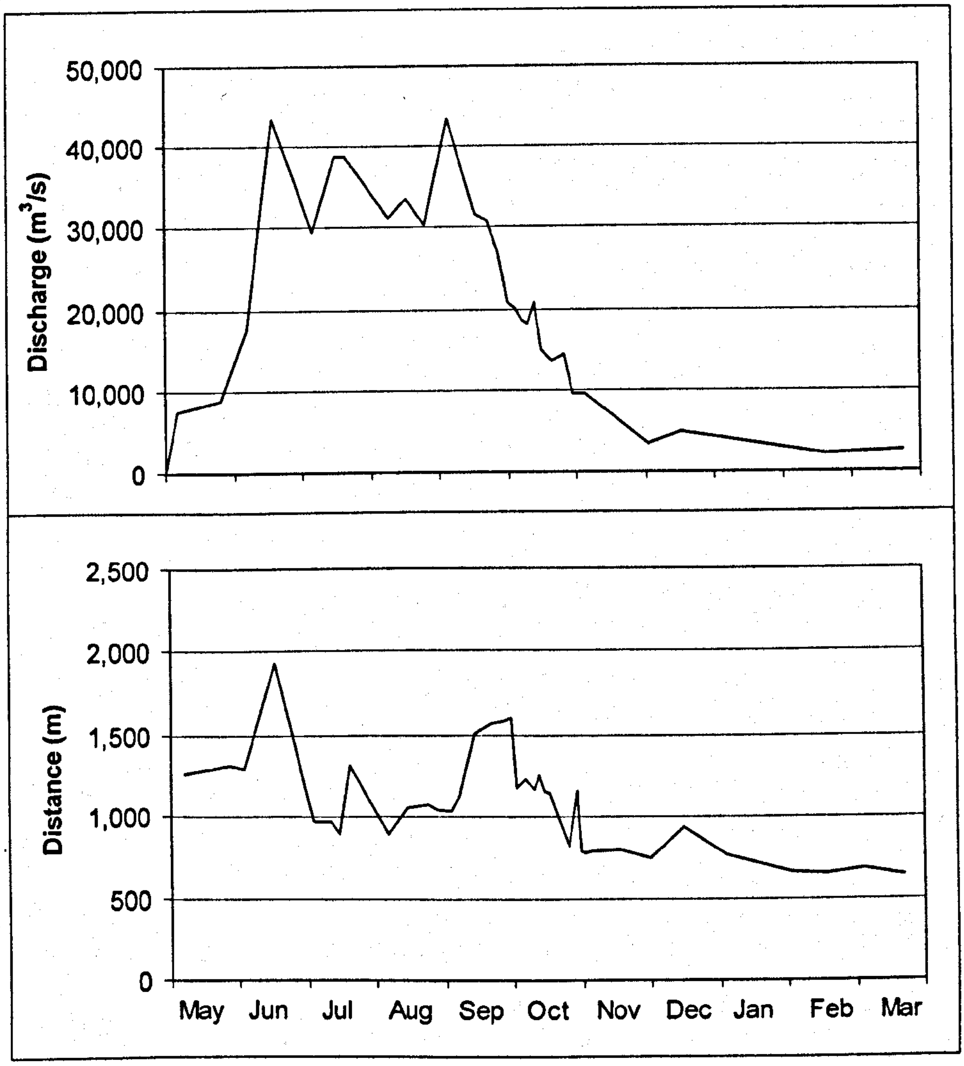


Figure 2.10: Discharge hydrograph of a year of the Jamuna River and corresponding thalweg movement (Data Source: Coleman, 1969)

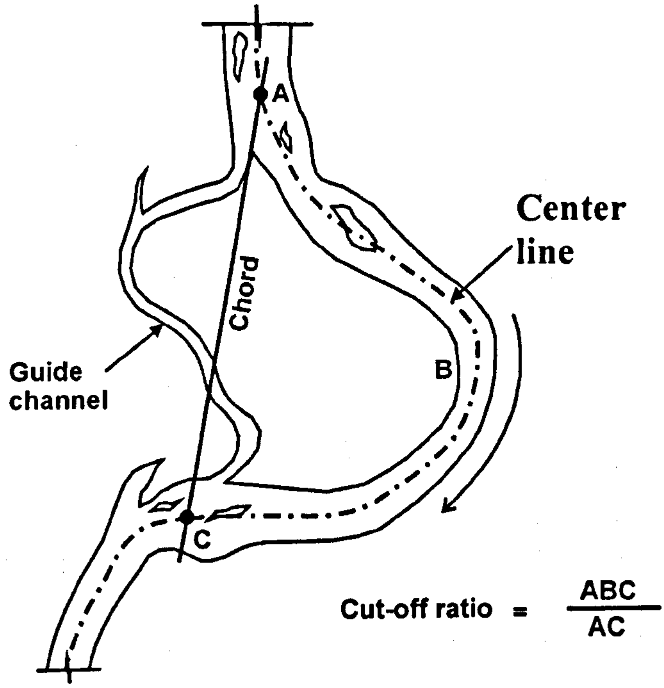


Figure 2.11: Illustration of cut-off ratio

Anabranches begin at a bifurcation, and conditional instability in the proportions of the discharge going down each anabranch (associated with morphological evolution and bar building in the confluence-diffluence unit around the bifurcation) inevitably leads to eventual decay of one channel and enlargement of the other. Changes in the balance of flows may also be driven by erosion and siltation occurring upstream of a bifurcation (erosion along a concave bend upstream of a bifurcation may cause narrowing or abandonment of the bifurcating channel of the same side) (EGIS, 2002b). Through time, there is a tendency for increase in the angle at which the bifurcated channels diverge. A high deviation angle (Figure 2.12) also increases the probability of abandonment of one of the bifurcating channels (note: deviation angle is the angle between the upstream approach channel and the channel downstream of the point of bifurcation). In case of the Jamuna River, abandonment occurs when the deviation angle is equal to or greater than about 65^0. Hence, channel abandonment is somewhat predictable. Conversely, the predictability of the other aspects of short-term anabranch development described above is very poor.

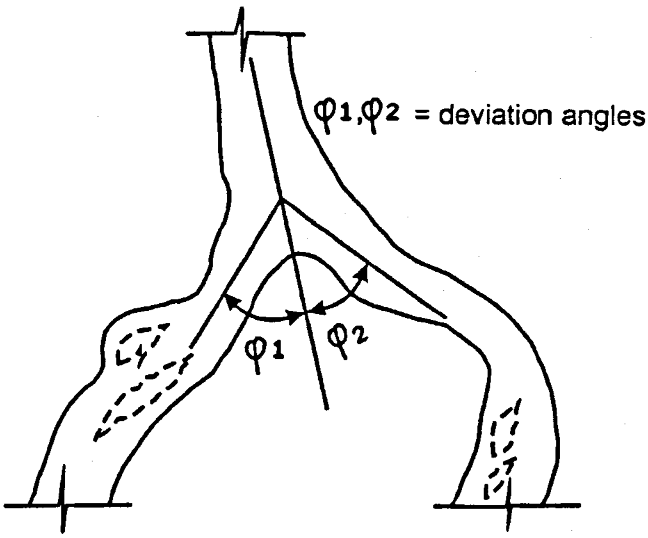


Figure 2.12: Illustration of deviation angle

The patterns and styles of short-term anabranch channel development, evolution and abandonment that result from the interplay of the processes described above can be illustrated by comparing classified satellite images of a 26 km reach of the Jamuna River in 2004 and 2005 (Figure 2.13). The process of classification of the satellite images is fully described in Chapter 5. Classifying the dry season satellite images into *water* and *others* reveals the alignment of dry season channels. Superimposing the classified images results im a channel change map. It is clear that processes driving channel shifting, enlargement and abandonment are very active in the Jamuna River (Figure 2.13). As a result, it is common for anabranch channels to develop, be abandoned or change their positions by several hundred metres to a kilometre within a year.

For example, channels A and B that were present in 2004 were abandoned in 2005. In each case, abandonment was related to channel erosion upstream of bifurcations with wide deviation angles. Generally, abandonment of one channel downstream of a bifurcation is associated with enlargement of the other channel. For example, abandonment of Channel A caused the enlargement of two other channels, C and E. Planform changes driven by anabranch shifting are complex and, apparently, chaotic. For example, instead of migrating outwards at its concave margin, Channel E migrated in the opposite direction between 2004 and 2005. As a result, the concave bank in 2004 was converted into a convex bank in 2005.

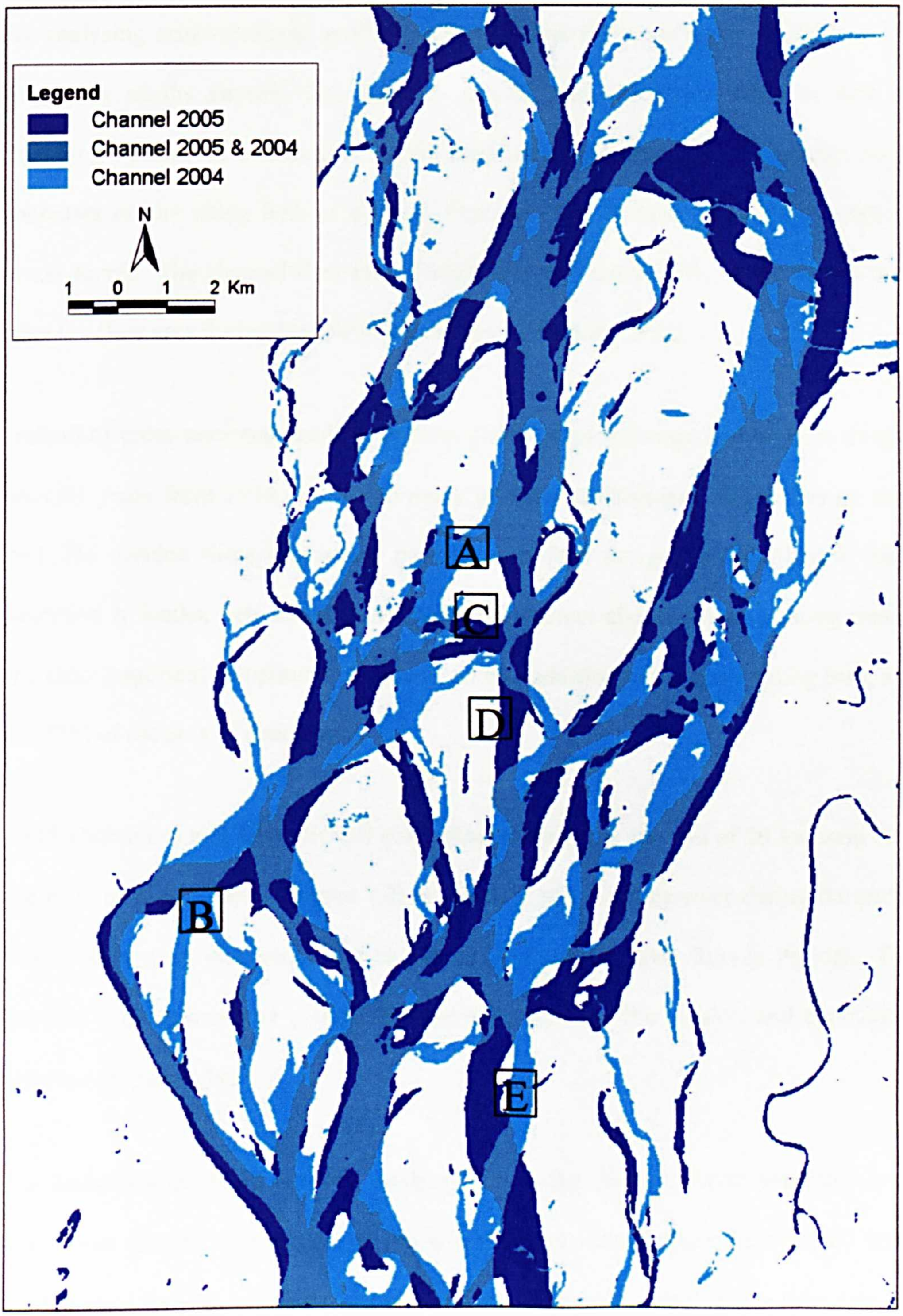


Figure 2.13: Channel change map 2004-2005 at Kamarjani area

Short-term scour and fill of the riverbed of the Jamuna River is both intensive and extensive thanks to the capacity of the flow to erode, transport and deposit massive quantities of sediment (Coleman, 1969). Coleman studied seasonal and short-term erosion and deposition by analysing cross-sectional profiles of the Jamuna River surveyed at different times of a year. His results showed that seasonal erosion and deposition result in bed elevations changing by tens of metres in a highly stage dependent manner. Generally, as discharge increases on the rising limb of a flood, flow area also increases (mainly through raising of water level). The channel flow area at high flow was temporarily as much as 3 times larger than the flow area during the low-water season (Coleman, 1969).

Instead of cross-sectional profiles, Bristow (1987) used old maps and satellite images spaced over 21 years from 1954 to 1985 to study patterns of short-term deposition on the channel bed. He divided these deposition patterns into four categories: addition to bars, lateral accretion to banks, new mid-channel bars and channel abandonment. Among these patterns the most important component of deposition was addition to the pre-existing bars, accounting for 53% of the area of deposition.

Delft Hydraulics and DHI (1996d) conducted bathymetric surveys of 20 km long stretches of the river at Bahadurabad (Figure 1.2) at different stages of the river during the period 1993-1996. This work was performed as part of FAP 24 the River Survey Project. The results provide a comprehensive picture of short-term patterns the erosion and deposition on the riverbed (Figure 2.14).

At Bahadurabad, there are two anabranches in the Jamuna River separated by a semi-permanent island. The length of the island varies through time between 20 and 30 km. Bathymetric surveys were carried out in the left anabranch, which at the time carried 65% of monsoon and 80% of dry season discharges (EGIS, 2002b). In Figure 2.14, the depth of water is referenced to the SLW (Standard Low Water), which is an inclined surface established for different locations along the rivers after analysing the several years of observations of water level. At Bahadurabad, the SLW of the Jamuna River is 12 m above mean sea level. Positive depths indicate that bed level is below SLW.

Mean water levels were more than 7 and 3 m above SLW in August and November 1993, respectively, while the maximum depth was about 15 m below SLW. Comparing the bathymetric surveys (Figure 2.14c) shows that erosion and deposition occur at almost every location in the common flow areas. During this period, within the 20 km long and 2.5 km wide channel, a total 65 million m^3 of deposition and 75 million m^3 of erosion occurred, resulting in changes in bed elevation that were of the order of 12 m. Locations of extreme erosion and deposition were associated with bend scour, confluence scour and other local scour holes. Movement of each of the scour holes involves the displacement of sediment on the scale of millions of cubic metres. An extreme example of short-term change at a confluence was studied by Best and Ashworth (1997) who reported that erosion and deposition associated with confluence scour resulted in bed level changes in the range of 14 m and 17 m, respectively during shifting of the Ganges-Jamuna confluence 3.5 km downstream.

These accounts of short-term changes in the morphology of the Jamuna River make it plain that erosion and deposition occur simultaneously in all areas of the river. However, at specific locations erosion and deposition may be unbalanced, resulting in rapid channel migration, scour or fill of the channel bed, or the creation of major bar forms. The quantities of sediment involved are huge. For example, in Channel X, net deposition was 4 million m^3, while in the subsequent downstream reach (Channel Y) net erosion was 8 million m^3 during August-November 1993 (Figure 2.14). These amounts are equivalent to 20% and 40% of the suspended bed material transport respectively as measured at Bahadurabad. These analyses of short term change not only indicate the rapidity and complexity of morphodynamics at the seasonal and inter-annual scale, they also reveal that a significant proportion of the river's energy is being used to entrain and transport sand-sized sediment from the riverbed (Mackin, 1948). The scale and extent of short-term changes within the braid belt suggest that the Jamuna River expends a significant amount of its available energy in re-arranging sand-sized sediments making up the riverbed and this has wider implications for the morphological response of the river to changes in discharge and sediment supply, its adjustment in the medium-term, and its longer-term evolution.

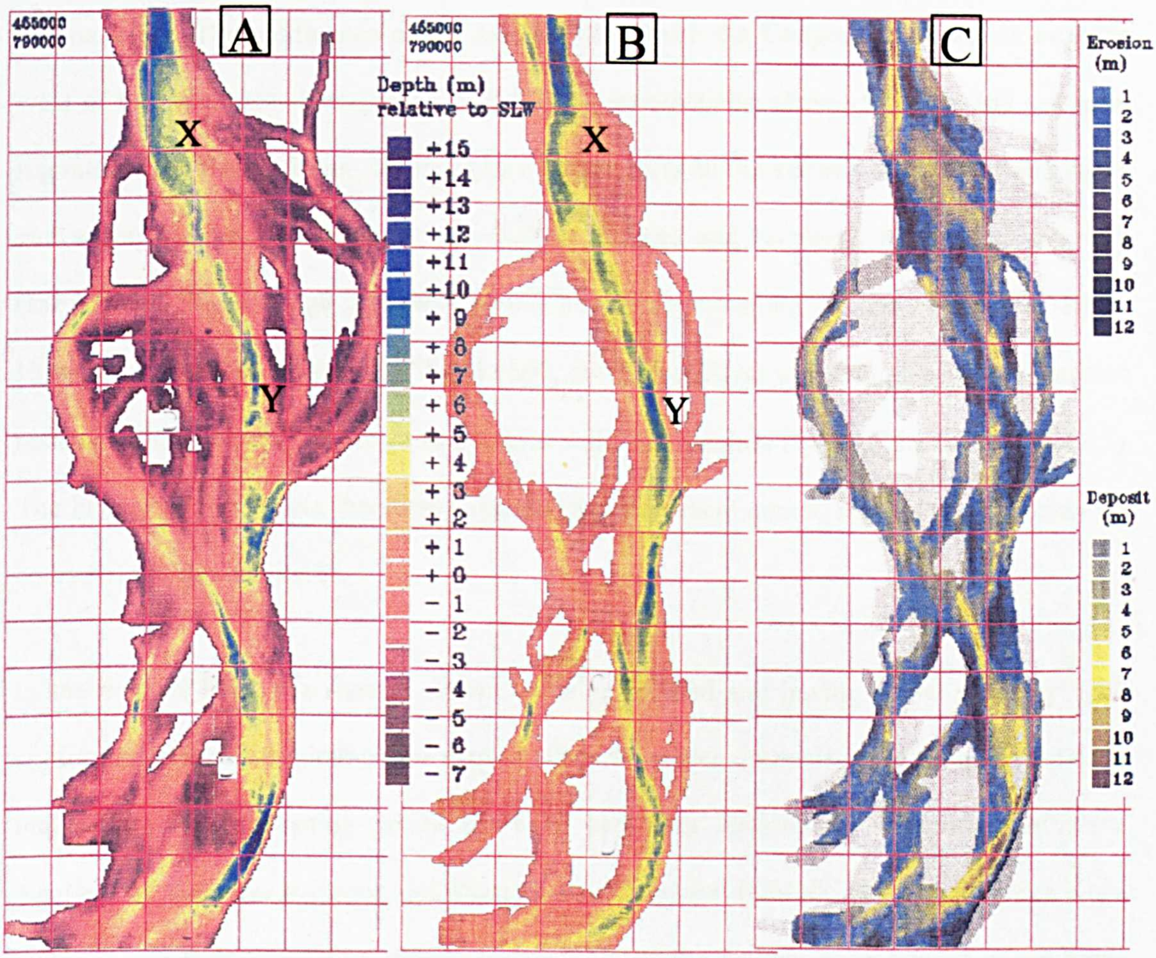


Figure 2.14: Bathymetric surveys (A) August 1993, (B) November 1993 and (C) difference map

2.7 Morphological development of the Padma River

Morphological developments of the Padma River have been described by ISPAN (1995b), Halcrow *et al.* (1993), Nippon Koei (2005) and CEGIS (2004 and 2005a). All these studies used historical maps, aerial photographs and satellite images to study planform development, bank line movement and centreline migration.

Up until 1779 the Padma River was simply the downstream continuation of the Ganges River. The planform reflected this, exhibiting meanders that continued the sinuous path from upstream (Figure 2.6). At that time, the Padma entered the Bay of Bengal approximately along the present course of the Arial Khan, which is now a right bank distributary of the Padma River. The confluence of the Jamuna River with the Ganges, following its avulsion west of the Madhupur between 1776 and 1830, substantially altered the flow and sediment regimes of the Padma River, leading to major increases in the volume of runoff, flood peaks and sediment load. In response, the Padma widened and increased its braiding intensity (ISPAN, 1995b), although it initially maintained its course along the line of the Arial Khan. However, sometime between 1830 and 1860, the Padma River cut through a band of erosion resistant Chandina clay at Mawa to combine with the Meghna River (Figures 2.6 and 2.15). The history of the Padma therefore suggests that its present course is even younger than the course of the Jamuna River.

In the map of 1942, the river is shown as being braided and having a low sinuosity. This configuration is also evident on the map of 1960. However, comparison of the maps indicates that during the intervening period the river had been consistently migrating northward. Analysis of historical evidence and lithological information (CEGIS, 2004 and Nippon Koei, 2005) shows that materials forming the left bank of the Padma River consist of relatively cohesive and consolidated sediment. Hence, northward migration of the river involves erosion of these sediments at many locations. The southeast orientation of the river axis has been maintained for more than 150 years. This is partly due to restraining effects of outcrops of erosion resistant bank materials along the left bank (ISPAN, 1995b).

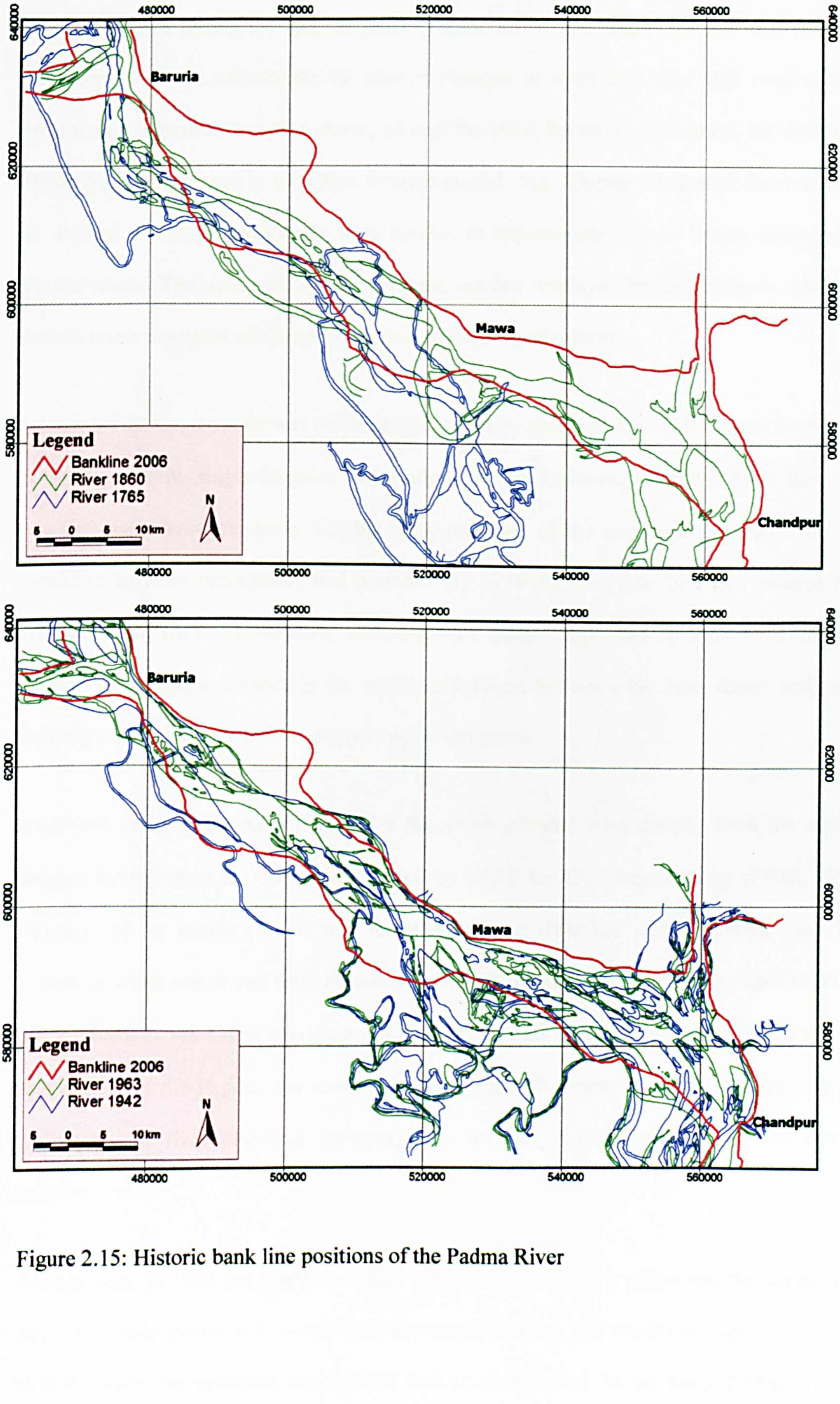


Figure 2.15: Historic bank line positions of the Padma River

CEGIS (2005a) analysed aerial photographs and time-series satellite images available for a variety of dates during the last 40 years (Figure 2.16). The results showed that planform metamorphosis was responsible for marked changes in width and very high rates of bank erosion and accretion. As noted above, up until the 1960, the river was braided, but during the 1960s the planform was in transition towards meandering. During this period the river could be divided into three particularly wide reaches of approximately equal length, separated by shorter nodes. The upstream and downstream reaches displayed braided patterns, while the middle reach consisted of a single-threaded meandering planform.

During the 1970s, the river was in the processes of straightening. By 1980 the planform of the river had become single-threaded and straight. In the following years the river showed a renewed meandering tendency but, by 1993, planform of the river again appeared to be in transition between meandering and braided. By 1999 the river planform had become fully braided, again with three distinct, multi-threaded reaches separated by short nodal reaches. Recently, the right anabranch in the middle multi-threaded reach has been abandoned, again creating a single-thread, meander-type loop in this reach.

Banklines defining the outer margins of the active channel were derived from the satellite images according to the criteria developed by EGIS for the Jamuna River (EGIS, 1997). Analysis of the results reveals that the width of the river has varied through time. The minimum width was found from time-series satellite images and aerial photographs to be 1.5 km at Mawa in 1967. The maximum width was found to be 20.5 km, in 2005 (Figure 2.17). In the case of the Padma, the extremely wide range of observed widths is a result of the propensity for river planform metamorphosis between straight, meandering and braided patterns.

For example, in 1967 the length-averaged width was 7.7 km at a time when the planform of the river was in transition between meandering and braided. The width was reduced to 6.7 km in 1980 when the planform was straight and single-threaded. In the early 1990s, the river started to widen at a very high rate (~260 my^{-1}) as the planform was in transition from meandering to braided. Continued development of the braided pattern resulted in the average width of the river reaching 10.3 km in 2004 (CEGIS, 2005a).

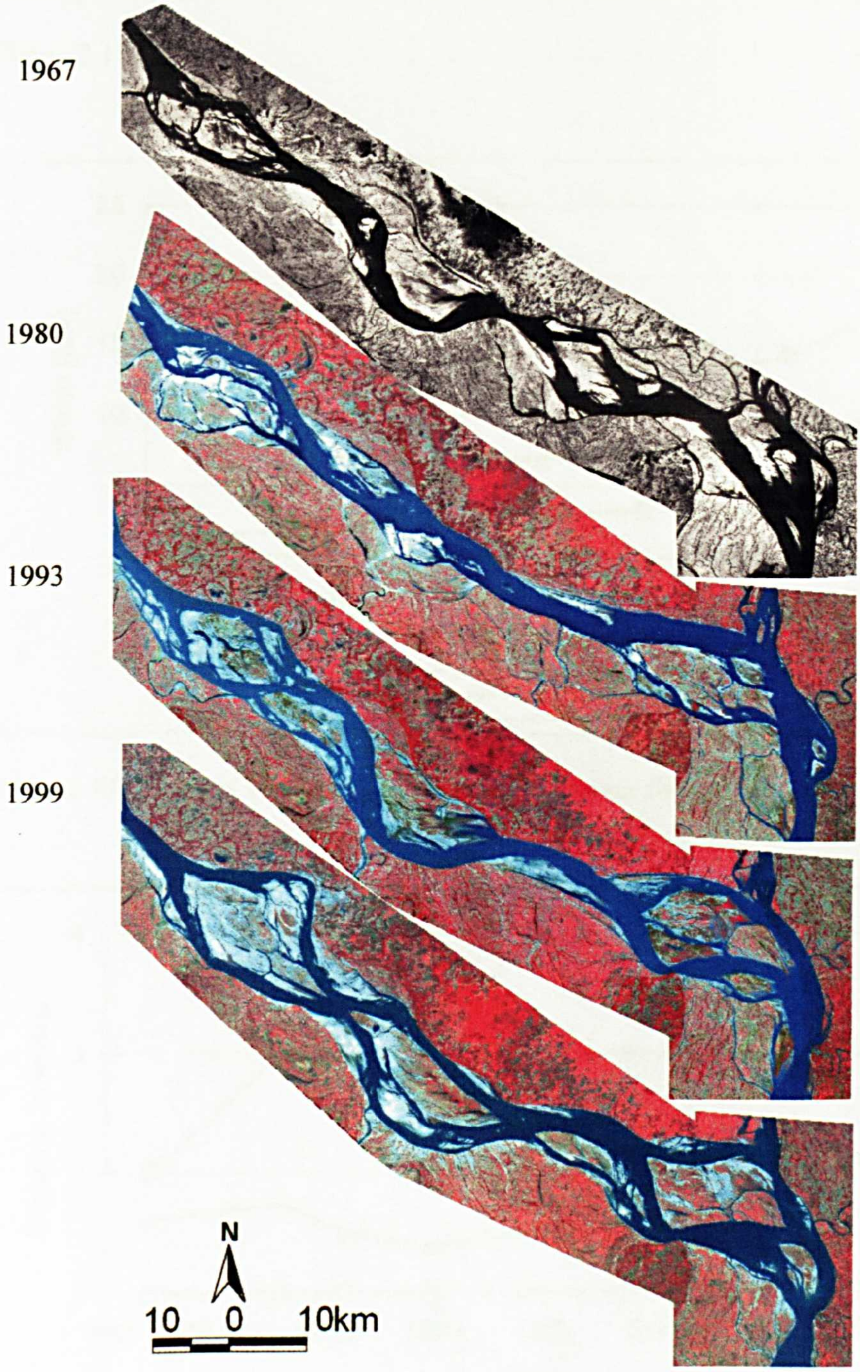


Figure 2.16: Time-series satellite images of the Padma River

Like the length-averaged width, the braiding intensity of the river has also changed as a function of planform evolution and metamorphosis. In the late 1960s and early 1970s the braiding intensity was around 1.7, but it decreased to 1.4 in the early 1980s. However, the braiding intensity started to increase in the 1980s and reached its maximum of 2.13 in 1997 (Figure 2.18).

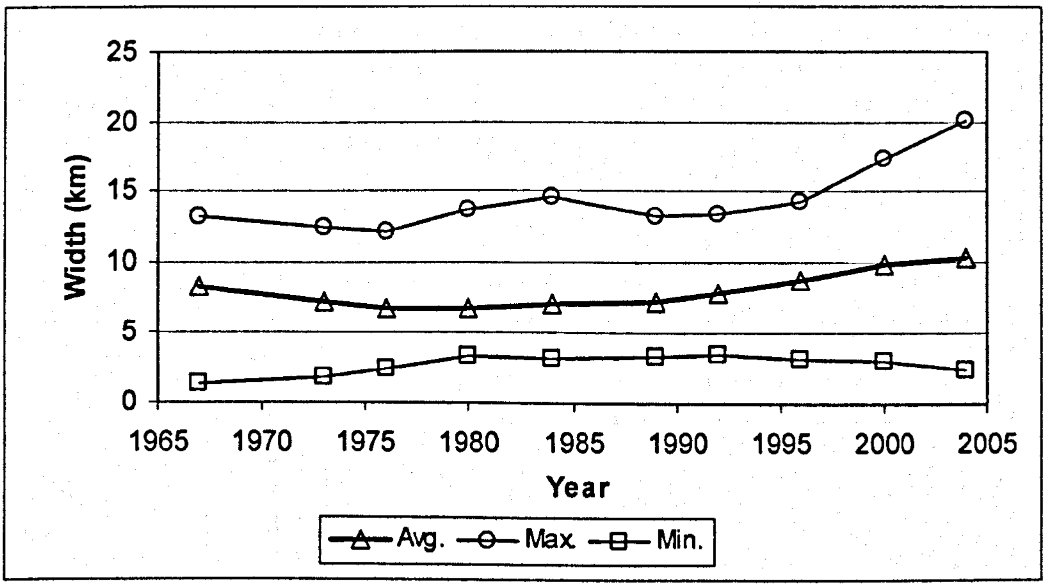


Figure 2.17: Changes in width of the Padma River over time

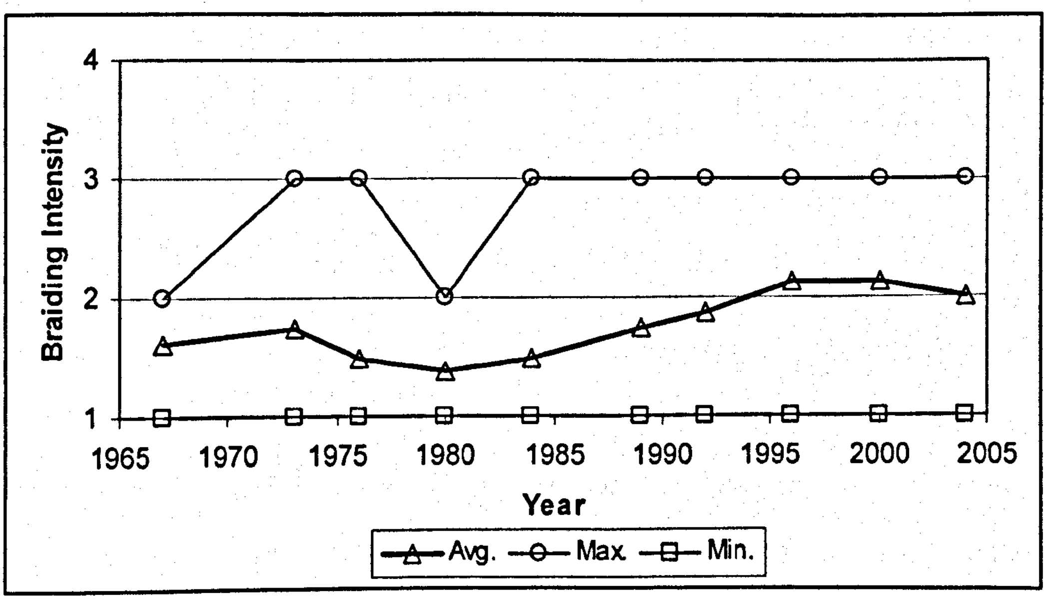


Figure 2.18: Changes in braiding intensity of the Padma River over time

Along the 100 km long reach of the Padma River, erosion and accretion are very common morphological processes. The amount of the erosion and accretion varies over time and is strongly related to changes in planform (Figure 2.19). When the Padma River altered its planform from meandering-braided transition to straight and single-threaded in the early 1970s, accretion was the dominant process. During this period, the mean annual rate of floodplain erosion was 1400 hay^{-1}, while the rate of accretion of new floodplain was 2850 hay^{-1}. From the late 1970s to the 1980s floodplain erosion and accretion were nearly balanced during a period when the planform of the river was straight. In the early 1990s, the rate of floodplain erosion increased to 2100 hay^{-1} when the river started to braid. At that time erosion became dominant and accretion was negligible (Figure 2.19).

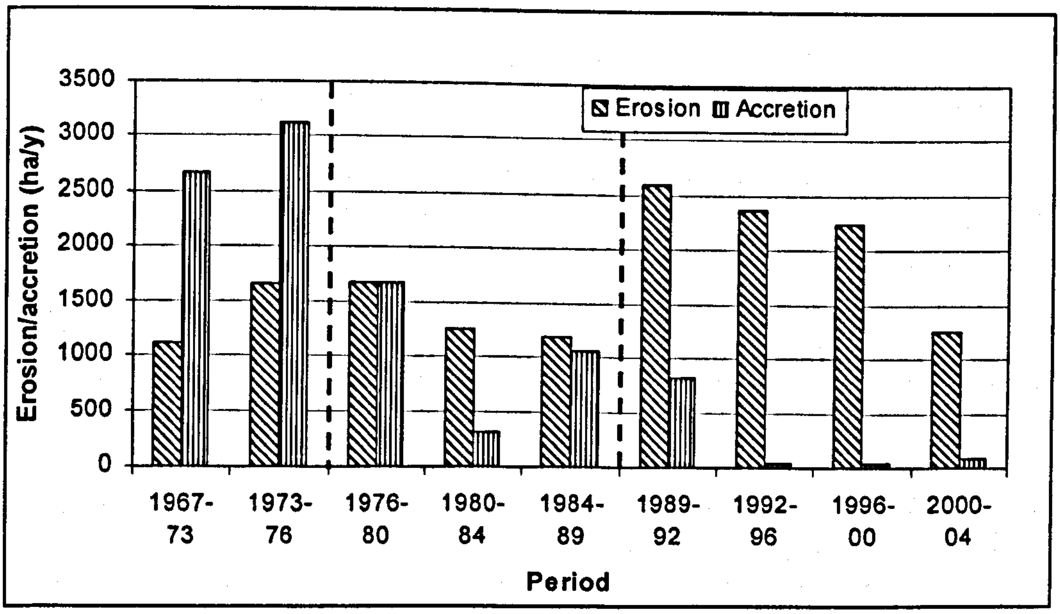


Figure 2.19: Erosion and accretion along the Padma River over time

Compared to the Jamuna, seasonal and short-term changes in the Padma River are subdued. Anabranch development or abandonment within a single year is uncommon. Once a meander bend develops in a meandering or braided reach, it may continue to grow and migrate through erosion at the outer bank for many years. For example, one such bend was found to erode continuously for 37 years. While this is exceptional, the average life-span of an eroding bend usually lies in the range of 15 to 20 years in the Padma River and bends develop both through lateral extension and downstream translation. These long-lived bends exhibit sustained, high rates of lateral extension that vary from 180 to 460 my^{-1} (CEGIS, 2005a). Over shorter periods, the rate of lateral erosion may sometimes exceed a kilometre per year.

Few studies have investigated short-term changes in the bed of the Padma River. Seasonal variation in bed levels and the location of the thalweg have been studied by Nippon Koei (2005), using cross-sectional surveys made by the BWDB during weekly or fortnightly discharge measurements. Results indicate that the thalweg generally does not shift during the low water season but that it begins change during the rising limb of the monsoon flood. The location of the thalweg then changes markedly during the medium to high stages.

2.8 Morphological development of the Lower Meghna River

Prior to 1779, the combined flow of the Brahmaputra and Meghna rivers used to enter the Bay of Bengal near the present location of the Lower Meghna River. After avulsion of the Brahmaputra River to the west of the Madhupur, flow in the Meghna River was reduced very significantly. Until about 1860, the combined flow of the Ganges and Jamuna River did not join with Meghna River, but after breaking through the Chandina clay at Mawa, the Padma River combined with the Meghna River at Chandpur. The river at this point then had to enlarge its channel to carry the combined discharge of three large rivers. The Lower Meghna thus transformed itself into the largest river to drain the Bengal Basin during the Holocene.

The Meghna River upstream of its confluence with the Padma River is relatively small. Its mean annual flow is 4,600 m^3s^{-1}, while that of the Lower Meghna River downstream of the confluence is 34,600 m^3s^{-1} (Table 2.1).

Unlike the Jamuna and Padma, the Lower Meghna is a tidally-influenced river. The average tidal variation during the dry season is about 1.5 m, decreasing in the upstream direction. During the monsoon the tidal variation drops to a few centimetres.

The planform of the river varies temporally and spatially. Width and braiding intensity also vary in concert with changes to the planform. Sarker and Thorne (2006) analysed a time-series of satellite images in order assess the morphological changes of the river over time.

In 1973, the minimum width was 2.8 km (Figure 2.20) in the upper reach immediately downstream of Chandpur, where the river was single-threaded. In the middle reach, the river was braided, having a maximum width 16.4 km. In its lower course, the river again became single-threaded as it approached Bhola Island. By 1990, the river had evolved to practically a single-threaded planform along its entire length, but in the following years it again started to braid.

During the late 1970s and early 1980s the length-averaged width of the Lower Meghna River was around 9.5 km. In 1990, the average width decreased to 7.6 km. In the 1990s the river widened at a rate of 190 my^{-1}. Similarly, the braiding intensity of the river has changed over the time. It was 1.9 in 1973 and dropped to 1.1 in 1990. Later, in the1990s, it increased again.

These changes in planform have strongly affected the balance of erosion and accretion in the river. During transition from braided to straight, accretion was the dominant process (Table 2.4). However, the balance was reversed in the 1990s, when the river started to develop a braided planform, with erosion becoming dominant.

Table 2.4: Erosion and accretion along the Lower Meghna River over time

Period	**Erosion (ha)**	**Accretion (ha)**
1973-1990	5,900	23,900
1990-2005	17,700	690

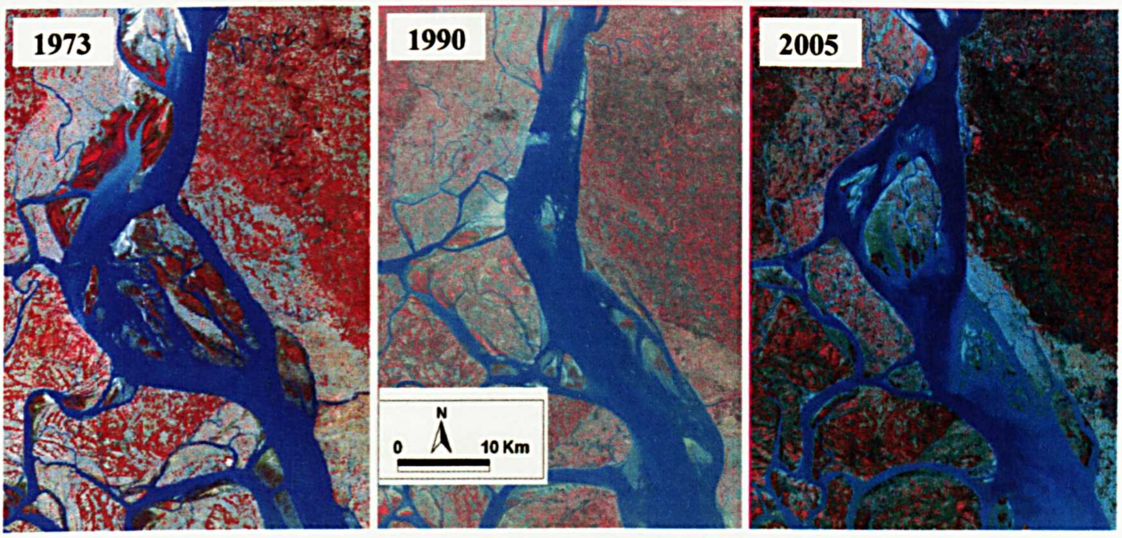


Figure 2.20: Satellite images showing the changes of planform of the Lower Meghna River over time

Chapter 3
River response

3.1 Introduction

Rivers are the agents of erosion and transportation, collecting the water and sediment supplied to them from the catchment and carrying it eventually to the ocean or to an endoergic drainage basin (Knighton, 1998). A river responds to various types of disturbance, natural and anthropogenic, such as climate change and changes in relative sea-level (Blum and Törnqvist, 2000, Goodbred and Kuehl, 2000b), tectonics (Burnett and Schumm, 1983; Dumont, 1994; Harbor *et al.*, 1994; Schumm and Spitz, 1996; Schumm *et al.*, 2000), seismic events (Bradley, 1983; Waitt and Pierson, 1994; Goswami *et al.*, 1999; Schumm *et al.*, 2000), and a wide variety of human interventions in the fluvial system (Galay, 1983; Chien, 1985; Simon, 1989; Lagasse, 1994, Simons and Simons, 1994; Winkley, 1994; Buchanon, 1994; Jiongxin, 1996; Kondolf *et al.*, 2002). The morphodynamic response to disturbance of a river can be explained in terms of cause and effect (Schumm, 1971a; Richards, 1982; Chang, 1986). In this context, changes to the independent variables governing river form and process are generally referred to as causes while subsequent changes to dependent variables are taken to be effects. Changes in exogenic factors, such as climate, sea-level or human actions affecting the fluvial system or endogenic factors such as tectonics or seismic events (Summerfield, 1991) may alter independent variables such as the amount and/or time distributions of catchment runoff and sediment yield. Alterations to these driving variables of channel form and process, in turn, produce effects such as changes in rate of sediment transport and the dimensions and morphology of the channel. In this way, a river responds to changes in the driving variables that may have either external or internal causes.

However, the response may not be simply proportional to the duration and magnitude of the disturbance. While some changes trigger a gradual response, geomorphological systems often respond in ways that are complex and non-linear, behaviour that has been described in terms of the existence of geomorphic thresholds (Schumm, 1977; 1979). A gradual change in an external cause that has for some time produced a muted response in the fluvial system may then produce a dramatic morphological response: this is referred as the crossing of an extrinsic threshold. The cumulative morphological effects of the system's gradual adjustment and evolution may also themselves trigger a sudden shift in the type or rate of channel change: this is referred as the crossing of an intrinsic threshold.

When attempting to characterise and predict patterns of river response to disturbance, it is important to understand the roles of exogenic and endogenic causes of change and account for the existence of threshold behaviour and complexity in morphological responses. The remainder of this chapter examines issues concerning process-response of the river system to externally and internally located causes, and examines some of the models that have been developed to explain and predict river response to disturbance.

3.2 Time-scale and variables

Cause and effect in the fluvial system changes depending on the temporal and spatial scales in question. Schumm and Lichty (1965) showed how variables that are independent in one time-frame may be dependent in another (Table 3.1). In their table, the number of variables listed could be greater if the all the dimensions of channel geometry were shown separately. For example, 'river morphology' encompasses channel slope, width, depth and planform pattern. Catchment sediment yield is not shown Table 1, though the sources of sediment are presented as independent variables in the graded time span.

Table 3.1: Variables during different time spans (Schumm and Lichty, 1965; Schumm, 1971b)

Sl.	Variables	Geologic	Graded	Steady
1	Time	I	N.R.	N.R.
2.	Initial relief	I	N.R.	N.R.
3.	Geology (lithology, structure)	I	I	I
4.	Palaeoclimate	I	I	I
5.	Palaeohydrology	D	I	I
6.	Relief or volume of system above base level	D	I	I
7.	Valley dimensions (width, depth, slope)	X	I	I
8.	Climate (precipitation, temperature, seasonality)	X	I	I
9.	Vegetation (type and density)	X	I	I
10.	Hydrology (mean discharge of water and sediment)	X	I	I
11.	Channel morphology	X	D	I
12.	Momentary water and sediment discharge	X	X	D
13.	Hydraulics of flow	X	X	D

Note: I = independent, D = dependent, N.R. = not relevant and X = indeterminate

In geomorphological study, time is generally divided into three broad classes – Geologic (or Cyclic), Graded and Steady (Schumm and Lichty, 1965; Schumm, 1971b; Schumm, 1977; and Richards, 1982), although there are no absolute dimensions or any sharp boundaries between these time-scales. The length of these time-scales may vary depending on the river environment (Richards, 1982). However, geologic time extends over the lifetime of an erosional cycle, which may be equivalent to one or more million years (Schumm and Lichty, 1965). According to Summerfield (1991) Geologic or Cyclic time is of the order of 10 million years. Over this time period a river is adjusting continually to the slow erosional modification of the entire drainage basin (Schumm, 1977). Consequently, no dynamic equilibrium exists at this time scale (Lane, 1955; Schumm, 1971b) because there can be no stable balance between the independent and dependent variables. Summerfield (1991) referred to the long term evolution of the landforms over this time span as a form of 'decay equilibrium'. In geologic time the initial relief, geology, palaeoclimate and palaeohydrology are the independent variables. These independent variables are responsible for the relief of the terrain above the base level, expressed through dependent variables such as the valley width, depth and slope.

Graded time refers to a shorter time scale during which the dependent variables may become adjusted to the independent variables so that a graded condition or 'dynamic equilibrium' prevails. Under these circumstances, the channel dimensions are adjusted to the discharge and sediment load and are said to be in a regime condition. Mackin (1948) defined the graded condition as one in which the river has adjusted its slope over a period of years so that it can just transport the sediment load supplied from the drainage basin upstream with the given discharge and the prevailing channel characteristics. In a graded stream, the relationship between process and form is steady and the morphology of the river remains constant through time (Knox, 1975). In graded time, equilibrium channel forms develop that are dependent on the channel forming discharge and associated sediment yield from the catchment upstream (Richards, 1982). According to Lane (1955), the condition of dynamic equilibrium is possible only over graded time. This is the case because in geologic time the basin and the river exhibit evolutionary change, while shorter time spans are too short to allow the dependent variable to adjust fully to the independent ones. In fact, geomorphological systems exhibit complex responses to disturbance and very few systems ever adjust fully to the prevailing conditions, either spatially and temporarily (Philips, 1992a). This has led to attacks on the concept of the graded river and the idea that inputs and outputs in a geomorphologic system can never be balanced (Philips, 1992b). However, even those who argue that equilibrium is never attained still recognise its value as a concept in geomorphologic reasoning.

The extent of graded time span was arbitrarily defined by Schumm (1971b) as a few hundred years, while Knox (1975) mentioned that graded time span should be measured in the scale of years. The length of this time span may, however, vary depending on the sensitivity of the channel to disturbance (Chang, 1986). Thus, according to Richards (1982), graded time may extend from decades to centuries, with equilibrium channel forms developing that are dependent both on the formative discharge of water and sediment and the valley characteristics derived in geologic time. In this context, 'channel form' refers to the width, depth, slope and planform, which are considered as dependent variables, and the valley slope, discharge and sediment supplied from the catchment, which are treated as independent variables. The research performed in the present study is set within the graded time-scale. Consequently, subsequent discussion of the influence of time on process-response mechanisms will focus on this time-scale only.

Lane and Richards (1997) object to the premise that while studying geomorphology over longer time-scales and at larger space-scales, it is permissible to average out the effects of processes that operate over shorter time-scales and at smaller space-scales. According to their arguments, the operation of small-scale short-term processes in the past has some definable and significant effects that cannot be represented solely through consideration of longer time-scale and larger space-scale processes. Therefore, dividing process-form relationships on the basis of time-scales such as Geologic or Graded may hamper the proper understanding of geomorphology. This argument is certainly valid, but considering the present level of geomorphological understanding and taking into account the capabilities of currently available tools in geomorphic analysis, it would be very difficult to develop explanatory or predictive models based on extrapolating the results of monitoring processes observed over short time-scales and at small space-scales (say, the cross-section scale) to make them applicable at a longer (Graded) time-scale and a larger (Catchment) space-scale. For this reason, the approach taken herein is not entirely 'process-based', but instead adopts the principles of process-response in the fluvial system at the reach scale – which is commensurate with the Graded time scale (decades) over which the explanations are valid and for which predictions need to be made to inform improved river management.

3.3 Role of variables

In a river system a large number of variables act together, and their roles in controlling river morphology are often understood only qualitatively. Quantitatively, the future condition of a river system is considered to be an indeterminate because the number of available theoretical relations linking the variables is insufficient to obtain a solution given the number of variables involved (Richards, 1982). Although it is not possible to solve morphology questions analytically, it is possible to establish the required number of relations empirically, using data from field measurements and laboratory experiments (Hey, 1978).

It is generally accepted that discharge, sediment load and sediment calibre are the most important independent variables operating in graded time. However, the characteristics of the bank materials are also considered to be an independent variable of some importance (Richards, 1982; Knighton, 1998; Eaton and Millar, 2004). Often channel slope is also considered as an independent variable (Lane, 1955; Lane, 1957; Leopold and Wolman, 1957; Parker, 1976), though many scientists designate channel slope as a dependent variable, preferring to take the valley slope as an independent variable (Bettess and White, 1983; Chang, 1988; Hey, 1997; van der Berg, 1995). Other parameters that may be considered for addition to the list of independent variables include temperature (Lane, 1957) and the degree of channel entrenchment (Rosgen, 1994). However, there is broad consensus that these parameters are not especially significant in determining channel morphology and they are not discussed further here.

The physical form of the fluvial system is considered to be the outcome of interactions between the potential stream power (proportional to the product of discharge and valley slope) with the sediments making up the bed and banks (Richards, 1982). It is through processes driven by energy dissipation that the river's dependent variables adjust to the independent variables imposed by catchment runoff, sediment yield, valley slope and the physical properties of the boundary materials. In the case of streams of small and intermediate scale, aquatic, riparian and floodplain vegetation may act as an additional independent variable, although this is less likely to be the case in very large rivers like those considered here.

The dependent variables that an alluvial river can adjust to include channel width, depth, velocity slope, sinuosity, meander wavelength and meander amplitude, and the amplitude and shape of bedforms (Hey, 1997). The involvement of a large number of variables and the non-linearity of the relations between them means that interactions between independent and dependent variables are complex and that a small change in any one of the controlling variables may produce a disproportionate and unpredictable response in some or all of the dependent variables.

Moreover, there exist different opinions regarding the best way to select representative values for particular variables. For example, discharge of a river varies continuously through time and space. This raises the issue of what value should be taken to be representative of the range of discharges experienced by the river when attempting to define the channel morphology and explain its relationship to discharge within the graded time-scale. In the literature, at least three defined flows have been used as the representative discharge, including the mean annual flow (Leopold and Maddock, 1953; Lane, 1957; Schumm, 1969), the bankfull discharge (Leopold and Wolman, 1957; Chang, 1979; Ferguson, 1987) and the mean annual flood (Robertson-Rintoul and Richards, 1993; van den Berg, 1995; Bridge, 2003). Similar disagreement in the literature also exists in relation to defining a representative size for graded bed materials.

3.3.1 Discharge

Attempts to establish quantitative relations between the controlling and dependent variables began with the need to design stable channels to convey water for irrigation. These stable canals can be considered as equilibrium channels. In the late 18th Century, Kennedy (1895) related the velocity to the depth of the channel using irrigation canal data from India. Lacey (1930) derived a number of relations for designing large water transfer canals in the Punjab, India. He derived 'Regime Theory' to predict the stable width, depth and slope of a canal as a function of its bankfull discharge. Later, Leopold and Maddock (1953) derived regime-type relations for rivers by the analyzing data from natural streams in the USA. Their relations became known as 'Hydraulic Geometry' equations, and express width, depth and velocity as functions of the channel forming discharge (Q), and have the form:

$$W = aQ^b, \qquad d = cQ^f, \qquad \mathrm{u} = kQ^m \qquad (3.1)$$

where W, d and u are channel width, average depth and mean velocity, respectively, a, c and k are empirical coefficients, and b, f and m are the exponents. Based on many subsequent measurements, the average values of the exponents are b = 0.5, f = 0.4 and m = 0.1. The exponents for discharge in the regime relations of Lacey (1930) are 0.5 and 0.33 for width and depth, respectively. That is, they are close to those of Leopold and Maddock (1953). It should be mentioned here that Leopold and Maddock (1953) used mean annual discharge in place of the bankfull discharge used by Lacey. Stevens and Nordin (1987) report that Lacey found that the exponent for discharge in relation to the slope is -1/6, indicating that channel slope decreases as discharge increases. In the following decades, many studies have further explored the hydraulic geometry relations for alluvial channels, though the basic tenets of Leopold and Maddock (1953) remain substantially unchanged.

Determination of stable channel geometry has invoked several theories and hypothesis (Singh, 2003) including not only regime theories (Lacey, 1930), but also tractive force theory (Lane, 1935 and 1953), stability theory (Callander, 1969; Parker, 1976) and extremal hypotheses (Yang, 1976; Chang, 1979; White *et al.*, 1982). Different approaches have expressed channel geometry parameters as a function of a single independent variable such as discharge (Leopold and Maddock, 1953, Singh *et al.*, 2003), or several variables such as discharge, sediment size and sediment transport (Griffiths, 1981; Julien and Wargadalam, 1995). The coefficients in Equation 3.1 have been found to vary from one geographical location to another, but the exponents of these equations are found to be consistent and seem independent of location (Parker, 1979). The constancy of the exponents in hydraulic geometry equations illustrates the strong dependency of channel geometry on discharge, but the fact that coefficients vary widely indicates that other variables are also influential.

Discharge has also been used to predict the planform pattern of alluvial rivers. In this regard, the pioneering work was performed by Leopold and Wolman (1957), who identified a continuum of channel patterns based on the bankfull discharge and slope of the channel. The threshold between the meandering and braided pattern is expressed as (Leopold and Wolman, 1957):

$$i = 0.013 Q_b^{-0.44} \quad (3.2)$$

Where, i = channel slope and Q_b = bankfull discharge in m^3s^{-1}. For given bankfull discharge, a river may be braided if its slope exceeds the threshold value as defined by Equation 3.2 or meander if the slope falls below the threshold value. A similar method for predicting channel pattern was developed by Lane (1957), while Ferguson (1984 & 1987), Chang (1986) and Robertson-Rintoul and Richards (1993) performed significant work following similar approaches. The later work employs different representative discharges and adds further independent parameters including sediment size, sediment concentration and valley slope in classifying channel pattern. Most recently, different forms of stream power have been used to predict planform (van der Berg, 1995 and Richardson and Thorne, 2001), based on the product of discharge and slope.

Debate has continued concerning the selection of a single discharge to represent the range of flows responsible for channel formation (Chang, 1979; van den Berg, 1995; Knighton, 1998; Bridge, 2003; Latrubesse, 2008). There is also debate about the influence of the annual variability in discharge on channel geometry and channel pattern (Howard *et al.*, 1970; Schumm, 1985; Knighton, 1998; Bridge, 2003). Generally, it is believed that the stable width of the channel is larger for a given formative flow in rivers where the seasonal variation of discharge is very high. It has also been proposed that this also encourages braiding (Knighton, 1998). On this basis, Klaassen (1995) employed Lane's balance to derive relations between the variability of discharge, width and braiding intensity of the form:

$$SD^{p}W^{\frac{n-3}{3}} \propto \alpha_{Q}Q^{\frac{n}{3}}i^{\frac{n}{3}} \qquad (3.3)$$

$$SD^{p}k^{\frac{n-3}{6}} \propto \alpha_{Q}Q^{\frac{n+3}{6}}i^{\frac{n}{3}} \qquad (3.4)$$

Where, S and Q are annual average sediment load and discharge, respectively, W = flow width, k = braiding index, i = channel slope, D = characteristics bed material size, p = exponent of grain size and n = exponent of velocity in a simplified sediment transport equation and α_Q = a factor that reflects discharge variability. For uniform flow, the value of α_Q is 1 and it increases as the seasonal flow distribution deviates from the mean discharge. Equation 3.3 indicates that if other parameters remain the same, the stable width of a river increases as discharge variability (α_Q) increases. Similarly, Equation 3.4 indicates that the braiding index also increases as discharge variability increases. These findings are in line with the arguments propos ed by Knighton (1998).

3.3.2 Size and input of bed material

Lane (1955) expressed the influence of size and input of bed material load on the slope of a stable channel using:

$$SD \propto Qi \tag{3.5}$$

where, S and D = amount and size of bed material load, Q = discharge and i = channel slope. This qualitative relation, often represented as 'Lane's balance', indicates how the slope of a channel responds to a change in any of the three independent variables: discharge, sediment load and sediment calibre given that the width and planform of the channel remain constant. The balance shows that, for a given discharge, an increase in the quantity or calibre of sediment load input to the reach cause the increase of slope of channel and *vice versa.*

Instead of the sediment load, Schumm (1969) investigated the effect of changes in the characteristic size of the boundary sediment on the geometry of the channel. He used the percentage of silt-clay in the channel perimeter materials as an independent variable controlling channel width, depth, slope and sinuosity. Schumm's analyses (1971a, 1985) indicated that as the percentage of silt-clay increases, the width and slope of a stable channel decrease, while depth increases. Schumm neglected the role of the sediment load in forming the channel though he did recognize the role of the sediment load in affecting the slope.

Chang (1979, 1986) and White *et al.* (1982) recognized the role of sediment load (quantity and size) in determining channel geometry. According to their analyses, increasing the sediment input and sediment size leads to an increase in the stable width and slope and decrease in the depth of the channel when both the bed and bank are composed of unconsolidated materials.

Based on stability analysis, Julien and Wargadalam (1995) expressed channel geometry as function of discharge, sediment size and Shield's parameter, while an attempt was made by Dade (2000) to relate cross-sectional channel geometry and planform pattern to sediment size and the different modes of sediment transport, again based on different transition values of the Shield's parameter.

The threshold line between meandering and braided channels derived by Leopold and Wolman (1957) (Equation 3.2) did not recognize the role of sediment load (quantity or calibre) in affecting channel pattern, although there is indirect recognition of the effect as, according Leopold and Wolman's threshold line, an increase of slope (driven by an increase of sediment load or calibre) may trigger planform metamorphosis cause meandering to braiding.

In the 1960s, 70s and 80s several threshold lines similar to that of Leopold and Wolman (1957) were added to account for the effect of bed sediment size as a controlling parameter (Henderson, 1961, Ferguson, 1984, Robertson-Rintoul and Richards, 1993). The typical form of these threshold lines is explemplified by that of Ferguson (1984):

$$i = 0.017 Q_b^{-0.49} D_{90}^{0.27} \qquad (3.6)$$

where D_{90} = diameter of bed material finer than 90% of the bed sediments. It is apparent from Equation 3.6 and also from the findings of other researchers such as van den Berg (1995) and Bridge (1993) that, for given slope and discharge, braiding becomes less likely as the size of the bed material increases. This finding is consistent with the earlier work of Chang (1986), and Bettess and White (1983), who also investigated the role of sediment concentration in determining the planform pattern. According to Bettess and White (1983), when all other conditions remain the same, braiding is more likely for lower sediment concentrations. However, Schumm (1985) indicated that braiding is more likely for higher sediment loads. This apparent contradiction is addressed later in this chapter.

3.3.3 Characteristics of the bank material

There is little consensus concerning the best way to parameterize the bank material characteristics as an independent variable with respect to channel morphology. The erosion resistance of bank materials is generally determined by their texture, sedimentary structure, cohesion and the reinforcing effects of any vegetation (van den Berg, 1995). Schumm (1963) considered the percent of silt-clay to parameterize the characteristics of the bank materials. He introduced quantitative relations between the percentage of silt-clay and sinuosity and width-depth ratio of the channel, indicating that, as the percent of silt-clay in the bank increases, the sinuosity increases and width-depth ratio decreases.

Observations by Brice (1964) on the North, South and Middle Loup rivers in the USA supported Schumm's (1963) finding that the percentage of silt/clay determines bank stability and thus sinuosity. However, Brice also found that swamp vegetation increased bank resistance in some reaches of the North and Middle Loup Rivers despite a very low concentration of silt and clay in the suspended load.

Rather than the consider the percentage of silt/clay as an independent variable representing the characteristics of the bank materials, Thorne (1988) preferred to take soil cohesion as the factor responsible for influencing channel geometry. This is consistent with the observation that channels with non-cohesive banks are wider and shallower than those with cohesive banks (Eaton and Millar, 2004). Braiding becomes much more likely where the river banks are cohesionless.

Vegetation is widely recognised as one the characteristics of the bank that influences channel geometry, but it is apparent that there are strong scales effects (Lane, 1957 and Eaton and Millar, 2004). While the presence of thick vegetation appears effective in reinforcing the banks of small rivers, so restricting their widths (Hey and Thorne, 1986), in the case of medium and large rivers, the role of vegetation in affecting the stability of the bank is more limited. Its effectiveness depends both on the type of vegetation, but also on the depth of rooting compared to the height of the banks (ASCE Task Committee, 1998; Bridge, 2003). This is the case because plant roots mechanically reinforce the soil but are only effective in stabilising the bank when the rooting depth is comparable to the bank height.

3.3.4 Valley slope

The valley slope is fundamentally important in determining the channel pattern (Richards, 1982; Bettess and White; 1983; Chang, 1988; Robertson-Rintoul and Richards, 1993; van der Berg, 1995). According to Richards (1982) channel patterns depend primarily on the availability of energy and the rate at which it is dissipated through processes of flow resistance, erosion and sediment transport. Resistance is strong dependent on the roughness of the channel, which is a function of its dimensions and geometry and the shape and size of the bed and bank sediments. Therefore, the independent variables are the total available stream power (represented by the valley slope and discharge), the channel size (represented by the discharge) and the characteristics of the bed and bank sediments. Based on these principles, Robertson-Rintoul and Richards (1993) derived a relation between total sinuosity (representing the area of the rough boundary for energy dissipation), discharge, valley slope and bed material size of the form:

$$\sum P = 1 + 3.42(Qi_v)^{0.40} D_{84}^{-0.04} \qquad (3.7)$$

Where, ΣP = total sinuosity, Q = 1.5 to 2.3 year return period flood, and i_v = valley slope. Total sinuosity is defined as the total length of active channel per unit reach length and can be used to represent the characteristics of both meandering and braided rivers as it represents the sinuosity of a meandering river and the braiding intensity of a braided river. In this respect, Robertson-Rintoul and Richards (1993) considered that meandering and braiding emerge from the same process. Hence, for a given value of *total sinuosity* the stable form of a river may be braided or meandering, depending on the characteristics of bank materials, the sediment concentration and the size of material in transport (Bettess and White, 1983). Bettess and White (1983) showed that, for a given energy condition and total sinuosity, braiding is more likely for larger sizes and/or higher concentrations of bed material load. In summary, the basic principles for discriminating between different stable channel patterns using the approaches of Bettess and White (1983) and Robertson-Rintoul and Richards (1993) based on the valley slope are very similar.

In contrast, van den Berg (1995) concluded that braided and meandering rivers are fundamentally different and derived a more conventional line discriminating between them based on the potential stream power (Figure 3.1). This is:

$$\omega_v = 50 D_{50}^{0.42} \qquad (3.8)$$

where ω_v = potential specific stream power defined as:

$$\omega_v = \rho g Q i_v / W \qquad (3.9)$$

where, ρ = density of water, g = acceleration due to gravity, Q = bankfull or average flood discharge, i_v = valley slope and W = width of the river derived from a suitable regime equation. Van den Berg's equation indicates that, for a given bed material size, braiding becomes more likely as the stream power increases. Van den Berg (1995) also shows that, similar to the finding of Leopold and Wolman (1957), straight channels (with a sinuosity < 1.3) are found at both sides of the discrimination line defined by Equation 3.8.

van den Berg's (1995) decision to use the regime width instead of actual width in calculating the potential stream power was criticized by Lewin and Brewer (2001). To avoid this criticism, van den Berg and Bledsoe (2003) proposed the use a plot of $Q^{0.5}*i_v$ vs. D_{50}, which yields the same discriminator as Equation 3.8 for braiding and meandering rivers. The exponent of 0.5 for discharge ($Q^{0.5}$) also represents specific stream power (Ferguson, 1987 and Bridge, 2003).

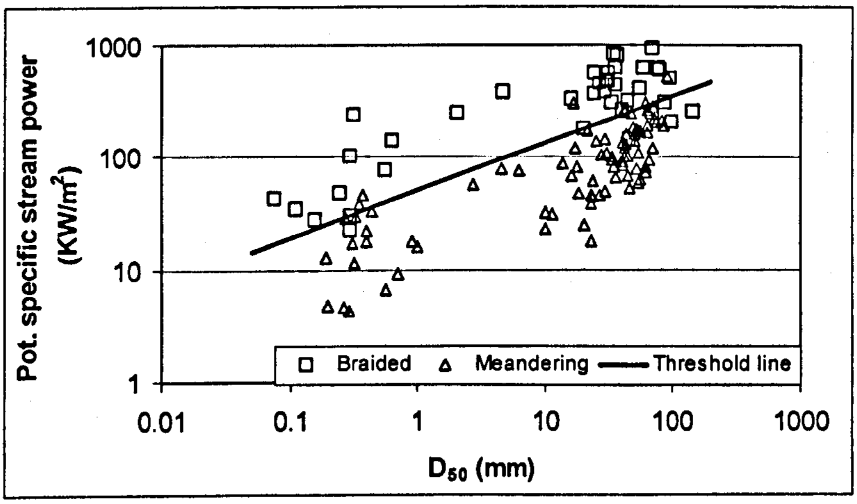


Figure 3.1. Channel pattern in relation to grain size and potential specific stream power, calculated using bankfull discharge (after van der Berg, 1995).

3.4 Natural and anthropogenic causes of channel change

3.4.1 Tectonics

Active tectonics may change the valley slope through subsidence or uplift or tilting. In fact, alluvial rivers are very sensitive indicators of change in valley slope (Schumm *et al.*, 2000). It was discussed in the previous section how a river adjusts its planform characteristics based on the valley slope to approach a stable state. Hence, if there is a change in valley slope due to neotectonic activity, a meandering river will adjust its sinuosity to recover a stable condition. Hence, a river that is being steepened by a downstream tilt will increase its sinuosity to recover a stable condition. However, if the increase in slope crosses the threshold between meandering and braiding, this may cause planform metamorphosis from meandering to braided. Conversely, a reduction of valley slope may cause a reduction in sinuosity or braiding intensity with aggradation promoting development of an anastomosing pattern. On the other hand, tilting of the valley floor may promote lateral migration of avulsion of the river across its floodplain (Jain and Sinha, 2005).

Schumm *et al.* (2000) present field evidence on the effects of neotectonics. They found that the braiding intensity increases in the aggradational environment associated with the valley upstream of an axis of or downstream of a subsidence axis (Figure 3.2). Conversely, in the degradational environment downstream of an uplift axis or upstream of a subsidence axis, the braiding index decreases (Schumm *et al.*, 2000).

Schumm and Spitz (1996) and Schumm et. al. (2000) report that the effects of tectonics are generally pronounced for small rivers but diminish with increasing stream power. Despite this, they report that the effects of faulting and uplift are discernible on the Lower Mississippi River, both through changes in flood extent and also in the projected valley slopes. Schumm and Spitz (1996) also reported the effects of uplift and tilt on the Black, Dan and St. Francis rivers in the mid-western U.S. Burnett and Schumm (1983) observed the effects of the Monroe and Wiggins Uplifts in the Lower Mississippi Valley on a number of rivers that cross the axes of these structures. The response of Big Colewa Creek to the Monroe uplift was typical. Upstream of the axis of the Monroe uplift, a reduction in the valley slope caused an increase in the frequency of flooding, a decrease in sinuosity and development of an anastomosing pattern. Downstream, where the axis of uplift is crossed, valley slope and channel sinuosity increase. Bogue Homo Creek displayed similar morphological changes where it crossed the Wiggins uplift, with the channel braiding as the valley slope steepened downstream of the axis of uplift.

Similar patterns of braiding in response to neotectonics have been observed on the River Indus, Pakistan. The Indus braids in the reaches where the valley slope is steeper and meanders where the valley slope is lower (Harbor *et al.*, 1994).

The Cadell Fault crosses the course of the Murray River in Australia, causing marked changes in the planform and development of an anastomosing pattern (Rutherfurd, 1994). The morphological response of the Murray is similar to that of the Big Colewa Creek upstream of the axis of the Monroe Fault.

These planform responses to changes in valley slope associated with neotectonic activity correspond to the experiments of the Bettess and White (1983), which showed that an increase in valley slope may cause a meandering river to increase its sinuosity, while a further slope increase may cause the river to start to braid. The observations also support the principle of Robertson-Rintoul and Richards (1993) that increasing valley slope causes an increase in total sinuosity.

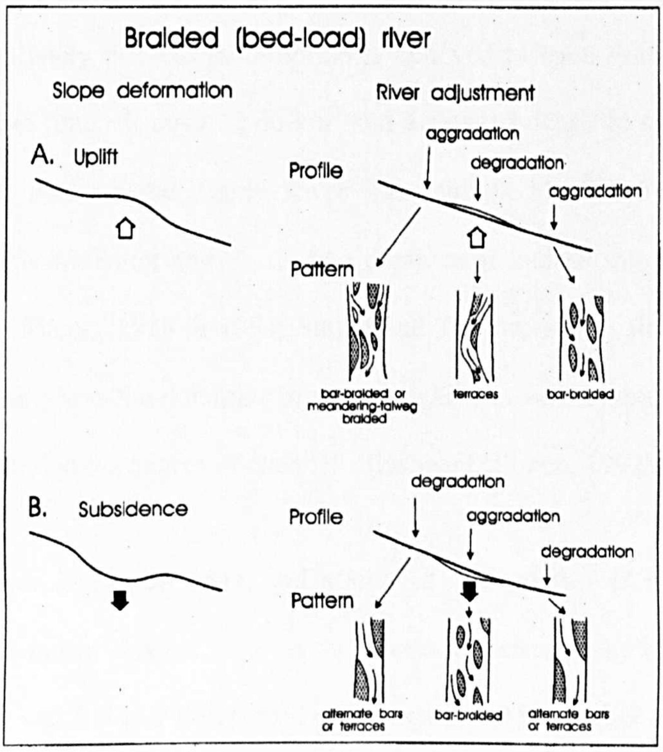


Figure 3.2 Adjustment of a braided river to (A) Anticlinal uplift and (B) Synclinal subsidence (from Schumm et. al, 2000).

3.4.2 Seismic events

Neotectonic activities such as uplift, subsidence or tilting act gradually over a long-period. In contrast, seismic events such as an earthquake or volcanic eruption occur over a short period, but they may still generate responses in river morphology that remain discernible for years or decades after the event that caused them (Schumm *et al.* 2000). Both earthquakes and volcanic eruptions can generate a huge input of sediment within the river basin and may also deform the shape of the basin through faulting, warping, uplift and/or subsidence. Not only may changes that occur during a seismic event impact a river, but also the sediment entering into the river system for months or years after the event may cause further changes in river morphology.

For example, the eruption of Mount St. Helens in Washington State, USA generated about three billion cubic metres of sediment (Bradley, 1983; Waitt and Pierson, 1994) during its eruption in 1980. The initial input of sediment converted the Toutle and Cowlitz Rivers from meandering to braided planforms (Bradley, 1983). The debris avalanche that occurred immediately prior to the eruption is believed to have been the largest landslide on earth in historic time. It covered 60 km^2 and deposited debris to an average thickness of 45 m. The North Fork of the Toutle River was initially blocked by the landslide, later developing through widening and decreasing depth as it incised into the deposits (Waitt and Pierson, 1994; Simon, 1989 & 1992; Simon and Thorne, 1996). However, it was found that channel widening was the dominant processes, which caused a rapid increase in energy dissemination that limited the degree of channel adjustment (Simon, 1992).

Between December 1811, and March 1812, a number of major earthquakes occurred in the New Madrid seismic zone in the Lower Mississippi Valley. The magnitude of the largest shock was 8.7 and it occurred on February 7, 1812. This catastrophic event generated huge swells in the river (Schumm et. al., 2000). The earthquakes wholly changed the course of the Mississippi River between New Madrid and Memphis, Tennessee. In this reach, the development of extensive bars and lodging of snags (woody debris jams) together with the mergence of rapids and waterfalls where faults crossed the Mississippi, created severe hazards to navigation. Another significant effect of the earthquakes on the Mississippi River was extensive bank erosion.

The New Madrid earthquake had heavy and prolonged impacts on the Lower Mississippi River. The great extent of bank failures introduced large quantities of sediment into the river, which caused a significant increase in the width of the river. In addition, the number of meander cut-offs increased following the earthquake. There is evidence that the effects of the earthquakes persist even after almost 200 years. For example, water level profiles at bankfull and medium stages still show a distinct convexity where the channel crosses the Lake County uplift.

A very strong earthquake occurred in the Indian State of Assam in August 1950. The magnitude of the earthquake was 8.6 on the Richter scale. The epicentre was near the Chinese border and the focus was 14 km below the earth's surface. About 52,000 sq. km of territory in Assam was seriously affected by the tremors and subsequent floods (Tillotson, 1951). A huge landslide occurred in the Himalayas due to the earthquake, the estimated volume of which was 45 billion m^3. Most of the debris generated by the earthquake entered the Brahmaputra River through its numerous tributaries. The fine fraction of the sediment travelled through the fluvial system rapidly, and contributed to accelerated accretion in the Lower Meghna Estuary during the 1950s. The coarser fraction of the sediment moved more slowly downstream generating changes in the elevation of the river bed, the channel width and the planform. A detail description of river response to the Assam earthquake of 1950 is presented in Chapter 6.

The Subansiri River in Assam (India's largest tributary to the Brahmaputra River) was temporarily blocked by rock debris generated by the landslides due to the earthquake (Goswami *et al.*, 1999). The huge, naturally created dam obstructed the entire monsoon discharge of the river for nearly three days. Outburst of the dam created a catastrophic flood, the greatest ever in the recorded history of the Subansiri River.

Prior to 1950, there was a balance between sediment supply and transportation in the Subansiri River, which resulted in a dynamically stable, meandering channel. After 1950, this balance was disrupted as the earthquake caused severe landslides in the hill tracts, which suddenly provided an additional and abundant source of sediment. The huge input of sediment, gradually aggraded the river channel, increasing its slope and initiating bank erosion that led to channel widening. Collectively, these factors contributed to the change in the channel pattern of the Subansiri River from meandering to braided.

3.4.3 Anthropogenic interventions

Human interventions in the river basin and/or in the river itself occur for many reasons, the most common being mineral extraction, farming, forestry, urbanisation, diverting/abstracting water and generating hydropower. These activities generally modify the flow and sediment regimes of the river, prompting morphological responses to changes in those independent variables. Adjustments to human perturbations tend to be rapid and they proceed in a complex manner (Jiongxin, 1996). The precise nature of the morphological responses depend on the magnitude and extent of the changes, and also on the adjustability of the boundaries of the river itself (Chien, 1985; Petts and Gurnell, 2005). In many rivers subject to human disturbance, one or more of the channel dimensions are fixed so that they cannot adjust in response to a perturbation. For example, in a river where the width is fixed by bank protection, adjustment tends to be focused on the bed, resulting in exaggerated and unnatural adjustments in bed elevation and slope.

Changes in catchment sediment yield or upstream sediment supply are a common anthropogenic cause of channel adjustment. They may occur due to deforestation in the catchment sediment mining from the riverbed itself (Madej and Ozaki, 1996; Kondolf *et al.*, 2002). For example, excess sediment generated by deforestation and mining activities caused the planform of Pine Creek in the USA to switch from single-threaded to braided, while the reduction of sediment supply due tosediment mining caused the Drome River in France to switch from braided to single-thread and incise by 1 to 4 m (Kondolf *et al.*, 2002). In Redwood Creek, USA, a series of large floods following the harvesting the trees from the river basin in the 1960s generated a sediment wave (Madej and Ozaki, 1996). This sediment wave moved downstream through the system with varying celerity, depending on local values of the unit stream power. The amplitude of the wave was attenuated as it moved downstream.

Degradation of the river bed is another common response to anthropogenic disturbance of the fluvial system. This may propagate upstream as a head cut, knick point or knick zone, changing the slope of the river as it does so (Galay, 1983). For example, straightening and enlargement of rivers in West Tennessee between 1959 and 1978 triggered degradation, which propagated upstream through head cutting (Simon, 1989). Lowering of the bed over-steepened the banks, rendering them unstable with respect to mass failure and driving rapid widening that limited the degree of degradation. This mechanism appears to limit degradation generally where the bank materials are erodible (Simon, 1992).

Meander cut-offs are a widely employed human intervention, designed to increase the slope of the river and speed flood flows through the fluvial system. However, unless steps are taken to stabilise the banks and restrict the river from re-meandering, its natural tendency will be to recover its former sinuosity and so adjust its slope towards a stable or regime value. This behaviour was observed on the Lower Mississippi River (Winkley, 1994; Biedenharn, *et al.*, 2000; Harmar, *et al*, 2005). Meander cut-offs during the 1940s and 1950s shortened the Mississipi River by about 300 km. Following the cut-offs, the higher-gradient reaches would have regained their sinuosity and reduced their gradients but for an extensive programme of bank protection works that locked in the river course, fixed its width and prevented such adjustment (Winkley, 1994). As the option of adjusting the slope through planform or width change has been denied to the river, the over-steepened slope has instead been accommodated through adjustment at the bed. Adjustments at the bed involve degradation, aggradation, changes in the bed material sediment size and/or changes in bed roughness. Biedenharn *et al.* (2000) noted bed scouring upstream of cut-offs and subsequent aggradation downstream, but no significant change in bed material size. Harmar *et al.* (2005) confirmed Biedenharn *et al.*'s results but further noted an increase in bed roughness that was achieved through an increased amplitude and reduction in the spacing of crossings (riffles) and pools.

The construction of a dam changes the flow and sediment regimes of a river. Buchanan (1994) reported the response of the Canadian and Red Rivers in the USA to the changes in the mean, peak and low flows. Due to the construction of dams, the mean and high flows of these rivers decreased and the low flow increased. As a result, braided reaches narrowed and changed their planform pattern to a single-thread channel. This change is in line with the theory of Klaassen (1995), as described in Equation 3.3.

In addition to changing the flow regime, dams also restrict the movement of sediment downstream, often leading to degradation below the dam that propagates downstream (Lane, 1955; Galay, 1983; Petts and Gurnell, 2005). Degradation and its propagation is attributed to a tendency for the river to reduce its slope in response to the reduced supply of sediment load, as indicated by Equation 3.5. The response of rivers to dam construction in China has been described and modeled by Chien (1985), Zhou and Pan (1994) and Jiongxin (1996). Similarly, Lagasse (1994), and Schumm and Galay (1994) studied the responses of the Rio Grande River in USA and River Nile in Egypt, respectively. These studies reveal that morphological responses to the altered flow regime and reduction of sediment load associated with dam closure are not as simple would be expected based on Equation 3.5. In nature, the manner and sequence of response may be different due to the particular conditions in that stream.

For example, in the Rio Grande River immediately downstream of Cochiti Dam, the bed was degraded and the braiding intensity was reduced. Coarsening of the bed material was also observed immediately downstream of the dam. However, further downstream aggradation occurred and a braided channel developed, leading to slope reduction through hinging (Lagasse, 1994). Conversely, parallel degradation was observed in the Nile downstream of the high Aswan Dam (Schumm and Galay, 1994) with no tendency to adjusting the slope through hinging. Similar, parallel bed adjustment was reported by Chien (1985) in the Yellow River. This behaviour may reflect the fact that adjustment of the slope along a very long reach of a large river through hinging (the mechanism proposed by Lane, 1955) and the development of a graded profile (according to Mackin, 1948) is practically impossible due to the huge amount of sediment required to be moved to attain such an adjustment (Chien, 1985; Chang, 1988; and Schumm *et al.*, 2000).

In addition to the river bed degradation, channel widening was one of the morphological responses observed in the River Nile downstream of Aswan Dam (Schumm and Galay, 1994). This adjustment may be explained as a response to the reduction in sediment supply below the dam as the river must expend the energy that was formerly used to transport sediment in some other way. This can be achieved by any of the following processes or combination of the processes: (i) decreasing slope, (ii) increasing width or (iii) increasing roughness (Jiongxin, 1996). Widening was also reported downstream of dams in the braided reach of the Lower Yellow, Hanjiang and Lower Yongdinghe Rivers, in China (Chien, 1985; Zhou and Pan, 1994; and Jiongxin, 1996). However, widening of a braided reach was not the unique form of response of the river to the operation of dam. In many cases, initial narrowing of the channel has also been observed followed by the widening (Jiongxin, 1996).

Armouring or coarsening of bed material through grain sorting is widely observed downstream of dams. This causes an increase in roughness. For example, Chien (1985) reported armouring of the river bed downstream of Guanting Reservoir of the Yong-ding

River in China and coarsening of bed material in the Yellow River downstream of Sanmenxia Dam.

3.5 Models of channel response to disturbance

Models available to predict stable channel morphology include analytical models (Callander, 1969; Parker, 1976; Chang, 1979; White *et al.*, 1982; Murray and Paola, 1997), empirical models (Lacey, 1930; Leopold and Wolman, 1957; Lane 1957; Schumm, 1963 & 1969; Ferguson, 1984 & 1987; Robertson and Rintoul, 1993; van den Berg, 1995), qualitative models (Lane, 1955; Schumm, 1969; Bettess and White, 1983), and models derived from observations made of particular cases (Simon, 1989; Madej and Ozaki, 1996; Jiongxin, 1996). Some of these models refer to the channel slope and long profile, some are concerned with the cross-sectional geometry, some are focused on the planform pattern but relatively few can be used directly to explain and predict the response of the channel to particular intervention or disturbance. Only models of this latter type are relevant to this study, and so are discussed in the following sections.

3.5.1 Lane (1955)

Lane proposed a qualitative relation as depicted in Equation 3.5. It relates the water discharge and channel slope to the bed material size and sediment load in a reach. The relation between these variables is usually characterised as 'Lane's Balance' (Figure 3.3). Lane (1955) presented six classes of change in the river that can cause aggradation or degradation. These are:

i. increasing the amount and/or size of the input sediment load,

ii. decreasing the amount and/or size of the input sediment load,

iii. raising of base level,

iv. lowering of base level,

v. moving the base level further away without changing its elevation, and

vi. moving the base level closer without changing its elevation.

Lane (1955) cited several examples for each of the cases as mentioned above. An important outcome of his model is that increasing the sediment load for a given discharge would have the same impact as decreasing the discharge for a given sediment load.

In its original form, Lane's balance is a one-dimensional relation in which, for a given discharge, a change in the sediment input may be compensated for only through a change in slope. According to Lane (1955), the effect of a change of base level may propagate for a very long distance through the fluvial system, through aggradation or degradation of the river bed. However, Schumm *et al.* (2000) used a flume experiment to demonstrate that this kind of adjustment may not propagate so far as Lane (1955) indicated. They found that aggradational and degradational responses were muted when the base level in their laboratory flume was lowered, with most of the impact being compensated for by an increase in sinuosity in the downstream reach of the channel coupled with increases in width and roughness. Similarly, changes in load have been shown to be compensated for by changing width in real rivers (Chien, 1985; Simon, 1992; Schumm and Galay, 1994). To address the limitations of Lane's relation, Klaassen (1995) added consideration of simplified equations for sediment transport, flow resistance and regime geometry to Lane's balance to derive Equation 3.5. This approach produced new relations showing the response expected to changes of discharge, sediment load and discharge variability in width, slope and braiding intensity (Equations 3.3 and 3.4).

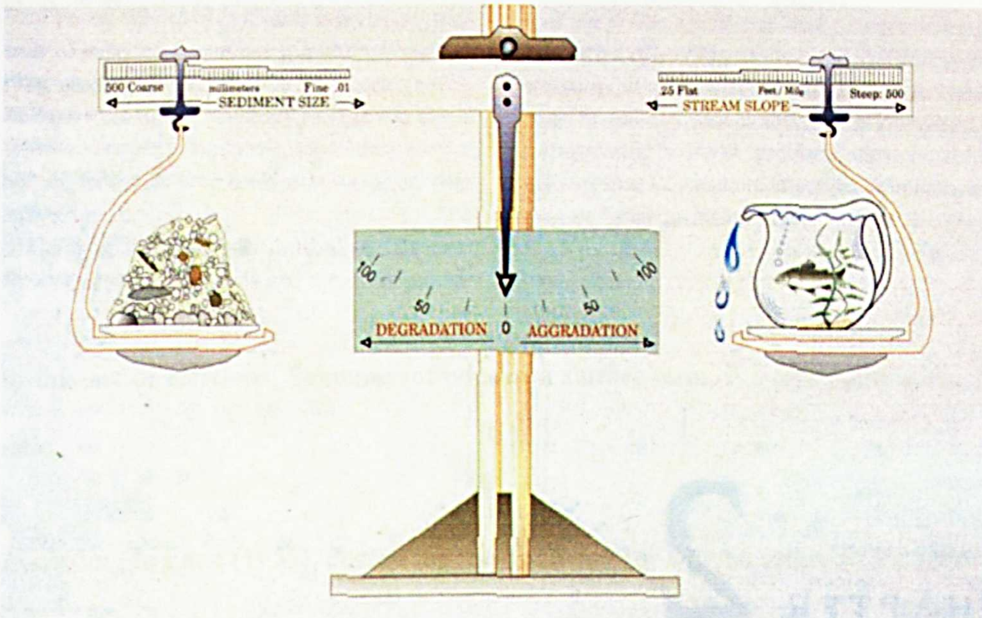


Figure 3.3 Lane's balance

3.5.2 *Schumm (1969)*

Schumm expressed the sense of adjustment of width, depth, meander wavelength, slope and sinuosity to changes in discharge (Q) and sediment load (S) in a series of qualitative relations. He presented the influence of changes in the individual independent variables on the dependent variable as follows:

$$Q^+ \approx W^+, d^+, \lambda^+, i^- \qquad (3.10)$$

$$Q^- \approx W^-, d^-, \lambda^-, i^+ \qquad (3.11)$$

$$S^+ \approx W^+, d^-, \lambda^+, i^+, P^- \qquad (3.12)$$

$$S^- \approx W^-, d^+, \lambda^-, i^-, P^+ \qquad (3.13)$$

where, W = width, d = depth, i = slope, λ = meander wavelength and P = sinuosity. In these relations, the + sign and – sign indicate an increase and decrease in each of the parameters. Schumm also presented relations for channel response to simultaneous changes in discharge and bed material load:

$$Q^{+}\, S^{+} \approx W^{+}, d^{\pm}, \lambda^{+}, i^{\pm}, P^{-}, F^{+} \quad (3.14)$$

$$Q^{-}\, S^{-} \approx W^{-}, d^{\pm}, \lambda^{-}, i^{\pm}, P^{+}, F^{-} \quad (3.15)$$

$$Q^{+}\, S^{-} \approx W^{\pm}, d^{+}, \lambda^{\pm}, i^{-}, P^{+}, F^{-} \quad (3.16)$$

$$Q^{-}\, S^{+} \approx W^{\pm}, d^{-}, \lambda^{\pm}, i^{+}, P^{-}, F^{+} \quad (3.17)$$

In this set of relations, Schumm introduced a further term, F , representing the width/depth ratio.

According to Lane (1955), decreasing the discharge for a given sediment load would have the same effect on the slope of the river as increasing the sediment input for a given discharge. Equations 3.10 and 3.13 suggest that positive and negative changes in discharge and sediment produce similar changes in slope.

It may be concluded that the slope response of the river to the changes of discharge and sediment input indicated by Schumm is in good agreement with that of Lane (1955). Schumm's analysis is, however, an advance over Lane's balance as Lane's model is unable to predict the trends of change in width, depth and planform parameters in response to changes in the independent variables of discharge and sediment input.

Schumm's relations indicate that width and depth responses occur in different fashions depending on the nature of the causal changes in discharge and/or sediment load, which is consistent with previous ideas on stable channel geometry. For example, width and depth both increase in response to an increase in discharge, which is consistent with regime theory for stable channel dimensions (Equation 3.1). On the other hand, increasing the bed material load causes an increase in width but a decrease in depth and vice versa (Equations 3.12 and 3.13). These relations have subsequently been supported by White *et al.* (1982) and Bridge (2003). Conversely, Chang (1979) indicated that for given discharge and sediment load a river may have two equilibrium widths, depending on the flow regime. The high sediment load associated with downstream propagation of a sediment wave often causes the widening of the river (Nicholas *et al.*, 1995; Miller and Benda, 2000; Bartley and Rutherfurd, 2005). However, opposite trends of adjustment have also been observed in nature, such as the braided reaches of the Lower Yellow, Hanjiang and Lower Yongdinghe Rivers (Chien, 1985; Jiongxin, 1996), which widened in response to a decrease in sediment input following dam construction upstream. In this regard, Equation 3.3 is more in line with the observed behaviour of the Chinese Rivers. It is potentially significant that the pre-disturbance planforms of the rivers studied by Schumm, that widened in response to an increase in sediment load, were single threaded. In contrast, the Chinese rivers that widened in response to a decrease in sediment load, were initially braided in planform. It may be concluded that Schumm's relations are mainly applicable to rivers that are single-threaded prior to disturbance and that in braided rivers, the width may increase with a reduction in the sediment load. This issue further addressed later in this review.

Schumm recognises that combined changes of both discharge and sediment load may generate uncertain responses (indicated by the +/- exponents in Equations 3.14, 3.15, 3.16 and 3.17) depending on the relative proportion of the changes in discharge and load.

3.5.3 Bettess and White (1983)

Bettess and White (1983) presented a framework within which the causes of braiding and meandering in channels that have achieved a state of dynamic equilibrium can be explained. In a manner similar to Chang (1979) and White *et al.* (1982), they considered that the slope of a stable channel is determined by its discharge, sediment load and sediment size. Increasing the sediment input or sediment size triggers a response through increasing the slope.

For given discharge and sediment input, Bettess and White (1983) estimated the equilibrium or stable slope of a channel, i_{R1}. A river having a stable slope may be straight, meandering or braided, depending on the relative values of the stable channel slope and the valley slope. According to Bettess and White, if valley slope $i_v = i_{R1}$, the stable channel will be straight. For $i_v > i_{R1}$, the river will try to attain its stable slope by meandering. In the equilibrium state, the sinuosity (p) is adjusted so that, $p = i_v/i_{R1}$. A difference between the valley slope and the stable slope can also be accommodated by braiding, which can be explained as follows.

While keeping the sediment concentration constant, a river may increase its slope through dividing its discharge. If the discharge of the river is divided equally between two channels, the stable slope for each sub-channel will increase. Thus, a river can also attain an equilibrium condition (stable slope) within the context of a steeper valley slope by dividing itself into two or more channels. The increased stable slope for two equal channels was referred by Bettess and White (1983) as i_{R2} and such a slope for three equal channels was referred as i_{R3} and so on. They presented a diagram showing how a river can adjust to an increased valley slope initially through meandering, then by braiding and then by increasing the number of braided channels (braiding intensity) (Figure 3.4). According to Bettess and White (1983), this sort of adjustment is favoured because this process is consistent with the natural tendency of rivers to minimize their stream power expenditure per unit length of channel. It should be mentioned here that for a braided river the term 'stream power per unit length' refers to the stream power of the unit length of an individual channel.

It follows from these arguments that there is uncertainty whether a river will meander or braid in situations where $i_v > i_{R1}$. There is no threshold value of i_v / i_{R3} at which a river may start to braid instead of meandering, but Bettess and White (1983) assumed that braiding is likely to occur when $i_v = I_{R3}$.

A later statement by Schumm *et al.* (1994, p37), "*Both field and experimental studies of river patterns have demonstrated that for a given discharge and sediment load a channel will remain straight on a gentle valley floor, but as the valley slope increases, the pattern changes* *from straight to meandering to braided*" lends further support to the framework of Bettess and White (1983). There are also field observations to suggest that their framework is sound. For example, those by Burnett and Schumm (1983) and Harbor *et al.* (1994) in Bogue Homo Creek, USA and the River Indus in Pakistan, respectively.

Bettess and White (1983) showed that meandering and braiding result from processes that minimize the expenditure of stream power per unit length of the channel through increasing the sinuosity or number of braid channels. The principle of minimization of the rate of stream power expenditure through meandering or braiding is similar to that proposed by Richards (1982) and Robertson-Rintoul and Richards (1993). Both approaches considered that meandering and braiding are generated by continuation of the same process of channel adjustment. The main difference between these approaches is that Richards (1982) and Robertson-Rintoul and Richards (1993) did not include sediment concentration as one of the independent variable influencing channel process and form.

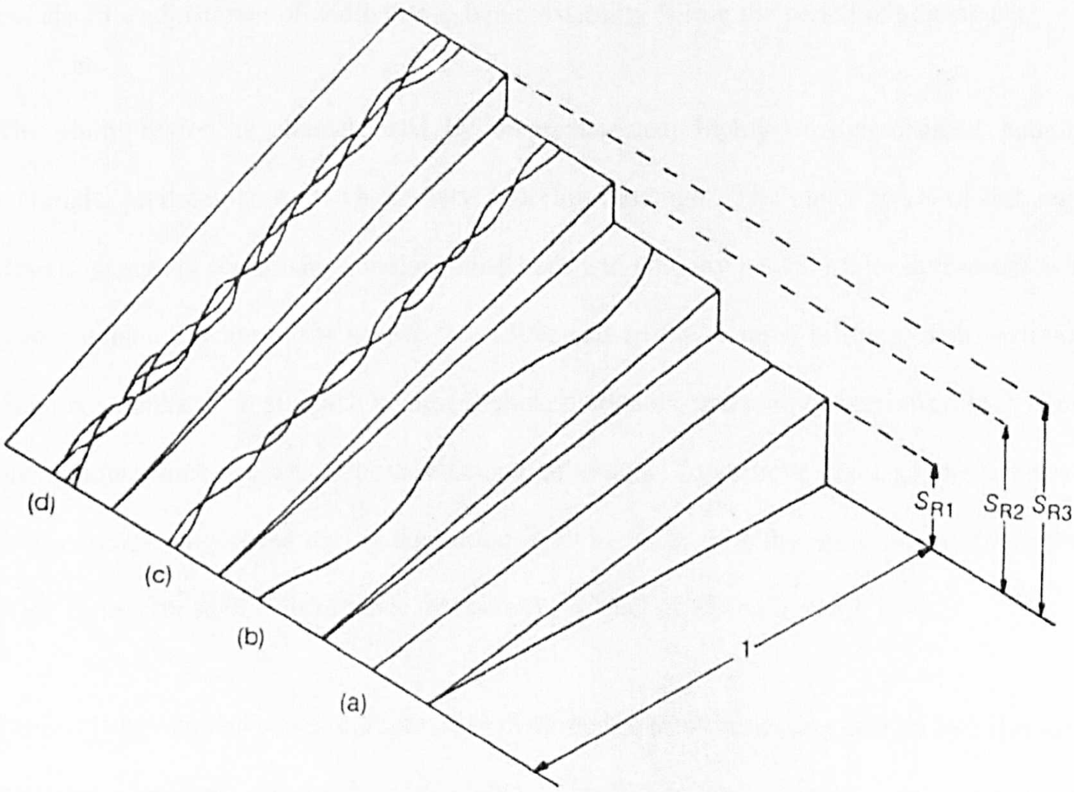


Figure 3.4 Schematic diagram response in planform to changing valley slope

In Bettess and White's (1983) analysis, increasing the sediment concentration increases the equilibrium or stable slope. As a result, in relatively steep valleys ($i_v > i_R$) the difference between the valley slope and stable channel slope will be reduced, triggering a reduction of the sinuosity or braiding intensity. This prediction of a reduction in sinuosity due to an increase in sediment concentration is consistent with the relations of Schumm (1969), as described in Equation 3.12. However, the proposition that an increase in sediment concentration should cause a reduction in braiding intensity does not match with Schumm's (1969 and 1977) principles.

3.5.4 Simon (1989)

Simon (1989) described the vertical and lateral responses of channels in West Tennessee, USA, to disturbance involving channel straightening and enlargement between 1959 and 1978. He developed an analysis that deals not only with degradation/aggradation at the bed, but also the adjustment of width due to bank instability during the period of adjustment.

The study region is characterized by unconsolidated, highly erosive channel boundary materials, predominantly of Quaternary and Holocene age. The major rivers of this region flow in channels comprising medium-sand beds and silt-clay banks. Major deforestation and severe upland erosion in the mid to late-1800s caused the channel infilling of the extremely sinuous streams. The sluggish sediment-choked streams frequently overflowed their banks, laying down thick deposits of post-settlement alluvium. To improve drainage, the rivers were dredged and straightened during the period 1959 to 1978. It is the responses of the rivers in West Tennessee to this disturbance that was the subject of Simon's study.

Simon (1989) studied some representative disturbed streams collecting data on bed elevations, gradients, channel top-width and channel length before, during and after channel modification. Due to dredging and straightening, channel lengths were shortened by over 40% and gradients were increased by up to 600%.

It is known that channel bed adjustments through time can be described mathematically by nonlinear functions, which asymptotically approach a condition of minimum variance. Although there is agreement regarding non-linearity in the rate of adjustment of the river bed, considerable disagreement exists regarding the mathematical form of the function. Examining exponential and power equations to describe the adjustment of the stream bed, Simon (1989) found that a power equation matched the observed data well. The form of the power equation is

$$E = a(t)^b \qquad (3.18)$$

where, E = elevation of the bed in a given year in metres above sea level, a = a coefficient, t = time since beginning of adjustment process in years and b = an exponent. For the case of riverbed degradation the value of b is negative, while it is positive for aggradation.

Maximum bed adjustment occurs in the Area of Maximum Disturbance (AMD). In the West Tennessee streams, the AMD was found to be where channel modification through enlargement and straightening terminates. Degradation occurred upstream of AMD and migrated upstream. Later, secondary aggradation migrates headward with time, apparently in response to excessive lowering (over adjustment) during the degradation phase.

Simon (1989) treated the bed level changes as the triggering agent for adjustment processes at the banks, which led to adjustment of the channel width. Specifically, bed lowering leads to mass failure of the banks that constitutes a major input of sediment to the fluvial system and leads to rapid widening. The input of sediment and increase in width together limit the degree of incision compared to what would be expected in a channel with fixed banklines. Simon (1989) considered that the adjustments he observed are inherent to fluvial responses, so that his characterisation of them should be useful in determining the sequential changes in any disturbed alluvial channel over the course of a major adjustment cycle.

According to Simon (1989), his model is particularly applicable to disturbed streams in the Mississippi embayment of the central United States. However, he also claims that streams in other areas display similar trends and sequences of adjustment. For example, Simon and Thorne (1996) found that the North Fork Toutle River behaved in a manner consistent with the Simon model following the eruption of Mount St Helens in 1980. Simon notes, however, that deviations from the expected behaviour are observed, mainly depending on the presence of local bedrock controls and variations in relief, soil properties, and climatic conditions.

3.5.5 Jiongxin (1996)

Jiongxin (1996) investigated channel pattern changes downstream of reservoirs and developed a descriptive model to explain the processes observed in three of the major rivers of China and a laboratory experiment. The three major rivers studied are the Lower Yongdinghe, the Lower Yellow and the Hanjiang rivers.

The Lower Yongdinghe River is a wandering, braided river in the North China Plain. Prior to construction of Guanting Reservoir, it had a very high mean annual suspended sediment concentration of 60.8 kgm^{-3}. Following reservoir construction, and a major reduction in sediment concentration, channel response was dominated by channel widening. The width to depth ratio at bankfull stage was greatly increased as a result, though the braided pattern remained unchanged.

The Lower Yellow River is the type site for wandering, braided rivers in China. During the period of operation of Sanmenxia Dam in water storage mode between 1959 and 1964, the width-depth ratio of the channel decreased massively and the sinuosity increased in the 174 km long reach downstream of the dam between Qinchang and Gaochum. Later, when the dam was operated in a flood detention mode, the width to depth ratio increased. The channel retained its typically wandering, braided planform throughout.

The Hanjiang River is the longest tributary of the Yangtze River and is located in the Middle Basin, having a sub-tropical, humid climate. Prior to the construction of Danjiangkou Reservoir, the middle Hanjiang River had a wandering braided channel that was shallow and wide, with numerous unstable bars. Operation of the reservoir resulted in the channel becoming narrower and deeper, with flow abandoning side branches and concentrating in the main channel. For a period, the width:depth ratio decreased and channel sinuosity increased. Later, these trends were reversed with width starting to increase and sinuosity to decrease.

Based on the observations of these three rivers and a laboratory experiment, Jiongxin (1996) developed a descriptive model for channel response to reservoir construction, which is as follows:

Stage I: Clear water is released from the reservoir, the channel is cut down, and water flow is concentrated in the main channel so that minor braids become feeble. Width:depth ratio decreases and channel sinuosity increases, leading the original wandering braided channel towards a meandering pattern.

Stage II: After reaching a minimum width:depth ratio and a maximum channel sinuosity, a marked tendency of channel widening occurs which is induced by increasingly intensified bank erosion. Then the width:depth ratio increases, the process towards a meandering pattern ceases, and a wandering braided pattern reappears.

Stage III: Both width:depth ratio and channel sinuosity tend to a constant, the channel slope becomes gentler and also tends to a constant. Bank erosion becomes weak, the development of mid- channel bars becomes lower, and finally a low sinuosity channel appears which is relatively stable with some mid-channel bars.

According to Jiongxin (1996), the occurrence of different trends of channel pattern change following reservoir construction is not due to different controlling mechanisms, but to different time durations of the first and second stages. For example, in the Yongdinghe River, *Stage I* of post-dam channel adjustment had a very short duration and before it became discernible channel adjustment had entered *Stage II.* When the outputs of water and sediment from the reservoir are similar, differences in channel adjustment are mainly determined by the differences in the mobility of the channel boundary materials and rate at which the channel is able to change through time.

Germanoski and Schumm (1993) simulated the effect of a reservoir in the laboratory and found that an incised, straight channel developed immediately downstream of the reservoir, with a braided pattern developing further downstream. Development of an incised, straight channel is similar to the response of the Yellow River immediately downstream of the Sanmenxia Dam in *Stage I* of adjustment.

Jiongxin (1996) also attempted to relate channel pattern change to energy expenditure. He argued that as the sediment input to the channel below the dam is greatly reduced, the river tends to reduce its unit energy expenditure. From consideration of the continuity equation for water and Manning's equation for flow resistance he obtained:

$$ui = n^{-0.6} Q^{0.4} i^{1.3} W^{-0.4} \rightarrow \text{minimum} \qquad (3.19)$$

where u = velocity, i = slope, n = Manning's roughness coefficient, Q = discharge and W = width. In order to make the unit water energy expenditure a minimum, one of the following must occur: (1) increase roughness, (2) increase channel width, (3) decrease slope. To decrease slope the river may either incise or increase its sinuosity.

During incision, scour-induced coarsening of the bed material increases grain resistance and the drag associated with bedforms to increase bed roughness. Hence, increased flow resistance tends to dominate the process of channel adjustment before slope adjustment becomes effective. In Jiongxin's model, although trends of channel pattern change vary as a function of the different stages of adjustment, the river always works towards the same goal: minimization of energy expenditure per unit width.

Jiongxin's (1996) observations and proposed model differs from that of Schumm (1969 and 1977) and Bridge (2003), but is very similar to the proposition made by Bettess and White (1983)

3.5.6 A scheme to resolve disagreements between the models

A scheme has been developed based on the framework of Bettess and White (1983) and the classification of braided rivers by Lane (1957) to resolve apparent disagreements between the models (Figure 3.5). The framework of Bettess and White (1983) was developed for predicting the stable channel morphology but it can also be used to assess the response of an alluvial river to a change in sediment input. According to them, for a given discharge and sediment size, increasing the sediment concentration causes an increase in the stable or regime slope (S_R). It is the difference between the valley slope (S_v) and stable slope (S_R) that determines the channel planform pattern. For a condition where the stable slope is flatter than the valley slope and the valley slope is fixed, an increase in sediment supply will cause the difference between the valley and stable channel slopes to diminish and thus the sinuosity or braiding intensity of the channel will decrease in response to an increase in sediment concentration in meandering and braided rivers, respectively. The opposite is also true: decreasing the sediment concentration may cause an increase in sinuosity or braiding intensity. If in Figure 3.4, instead of increasing the valley slope (the valley slope was kept the same), the initial response to decreasing the sediment concentration would be an increase in river meandering, while a further decrease in sediment concentration may cause the river to braid, as indicated in Figure 3.5. Bettess and White (1983) did not directly formulate these statements, but their framework fully matches with them and the scheme as presented in Figure 3.5. The widening observed in the braided reach of the Lower Yellow, Hanjiang and

Lower Yongdinghe rivers downstream of dams (Chien, 1985; Jiongxin, 1996) is also in line with this statement. Equation 3.4, derived by Klaassen (1995) yields a similar conclusion.

The apparent disagreement between the relations of Schumm (1969) (Equations 3.12 and 3.13), the framework of Bettess and White (1983) and Figure 3.5 can be resolved through consideration of Lane's (1957) classification of the braided river. Lane (1957) classified braided rivers into two sub-classes: (I) braiding due to steep slopes and (II) braiding due to aggradation. These two sub-classes were further divided into 5 sub-divisions to cover various combinations of the two causal factors in forming a braided river. These are;

1. braiding due to steep slope with degradation,
2. braiding due to steep slope with approximate equilibrium,
3. braiding due to steep slope with aggradation,
4. braiding due to aggradation with moderate slope, and
5. braiding due to aggradation with low slope.

It should be noted that according to Lane's detailed definitions, all braided rivers are in disequilibrium except those in sub-division 2. It was equilibrium braided rivers of this type that were considered by Bettess and White (1983). Figure 3.4 is therefore valid for braided rivers in dynamic equilibrium, classified under sub-division 2. However, if the sediment supply is increased in a stable, straight channel, Figure 3.5 suggests that a braided channel with the form of sub-division 3 is likely to develop (Figure 3.5). Rivers of the types studied by Schumm (1969; 1977) are likely to be in the forms of Types 1, 2 & 3 of Figure 3.5, but are unlikely to be in the forms of Types 4 and 5. Under these circumstances, an increase in sediment concentration is likely to drive an increase in width and a decrease in sinuosity (Equations 3.12 and 3.13). A further increase of sediment load is liable to trigger braiding. The scheme as presented in Figure 3.5 is thus in agreement with Schumm (1969; 1977).

There are similarities between the descriptive model of Jiongxin (1996) and the scheme presented in Figure 3.5. Prior to construction of the reservoirs, all three rivers were braided: the Type 1 case in Figure 3.5. Following operation of the reservoir, the rivers started to decrease their braiding intensity. Thus, *Stage I* of the Jiongxin model corresponds to the change from Type 1 to Types 2 and 3, *Stage II* adjustment corresponds to further changes associated with Types 4 and 5 in the scheme. *Stage III* is the equilibrium condition, representing the new stable form of the channel when it has adjusted close to Type 4 or 5 in Figure 3.5.

There is, however, also a difference between the model of Jiongxin (1996) and the scheme represented by Figure 3.5. In Jiongxin's account, it is assumed that reduction in sediment supply to the study reach occurs suddenly, as soon as the dam is closed and the reservoir becomes operational. Consequently, the sequence of channel adjustments described by Jiongxin is solely a function of time since closure. However, detailed descriptions of channel adjustments by Chien (1985) and Jiongxin (1996) indicate that the reduction in sediment supply due to dam construction and operation of a reservoir actually propagates downstream after closure. Hence, it requires some time for the reduction in sediment concentration to move to the study reach and then further on downstream. Based on this, it must be the case that the adjustment stages are not only dependent on time since closure, but also on the gradual reduction of sediment input in downstream reaches. Thus, the sequence of channel changes shown in Figure 3.5 can be treated as representative of the response of downstream reaches in a braided river to a gradual reduction in sediment concentration, as accounted for by Jiongxin (1986).

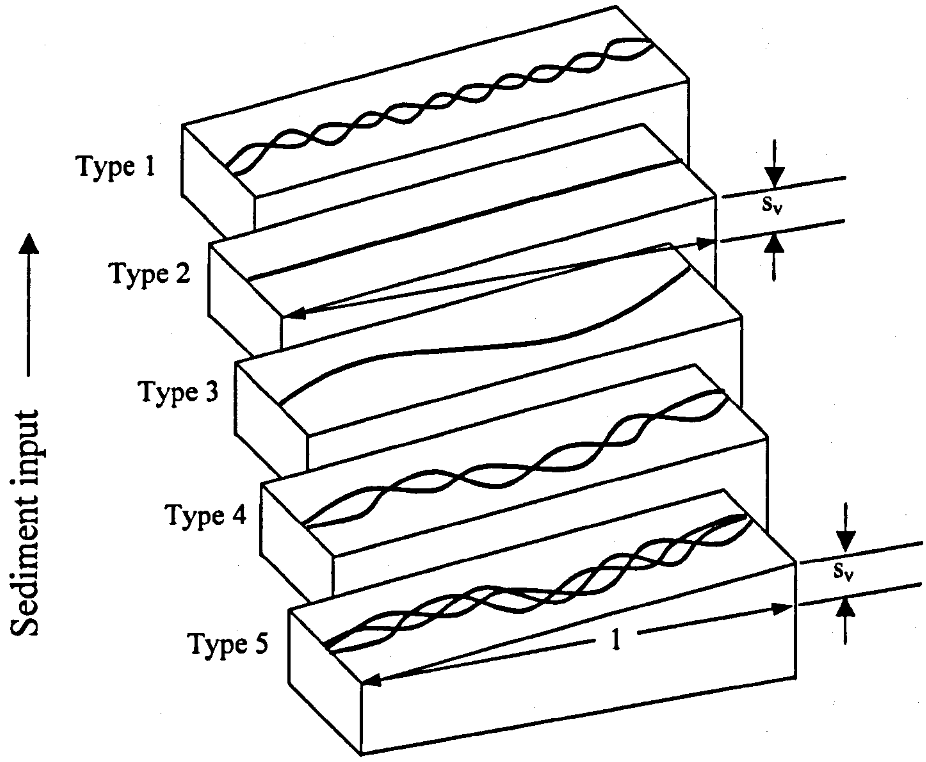


Figure 3.5 Schematic diagram showing planform response to changes in sediment load

Chapter 4
Data Used in this Study

4.1 Introduction

Satellite images are the main sources of information for this research. In addition, the research utilizes different types of hydrological and morphological data. Data includes Corona photographs, historical maps, cross-section soundings, water levels, discharges, sediment sizes, and sediment concentrations. The sources and collection procedures for these data are different and their accuracy varies across a large range.

The instruments and collection procedures related to the various data are described in this chapter. It is recognised that errors are present in the data due to natural variability, the limitations of the different measuring instruments and uncertainties concerning the procedures employed to collect, process and store the data. Hence, descriptions of the accuracy and reliability of the data are also presented in this chapter.

4.2 Satellite Images

4.2.1 Types of satellite images used

Different types of satellite images of the Brahmaputra–Jamuna River, Padma River and Lower Meghna River corridors in Bangladesh are available in the CEGIS archive for dates between 1973 and 2005. The appropriate satellite images were selected from this archive for the research.

Optical images of the dry season from a number of different sensors were used based on availability. These sensors are: Landsat MSS, TM, ETM+, IRS-1D LISS III and IRS-P6 LISS III. Radar images from RADARSAT-1 (Standard Beam, S7) were also available, but only for the Jamuna River. Tables 4.1, 4.2 and 4.3 show the different types of satellite images that have been acquired over the 32 years between 1973 and 2005 for the Jamuna, Padma and Ganges rivers. Table 4.1 shows the Path/Row and number of frames/scenes required for each sensor to cover the Jamuna, Padma and Lower Meghna rivers. The Path/Row information for Landsat images covering Bangladesh is presented in Figure 4.1.

Table-4.1: Number of Frames, Path and Row of Satellite images of each sensor for Jamuna, Padma and Lower Meghna River

River Name	Sensor	Path	Row	Frames/ Scenes
Jamuna	Landsat MSS	148	42 and 43	2
	Landsat TM	138	42 and 43	2
	Landsat ETM+	138	42 and 43	2
	IRS-1D LISS -III	109	53, 54, 55	3
	IRS-P6 LISS -III	109	53 (70% downward shifting) 54 (60% downward shifting	2
	RADARSAT	-	-	3
Padma	Landsat MSS	147	44	1
	Landsat TM	137	44	1
	Landsat ETM+	137	44	1
	IRS-P6 LISS -III	109, 110	55	2
Meghna	Landsat MSS	147	44	1
	Landsat TM	137	44	1
	Landsat ETM+	137	44	1
	IRS-P6 LISS -III	110	55 and 56	110

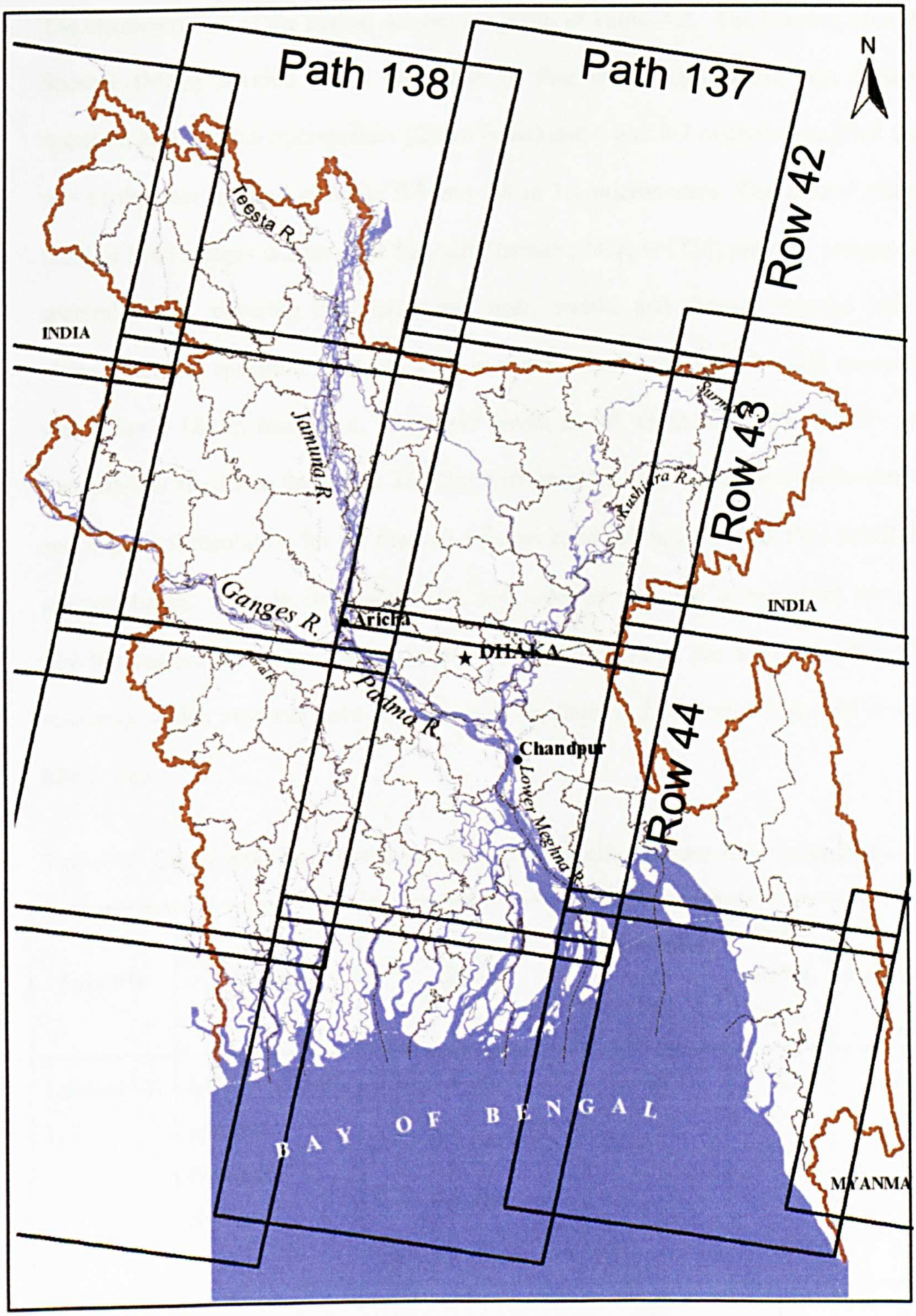


Figure 4.1: Path/Row of Landsat images covering the Jamuna, Padma and Lower Meghna rivers (generated by CEGIS based on corner coordinates of images)

The characteristics of the optical sensors are given in Table–4.2. The Landsat Multi Spectral Scanner (MSS) covered a 185 km swath in four wavelength bands: two in the visible spectrum at 0.5 to 0.6 micrometers (Green Band) and 0.6 to 0.7 micrometers (Red Band) and two in the near infrared at 0.7 to 0.8 and 0.8 to 1.1 micrometers. The ground resolution of Landsat MSS images is 80m. The Landsat Thematic Mapper (TM) provides imagery in seven spectral bands, covering the visible and near, middle and thermal infrared parts of the electromagnetic spectrum. TM has a 30 m ground resolution for all bands except Band 6, which has a 120 m resolution. Its ground swath is 185 kilometres. The ETM+ sensor on Landsat-7 is similar to the earlier TM, but adds an extra 15 m resolution panchromatic band, and improved resolution for the thermal-infrared band (60-m). The IRS P6 LISS-III has four spectral bands, three in the visible and near infrared and one in the short wave infrared (SWIR) region. The new feature in the LISS-III camera is the SWIR band (1.55 to 1.7 microns), which provides data with a spatial resolution of 23.5 m. Its ground swath is 141 kilometres.

Table 4.2: Characteristics of optical sensors of the satellite images used in the study

Satellite	Sensor	Band	Resolution (m)	Swath width (km)	Path and Row
Landsat 1, 2, 3	MSS (Multi-spectral Scanner System)	0.5 – 0.6 μm 0.6 – 0.7 μm 0.7 – 0.8 μm 0.8 – 1.1 μm	80	185	148/42 and 148/43
Landsat 4, 5	TM (Thematic Mapper)	0.45 – 0.52 μm 0.52 – 0.60 μm 0.63 – 0.69 μm 0.75 – 0.90 μm 1.55 – 1.75 μm	30	185	138/42 and 138/43

Satellite	Sensor	Band	Resolution (m)	Swath width (km)	Path and Row
		2.08 – 2.35 µm 10.40 – 12.50 µm	 120		
Landsat 7 (1998)	ETM+ (Enhance Thematic Mapper)	0.50 – 0.90 µm 0.45 – 0.52 µm 0.52 – 0.60 µm 0.63 – 0.69 µm 0.75 – 0.90 µm 1.55 – 1.75 µm 2.08 – 2.35 µm 10.40 – 12.50 µm	15 30 60	185	138/42 and 138/43
IRS-1D	LISS -III	0.52 – 0.59 µm 0.62 - 0.68 µm 0.77 - 0.86 µm 1.55 – 1.70 µm	23.5	127	
IRS-P6	LISS –III	0.52 – 0.59 µm 0.62 – 0.68 µm 0.77 – 0.86 µm 1.55 – 1.70 µm	23.5	141	109/53 (70% downward shift) 109/54 (60% down ward shift)

Each RADARSAT scene contains one channel of data and is produced by using a single microwave frequency known as the C-band (5.3 GHz frequency). The specification of RADARSAT Sensor images area given in Table 4.3. The sensor on the RADARSAT satellite transmits its microwave energy in a horizontal plane. The energy, which returns to sensor, is captured using the same polarization. This is known as an HH polarization system. Variation in the returned signal (backscatter) is a result of variations in the surface roughness and topography as well as physical properties such as moisture content. In this study, RADARSAT Standard Beam S7 images with a normal resolution of 25 m were used. The incidence angle of S7 images is 45 – 49 degrees and the swath width is 100 km.

Accuracy of the satellite images depends on the resolution of the images and also on the processing of the images. In Chapter 5, accuracy of the processed images will be discussed.

Table 4.3: Specifications of RADARSAT Standard Beam (S7) image

Satellite	Band	Beam Position	Normal Resolution (m)	Dimensions of Normal Area (km)
RADARSAT -1	C-band (5.3 GHz frequency)	S7	30 m	100 X 100

Each satellite image selected for the time series was collected during the dry season, when water levels are relatively low. To allow comparison between consecutive images, it is important that the river stage in each image is approximately the same. The water levels in Jamuna River at Bahadurabad station, Padma River at Baruria Station and Lower Meghna River at Chandpur station on the image acquisition dates are listed in Tables 4.4, 4.5 and 4.6.

Table 4.4: Water levels of Jamuna River at Bahadurabad station on image acquisition date

Image acquisition Dates	Image type	Water level at Bahadurabad (m)
21/2/1973	Landsat MSS	13.09
10/01/1976	Landsat MSS	13.54
22/02/1978	Landsat MSS	13.08
21/02/1980	Landsat MSS	13.53
05/02/1983	Landsat MSS	13.23
25/02/1984	Landsat MSS	13.11
25/02/1985	Landsat MSS	13.49
07/02/1987	Landsat MSS	13.3
28/02/1989	Landsat TM	13.94
08/03/1992	Landsat TM	13.76
25/01/1994	Landsat TM	13.61
28/01/1995	Landsat TM	13.07
31/01/1996	Landsat TM	13.53
18/021997	Landsat TM	13.26
05/02/1998	Landsat TM	13.01
23/01/1999	Landsat TM	13.52
19/02/2000	Landsat ETM+	13.56
28/01/2001	Landsat ETM+	13.36
24/02/2002	Landsat ETM+	12.96
08/03/2003	IRS LISS	13.30
16/02/2004	IRS LISS	13.16
17/01/2005	IRS LISS	13.49

Table 4.5: Water levels of Padma River at Baruria station on image acquisition dates

Year	Image Type	Water level at Baruria (m)
21/02/1973	Landsat MSS	2.51
10/01/1976	Landsat MSS	-
21/02/1980	Landsat MSS	2.00
25/02/1984	Landsat MSS	1.66
28/02/1989	Landsat TM	2.33
11/03/1993	Landsat TM	2.14
31/01/1996	Landsat TM	2.17
18/02/1997	Landsat TM	2.06
19/01/1999	Landsat TM	2.53
28/01/2001	Landsat TM	1.77
24/02/2002	Landsat TM	1.61
19/01/2003	Landsat TM	1.99
08/01/2005	IRS-P6 LISS III	2.33

Table 4.6: Water levels of Lower Meghna River at Chandpur station on image acquisition dates

Year	Image Type	Water level at Chandpur (m)	
		Low tide	High tide
21/02/1973	Landsat MSS	1.07	1.87
10/01/1976	Landsat MSS	0.85	1.19
21/02/1980	Landsat MSS	0.93	1.92
25/02/1984	Landsat MSS	0.8	1.15
28/02/1990	Landsat TM	0.82	1.3
11/03/1993	Landsat TM	0.84	1.92
18/02/1997	Landsat TM	0.64	1.41

Year	Image Type	Water level at Chandpur (m)	
		Low tide	High tide
19/01/1999	Landsat TM	1	1.85
28/01/2001	Landsat TM	0.93	1.86
19/01/2003	Landsat TM	-	-
08/01/2005	IRS LISS	-	-

4.2.2 Band Selection

Careful consideration was given to selecting the bands from the sensors for use in the study. The bands selected for the various sensors have very similar bandwidths in the visible and infrared portions of electromagnetic energy, making it easier to interpret the images visually and identify the morphological features, thus bringing consistency in the dataset. Basically, the infrared, red and green bands were used from all the optical sensors. This band composition, which gives a colour-infrared composite, was found to be useful for land/water delineation. Figure 4.2 shows the bandwidth of the visible and infrared bands used from the different sensors. For the MSS images, bands 4, 5, and 7 were used for the study, while for the TM, ETM+ and LISS III images, bands 2, 3, and 4 were used.

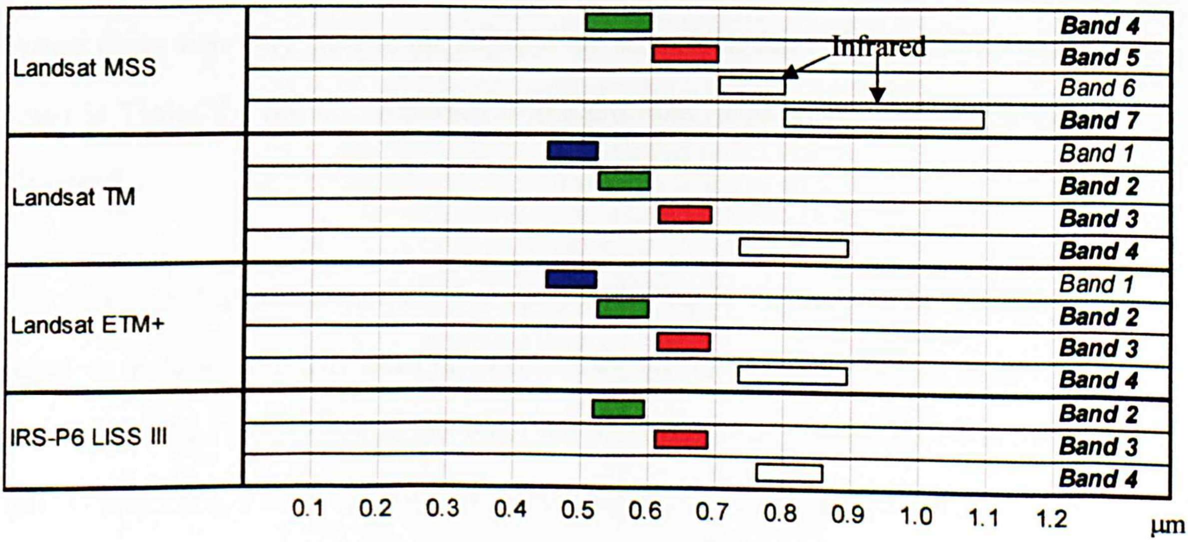


Figure 4.2: Band width of visible and infrared bands for different optical sensors

4.3 Corona photographs and map of 1953

Corona reconnaissance satellites were operated under a CIA program with substantial assistance from the US Air Force. CORONA was the codeword, not the acronym of the project. These satellites were used for photographic surveillance of the Soviet Union, China and other countries from June 1959 until May 1972.

The Corona satellites used 9,600 m of special 70 mm film with a 0.6 m focal length lens. Initially, the cameras could resolve images on the ground down to 7.5 m. Later, the resolution of the photographs was improved to 2.75 m and then 1.8 m, as the satellites used a lower altitude pass. The photographs were officially secret until 1992, but on February 22, 1995 the photographs taken by the Corona satellites were declassified.

CEGIS received the Corona photographs in digital form from Mr. Tetsuya Takagi of the University of Tokyo, Japan in 2003. He received the positive film from the US Geological Survey and scanned it into digital images with a 10 m ground resolution (Takagi *et al.*, 2007). The photographs covered a major part of Bangladesh including the courses of the Jamuna and Padma rivers. The width and length of the frame of each photograph are 20 km and 120 km, respectively. The photographs were taken in March 1967, when the stages in the Jamuna and Padma rivers were very close to the stages at the acquisition dates of the satellite images as listed in Tables 4.4 and 4.5. Accuracy of the processed photographs will be discussed in Chapter 5.

The Survey of Bangladesh published a topographic map at the scale of 1:50,000 in 1957, based on aerial photographs taken in 1953. Using the topographic map, the Jamuna River was digitised by FAP 1 (Flood Action Plan) and fitted to the Bangladesh Transverse Mercator (BTM) projection. FAP 1 and FAP 19 worked together to check the accuracy of the map, together with the accuracy of other historical maps covering the Jamuna River. As FAP 19 is the predecessor of CEGIS, a digital copy of the map was available at CEGIS. According to ISPAN (1995a), the accuracy of the 1953 map is very good and the map has been properly co-registered with the satellite images.

4.4 Cross-sectional survey

The Bangladesh Water Development Board (BWDB) established a river survey network covering major and minor rivers for the whole country in the mid-1960s (Figure 4.3). The network comprises 667 monumented river cross-sections, and the interval of the cross-sections is 6,436 m (4 miles). The cross-sections of the major rivers such as the Jamuna, Ganges, Padma and Lower Meghna are resurveyed every year. There are 144 such monumented cross-sections. The cross-sections of the medium to minor rivers are surveyed once in two to three years.

A standard cross-section of BWDB is defined by at least two monuments/pillars at one bank and one monument/pillar at another. Every cross-section has a fixed alignment, generally defined by its bearing with reference to the magnetic north. The monuments/pillars are erected at the river bank on the alignment of the cross-section. They are placed at a safe distance away from the river course on a relatively permanent bank, so that they may not be eroded frequently. Recently, the position of all the monuments/pillars at the standard cross-sections has been defined by geographical coordinates. Earlier, the horizontal position is defined by a description of the plot of land where the monument/pillar was placed. If a monument/pillar was lost due to river bank erosion or for other reasons, this made it very difficult to relocate its position with reasonable accuracy.

The survey starts from the monument/pillar on the floodplain towards the river. The cross-section line is set by a theodolite following the predetermined bearing. The elevation of land along the cross-section is measured by levelling and the distance is measured by measuring tape.

In the water part of a cross-section, the depth to the river bed is measured by echo-sounder on a powered boat. The water level is recorded simultaneously by two levelling instruments set on both banks just before the sounding begins. During sailing, the boat tries to maintain the alignment of the cross-section by following flags erected on high land along the line of the cross-section. The position of the survey boat in the river is determined using a sextant or theodolite. In the case of smaller channels, a sounding weight and rope are used for measuring water depth. While surveying the cross-section of the Jamuna River, a number of channels and islands are surveyed. The total length surveyed varies between 15 and 20 km, requiring 2 to 3 days for a team to complete each section. Initially, the cross-sections are set out to be perpendicular to the river axis or the direction of the main flow in the river, but after a few years the river axis and/or direction of the main flow may have changed. Thus, the cross-sections are no longer perpendicular to the axis of the river or to the direction of the main flow. As the alignment of the cross-section deviates from being orthogonal to the axis of the channel or the direction of the main flow, estimates of the flow area or conveyance capacity of the section will become less and less accurate.

During the 1990s, the reliability of BWDB cross-sectional surveys in the Jamuna, Ganges and Padma rivers was checked by different studies (Halcrow *et al.*, 1994; Delft Hydraulics and DHI, 1996a, 1996b, 1996e). It was discovered that errors have been generally introduced in the vertical and horizontal data for many sections due to errors in the datum elevation and position. Halcrow *et al* (1994) recommended that the results of the analysis of cross-section surveys should be used cautiously and considered as being qualitative only.

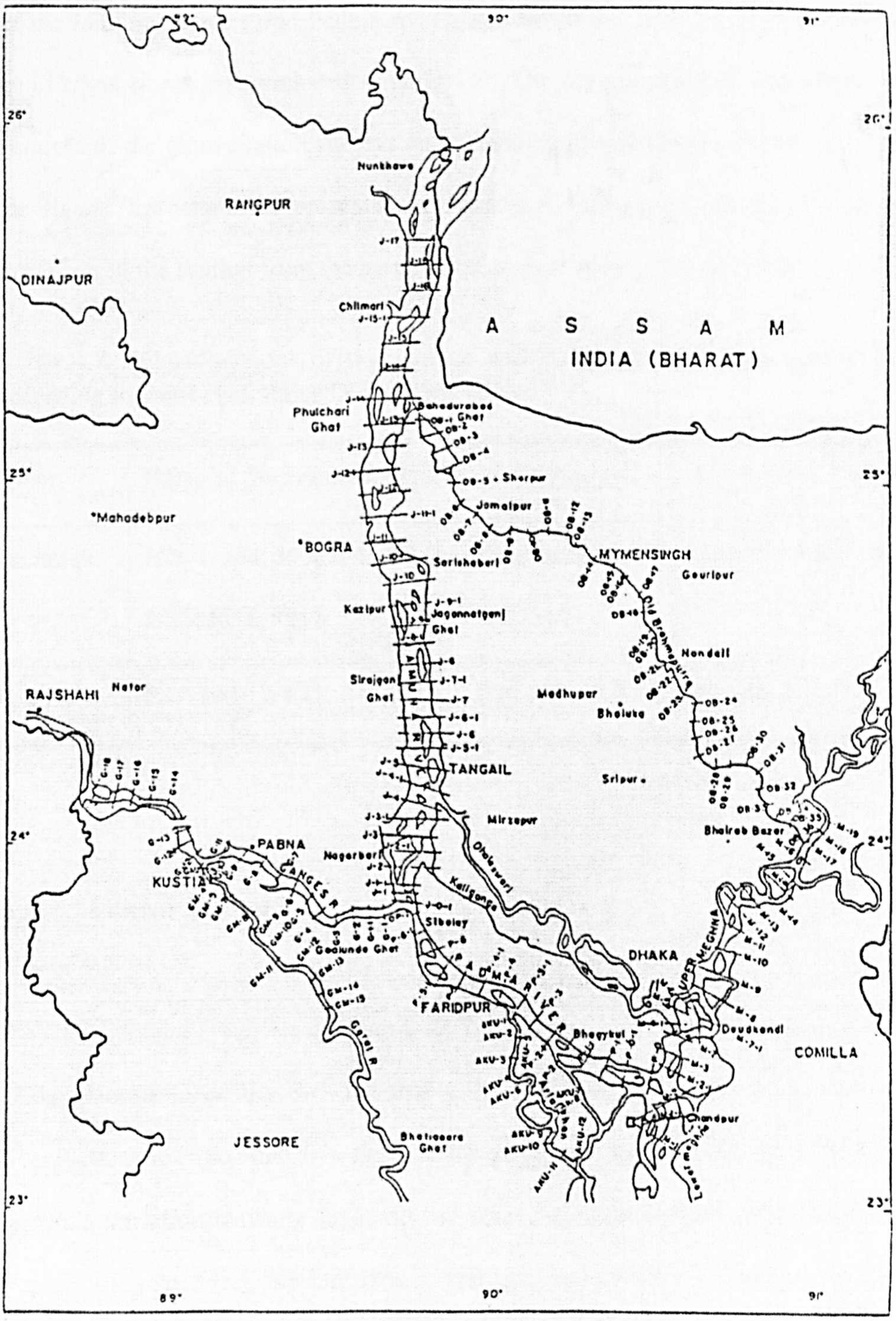


Figure 4.3: BWDB's cross-sectional survey network in Bangladesh

Delft Hydraulics and DHI (1996a and b) checked horizontal and vertical controls of the cross-section surveys as well as the history of the monuments and pillars. They used satellite images for checking the horizontal shifting of the cross-section surveys and how perpendicular the cross-sections were to the channels. After their analysis they published a list of those cross-sections and surveys that could be used with confidence to assess the attributes of the Jamuna, Ganges and Padma rivers. The list of the good quality surveys in the Jamuna and Padma rivers is reproduced in table 4.7. The present research also checked the vertical controls of the cross-section surveys and investigated whether they were the perpendicular to the river. The details are presented in Chapter 5. Only good quality surveys with a small deviation of the section from the perpendicular were used in the research.

Table 4.7: Cross-sections of the Jamuna and Padma rivers which were of good quality according to Delft Hydraulics/DHI (1996a & b)

River	Name of the cross-sections
Jamuna	J#2_1, J#4, J#5, J#6, J#6_1, J#7, J#8, J#9, J#10_1, J#11, J#12_1, J#13, J#14_1, J#15, J#16, J#17
Padma	P#1, P#1_1, P#2, P#3, P#3_1, P#4, P#4_1, P#5, P#6, P#6_1, P#7

4.5 Water Level

BWDB maintains water level gauging stations in the main or minor rivers covering the whole of Bangladesh. Generally, wooden staff-gauges are used to measure water levels (Figure 4.4). Observations are recorded five-times a day at regular intervals between 06:00 to 18:00 hrs. Seasonal variation in water levels in the main rivers of Bangladesh is 4 to 7 m. With the changes of water level, the locations of staff-gauges change by distances of a few metres to several hundred metres. Also, due to bank erosion or non-accessibility of the gauge site during the summer monsoon, the location of the gauge may also change at the scale of kilometres. During the shifting of a water-level gauge, the two gauges are read and recorded simultaneously and a relation is established between the old and new locations.

Wind waves reduce the accuracy of the water level data. Also, repeated shifting may loosen the fittings that hold the staff-gauge to the anchor pole, or could introduce other errors. The result of relocation errors may be gradual or sudden shifts in the measured water level that are not real. Further error may introduced in the anchor pole that is used to tether a survey boat. However, checking of the gauge level datum from a nearby datum is carried out weekly or fortnightly, so that error should be detected quickly. Water level corrections are carried out as necessary at the field office before the data are transferred to Dhaka for processing and archiving.

BWDB maintains about 19 water level gauging stations along the Jamuna River. These stations have records stretching back several decades. For example, the records at Bahadurabad go back to the 1950s and data from this gauging station from 1960 onwards have been used in the study.

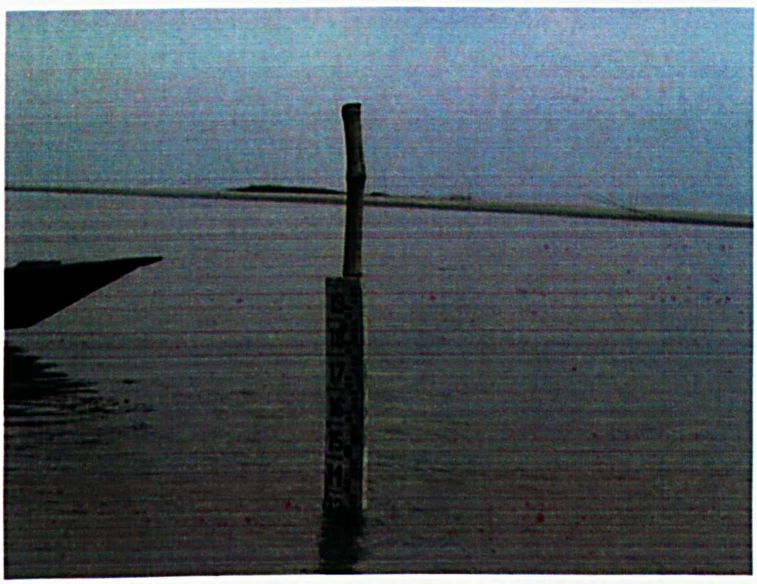


Figure 4.4: Wooden staff gauge used by BWDB to measure water level

4.6 Discharge

When stream gauging, BWDB use Ott current meters to measure flow velocity (Figure 4.5). This is a one-directional current meter deployed from a survey boat. The direction of flow at the water surface is determined at each measuring point by tracking a floating bottle using a sextant. At each vertical, the velocity is measured at 0.2 and 0.8 of the depth. A depth-averaged velocity is determined by the Straub method. The measuring time in each point of the vertical is 100 seconds. To determine the discharge, BWDB uses the velocity-area method. During the flow measurement the survey boat is dynamically positioned. Its location in the transect is determined by sextant. The suspension cable is used to determine the depth of the current meter in the vertical. Measurements are taken at several verticals, the number of which varies with flow stage. Generally, the area represented by one vertical should not convey more than 10% of the flow in a channel. In a braided river like the Jamuna, flow measurements are carried out at several tens of verticals. It takes about two days to complete one discharge measurement in the Jamuna River.

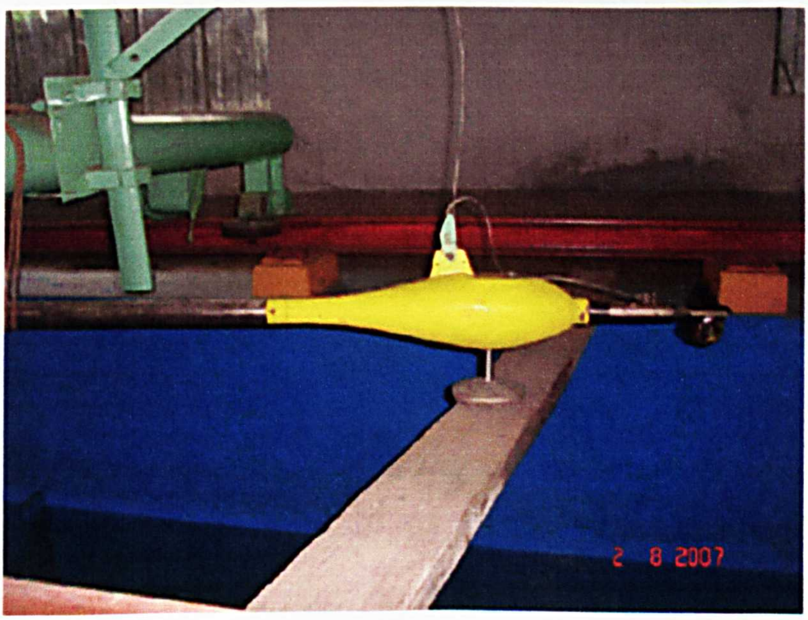


Figure 4.5: Ott current meter used by BWDB to measure flow velocity for stream gauging

Discharge measurements are carried out weekly during the summer monsoon and fortnightly during the dry season. Stage-discharge rating curves are prepared by relating the measured water level and discharge every year. The relation changes every year due to changes of the morphology of the river reach containing the gauging section. The rating curves are used to estimate the daily discharge, with the daily data aggregated to derive monthly, seasonal and annual values.

Several types of error may be introduced during the measurement of the discharge. These include: instrument errors, errors in the time allowed for measurement of each point velocity, and variability in the number of points in the vertical and number of verticals used in the cross-section. Besides these, errors may also be introduced due to the use of the one-directional Ott current meter in a highly 3-dimensional flow field and in measuring the position of the survey boat using a sextant.

During the summer monsoon, water levels in the Jamuna River may fluctuate by 50 to 80 cm daily. It takes about two days to measure the discharge in the Jamuna River and BWDB takes the average of the gauge reading at the beginning and end of the measurement period to represent the river stage for the gauged discharge. Clearly, fluctuations in stage and discharge during the gauging procedure introduce uncertainty into the recorded data. Also, the development and movement of bedforms during the summer monsoon and hysterisis effects during the rising and falling limbs of the monsoon hydrograph substantially change the hydraulic characteristics of the river. Coleman (1969) pointed out that until the mechanics and patterns of bedform movement are more thoroughly documented, any discharge measurement in the Jamuna must be treated as an estimated approximation.

River Survey Project (FAP 24), a component of the Flood Action Plan, jointly measured discharges at eight different transects of the Jamuna, Ganges and Padma rivers in 1995 (Delft Hydraulics and DHI, 1996f). FAP 24 used sophisticated equipment such as Acoustic Doppler Current Profilers (ADCP) and Differential Global Positioning System (DGPS) for measuring the flow velocity and the position of the survey vessel respectively. BWDB uses different equipment as mentioned earlier for measuring these parameters. Delft Hydraulics and DHI (1996f) compared the measurements and found that BWDB measured higher discharges than FAP 24, varying from – 3 to +13%, because of differences in the measurement of the width of transect, depth of the vertical sections, flow velocity and angle of flow direction.

BWDB has been measuring the discharge of the Jamuna River at Bahadurabad Transit since 1956. This is the only discharge gauging station in the Jamuna River. There were three other discharge gauging stations along the river, but measurements at these stations have only been performed for periods of 1 to 3 years. Hence, only long-term discharge data for the Jamuna River measured at Bahadurabad have been used in this research.

BWDB also measures the discharges of some of the major tributaries and distributaries of the Jamuna River. In this context, Mymensingh is a discharge gauging station on the Old Brahmaputra River from which data have been used in this study.

4.7 Bed material samples

The BWDB used the Kolb bed sampler to collect samples of the river bed material. The instrument is made up of two, spring operated jaws. It is lowered to the river bed using suspension cables. When the sampler reaches the bed, tension in the spring is released, allowing the jaws to snap shut and pick up a sample of the river bed material. The samples are retrieved, stored in a plastic bag and sent for grain size analysis.

For many years, BWDB collected bed material samples for grain size analysis from the river bed during every routine discharge gauging and whenever measurements were made of the suspended sediment load. Generally, five to six samples were collected during each measurement transect. However, after 1977, BWDB ceased collection of bed material samples on a regular basis.

Various studies have collected and analyzed bed material samples for project-related purposes at different times from the Jamuna River. During the survey of inland waterways and ports about 15 samples were collected from the river and analyzed by NEDECO (1967). NEDECO presented grain size distribution curves and values of the D_{90} (size for which 90% of the sample was finer). Values of D_{50} ranged from 0.02 to 0.33 mm.

During the appraisal study for the Jamuna Multipurpose Bridge, RPT *et al.* (1987) prepared an inventory of existing bed material samples from the Jamuna River between Chilmari and Aricha for the period 1965 to 1977. The Brahmaputra Right Embankment Project collected 95 samples downstream of Sirajganj in 1990. The average D_{50} of the samples was 0.15 mm (Delft Hydraulics and DHI, 1996g).

In 1993, River Survey Project (FAP 24) collected 138 bed material samples from the Jamuna River - 104 from Bahadurabad and 34 from Sirajganj. The average D_{50} of the samples from Bahadurabad was 0.20 mm and that from Sirajganj was 0.19 mm.

4.8 Sediment concentration

The BWDB measures the concentration of suspended sediment transport at some locations along the main rivers of Bangladesh. It does not measure the bed load transport. In sampling suspended sediment transport, the standard instrument used by the BWDB is the Brinkley silt sampler. This point sampler consists of three short brass cylinders of about 10 cm in diameter in line and connected to each other by rubber sleeves (Figure 4.6). The Brinkley Sampler has a tail unit to keep the instrument pointed into the stream. The instrument is deployed using a suspension cable and it is raised and lowered by means of winch. After trapping one litre of water and suspended sediment, the Brinkley sampler is raised to the surface, opened and emptied into the conical elutriator, thus separating the sand and silt/clay fractions of the sample. BWDB divide the suspended sediment samples into two fractions: the suspended bed material load or sand fraction with particle diameter larger than 0.063 mm, and the wash load or silt and clay fraction, with particle diameter smaller than 0.063 mm. As wash load plays a minor role in channel adjustments compared to that played by the bed material load, only the suspended bed material fraction of the measured load has been considered in this study.

Sediment transport measurements are generally made in conjunction with discharge measurements, with point samples of suspended sediment being collected at each alternate vertical assigned for flow velocity measurements. Sediment samples are taken at just one point at a vertical, at a relative depth of 0.6, it the local depth is less than one metre and at relative depths 0.2 and 0.8 if the local depth is more than one metre.

Figure 4.6: Brinkley Silt Sampler used by BWBD for sampling suspended sediment

BWDB began collecting sediment samples in 1956. Initially, sediment samples were taken by simply filling a normal bottle with a sample of river water and suspended sediment. The data generated related only to total measured suspended load, with no attempt to separate this into sand and silt/clay fractions representing the bed material load wash load, respectively. From 1965 onwards, BWDB began collecting suspended sediment samples using the Brinkley Silt Sampler and to report the wash load and bed material load separately for a number of locations along the major rivers of Bangladesh. This study used the post-1965 measured suspended bed material loads at the Bahadurabad gauging station on the Jamuna River.

The quality of measured sediment load data depends on the instrument used, the gauging procedure employed and natural variability at the gauging location. The Brinkley sampler collects an instantaneous sample of water and sediment when its nozzle is opened. However, in the highly turbulent flow in a river like the Jamuna, the flux of water and sediment at a point varies widely. This means that there is room for considerable uncertainty concerning how well a single, instantaneous sample can represent the time-averaged sediment concentration at any point in the river. However, the BWDB have chosen to continue using the Brinkley Silt Sampler even though more sophisticated and accurate devices have emerged since 1965. While this limits the quality of the data it, does at least mean that uncertainties associated with changes of equipment have been avoided and a consistent database covering a long period has been accrued.

BWDB measure the depth at which the suspended sediment sample is taken based on the length of the suspension cable. During high stages, the deflection angle of the cable from the vertical increases and these result in sampling at shallower sample depths than those indicated by the length of cable that has been deployed. This implies that the true rate of sediment transport is likely to be underestimated during the summer monsoon. Delft Hydraulics and DHI (1996h) mentioned that in the 1960s BWDB used to take steps to reduce the deflection angle, but that this practice was not kept up.

The sediment transport rate calculated from samples taken at one or two points in each vertical and at points that are relatively widely-spaced across the river are subject to errors associated with natural variability in the channel morphology at the gauging location. As BWDB measuring transects are fixed and are independent of changes in the local morphology, this also introduces uncertainty in the measured data.

Like the discharge measurement, FAP 24 measured sediment concentration with BWDB at several verticals in the Jamuna and Padma rivers in 1995 (Delft Hydraulic and DHI, 1996f). FAP 24 used a pump bottle sampler and measured the sediment concentrations at a relative depth of 0.2 and 0.8 at the verticals. BWDB used the Brinkley Silt Sampler during their measurements. Comparison of the measurements showed that BWDB measured sediment (sand fraction) concentration very close to that measured by FAP 24 when the flow velocity was less than 2 ms^{-1}. When the flow velocity was higher than 2 ms^{-1}, BWDB measured much lower concentrations. Delft Hydraulics and DHI (1996f) concluded that BWDB's measurement reflects much lower sediment transport than the river actually carries.

Chapter 5
Methodology

5.1 Introduction

Spatial resolution of the satellite images used in the research varies from 80 m to 24 m. Satellite images are being used to study the morphology of the Jamuna, Padma and Lower Meghna rivers of Bangladesh (Bristow, 1987; Thorne *et al.* 1993; Thorne and Russel, 1993; Klaassen and Masselink, 1992; Halcrow *et al.*, 1994; ISPAN, 1995a; Consulting Consortium FAP 21/22, 1993; EGIS, 1997; EGIS, 2002b, Takagi *et al.*, 2007). Annual channel changes exhibited through the movement of anabranches and the rates of bank erosion in these rivers are very large compared to the resolution of the images, making it possible to investigate morphological processes using remote sensing. However, to result in a reasonable level of accuracy for the coarser images, scenes taken two to three years apart were used when investigating channel changes for the images of 80 m spatial resolution. The temporal resolution of the images was reduced to one or two years for images with a spatial resolution of 30 to 24 m.

CEGIS have the archives of processed and geo-referenced images covering the main rivers of Bangladesh. These images are regularly procured, processed, geo-referenced and classified to study a range of morphological aspects of the rivers of Bangladesh by different projects and researchers. Therefore, the processed and geo-referenced images were used in this study to delineate the bank lines, estimate the width and measure the braiding intensity of the study rivers. CEGIS also use RADARSAT images for monitoring summer monsoon floods. These images have been processed, georeferenced and classified by CEGIS and were also used in this research project to assess the stage dependency of braiding intensity.

In addition to the satellite images, several types of hydro-morphological data were also used in the research, including cross-section surveys, water levels records from stage boards, gauged discharges, rainfall records, measurements of bed material size and measured bed material loads. Several past studies and projects (Klaassen and Vermeer, 1988; RPT *et al.*, 1987; CBJET, 1991; Thorne *et al.*, 1993; Delft Hydraulics/DHI, 1996a, 1996b and 1996c) have analysed cross-sectional survey data for different purposes, such as determining the braiding index, assessing the movement of the channel centre line and estimating channel dimensions. In this research, cross-sectional survey data were used to assess changes in the flow area below the bankfull stage in the Jamuna and Padma rivers. Checking the quality of the data has been shown to be crucial to producing reasonably accurate results. Hence, in this study only cross-sectional survey data whose quality had been assured in earlier studies were used and further quality checking of the cross-sectional data was performed using the satellite images.

Water level and discharge data were used to perform a specific gauge analysis for the Jamuna River at Bahadurabad. The purpose of the specific gauge analysis was to assess changes in the bed elevation through time. This specific gauge analysis drew on and further developed the earlier analyses undertaken by CBJET (1991), Halcrow *et al.* (1994), and Zhou and Chen (1998). The discharge records were also analysed to establish whether there is any trend of change in the runoff draining through the study rivers.

Sediment rating curves were derived to relate the sediment load to the water discharge at each of the gauged transects of the rivers. This work also built on earlier results from past studies by CBJET (1991), Halcrow *et al.* (1994), Zhou and Chen (1998) and Delft Hydraulics and DHI (1996h), each of which derived sediment rating curves for the Jamuna River. In this respect, the study by Delft Hydraulics and DHI (1996h) is particularly important as it presents a comprehensive appraisal and analysis of BWDB sediment data performed to study the sediment balance in the main rivers of Bangladesh and the sediment rating curves developed for the Jamuna River by Delft Hydraulics and DHI were adopted for use in this research project.

Detailed methodologies employed in analysing the data obtained from various sources and studies are described in the following sections.

5.2 Processing, geo-referencing and classifying satellite images

5.2.1 Processing

Processing and analysis of the satellite images were performed using standard image processing software provided in ERDAS IMAGINE. ArcGIS and ArcView GIS software were used for vector analysis. All the digital satellite data were in their original form on tape or CD and were imported into a digital image processing system. After reading the images into the computer, they were pre-processed to remove data errors and anomalies. Image enhancement techniques were applied to make important features of raw, remotely sensed data more easily interpretable to the human eye.

5.2.2 Georeferencing

Each of the satellite images was georeferenced. Geo-referencing requires the collection of ground control points (GCPs) or reference points: features on a ground or on a map which can be identified on the satellite image and for which the ground coordinates are known.

Satellite images of the Jamuna Rivers acquired between 1973 and 1997 were georeferenced using a set of reference points taken from 1:50,000 high-resolution color maps of SPOT satellite images acquired in 1989. Permanent features, such as road intersections, airport runways or large buildings were selected on the SPOT maps and used as reference points. Since there are few such features within the river corridor, and this is especially true for reference points that can be identified on the lower resolution MSS images, other features such as ponds and uniquely shaped water bodies were used. Twenty five or more GCPs were used in each pair of satellite images to georeference the river corridor area. For each reference point, the ground coordinates were obtained from the SPOT maps and entered into a data file together with the input coordinates of the same reference point identified in the digital satellite image. The coordinate pairs were used to compute a first order transformation matrix, which was applied to the entire digital satellite image to compute rectified coordinates for each image pixel. For each image transformation, a root mean square (RMS) error was calculated: a measure of the accuracy of the georeferencing procedure. The maximum RMS error was 1.2 pixels for the MSS and 1.5 pixels for the TM images; this corresponds to a ground distance of 96 m and 45 m for the MSS and TM images, respectively.

The satellite images acquired between 1998 and 2005 were georeferenced using previously georeferenced satellite images taken in 1996. For each satellite image, a set of GCPs was taken from the georeferenced image of 1996, which in turn were georeferenced using ground control points from 1:50,000 color maps derived from 1989 high resolution SPOT satellite images. For each GCP, the map coordinates were obtained from the satellite image of 1996 and entered into a data file together with the file coordinates of the same GCP identified in the digital satellite image. Twenty five GCPs were used for georeferencing the river corridor area in each pair of satellite images. The RMS error was 1 pixel, which is a ground distance of 30 m.

In georeferencing the Corona photographs, individual scenes were first co-registered with the reference of overlapping areas in another scene. Then each individual image was geo-referenced using as a reference DGPS corrected, IRS Panchromatic image with 6m spatial resolution. To join individual geo-referenced images together to form a larger image, a process known as 'mosaic' was conducted. Finally, the mosaic image was geo-referenced using the Landsat TM mosaic image.

Errors up to 6m (equivalent to 1.0 pixel of IRS panchromatic image) were found in the reference DGPS corrected image, while errors of 15m (equivalent to 0.5 pixels) were found in the Landsat TM mosaic image.

Using this procedure, each raw satellite image of the Jamuna, Padma and Lower Meghna rivers was resampled, using the nearest neighbor algorithm, and transformed into a file referenced to the Bangladesh Transverse Mercator (BTM) projection. The BTM projection, described by ISPAN (1992), has the following features:

Ellipsoid	:	Everest 1830
Projection	:	Transverse Mercator
Central meridian	:	90 ^{0}E
False easting	:	500,000 m
False northing	:	-2,000,000 m

RADARSAT images were geo-referenced after removing the speckle noise. To remove speckle noise, the coefficient of variation was first calculated using 3 X 3 windows and later it was used as a parameter for Gama-MAP filtering. After the speckle noise was removed, a set of 35 reference points was collected from georeferenced images taken in 2004. Finally, the RADARSAT images were transformed into the BTM coordinate system. The cubic convolution method was used to transform the image grid system to the referenced grid system for all RADARSAT images.

Coordinate matching was checked between images of different years. The differences in the coordinates of a feature were found to be within one pixel. This is crucial to accurate bank line delineation and change detection. After georeferencing, the upper and lower images were spectrally enhanced and digitally mosaiced together to form one file covering the entire Jamuna river corridor.

5.2.3 Classification

The digital satellite images were classified using image processing techniques to enable the assignment of land cover classes to areas with similar spectral characteristics. For each of the eight Landsat MSS satellite image pairs, the procedure involved stretching and scaling the range of digital values by histogram matching to the 1976 image for Jamuna river. This modification of the data resulted in images with similar spectral characteristics which simplified classification and interpretation of the historic images. A series of tests was carried out using statistical clustering to derive a set of signatures that was used to classify the images. The tests were successful for seven of the eight MSS images of the Jamuna River, but the 1980 MSS image of the Jamuna River had to be classified using a slightly different signature.

Each Landsat TM, ETM+ and LISS III image of the Jamuna, Padma and Lower Meghna rivers was classified independently using an iterative classification procedure. An unsupervised classification algorithm was used to derive signature statistics which were examined by an image processing analyst, modified as appropriate and used with a maximum likelihood classifier. Results were examined and acceptable classes were assigned to land cover categories. Image pixels corresponding to inadequate classes were digitally extracted, resubmitted to the unsupervised clustering routine and reclassified.

Four broad land cover classes were assigned to each of the 13 image pairs acquired between 1973 and 1996 in the time series of the Jamuna River: water, sand, cultivated land and vegetated land. The image dates between 1997 and 2005 were classified into three broad classes: water, sand and land (including cultivated/vegetated land). These broad classes were used in other elements of the EGIS project and were successfully used in the predecessor project, Flood Action Plan 19 (Geographic Information System), for mapping land cover in a similar study of the Brahmaputra-Jamuna River (ISPAN, 1995a). Satellite images of the

Padma and Lower Meghna rivers were classified using similar techniques to those described above.

For classification of RADARSAT images, a field trip was carried out on the image acquisition date in order to collect information on ground conditions. The focus of this trip was to identify, map and monitor homogeneous areas of permanent water, seasonal water bodies and land uses. The geographic position of the field polygons was established using GPS. Photographs were also taken, focusing on the area within these field polygons and their surroundings. Using the field polygon sites of water bodies a *Digital Number* (DN) value or threshold value was selected. The pixels having DN values less than the threshold value were then classified as "Open water extent" and those greater than the threshold value were classified as "*Others*".

The accuracy of the satellite image classification was considered and, although it was impossible to assess the historic images which date back to 1973, a field programme was planned for assessing the 1996 data from the Jamuna River. Unfortunately, it was not possible to conduct the field effort in the months following the January 31 data acquisition date due to political disturbances and strikes. However, since the image processing techniques and land cover classes used were very similar to those developed in an earlier river morphology study, the extensive field assessment carried out in 1992 should be indicative of the accuracy expected under the present study. The 1992 field effort, as described by ISPAN (1995a), involved several visits to the Jamuna River where fluvial processes, land cover, and agronomic practices were observed and documented. Two hundred and forty five sites along the entire course of the river within Bangladesh were visited. An overall accuracy of 88 percent was found for three broad classes: water, sand and land. The accuracy of classification of RADARSAT images was found to be 85% for "*Open water extent*".

5.3 Delineation of bank line

Planform development of a very large and dynamic river like the Jamuna and Padma rivers can be studied using maps and time-series satellite images having a coarse resolution (80m X 80m or 30m X 30m). In using satellite images to study planform development, bank line delineation is an important task. Delineation of the bank lines of a braided river is not a straight forward activity. It is easy to delineate bank line along an eroding bank, but the presence of attached islands and marginal sub-channels often make it difficult to delineate the bank line in a consistent manner.

In this study, the bank line is defined as the line that separates the floodplain from the river channel. The channel of a braided river includes channels, sand bars and vegetated islands within the braid belt. Where a large anabranch channel within the braided river flowed along the edge of the floodplain (typically ranging in width from a few hundred metres to several kilometres), bank line delineation is simple and uncontroversial. However, where smaller sub-channels flow next to the bank, the sub-channel width, length, flow direction and meandering characteristics must be considered when deciding whether to include it within the bank line or treat it as a channel formed in the floodplain.

The Environment and GIS Support Project (EGIS) developed criteria for delineating bank lines of the Jamuna River using Landsat MSS (80m X 80m) and TM (30m X 30m) images (EGIS, 1997 and Hassan *et al.*, 1997). A team of consultants and experts from the EGIS project and Bangladesh University of Engineering and Technology (BUET) defined bank line delineation criteria for the Jamuna River to ensure consistent interpretation. These criteria were used for delineating the bank lines of the Padma and Lower Meghna rivers. The criteria are as follows (Hassan et at., 1997):

1. If a sub-channel offshoots from the braided river but redirects its course to rejoin the main river downstream and thus remains part of the braided channel system then the channel is considered to be within the Jamuna bank line.

2. If a channel is less than 100 m in width, it is most often not considered to be within the banklines of the Jamuna, i.e. the channel separating an island char from mainland floodplain should be wider than 100 m.

3. If a channel has a meander radius less than 1 km then it is not included within the banklines.

4. If a sub-channel offshoots from the braided river and takes a different course, i.e. it does not return to the main river, then the land between the channel and the river is considered to a part of the floodplain and hence the offshoot channel is not included within the banklines.

5. Crevasee splays (silts and clays deposited by over bankflows) have signatures in the image that are somewhat similar to that of attached sand bars, but are actually part of the floodplain and are thus not included with the banklines.

Keeping in mind that bankline movement is used to identify areas of erosion and accretion, a bankline should be delineated such that for an area to be shown as accreted it must have fully developed the characteristics of floodplain land as seen from the spectral signatures of the image. Similarly, for an area to have been eroded it must have lost most of its floodplain characteristics and should resemble a channel, an island or a braid bar.

There are other challenges in delineating banklines, especially around the confluences of tributaries such as the Teesta and Dharla rivers and at off-take areas of distributaries such as the Old Bramaputra and Dhaleswari rivers. Interactions between the multiple channels of the Jamuna River and the channels of the tributary or the distributary make it difficult to delineate the bank line.

The digital satellite images were displayed on a computer screen and digital bank lines were drawn following the above listed criteria in a GIS environment. The bank lines derived are shown in Figure 5.1. The coordinates of the right and left banks were derived from the intersections of the bank lines with east-west transects spaced at 500 m intervals along the entire Jamuna River.

Figure 5.1. Bankline drawn on satellite image of 16 February 2004

5.4 Estimating the river width

River width at a certain location is usually defined as the shortest distance between the right and left banks. However, EGIS (1997) determined the width of the Jamuna River in a different way. The Jamuna River is aligned almost due north-south. Hence, the width of the river was determined along east-west transects spaced at 500 m intervals, by subtracting the easting of the right bank from that of the left bank (Figure 5.2). EGIS also determined the width of the river from historical maps using the same method. This research adopted the width data for the Jamuna River at 500 m intervals as determined by EGIS (1997) from time-series satellite images from 1973 to 1996. The same method of width measurement was employed for the more recent years (1997-2005). The width of the Padma and Lower Meghna rivers was determined in a different way, as described later.

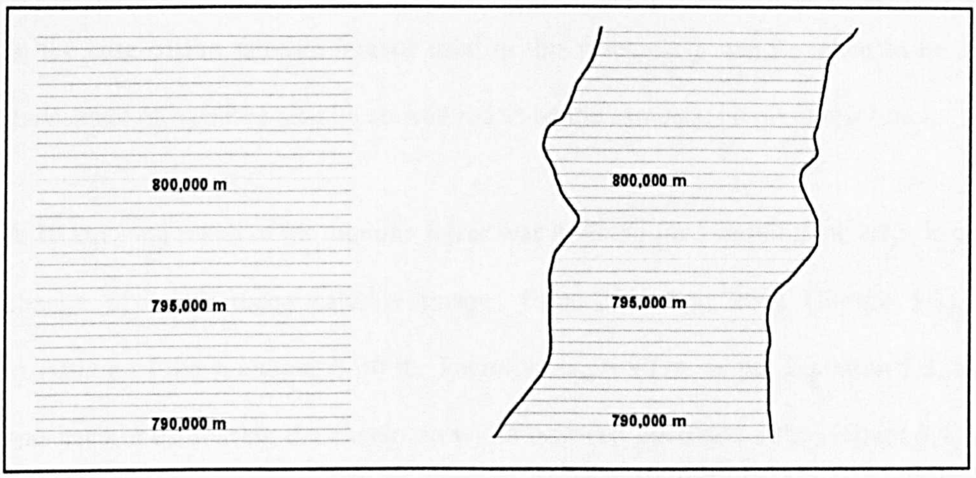


Figure 5.2: Method of estimating the river width

Mount *et al.* (2003) and Mount and Luis (2005) estimated the errors involved in calculating changes in bankfull width from temporally sequenced, raw and corrected aerial photographs. They also estimated the errors involved in calculating rates of river channel shifting from aerial imagery. Their approach to estimating errors in width change calculations can be applied to width calculations for the Jamuna River based on time-series satellite images despite the fact that the criteria used to delineate the bank lines in this research are different to those used by Mount *et al.* (2003).

According to Mount et al. (2003), error occurs due to:

(i) inability to locate the bankfull position precisely on each image, and
(ii) spatial distortions remaining in each image after processing.

The total absolute bankfull width measurement error (m) is expressed as follows:

$$e_w = \sqrt{2}pR + 2o \qquad (5.1)$$

where, p is the uncertainty in identifying bankfull in x direction (number of pixel columns) or y direction (number of pixel in y direction) and R is the pixel resolution. In case of the Jamuna River, the width was measured only in the x direction (Figure 5.2) and, therefore, the first term ($\sqrt{2}pR$) on the right hand side of Equation 5.1, must be replaced by pR to yield:

$$e_w = pR + 2o \qquad (5.2)$$

In the case of the satellite images used in this research, p can be taken to be one pixel and magnitude of o can be also be considered to be the same as the pixel resolution.

A 10 km long reach of the Jamuna River was selected for assessing the error in estimating the change of width using satellite images from 2000 and 2001 (Figure 5.3). The spatial resolution of these images is 30 m. Therefore, e_w = 90 m, as per Equation 5.2, and this value was used in estimating the change in width between 2000 and 2001 (Figure 5.4). In this case, the measured change greatly exceeds the total absolute measurement error, which accords with the finding by Mount *et al.* (2003) that measurements using satellite images are valid when annual changes in width are large – as they are in the Jamuna River.

In this study, aerial photographs taken in 1967 and 22 years of satellite images (from 1973 to 2005) were used to extract data for width. To confirm the presence of trends of change in width both at small and large-scales, width was analyzed for different reaches having different lengths. Initially, data were averaged for 20 km reaches. Later, the 200 km length of the Jamuna River was divided into 5 equal reaches. Reach-averaged widths are shown in Figure 5.3. The widths of the most upstream reach and the two reaches furthest downstream decreased initially, but then increased at a higher rate during the 1980s. The rate of increase then decreased from the 1990s onwards. Further analysis of the width of the river showed that the trend in width change in two, 100 km long, reaches were similar to that observed in the five, 40 km long reaches or in the eight 20 km long reaches. Full discussion of these findings follows in the next chapter.

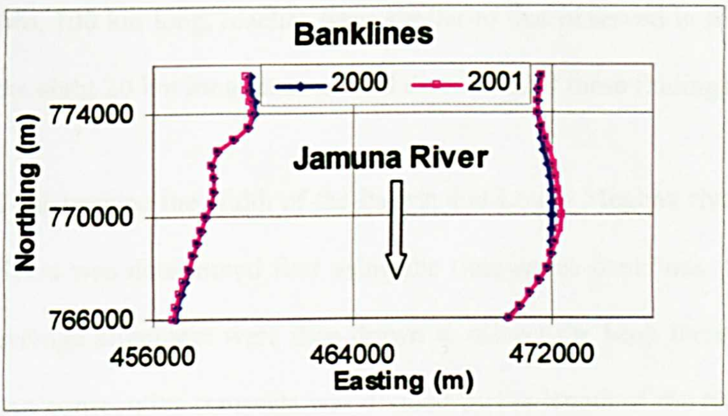


Figure 5.3: Bank lines of a short reach the Jamuna River as measured from satellite images of 2000 and 2001

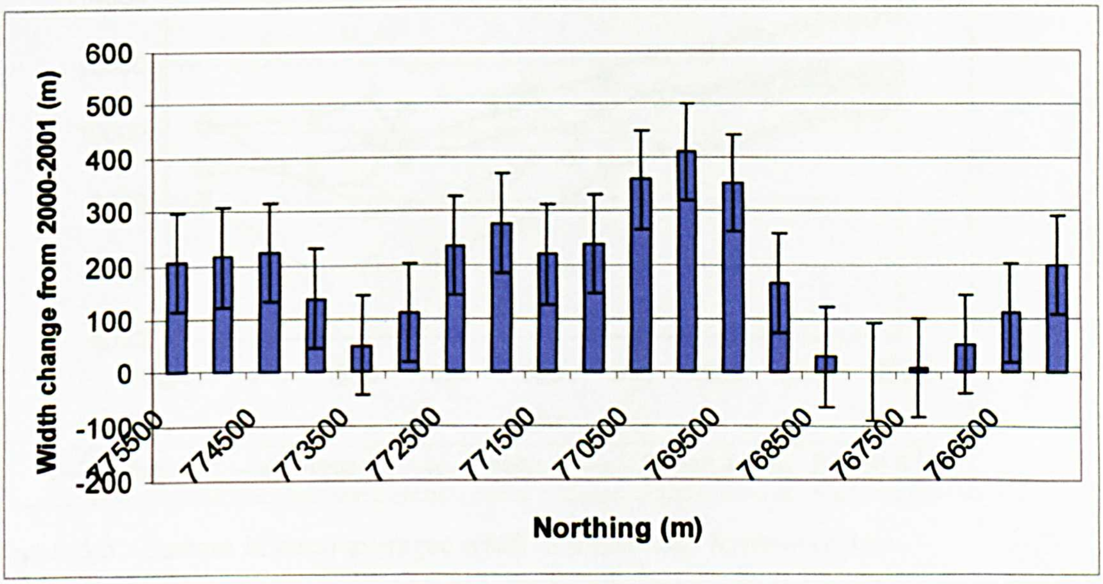


Figure 5.4: Changes in width of the reach of the Jamuna River as shown in Figure 5.3 at 500 m interval and with error bar as estimated using Equation 5.2.

In this study, aerial photographs taken in 1967 and 22 years of satellite images from 1973 to 2005 were used to extract data for width. To confirm the presence of trends of changes in width both at small and large-scales, width was analyzed for different reaches having different lengths. Initially, data were averaged for 20 km reaches. Later the 200 km length of the Jamuna River was divided into 5 equal reaches. Reach-averaged widths are shown in Figure 5.5. The widths of the most upstream reach and two downstream reaches decreased initially but then increased at a higher rate in the 1980s. The rate of increase decreased from the 1990s onwards. Further analysis of the width of the river showed that the trend in width change in two, 100 km long, reaches were similar to that observed in the five, 40 km long reaches or in the eight 20 km long reaches. Full discussion of these findings follows in the next chapter.

To determine the width of the Padma and Lower Meghna rivers, the average alignment of the rivers was determined first using the time-series banklines. Cross-lines perpendicular to the average alignment were then drawn to dissect the bank lines. The area within the banks and two consecutive transects was divided by the length of the river reach along the alignment to yield the reach-averaged width of the river (Figure 5.6). The results of this analysis are presented and discussed in the next chapter.

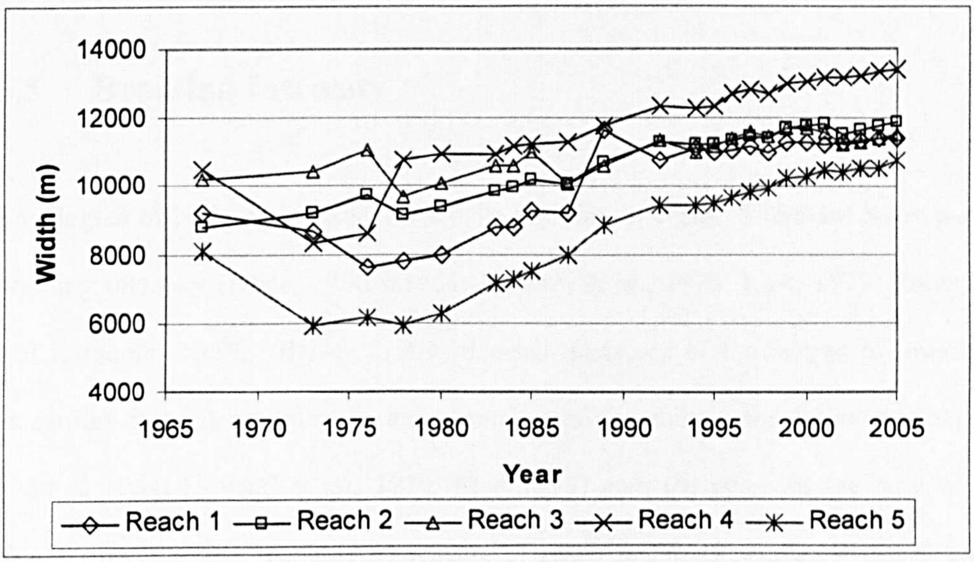


Figure 5.5: Changes in reach-averaged width of the Jamuna River over time

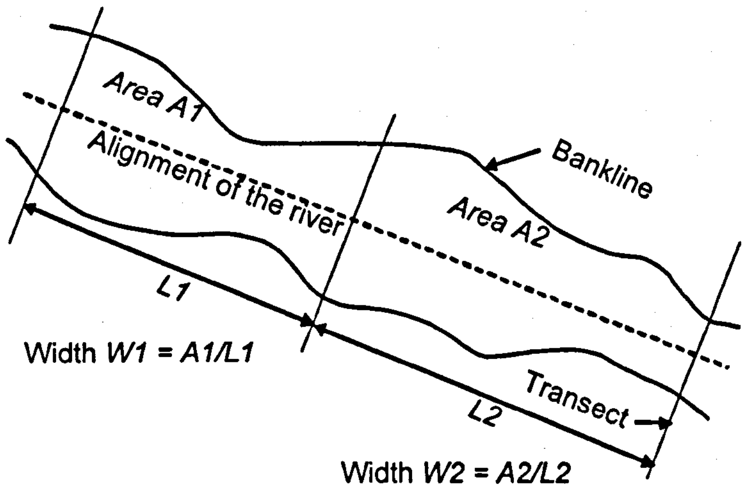


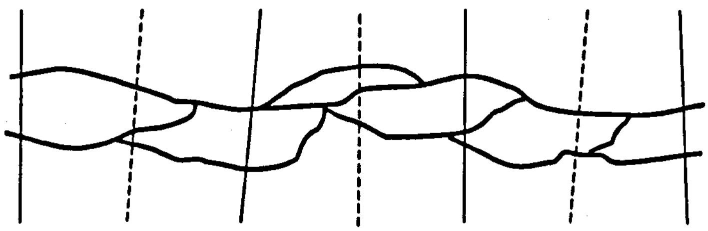
Figure 5.6 Definition diagram of reach-averaged width

5.5 Braiding Intensity

The degree of braiding is measured by the braiding intensity. There are many ways to define braiding intensity (Brice, 1960 &1964; Howard *et al.*, 1970; Rust, 1978; Robertson-Rintoul and Richards; 1993). Bridge (1993) divided measures of the degree of braiding into two categories that: (i) consider the mean number of channels in the active channel belt (Brice, 1960 & 1964; Howard *et al.*, 1970; Rust 1978) and; (ii) consider the ratio of the sum of channel lengths in a reach as a measure of reach length (Robertson-Rintoul and Richards; 1993). According to Bridge (1993) the first category is the better measure of braiding intensity.

The braiding intensity of the Jamuna River was studied by Klaassen and Vermeer (1998), Halcrow *et al.* (1994) and EGIS (1997). They all used time-series satellite images to estimate the braiding intensity, following the method suggested by Howard *et al.* (1970). This research also applied Howard *et al.*'s method to assess the braiding intensity of the Jamuna River. This facilitates comparison with the results of other studies.

The braiding index is measured as the average number of anabranches bisected by transects at each end and the centre of a reach (Howard *et al.*, 1970). Howard *et al.* (1970) were aware that the braiding index as defined by them is stage dependent. A rise in stage may submerge low bars and at the same time it may activate the ephemeral sub-channels. They suggested using photographs taken at near the median discharge when measuring the braiding index. They also suggested some conventions to use when measuring the braiding index. A typical length of the channel should be selected without any large tributaries. The river is then divided into reaches of equal length by perpendicular transects. The length of each reach should be approximately twice the average width of the river. Each reach is bisected by a centre transect (Figure 5.7).



E = 2.33 *E* = 2.67 *E* = 2.33

Figure 5.7: Definition diagram of braiding index based on Howard *et al.* (1970)

Based on the hierarchy of channels within the Jamuna River, Bristow (1987) divided the channels into three categories – (i) first-order channel, (ii) second-order channel, and (iii) third-order channel. The first-order channel comprises the entire river, which includes several second order channels (Figure 5.8). The second-order channels maintain their characteristics at all stages. Some of the third-order channels may be produced during the falling stage, while others appear at bankfull stage. In measuring the degree of braiding, it is required to know the braiding intensity of second or third order channels.

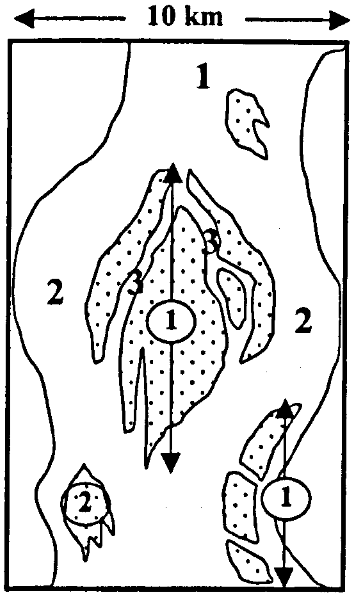


Figure 5.8: Channel hierarchies in the Jamuna River. Numbers in circles refer to bars. Other numbers refer to channels (Bristow, 1987).

Klaassen and Vermeer (1988) divided the Jamuna River into six equal reaches. The length of each reach was 30 km. Using the dry season satellite images of 1973, 1978, 1981 and 1987, they measured the braiding indices of every reach in terms of second and third-order channels. Their main findings were: (i) the degree of braiding decreases in the downstream direction, and (ii) the degree of braiding increased after 1981. Halcrow *et al.* (1994) divided the Jamuna River into seven reaches based on the presence of islands and cross-overs (nodes). They used all satellite images as used by Klaassen and Vermeer (1988) plus two more recent images of 1989 and 1992. Their findings are similar in that they identified a clear tendency for braiding indices to decrease in the downstream direction. However, they concluded that this was not a stable pattern.

EGIS (1997) measured temporal and spatial variations in the degree of braiding intensity of second and third order channels in the Jamuna River. EGIS (1997) used 13 sets of satellite images covering the period from 1973 to 1996. According to EGIS (1997), from 1973 to the mid-1980s the braiding index was constant or reduced slightly. From the mid-1980s to 1996 it was increasing. EGIS concluded that the degree of braiding would increase further.

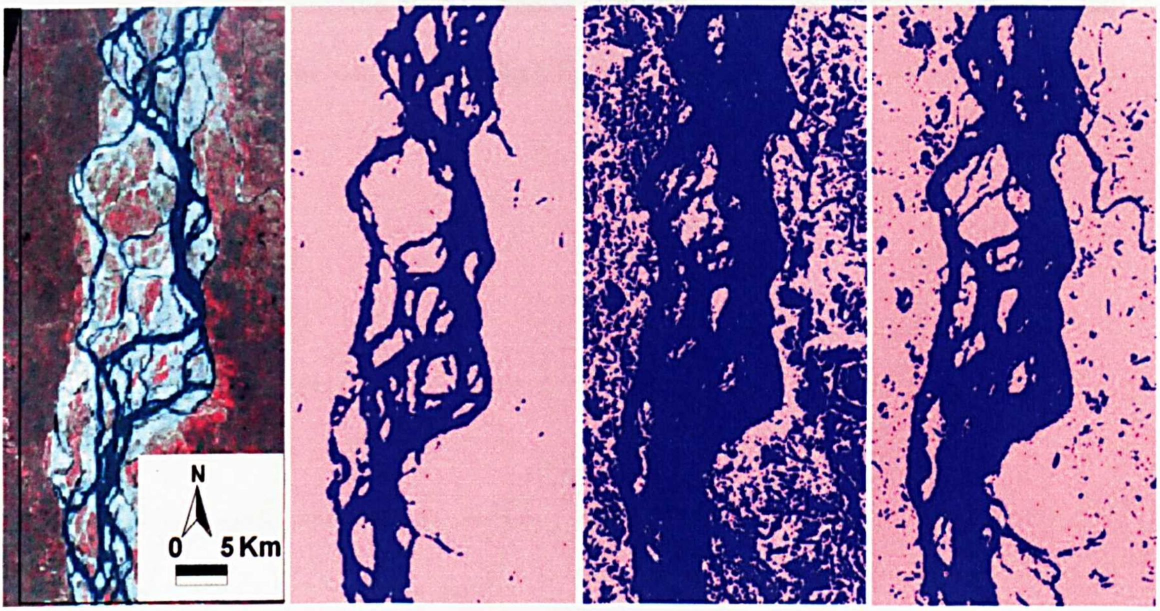
During this study braiding indices were measured for second-order channels using CORONA photographs of 1967 and time-series satellite images from 1973 to 2004. Tables 4.1, 4.2 & 4.3 describe the satellite images. The definition of second-order channels is similar to that of Bristow (1987), but to define them more specifically, one further criterion was added. Other than the first-order channel, a second-order channel was considered to be a single channel if it encompasses a bar or cluster of bars or islands more than 10 km long. The lengths of the bars were measured from satellite images. The minimum length of the bar considered when defining a second order channel is close to the average width of the Jamuna River.

Braiding intensity is strongly stage dependent (Bridge, 1993; and Nanson and Knighton, 1996) as is the size of the bars. As defined by Bristow (1987), the characteristics of the second-order channels remain the same at all stages, though the braiding indices of a second-order channel may change with changing stage. With an increase in stage, the size of the bar will reduce and, at the same time, a new channel may appear. These two simultaneous processes may cause changes in braiding index with variation in stage.

One optical image taken during the dry season and three radar images taken during the monsoon and covering a reach of the Jamuna River (Figure 5.9) were used to show how the braiding index varies with stage. Satellite images and stages of the Jamuna River at Bahadurabad are presented in Table 5.1. The variation in water levels during the image acquisition period is more than 7 m. With the increasing of water level, the size of the bars decreases and the alignments of the second-order channels change (Figures 5.9 and 5.10) and braiding indices decrease (Table 5.1). These results support the findings of Bristow (1987) and Nanson and Knighton (1996)

Table 5.1. Optical and radar images of 2004 used to study the variation of braiding index with stage

Date of image acquisition	Type and resolution of images	Stage of the Jamuna River at Bahadurabad (m PWD)	Braiding index
16 February	Optical	13.15	2.8
5 June 2004	Radar	16.53	2
23 July 2004	Radar	20.30	1.8
16 August	Radar	18.78	1.8



16 Feb. 2004 5 June 2004 23 July 2004 16 Aug. 2004

Figure 5.9: Optical and radar images of 2004 covering a reach of the Jamuna River

To investigate changes in the braiding index in this study, a 200 km long stretch of the Jamuna River from Northing 640 km to 840 km was selected. Like Klaassen and Vermeer (1988), Halcrow *et al.* (1994) and EGIS (1997), dry season optical images were selected for measuring braiding index although Howard *et al.* (1970) recommend using air photographs taken at the median discharge, the greater availability of time-series dry season optical images encouraged their use. Stages in the river on the acquisition dates of the dry season satellite images were very close (Tables 4.4, 4.5 & 4.6). Thus, comparison of braiding indices measured from the dry season satellite images to assess the changes in braiding index over time is justified.

As suggested by Howard *et al.* (1970), perpendicular cross-lines at a spacing of about the width of river, i.e. approximately 10 km, were constructed for counting the number of channels dissected. Braiding indices for the reaches having lengths of 40 km are presented in Figure 5.11. The following braiding index characteristics were revealed: (i) braiding indices of the reaches having different lengths shows similar trends of changes, and (ii) changing braiding indices of third-order and second-order channels also show almost similar trends and indicate the consistency of the trends. Braiding indices for the Padma and Lower Meghna rivers were measured using the same method. The consistency of trends of change in the braiding indices over time was also checked by measuring the braiding indices for reaches having different lengths.

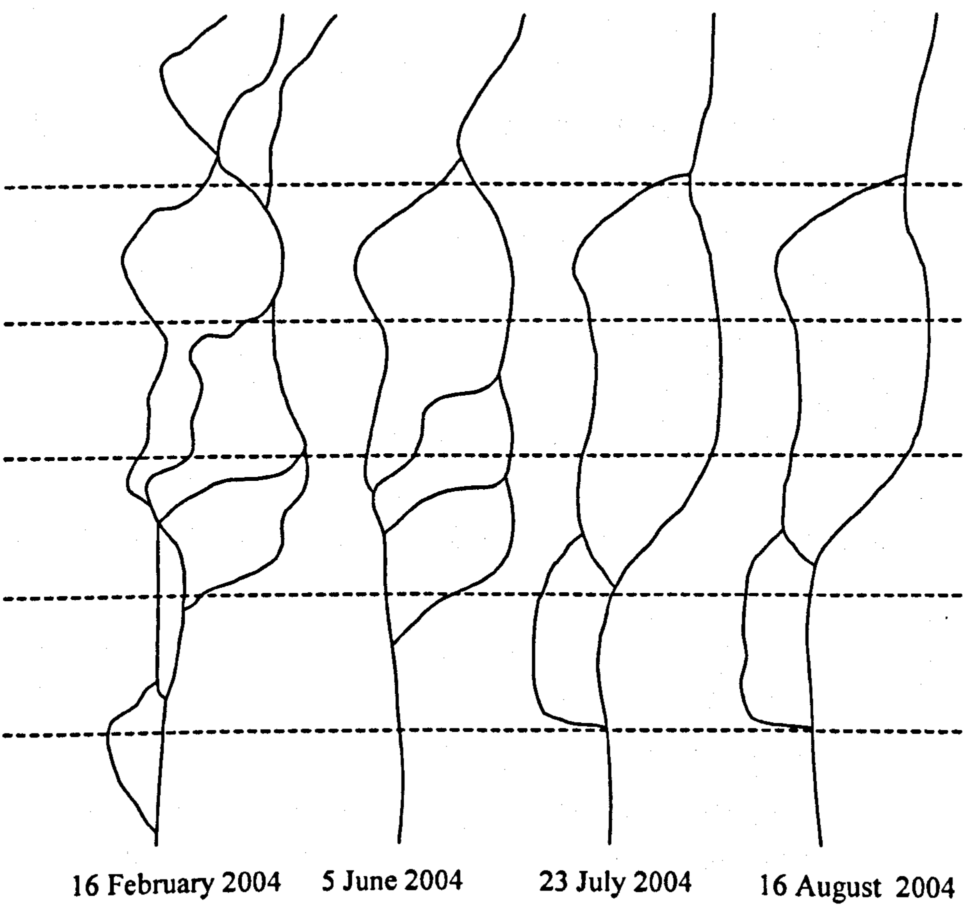


Figure 5.10. Alignment of second-order channels as observed in the satellite images presented in Figure 5.9.

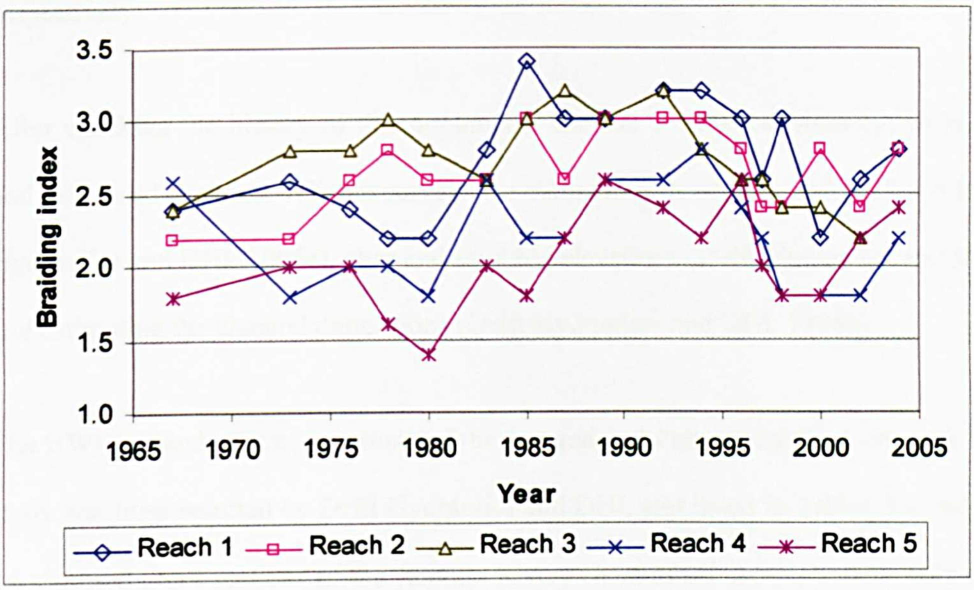


Figure 5.11. Braiding index of the Jamuna River

5.6 Cross-sectional data analysis

Several studies have analysed BWDB surveyed cross-sectional data from the Jamuna River (Klaassen and Vermeer, 1988; RPT *et al.*, 1987; CBJET, 1991; Thorne *et al.*, 1993; Delft Hydraulics and DHI, 1996a and1996b). Most of them found inconsistencies in the surveys. After going through the histories of the monuments and pillars of the cross-sections, RPT *et al.* (1987) selected the more reliable BWDB cross-sections. Similarly, Delft Hydraulics and DHI (1996a and 1996b) undertook extensive quality checking before selecting the surveyed data that was suitable for use. They checked for the vertical consistency, horizontal consistency and also checked whether alignment of the cross-section was perpendicular or close to perpendicular or not. Vertical consistency was checked by plotting the surveys of the same cross-section of different years (Figure 5.12). If the floodplain elevation varied substantially from one year to another, the surveys were treated as inconsistent. In case of the example presented in Figure 5.12, a survey of BWDB standard cross-section J#6_1 in 1966 was considered as consistent, whereas the surveys of 1967 and 1968 were considered inconsistent due the erroneous level of the floodplain and discontinuities in the soundings, respectively.

After checking the history of the monuments and the vertical consistency, Delft Hydraulics and DHI used the more reliable surveys for estimating floodplain and bank top levels (Delft Hydraulics and DHI, 1996a), char and sand bar elevations (Delft Hydraulics and DHI, 1996b) and estimating the channel dimensions (Delft Hydraulics and DHI, 1996b).

The BWDB standard cross-sections of the Jamuna and Padma rivers which were used in this study are those selected by Delft Hydraulics and DHI, and listed in Tables 5.2 and 5.3. Out of 34 standard cross-sections of the Jamuna River, 16 standard cross-sections were accepted as reliable. Along the Padma River there are 15 standard BWDB cross-sections, of which Delft Hydraulics and DHI used 11.

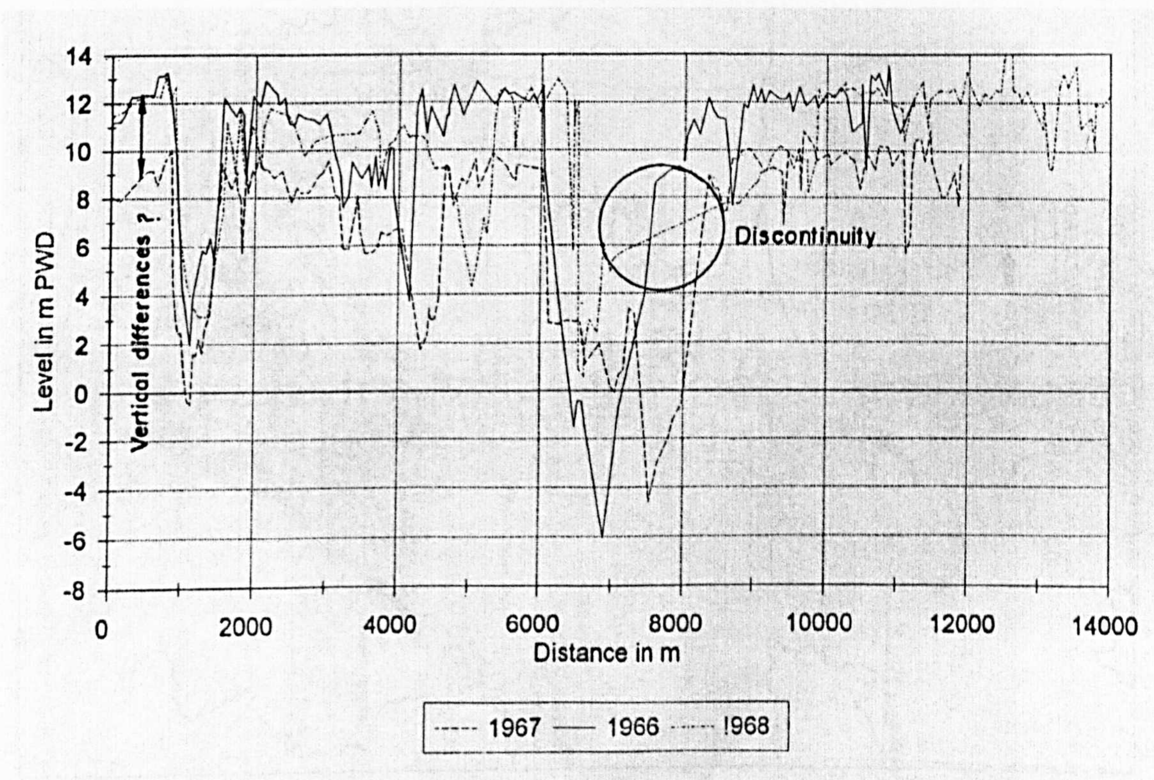


Figure 5.12: Inconsistencies in the BWDB's cross-section surveys (Delft Hydraulica and DHI, 1996a)

The BWDB surveys follow a fixed alignment for each standard cross-section. Consequently, an oblique cross-section profile is often retained, which differs from the direction perpendicular to the flow of the channel (Figure 5.13). Only those BWBD cross-sections that are nearly perpendicular to the alignment of the main channel were used in the analysis. This check was made using the geographical position of the monuments for fixing the alignment of the standard cross-section and satellite images of the surveyed year.

The Institute of Water Modelling (IWM) measured the geographical coordinates of the monuments and pillars of the cross-sections using a Differential Global Positioning System (DGPS) and reported their results in IWM (2003). They could not find the monuments and pillars for all BWDB standard cross-sections, and in some cases all the monuments and pillars were missing. Those cross-section survey data were not used in the analysis. In case of missing the monuments or pillars on one bank, the bearing of the cross-section with respect to the magnetic north and the geographical coordinates of the monument or pillars on the other bank were used to find the alignment.

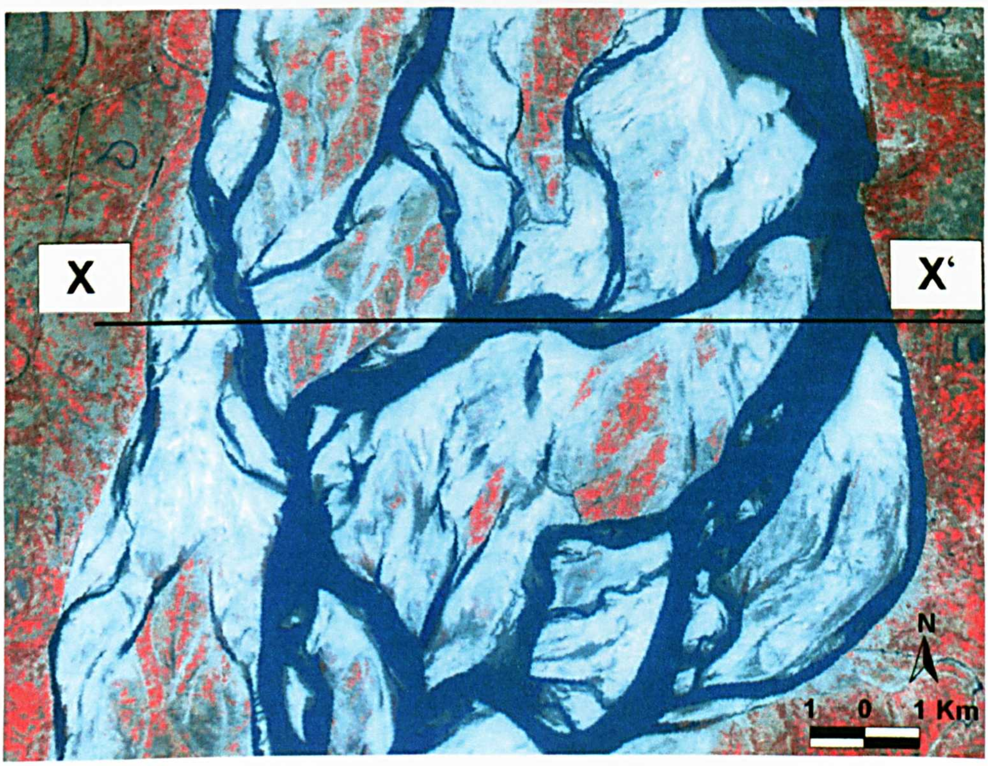


Figure 5.13: Cross-section X-X' crossed the mid channel obliquely

When checking that cross-sections were approximately perpendicular to the channel alignment using satellite images, in cases where a suitable image was not available for the surveyed year, images from the preceding or subsequent years were used. Cross-sections were not analyzed if they deviated significantly from the perpendicular, or if they were located at bifurcations (Figure 5.13). This type of quality checking is similar to that undertaken by Delft Hydraulics and DHI (1996a and 1996b) prior to their analyses. A total of 13 and 8 BWDB standard cross-sections of the Jamuna and Padma rivers, respectively (Figures 5.14 and 5.15), were retained for analysis after quality checking. The dates of the surveys were selected to cover the periods of marked channel adjustment, such as narrowing, widening or changes in braiding intensity, that were identified from satellite images. Cross-sectional surveys were used to assess changes in the bankfull channel flow area. The mean bank-top elevations of the Jamuna and Padma rivers determined by Delft Hydrualics and DHI (1996a), and listed in Tables 5.2 and 5.3, were used to define the bankfull condition when calculating the bankfull cross-sectional area. It follows that, as the bankfull condition was defined by a stage elevation rather than a discharge, the bankfull discharge is not constant.

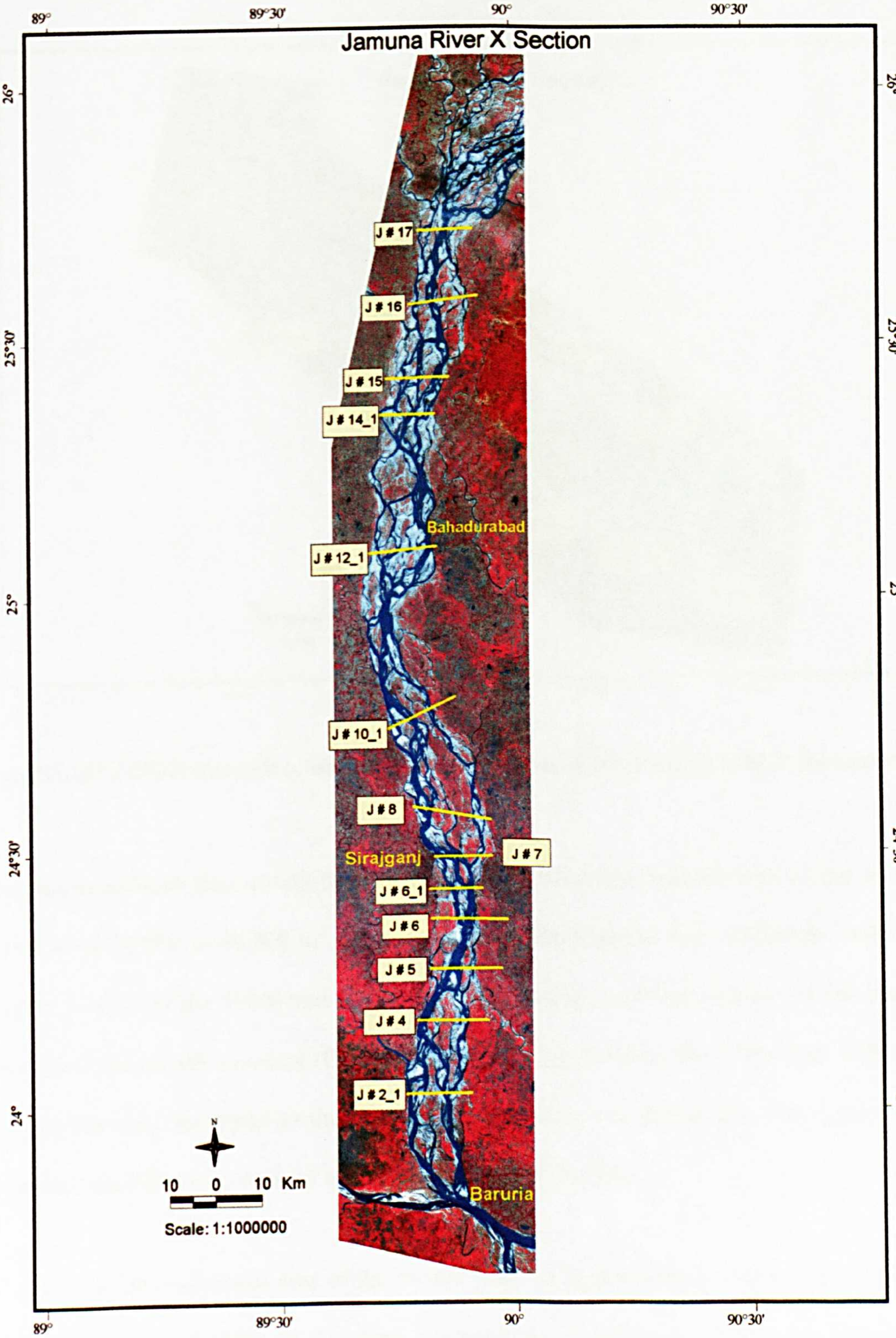


Figure 5.14: BWDB standard cross-sections of the Jamuna River surveys used in the research

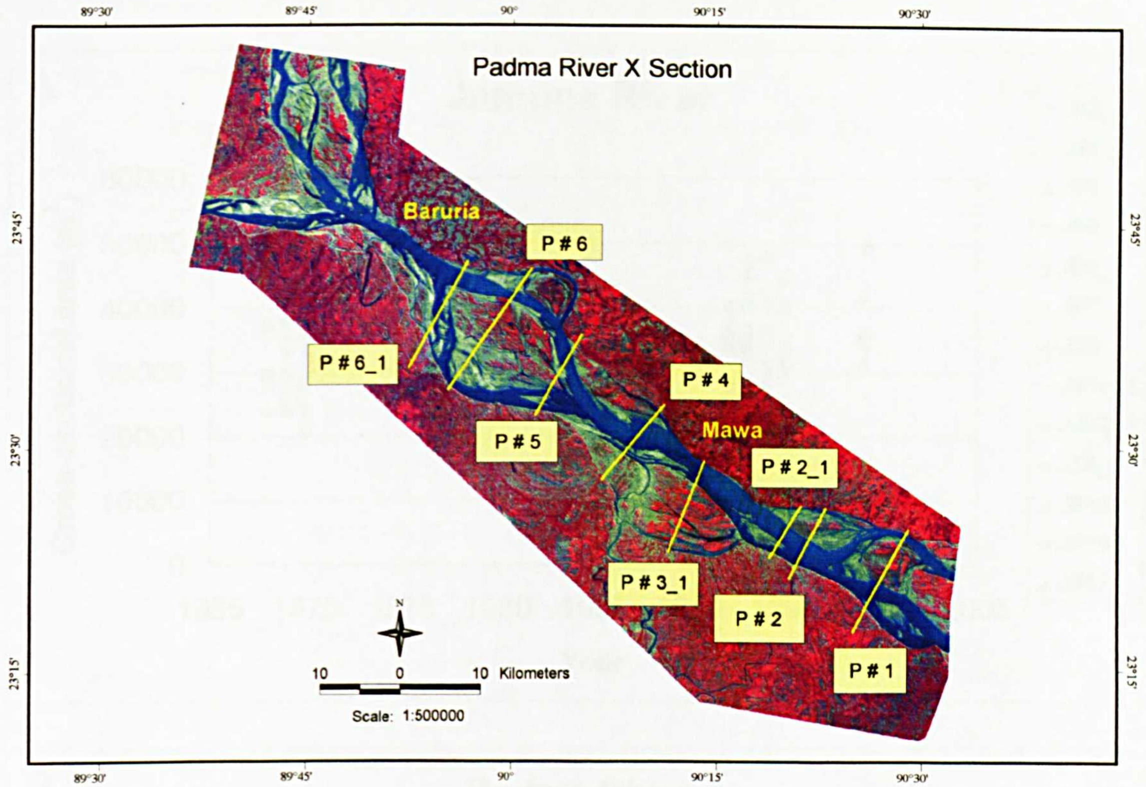
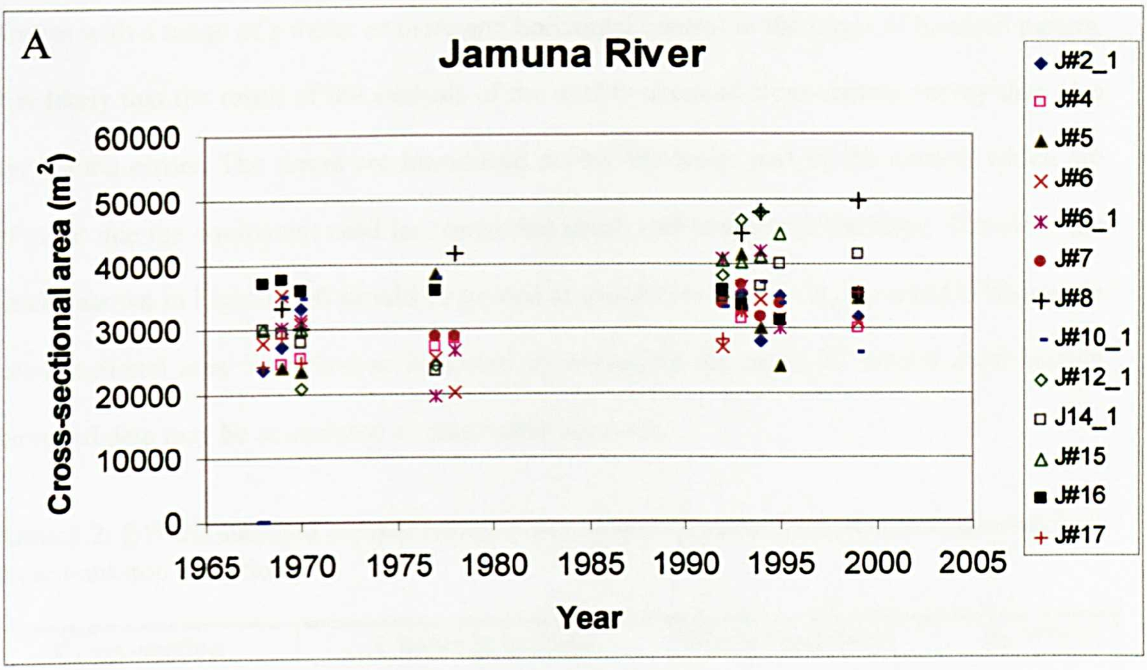


Figure 5.15: BWDB standard cross-sections of the Padma River surveys used in the research

The results indicate that during the late 1960s and 1970s, the bankfull area of the Jamuna varied from 20,000 to 40,000 m^2, whereas in the 1990s it varied from 30,000 to 50,000 m^2 (Figure 5.16A). In the 1960s and 1970s, the width and the braiding intensity of the Jamuna River were practically constant (Figures 5.5 and 5.11), but during the 1990s both width and braiding intensity increased to the maximum values observed during the study period. The cross-sectional area also attained its maximum value at that time.

In 1967, the cross-sectional area of the Padma River at bankfull stage varied from 32,000 to 60,000 m^2 (Figure 5.16B). At that time, the planform of the Padma River was transitional between meandering and braided (Figure 2.16). The planform of the river straightened in the mid-1980s. The bankfull cross-sectional area was a minimum at that time, varying between 30,000 to 45,000 m^2. In the late-1990s, when the planform became braided, its cross-sectional area increased somewhat and varied from 42,000 to 55,000 m^2.



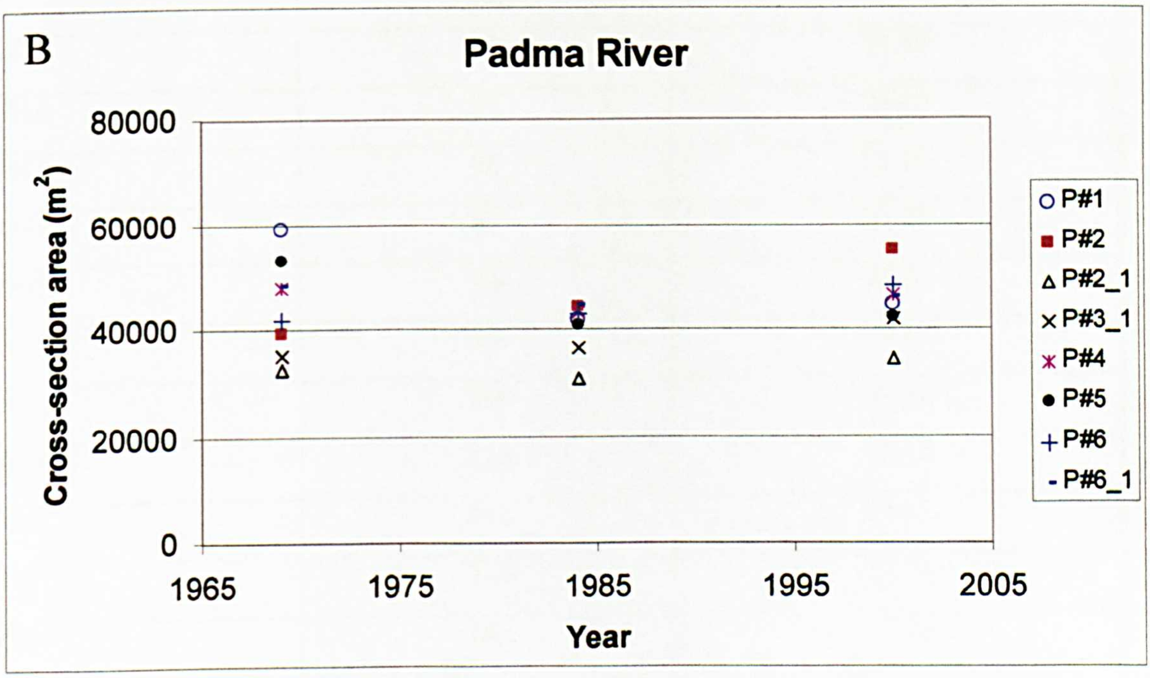


Figure 5.16: Changes in cross-sectional area at bankfull level of (A) the Jamuna River and (B) the Padma River

Quality checking eliminated the cross-section surveyed data, which have errors in the vertical control with a range of a meter or more and horizontal control in the range of hundred meters. It is likely that the result of the analysis of the quality checked cross-section survey data also have some errors. The errors are introduced during the water part of the survey, which are inherent due the equipment used for measuring depth and position in the river. Therefore the results shown in Figure 5.16 should be treated as qualitative. However, the trend of change in cross-sectional area over time as indicated by averaging the result of several cross-section surveyed data may be considered as reasonably accurate.

Table 5.2: BWDB standard cross-sections of the Jamuna River selected for analyses and their mean bank-top elevations.

Cross-section	**Chainage in 1989 (km)**	**Mean bank level (m PWD)**
J#17	25	24.40
J#16	37	23.22
J#15	56	21.85
J#14_1	63	21.17
J#13	85	18.93
J#12_1	84	18.31
J#11	118	16.32
J#10_1	127	15.43
J#9	142	14.65
J#8	150	13.77
J#7	162	13.35
J#6_1	171	12.39
J#6	178	12.31
J#5	188	11.27
J#4	201	10.57
J#2_1	220	8.80

Table 5.3: BWDB standard cross-sections of the Padma River selected for analyses by Delft Hydrualics/DHI (1996a) and mean elevations of left and right bank tops.

Cross-section	Chainage in 1992-93	Mean bank level (m PWD)	
	(km)	Left bank	Right bank
P#7	0	8.26	7.56
P#6_1	5.4	7.01	7.10
P#6	11	6.68	6.83
P#5	21.5	6.83	6.98
P#4_1	28.5	6.67	6.66
P#4	36.5	6.67	6.86
P#3_1	49	6.50	5.94
P#3	55.5	5.51	5.69
P#2	67	5.00	5.40
P#1_1	72	4.91	5.38
P#1	77	5.10	5.28

5.7 Specific gauge analysis

Specific gauge analysis is used to identify trends with time in the elevation of water surface corresponding to a given discharge (Halcrow *et al.*, 1994). These changes reflect long-term changes of channel form (especially bed elevation) and roughness. The analysis can also be performed to investigate the changes of low-water stage for a given baseflow discharge (Zhou and Chen, 1998).

Halcrow *et al.* (1994) selected Bahadurabad as the hydrometric gauging station for their analysis. Bahadurabad is the only discharge gauging station along the Jamuna. According to Halcrow *et al.* (1994) this station is an ideal location for specific gauge analysis. They selected the discharges 7,000, 14,000, 28,000, 42,000, 60,000 and 80,000 m^3s^{-1} and corresponding water levels for each year were taken from the rating curves for analysis. The time period of the data for analysis was from 1963 to 1988. From the analysis, Halcrow *et al.*

(1994) suggested that there was a small, overall rising trend in water levels. Examination of their plot of changes in water level for the specific discharges shows that water levels rise for several discharges mainly during the period 1963 to 1974. The rate of rising is higher for the low and middle discharges (7,000 to 28,000 m3s-1) than for high discharges (>40,000 m^3s^{-1}).

A similar analysis was performed for Sirajganj, but some assumptions were necessary because no discharge measurements are available for this station, only water levels. The main assumption was that while the flow remains within banks there is a unique relation between the discharge at Bahadurabad and the water level on the same day at Sirajganj. Halcrow *et al.* (1994) did not find any significant trend of changing of water levels for given discharges and therefore concluded that there were no significant bed level changes at Sirajganj during their study period.

Zhou and Chen (1998) examined the water levels at different water level gauging stations along the Jamuna River when the discharge at Bahadurabad was 20,000 m^3s^{-1} for the years 1962 to 1988. They found that water levels along the Jamuna River had remained unchanged during the study period. However, they also found that the water level at Bahadurabad for discharge 20,000 m^3s^{-1} had risen by 0.3 – 0.5 m during the period.

In interpreting these findings, Halcrow *et al.* (1994) noted that stage-discharge relationships in a braided river are complex. The movement of dunes, braid bars and chars may change the flow resistance characteristics of the channel and thus the relationship between the discharge and corresponding water level even if the bed elevation remains unchanged.

In a braided river like the Jamuna, the distribution of discharge between sub-channels may vary substantially, with impacts on water levels in the braided channel and the individual anabranches. This variation particularly depends on conditions at the bifurcation points. When sedimentation occurs in and around an off-take of an anabranch, the water level falls very rapidly near the off-take during low flow and mid-flow discharges, generating a difference in the water levels in two parallel channels at a cross-section (Figure 5.17). The magnitude of difference is dependent on the length of the bifurcating channels, the water surface slopes in each channel and the nature of sedimentation in and around the off-take. Therefore, observed changes in water level for a given discharge may represent off-take dynamics rather than the aggradation or degradation of the braided river at that cross-section. When considering the results of specific gauge analysis in a braided river, it is important to remember that trends may represent changes in the morphology of the braided channel generally, rather than simply indicating changes of bed elevation due to aggradation or degradation acting alone.

This is significant because the development and abandonment of sub-channels in the braided system is a very common phenomenon in the Jamuna River (Klaassen and Masselink, 1992). A particular anabranch may remain one of the main channels for a few years or even a decade, but later it may be abandoned completely or survive only as a minor channel. The water level at a gauging station that crosses that anabranch will represent the corresponding section of the river when it is on the main channel. But when the anabranch becomes a minor one, the same gauging station may represent the condition of that channel disproportionally, rather than the corresponding section of the new main channel. Therefore, the water level gauging stations used for the specific gauge analysis by Halcrow *et al.* (1994) and Zhou and Chen (1998) might not be representative of the *main* anabranch channel sections, because it is not known whether the corresponding studies checked how channel morphology changed during the study period.

In this study, the historical map of 1953, CORONA photograph of 1967 and time series satellite images from 1973 to 2005 were examined to identify the types and timings of channel changes at the Bahadurabad water level gauging station. This examination established that the dominance of the main channels at Bahadurabad did not change during the study period. Therefore, Bahadurabad is a suitable location for specific gauge analysis in the Jamuna River.

In performing the specific gauge analysis for the present research, discharge and water level data for the period 1960 to 2000 were used. Instead of rating curves, daily discharges as estimated by BWDB and corresponding water level were used for the analysis. Further discussion of the specific gauge analysis is presented in Chapter 6.

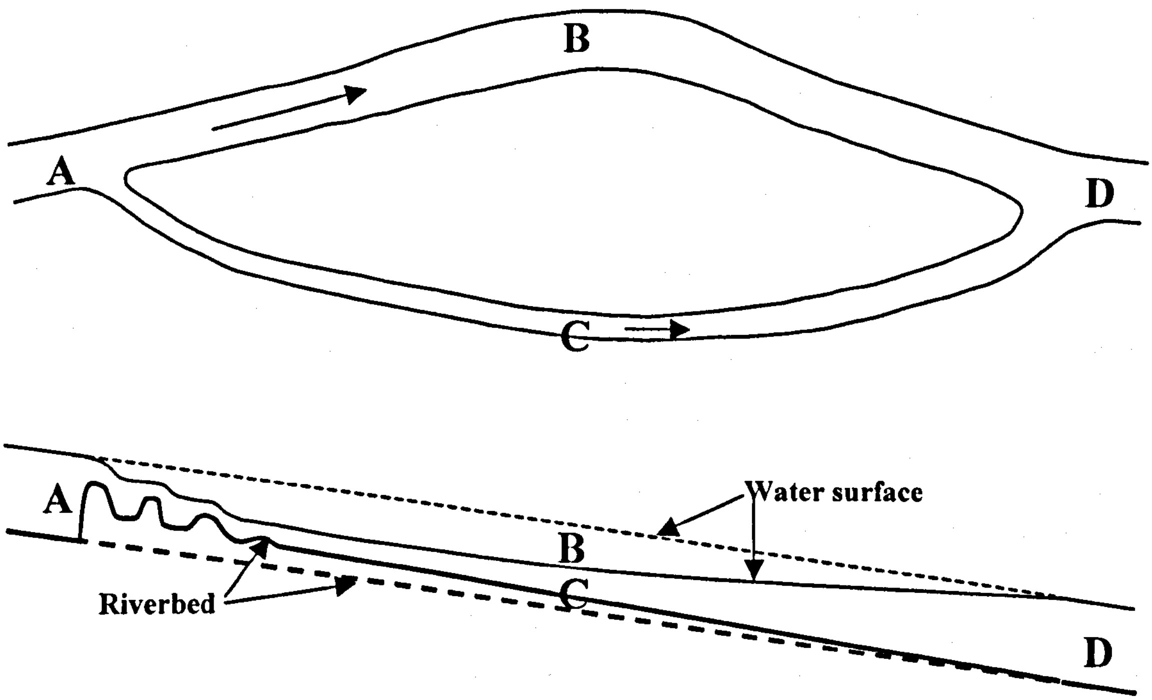


Figure 5.17: Schematic diagram shows the water level differences in two parallel channels

5.8 Sediment rating curves

A sediment rating curve is an empirical relation between the water and sediment discharges measured at a transect. It has the form of a power function and is derived either by regression analysis or some other form of curve fitting for a graph with logarithmic scales on both axes. The general form of the equation is:

$$S = AQ^B \qquad (5.3)$$

where S = sediment transport rate, Q = discharge and A = the regression coefficient and B = the regression exponent. These curves are widely used to estimate the sediment load or sediment transport.

Previous studies have derived sediment rating curves and estimated the sediment load of the Jamuna River (Alam and Hossain, 1988; RPT *et al.*, 1987; CBJET, 1991, Hossain, 1992, Halcrow *et al.* 1994; Delft Hydraulics and DHI, 1996h; Islam *et al.*, 1999) using different types of sediment data and for different periods. Alam and Hossain (1988) used the data measured at Nakfatarchar (close to Sirajganj) in 1969 and 1970, and at Nagarbari in 1970 and 1972 to derive sediment rating curves and calculate sediment loads. However, sediment gauging at these locations did not continue after 1972. Alam and Hossain (1988) estimated the total suspended sediment load at Nakfatarchar as varying from 439 million tons to 575 million tons per year.

Instead of total suspended sediment transport, RPT *et al.* (1987) derived rating curves for the suspended bed material load, considering that this is more important to driving morphological channel changes. They used sediment and discharge data for the period 1968 to 1970. According to them, suspended bed material load can be estimated from the following relation:

$$S = 4.1 * 10^{-6} Q^{1.38} \qquad (5.4)$$

where S = suspended bed material load (m^3s^{-1}) and Q = discharge (m^3s^{-1}). RPT *et al.* also estimated bed load transport using dune tracking. According to them bed load is about 10% of the suspended bed material load. Hence, in estimating total bed material load they added 10% to the estimated suspended bed material load, as expressed by Equation 5.4.

The China-Bangladesh Joint Expert Team (CBJET) analysed sediment transport data for the Jamuna River from 1968 to 1989 (CBJET, 1991). They derived different sediment rating curves for total suspended sediment load using sediment data for different periods (Figure 5.18). Rating curves for total suspended transport for these periods vary substantially from each other and it was concluded that total suspended sediment discharge varies markedly over time. According to CBJET, sediment transport in the Jamuna River varied from year to year within the range of 240 million tons to 770 million tons per year. From the mid-1960s to the early-1970s, the mean of annual sediment load in the Jamuna River was about 650 million tons per year, which was reduced to 320 million tons per year in the 1980s.

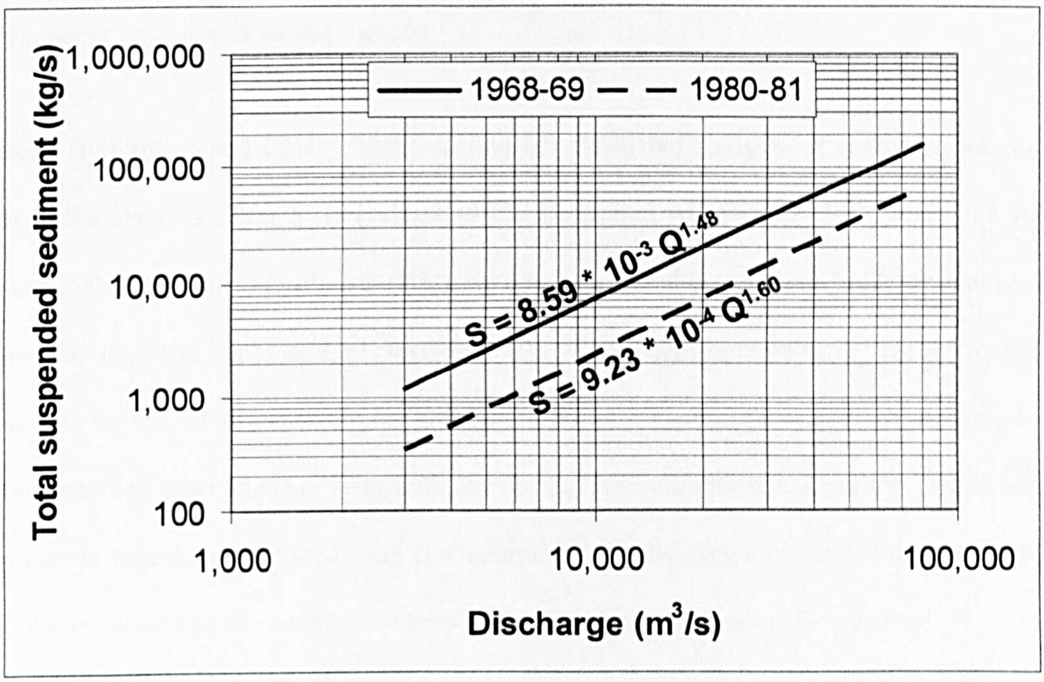


Figure 5.18: Sediment rating curves for the Jamuna River as derived by CBJET (1991)

Instead of using the measured sediment data, Hossain (1992) derived rating curves using the estimated total sediment transport of the Jamuna River. Total sediment transport was estimated by Hossain's (1987) dimensional approach using hydraulic data for the Jamuna River from 1982 to 1988. Using his rating curve, total annual sediment load was found to vary from 405 to 840 million tons, with an annual average of about 700 million tons.

Suspended bed material load data for the Jamuna River at Bahadurabad for the period 1968 to 1988 were analysed by Halcrow *et al.* (1994). They found that the sediment rating curve derived from data for 1968-70 yielded three times the sediment transport estimated using rating curves generated from data for 1982-88. An increase in sediment transport by a factor of 3 would require to increase in mean flow velocity on the order of 30% to 40%. According to Halcrow *et al.* (1994) this could only be possible if significant morphological changes had taken place, but there was no indication of such large morphological changes at the time of the measurements. Halcrow *et al.* (1994) attempted to explain the large observed difference in sediment transport on the premise that either BWDB changed either their measuring procedure or data processing method.

Delft Hydraulics and DHI (1996h) carried out extensive analysis of sediment gauging data from the Jamuna River at Bahadurabad for the period of 1965 to 1993. They analysed the sand (>0.063 mm) and silt (<0.063 mm) fractions of the sediment load separately as bed material load and wash load, respectively. They produced separate rating curves for different periods for each sediment gauging station on the main rivers of Bangladesh, considering that the measured sediments are representative for the period under consideration. Daily sediment transport was then estimated from the mean daily discharge using the sediment rating curve. The consistency of the sediment transport data at each station was also checked.

Like CBJET (1991) and Halcrow *et al.* (1994), Delft Hydraulics and DHI (1996h) found that the sediment rating curve varies from one period to another. Initially, Delft Hydraulics and DHI (1996h) divided the sediment transport data into two periods: 1966-70 and 1976-88, based on data consistencies and statistical correlations. It should be noted that sediment data for Bahadurabad for the period 1971-1975are missing. A gradual decrease in the rate of sediment transport for a given discharge was also observed for the period 1976-88. To produce more consistency in the correlations with discharge, Delft Hydraulics and DHI (1996h) again divided this period into two equal halves. The rating curves for suspended bed material load (sand) derived by Delft Hydraulics and DHI for three different periods are as follows:

$$S = 0.35 * Q^{1.42} \qquad \text{data used for the period 1966 - 70} \qquad (5.5)$$

$$S = 0.28 * Q^{1.39} \qquad \text{data used for the period 1976 - 82} \qquad (5.6)$$

$$S = 1.00 * Q^{1.21} \qquad \text{data used for the period 1982 - 88} \qquad (5.7)$$

where S = suspended bed material load ($tonday^{-1}$) and Q = discharge (m^3s^{-1}).

The rating curves show a gradual decrease in suspended bed material transport in the Jamuna River (Table 5.4). These rating curves (Equations 5.5, 5.6 and 5.7) have been used in this research project to estimate changes in the suspended bed material load of the Jamuna River. The value of co-efficient of determination (R^2) for Equation 5.5 is 0.90, but values of R^2 for the other two equations were unfortunately omitted by Delft Hydraulics and DHI (1996h). Plotting the bed material transport data from Bahadurabad for the periods 1968-70 and 1982-88 also indicated a reduction in load between the two periods (Figure 5.19). The Equations of the regression lines for the periods 1968-70 and 1982-88 are very similar to those of Equations 5.5 and 5.7 as are the relevant values of co-efficient of determination (R^2), which are 0.89 and 0.88, respectively (Figure 5.19). In deriving Equations 5.5 to 5.7 Delft Hydraulics and DHI (1996h) also used the data presented in Figure 5.19. They processed the data and also eliminated some outliers. It can, therefore, reasonably be assumed that the values of co-efficient of determination for Equation 5.7 would also be close to 0.90.

Error bars are introduced with the data points in Figure 5.19 for Standard Error (S.E.) of the data. S.E. reads as:

$$S.E = \sqrt{\frac{\sum_{s=1}^{m}\sum_{i=1}^{n} y_{is}^{2}}{(n-1)n}} \qquad (5.8)$$

where, s = series number, i = point number in series s, m= number of series for point y in chart, n = number of pioints in each series and y_{is} = data value of series s and the ith point.

Delft Hydraulics and DHI (1996h) indicated that probably BWDB changed their procedure of measuring in the 1970s and that was the reason why the gauging showed a decreasing sediment load over time. If this premise is true, the data would show a sudden decrease in sediment load in the 1970s, instead of gradually decreasing in the 1970s and 1980s.

Gauging at Bahadurabad showed that the sediment load in the late 1980s became about one third of that measured in the late 1960s. This decreased amount is very large compared to the random error due to the instrument or error due to the measuring procedure. Irrespective of error in sediment gauging, it can be considered that the sediment load in the Jamuna River at Bahadurabad reduced significantly in the 1970s and 1980s.

Table 5.4: Changes in sediment load of the Jamuna River over time

Rating curves derived by using data	Annual av. Sediment load (10^6 $tony^{-1}$)
1966-70	201
1976-82	118
1983-88	65

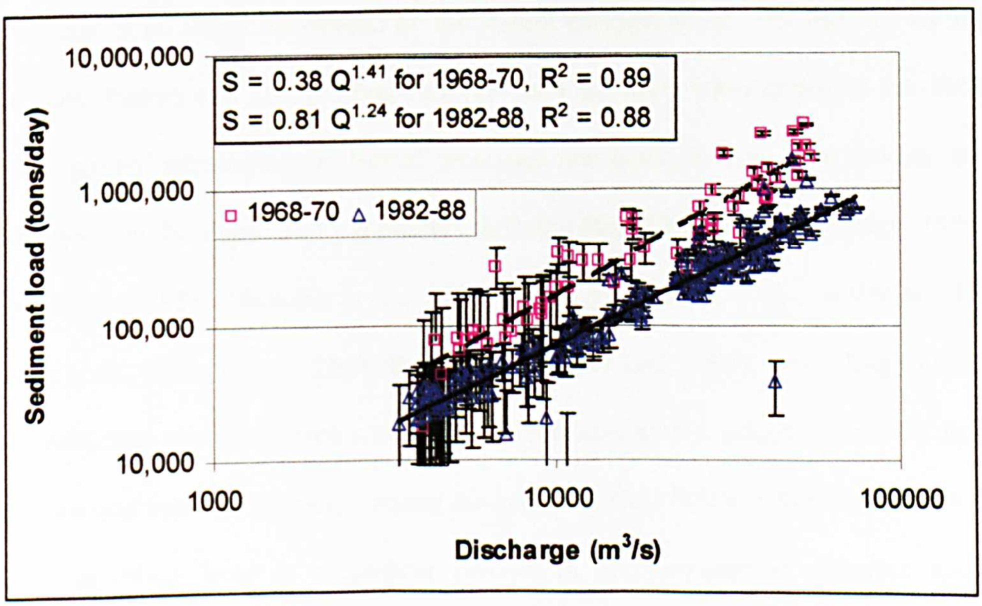


Figure 5.19: Sediment rating curves showing the relation between bed material load and discharge measured at Bahadurabad on the Jamuna River at different period.

Chapter 6
Conceptual model

6.1 Introduction

The rapid width changes observed in the Jamuna, Padma and Lower Meghna rivers during the late-20th and early-21st centuries indicate that these rivers are not in dynamic equilibrium, but are more likely to be in the process of adjusting to disturbance. This implies that other parameters, such as mean depth, bed elevation, channel slope, and braiding intensity of the rivers are also likely to be in the process of adjustment. Morphological adjustments occur in response to a change in one or more of the independent variables governing channel form and process, such as the flow regime (Leopold and Maddock, 1953; Lane, 1955; Schumm, 1969), sediment regime, bed material characteristics (Lane, 1955, Schumm, 1969; Chang, 1976; 1986 and 1988; White *et al.* 1982; Bettess and White, 1983; Bridge, 2003) or valley slope (Burnett and Schumm, 1983; Harbor *et al.* 1994; Schumm, *et al.*, 2000). According to the working hypothesis presented in Chapter 1, downstream propagation of the coarse fraction of the mass of sediment introduced by the Assam earthquake of 1950 through the Brahmaputra, Jamuna, Padma and Lower Meghna rivers as a sediment wave could be the disturbance that has triggered adjustments in fluvial processes that have, in turn, been driving morphological responses in the dependent parameters defining the channel form (Bradley, 1983; Ribberink and Sande, 1985; Nicholas *et al.*, 1995; Madej and Ozaki, 1996; Miller and Benda, 2000; Lisle *et al.*, 2001; Korup, 2004; Bartley and Rutherfurd, 2005). According to this hypothesis, the sediment wave has been travelling downstream with a celerity governed by the laws of physics and river mechanics, causing the sediment load first to increase and then return to the pre-disturbance level in successive reaches in the downstream direction and so causing sequential changes in various aspects of channel morphology. As the sediment wave travelled from upstream to downstream through the fluvial system, there should be some sort of downstream phase lag in the sequence of morphological changes observed in each reach.

Discussion of the underlying principles of process-response in alluvial channels presented in Chapter 3 established that changes in the flow regime (discharge) or bed sediment characteristics (size) may trigger morphological responses that are similar to those associated with disturbance of the sediment regime. Studies were therefore performed in this project to establish whether such changes have in fact occurred within the Brahmaputra-Jamuna-Padma-Lower Meghna system and these are reported later in this chapter.

To understand and explain the morphological responses displayed by the Jamuna-Padma-Lower Meghna river system and to be able to predict its future morphological behaviour, requires that the causal links between the relevant independent and dependent variables are established. To achieve this, a conceptual model has been developed to establish the relationships between the drivers and responses, based on the principles outlined in Chapter 3, the data sources and analyses recounted in chapters 4 and 5 and the observed behaviour of the Jamuna River. The conceptual model was subsequently validated using information on changes to independent variables and the morphological changes observed in the Padma and Lower Meghna Rivers.

Unfortunately, the availability of quantitative information on the relevant variables and parameters is limited, especially considering the temporal and spatial scales of change. This is particularly true for the key independent variable - the sediment load. Conversely, the availability of satellite images and aerial photographs since the end of the 1960s gives a satisfactory record of planform changes, so that reliable histories can be established for morphological responses in channel width and braiding intensity for the study rivers within Bangladesh. On the other hand, there is very limited information available from upstream of the Bangladeshi border. To fill the gaps in data availability, several assumptions had to be made during development of the conceptual model and these are highlighted in the description that follows.

6.2 Celerity of the disturbance in a riverbed

According to one-dimensinal approach of de Vries (1993), the celerity of a small disturbance to the riverbed can be expressed as:

$$C = \frac{ns}{d(1-Fr^2)} \cong \frac{ns}{q}u \qquad (6.1)$$

where, u = depth-averaged velocity (ms^{-1}), n = exponent of 'u' in a simplified sediment transport equation (no units), s = sediment transport rate per unit channel width (m^2s^{-1}), d = mean flow depth (m), and q = discharge per unit channel width (m^2s^{-1}). In the article de Vries did not define the term 'small disturbance'. It is considered here that this term indicates a disturbance that can be propagated as wave like form, without disrupting the whole fluvial system. Equation 6.1 provides a preliminary basis of estimating the speed with which the disturbance of the bed associated with a sediment wave introduced in the Assam valley could travel downstream through the Brahmaputra-Jamuna-Padma-Lower Meghna system.

To apply Equation 6.1 to the Jamuna, it is necessary to specify representative values for the relevant variables. For assessing celerity during the periods 1966-70 and 1982-88, sediment loads have been estimated using Equations 5.5 and 5.7. Delft Hydraulics and DHI (1996b) derived regime type relations for secondary channels of the Jamuna River which read as:

$$W = 10.34Q^{0.55} \qquad (6.2)$$

$$d = 0.31Q^{0.29} \qquad (6.3)$$

Where, W = water surface width (m) and d = average depth of water (m), for discharge Q (m^3s^{-1}) in the channel concerned. These equations have been used for estimating flow velocity, u (ms^{-1}), and unit discharge, q (m^2s^{-1}). Delft Hydraulics and DHI (1996i) estimated the value of the exponent 'n' in the sediment transport equation to be 3.66 for the Jamuna River. To assess the sensitivity of estimated celerity to uncertainty in the input parameters, two representative discharges: mean annual flow (20,000 m^3s^{-1}) and bankfull discharge (50,000 m^3s^{-1}) were used to calculate these parameters. The results are presented in Table 6.1.

Table 6.1. Estimating of celerity of a disturbance of the riverbed for different periods and different representative discharges.

Period	**Discharge** (m^3s^{-1})	**n**	**s** (m^2s^{-1})	**u** (ms^{-1})	**Q** (m^2s^{-1})	**Celerity** (m per day)	**Celerity** (kmy^{-1})
1966-70	20,000	3.66	0.0015	1.52	8.34	87	32
	50,000	3.66	0.0033	1.76	12.59	146	*21
1982-88	20,000	3.66	0.00047	1.52	8.34	27	10
	50,000	3.66	0.00104	1.76	12.59	46	*7

** for estimating celerity per year, effective bankfull discharge has been assumed to pertain for 146 days per year*

During the late-1960s, when sediment load was high, estimated celerities were found to be 32 kmy^{-1} and 21 kmy^{-1} based on mean annual discharge and bankfull discharge, respectively. The estimated value of celerity for the bankfull discharge also depends on assumptions made for the number of days of bankfull discharge in a year. While estimated values of celerity based on Equation 6.1 are sensitive to the value selected for the representative discharge, the resulting values for the representative discharges investigated are within the range permissible for a preliminary assessment.

The speed at which sequential patterns of morphological adjustment are propagated downstream should be similar to the celerity of the disturbance triggering them, so that those that occurred in the early stages of response should have moved downstream at about 20 to 30

kmy^{-1}, while the downstream migration rate of adjustments that occurred in the latter stages of response in the Jamuna should be of the order of 7 to 10 kmy^{-1}, reflecting the lower sediment transport rate that developed through time as the wave moved downstream of the Jamuna.

According to Nicholas et al. (1995), the celerity of a sediment wave depends on several factors such as calibre of sediment, scale of sediment slug, flood regime and the planform of the river. The celerity decreases as the sediment wave is attenuated. Madej and Ozaki (1996) found that the celerity of a sediment wave is directly proportional to the stream power in a reach. In this case, it would be expected that celerity would be higher at the upstream limit of the study reach in Assam, India where the slope of the river is the highest and scale of sediment slug is also high, and lower in the Padma and Lower Meghna downstream limit of the study reach where the sediment wave was attenuated and gradient flattens.

Although these results are indicative at best, they serve to demonstrate that a wave of coarse sediment introduced into the fluvial system in Assam would, according to the theories of wave and river mechanics, require not less than thirty and probably about fifty years to travel the 1,000 km from Assam to the Bay of Bengal. This establishes a time base from which to examine the records of channel changes in the Brahmaputra-Jamuna-Padma-Lower Meghna system since the 1960s to the early part of the 21st century when searching for evidence of morphological response to the propagation of a sediment wave downstream from Assam.

6.3 Changes in the Independent Variables

6.3.1 Changes in the flow regime

In a natural river, discharge varies seasonally and annually according to the flow regime. Changes in mean discharge, flood discharge or the annual variability of discharge drive semi-continuous adjustments in the morphology of alluvial reaches (Klaassen, 1995; Knighton, 1998, Bridge, 2003). However, such adjustments fall within the realm of dynamic equilibrium provided that the morphological characteristics and dimension of the channel do not change significantly over periods of decades. Conversely, either an impulse or a step change in the flow regime (due to, for example, a major flood or land-use change in the catchment, respectively) may trigger more pronounced adjustments that take the channel away from its equilibrium condition and render it unstable. It is therefore possible that such a change in the flow regime is responsible for the morphological adjustments and channel instability observed in the Jamuna-Padma-Lower Meghna river system.

In the case of the Jamuna River, the flow regime does not change significantly throughout its 200 km length. Although the Jamuna has a substantial tributary (the Teesta) and a significant distributary (the Old Brahmaputra) (Figure 2.1), the mean annual discharges of the Teesta and Old Brahmaputra are only about 5% and 2% of the Jamuna, respectively. No changes in the mean annual discharge of the Teesta River have been observed during the last several decades, though flows spilling into the Old Brahmaputra have been decreasing somewhat.

As the flow regime of the Jamuna does not vary along its length, data from the only gauging station at Bahadurabad may be taken to represent the whole river. Analysis of the available data since the mid-1950s is presented in Figures 6.1 and 6.2. Annually, between 500 km^3 and 800 km^3 water passes through the Jamuna River, with an average annual runoff of 619 x 10^9 m^3. Variability in the annual volume of runoff was lower in the 1950s and 1960s compared to that in the following three decades, which could indicate that climate change is affecting the summer monsoon (Figure 6.1).

The mean annual flood flow in the Jamuna River is about 70,000 m^3s^{-1}, but maximum annual floods vary in magnitude from 40,000 m^3s^{-1} to over 100,000 m^3s^{-1}. Variability in the maximum annual flood was lower in the 1960s and 1970s than in the following decades (Figures 6.1B and 6.2A). There is a slight increase in the magnitude of the maximum annual flood with time, although this is not significant. Statistical analyses also found no changes in peak discharge at Bahadurabad (Mirza, *et al.*, 2001).

The average annual minimum flow in the Jamuna River is about 4,000 m^3s^{-1}. The ratio of the maximum to the minimum flow varies from 9 to 26, with an average value of 16. No increasing or decreasing trends in the minimum flow or the ratio of the maximum to minimum flow are apparent in Figure 6.2.

The mean annual discharge is about 20,000 m^3s^{-1} and like the other parameters defining the flow regime, only a small increase is apparent during the last few decades. This small increase is probably due to the decrease noted in flows spilling to the Old Brahmaputra distributary.

It may be concluded that analysis of time-series discharge records for the Jamuna River at Bahadurabad suggests that there have been no significant changes in annual runoff, mean discharge, or annual peak flood or low flows during the last 50 years (Figures 6.1 and 6.2). Therefore, impulse or step changes in the flow regime may be ruled out as a possible cause of the observed changes in the morphology of the Jamuna River.

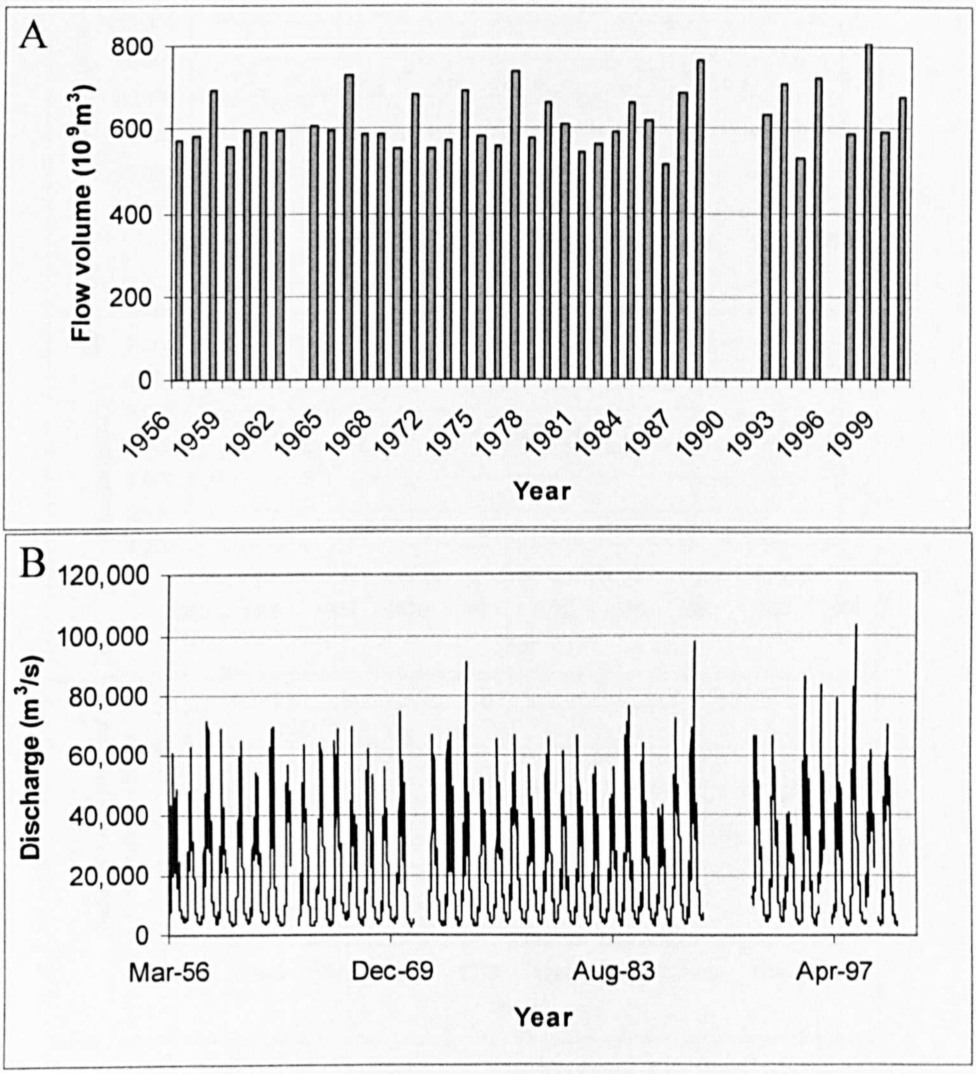


Figure 6.1. (A) Flow volume and (B) time-series discharge of the Jamuna River at Bahadurabad

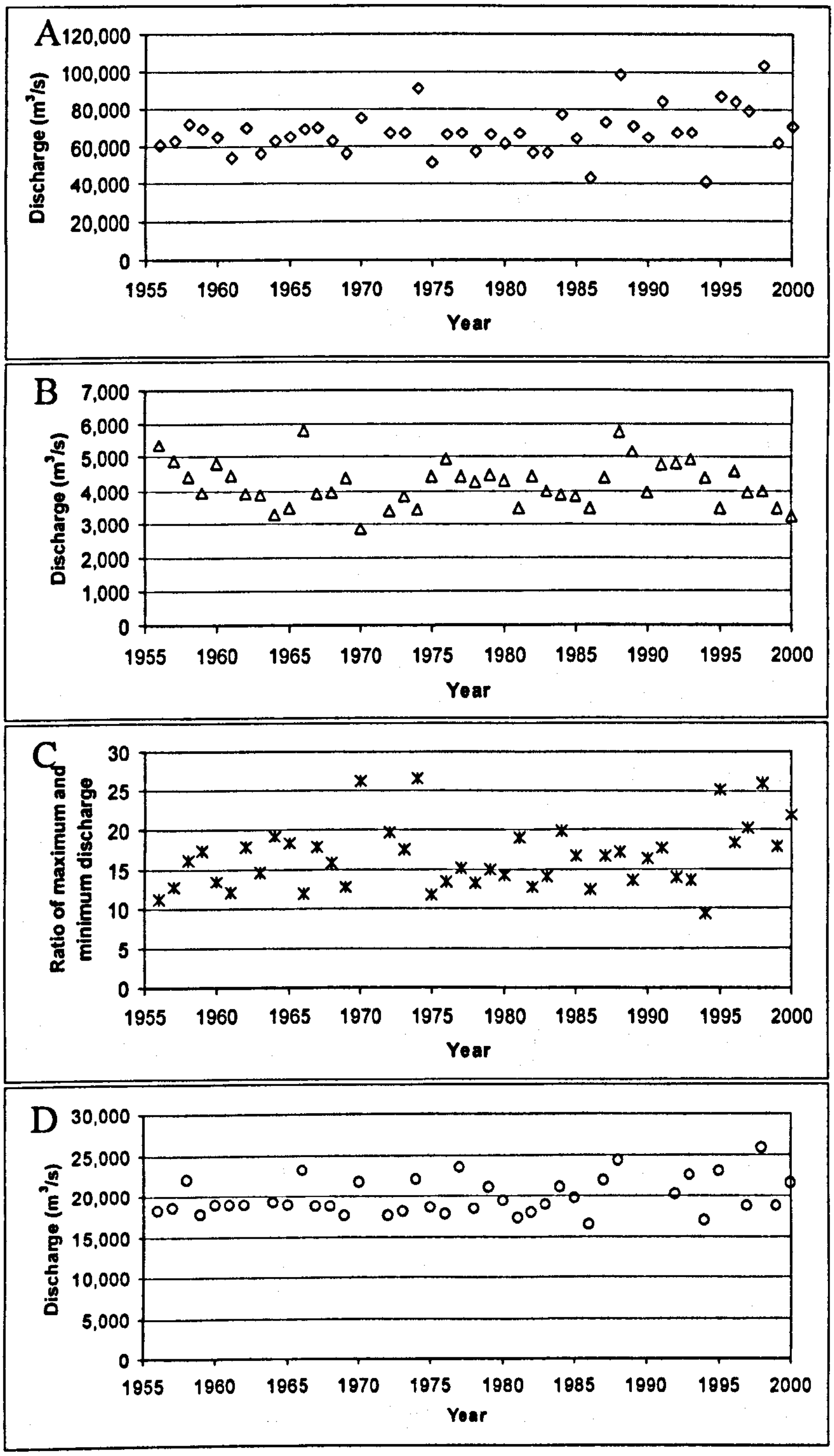


Figure 6.2: Changes in (A) maximum annual discharge, (B) minimum annual discharge, (C) ratio of maximum to minimum discharge and (D) mean annual discharge of the Jamuna River over time.

6.3.2 Changes in bed sediment size

The size of the bed materials in an alluvial river is not constant along its length, but varies in the downstream direction. It may also vary laterally. Generally, bed particle size decreases in downstream direction, but the rate of reduction in particle size with distance tends to decrease where the bed material is finer (Knighton, 1998).

During downstream propagation of the sediment wave, the size of the transported sediment was found to be finer during the aggradation phase and coarser during the degradation phase (Miller and Benda, 2000; Bartley and Rutherfurd, 2005).The size distributions of bed materials sampled in the Jamuna River during the period 1966 to 1977 were reported by the Appraisal Study of the Jamuna Multipurpose Bridge (RPT *et al.*, 1987). In 1993, the River Survey Project collected 104 samples of bed material from the Jamuna River at Bahadurabad and a further 34 at Sirajganj (Delft Hydraulics and DHI, 1996c). The average median grain size (D_{50}) of bed material samples collected over the period is plotted in Figure 6.3. Because of the sparse temporal resolution of the data, it is very difficult to draw any conclusion concerning trends in the median bed material size. The only location where bed material samples were collected for three different periods (1968-70, 1972-77 and 1993) is Sirajganj, where D_{50} varied from 0.16 mm to 0.21 mm. However, this relatively small amount of difference might be simply related to natural variability and sampling uncertainty.

In contrast, examination of spatial variability in bed material samples taken from the Jamuna River indicates that the expected trend for downstream fining of bed material size is present. The rate of downstream fining reported by RPT *et al.* (1987) was 0.04 mm per 100 km, though Delft Hydraulics and DHI (1996g) reported that it was only 0.01 mm per 100 km.

Data presented by Delft Hydraulics and DHI (1996a) suggest that valley slope is greater than 9 $cmkm^{-1}$ at the upstream limit of the Jamuna, but that it gradually decreases to 7 $cmkm^{-1}$ at the downstream limit. This supports the premise that downstream fining of the bed materials is reflected in concavity of the longitudinal profile of a river (Sinha and Parker, 1996). However, no indication of temporal variation in the concavity of the river was apparent.

It may be concluded that analysis of available bed material sampling records for the Jamuna River suggests that there have been no significant changes in median particle size during the last 40 years (Figure 6.3). Therefore, impulse or step changes in the bed material characteristic may be ruled out as a possible cause of the observed changes in the morphology of the Jamuna River.

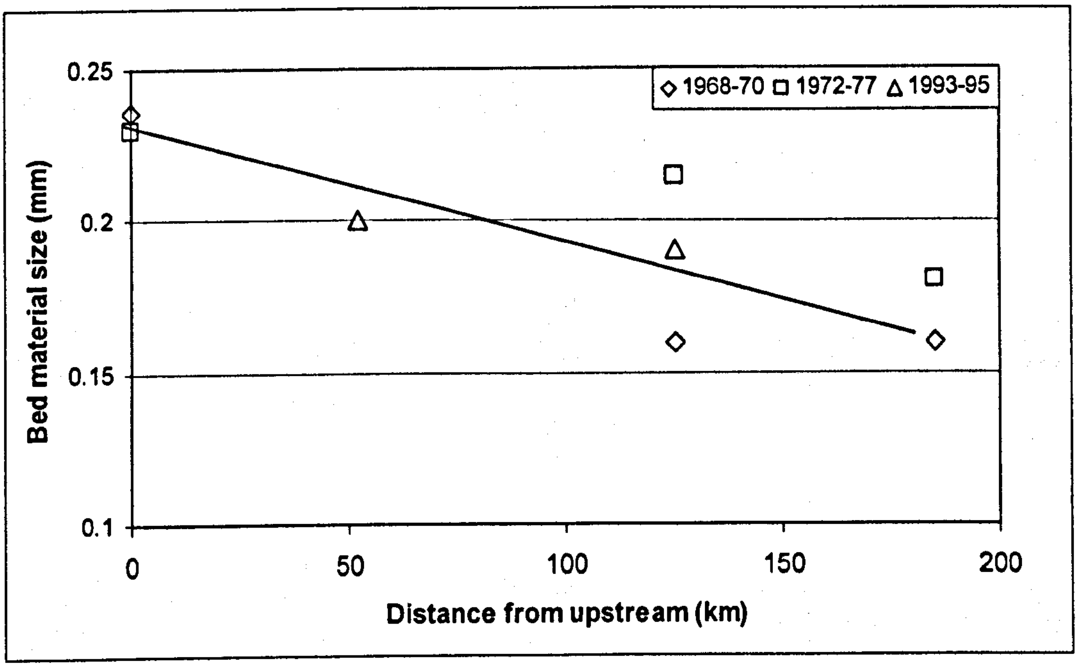


Figure 6.3. Median bed material size based on samples from the Jamuna River

6.3.3 *Changes in the sediment regime*

The sediment regime is extremely important in determining the channel morphology. Changes in the sediment supplied to a reach have been shown to cause sequential changes in the form and roughness of the channel bed as well as the channel width, depth and planform characteristics (Lane, 1955; Schumm, 1969, 1985; Chang, 1976, 1986 & 1988; White *et al.* 1982; Bettess and White, 1983; Bridge, 2003). However, reliable field data on the sediment regimes and loads carried by natural rivers remain very sparse (Schumm, 1971a; Richards, 1982; Knighton, 1998).

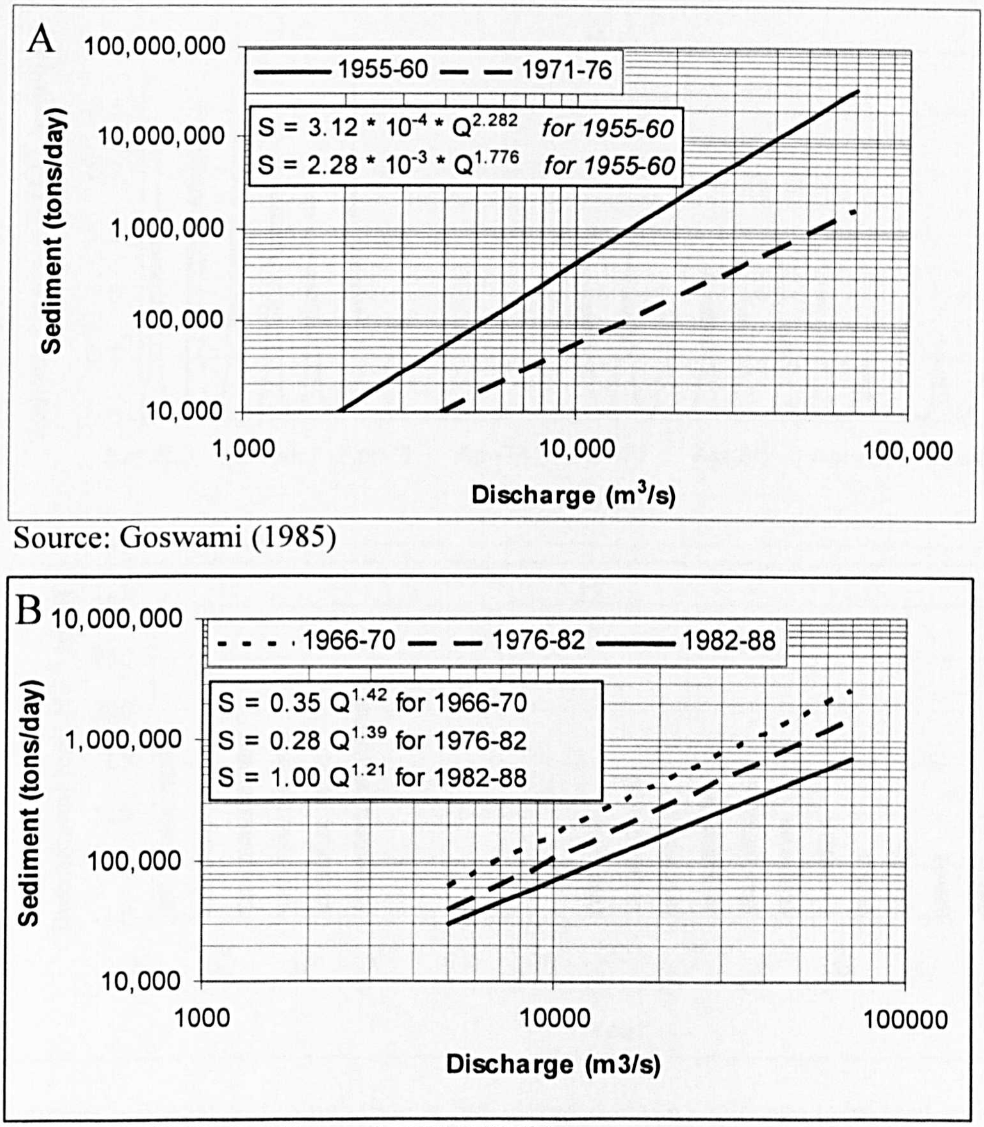
This is also the case for the Brahmaputra-Jamuna-Padma-Lower Meghna system, for which there are no continuous, long-term measurement records of sediment transport. Hence, in recounting the history of the sediment regime and the spatial distribution of sediment movement and temporary storage in the system, reference can only be made to a few short periods of measurement at just two locations. Goswami (1985) reported on measured total sediment loads in the Brahmaputra at Pandu, about 390 km downstream of Dibrugarh. He presented sediment rating curves for the periods 1955 to 1960 and 1971 to 1976 (Figure 6.4A). Unfortunately, Goswami did not report the co-efficient of determination (R^2) values for the rating curves and despite extensive efforts by this author it has proved impossible to obtain them. However, the implication of these curves is clear in that they indicate that for the same discharge, the sediment load measured at Pandu was several times higher between 1955 and 1960 than it was between 1971 and 1976. Lack of data prevents statistical analysis to corroborate this finding, however.

Delft Hydraulics and DHI (1996h) compiled and analyzed sediment measurements performed by BWDB in the Jamuna at Bahadurabad, about 270 km downstream of Pandu. They produced sediment rating curves (Figure 6.4B and Equations 5.5 to 5.7) and reported significant reductions in suspended sediment transport through time, especially for the suspended bed material load. Like Goswami (1985), Delft Hydraulics and DHI (1996h) did not report values for the co-efficient of determination (R^2) for rating curves presented in Equations 5.6 and 5.7. However, as discussed in the previous section, the likely values of R^2 for the rating curves presented in Figure 6.4B and Equations 5.5 and 5.7 have been found to close to 0.90. Consequently, although this cannot be tested statistically due to lack of access to the original data, it seems entirely reasonable to assume that the differences between the curves result from actual differences in measured sediment loads rather than random chance. On this basis, the rating curves indicate that, for the same discharge, the sediment load at

Bahadurabad section was very high during the late-1960s, but gradually declined during the 1970s and 1980s. This is a similar pattern of decreasing sediment transport to that noted by Goswami (1985), but it is phase lagged somewhat.

The rating curves for different periods have been used in this study to generate daily mean bed material loads at Bahadurabad for the period 1965 to 1988 (Figure 6.5A). Annual bed material discharges (by volume) have also been estimated (Figure 6.5B and Table 5.4). These results indicate that the bed material load during the late-1980s was only about 33% of that carried during the 1960s.

While the measured data are sparse, it may nonetheless be concluded that analysis of available measured suspended sediment transport records for the Brahmaputra and Jamuna Rivers suggests that there have been significant changes in the load, especially for the suspended bed material, during the last 50 years (Figures 6.4A and 6.5B). Sediment loads were very high in the 1950s and 1960s, but have declined since then to more normal levels. Therefore, an impulse change in the sediment regime of the Jamuna River due to a temporary increase in the rate of bed material supply to the river from the Brahmaputra River upstream has been established as a possible cause of the observed changes in the morphology of the Jamuna River.



Source: Goswami (1985)

Source: Delft Hydraulics and DHI (1996h)

Figure 6.4. Sediment rating curves for (A) Pandu and (B) Bahadurabad

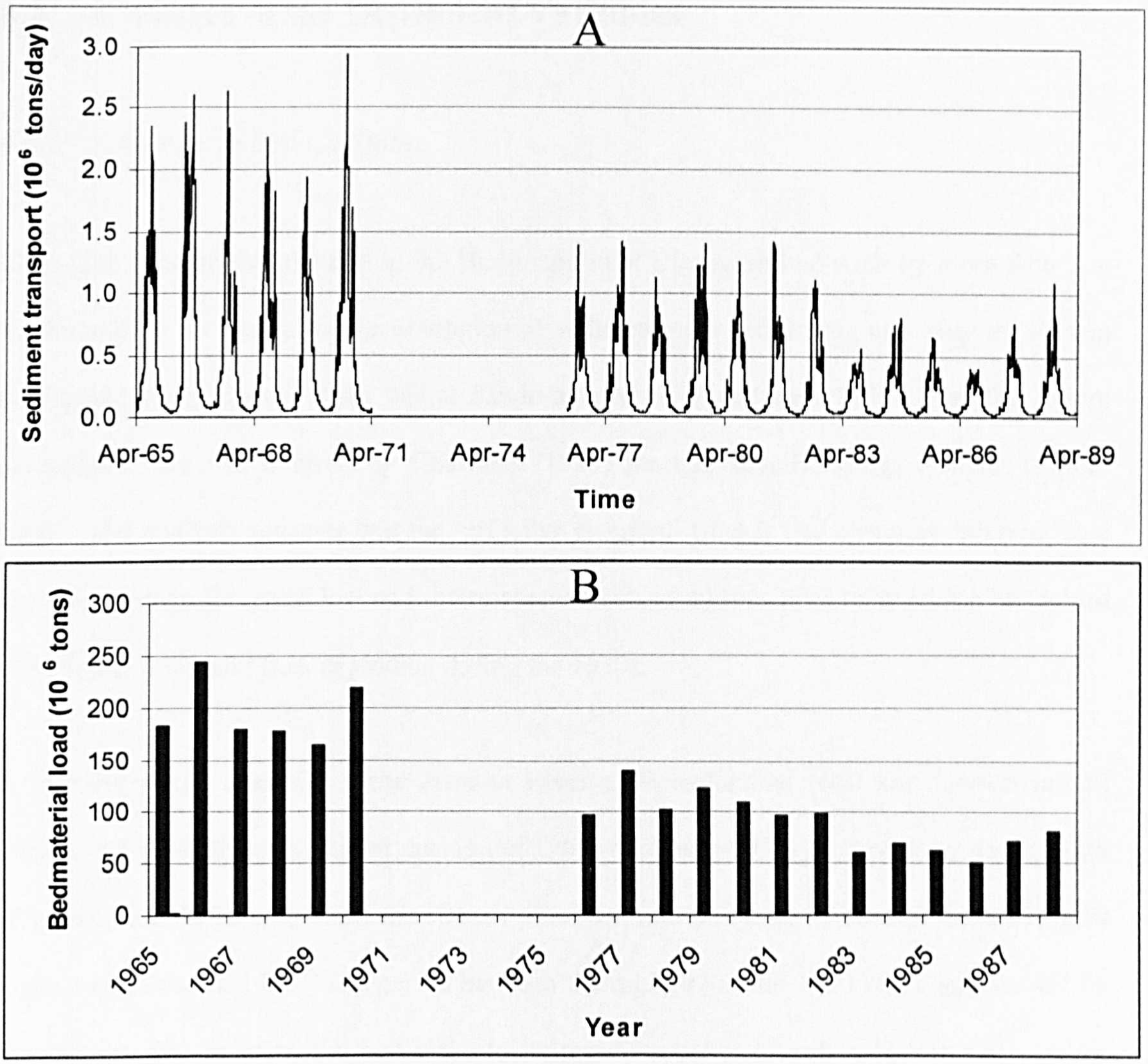


Figure 6.5. Variation through time at Bahadurabad for (A) daily sediment load and (B) annual sediment load

6.4 Changes in the Dependent Variables

6.4.1 Changes in bed elevation

Krug (1957) noted that the bed of the Brahmaputra at Dibrugarh had risen by more than 3 m by the mid-1950s due to the accumulation of sediment supplied during and after the Assam earthquake. Aggradation of the bed at Pandu as a result of sediment influx from the Assam earthquake was also inferred by Goswami (1985) through specific gauge analysis (Figure 6.6A). His analysis suggests that the 'effective riverbed' (that is bed elevation inferred from changes in stage for given low and intermediate discharges) rose by 2 m, reaching its highest elevation in 1969 and then degrading during the 1970s.

A specific gauge analysis of the Jamuna River at Bahadurabad (660 km downstream of Dibrugarh) indicates aggradation during the 1960s and early-1970s, followed by degradation (Figure 6.6B). At Bahadurabad, the effective bed was raised in total by about 1 m, reaching its highest elevation in 1974. The period between the mid-1970s and 1990 was characterised by degradation that returned the bed close to its pre-disturbance elevation by the early 1990s. The 1990s feature a second phase of aggradation at Bahadurabad (Figure 6.6B). This pattern of aggradation followed by degradation and then a shorter period of renewed aggradation is similar to the damped oscillation in bed elevations observed in disturbed river systems in the USA and reported by Simon (1989).

In this study, two further analyses were performed to support or refute the reliability of the changes in effective bed level inferred by specific gauge analyses. First, the water surface area along the 200 km extent of the Jamuna River was extracted from the time-series dry season satellite images. The results show that the extent of the water surface in the images increased by 18 % between 1973 and 2000. On the other hand the relations between stages with time, and stages with extent of water do not show any significant relations (Figure 6.7). This indicates increasing low flow width, which may correspond to lowering of the bed and an increase in flow area for a given water level since the late 1970s. Second, analysis of cross-sections measured by the BWDB provides evidence that the flow area below the bankfull level increased by a further 20% during the 1980s and 1990s. These results support the inference of lowering of the effective bed level drawn from the specific gauge analysis for this period. Moreover, there is evidence that in the Jamuna River flooding was increased for the same discharge in the late 1960s and early 1970s, which was significantly reduced in the 1980s (Personal communication with Brammer, and Ibrahim, 1984).

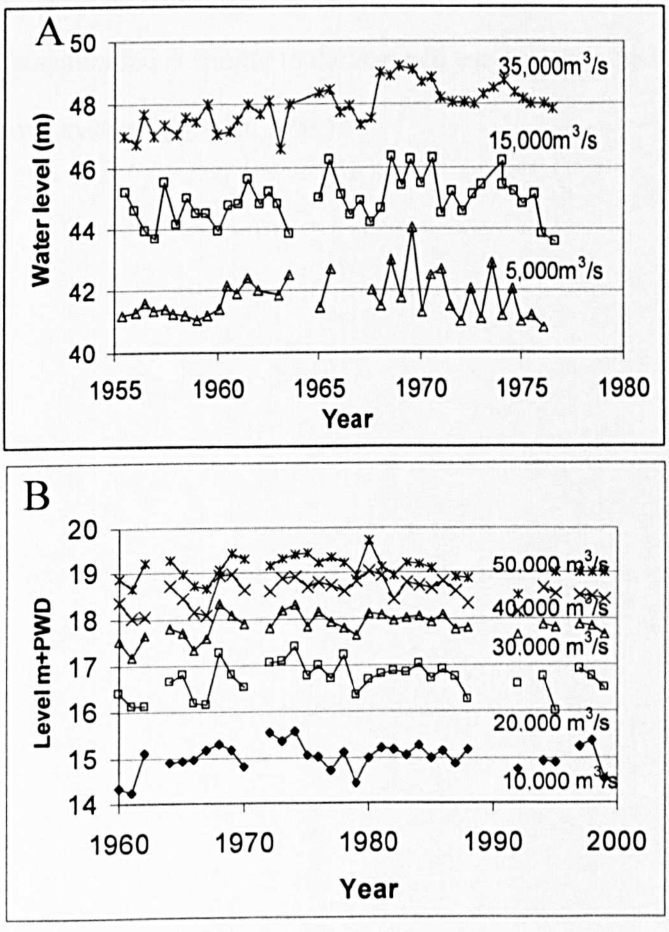


Figure 6.6. (A) Specific gauge analysis of the Brahmaputra River at Pandu and (B) specific gauge analysis of the Jamuna River at Bahadurabad

These records of bed elevation change support the working hypothesis concerning morphological responses to the earthquake in three important ways. First, they establish that the magnitude of bed response was a maximum at Dibrugarh, close to the point of maximum disturbance where most of the earthquake-derived sediment entered the Brahmaputra River, and they show that the magnitude of riverbed response decreased in the downstream direction to 2 m at Pandu, and 1 m at Bahadurabad. This finding is consistent with Simon's (1989) observation that maximum bed level changes occur close to the point of greatest disturbance. It is also consistent with other analytical solutions and empirical observations reported in the literature, which suggest that the degree of riverbed rise due to overloading declines with distance downstream (Ribberink and Sande, 1985; Madej and Ozaki, 1996, Lisle *et al.*, 2001, Cui *et al.* 2005). Second, the records reveal a clear downstream phase lag in the timing of bed level rises in that the riverbed reached its maximum elevation in the 1969 at Pandu and 1974 at Bahadurabad. Third, the sequence of aggradation-degradation-aggradation observed at Bahadurabad is similar to the damped oscillation in bed elevations observed in other disturbed river systems (Simon, 1989).

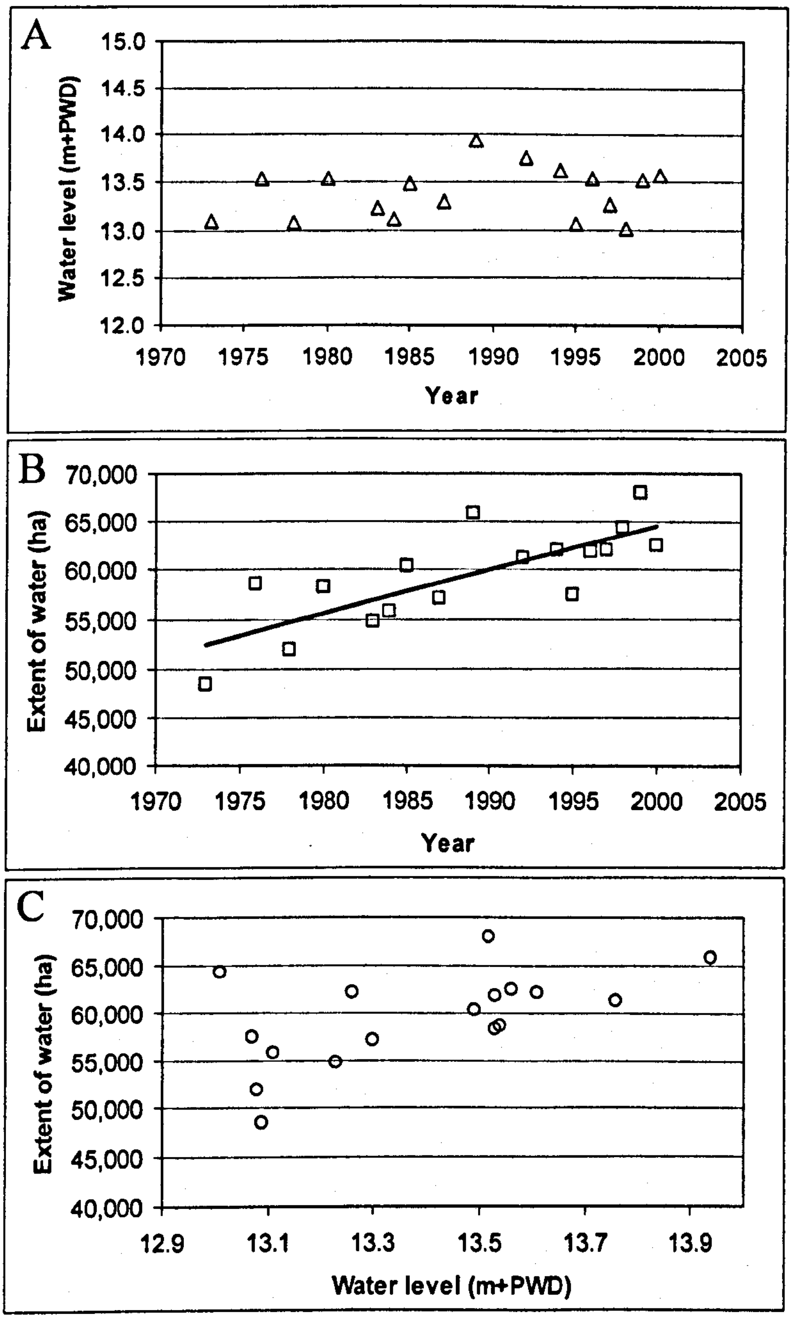


Figure 6.7: (A) Water level and (B) extent of water (derived from time-series of satellite images) on day of satellite image acquisition, and (C) relation between stage and extent water

6.4.2 *Changes in width*

The way that the width of an alluvial river is defined may vary, depending on the planform of the river, the type of data available (historical maps, cross-sections, aerial photographs, satellite images) and the criteria used to delineate the bank lines. While every effort has been made to use a consistent basis for comparing widths and width changes, this must be borne in mind when assessing the evidence for width change in the Brahmaputra-Jamuna-Padma-Lower Meghna system.

Goswami (1985) derived changes in the width of the Brahmaputra in Assam by analyzing cross-sections surveyed between Dibrugarh and Bessamara for the years 1971, 1977 and 1981. He found an average widening rate of 220 my^{-1} during 1971-77, which reduced to 37 m/y during 1977-81. Unfortunately, no information is available on widening prior to 1971.

In this study, the time series of satellite images was used to define the width and establish rates of widening for the river system in Bangladesh. The criteria used in delineating the bank lines and the definition of width were presented in Chapter 5. The width of the river includes the widths of channels, sand bars and islands (chars) within the braid-belt. The criteria for bank line delineation may cause the time lag between the estimated and effective reduction in width due to abandonment of anabranches, while the estimated increase in width due to bank erosion or development of flanking anabranches will be immediate.

For width analysis, the Jamuna was divided into two, 100 km reaches. The upper reach extends from the Indian border to around Sariakandi and the lower reach from Sariakandi to the Ganges confluence. The upper reach maintained a nearly constant width from 1967 to 1978, after which it widened at a very high rate of about 200 my^{-1} (Figure 6.8). The widening rate suddenly decreased to about 35 my^{-1} after 1989. The lower reach suddenly reduced its width by 1.5 km from 1967 to 1973 (Figure 6.8). It then widened at about 140 my^{-1}

throughout the period 1973-1999. However, it appears that the rate of widening in the lower reach has decreased markedly to around 50 my^{-1} since 1999.

Between 1967 and 1978, the upper reach of the Jamuna maintained a constant average width while in contrast the lower reach initially reduced its width and then widened. In the late-1970s both reaches began to widen rapidly. High rates of widening in the upper reach ceased after 1989, but the high rates persisted in the lower reach for another decade, finally decreasing in the late-1990s.

Based on the dates at which rapid widening ceased in the Brahmaputra and the upper and lower reaches of the Jamuna, it is possible to infer a downstream phase lag in the sequence of morphological responses to disturbance. The phase lag in the cessation of rapid widening in the Brahmaputra between the Dibrugarh to Bessamara and in the upper reach of the Jamuna is about 15 years. The river distance separating these reaches is about 620 km. This indicates a speed of downstream propagation in morphological response of about 40 kmy^{-1}. The phase lag between the end of rapid widening in upper and lower reaches of the Jamuna is 10 years. The distance between the central points of these reaches is 100 km, indicating a propagation speed of 10 kmy^{-1}. These propagation speeds are consistent with the estimated celerities of a sediment wave in between these reaches of about 32 kmy^{-1} and 10 kmy^{-1}, respectively.

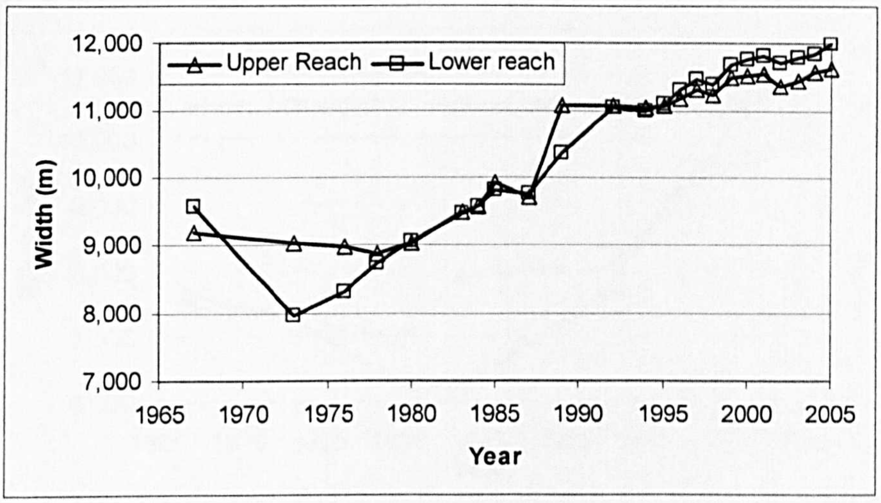


Figure 6.8. Changes in average width of the Jamuna River

Considering the Padma River in two 50 km long reaches shows that the upstream reach started widening in 1980, while the downstream reach did not begin widening until 1984 (Figure 6.9A). The Lower Meghna began widening in 1990 (Figure 6.9B). Both rivers are still continuing to widen rapidly up to the present day. Interestingly, like the lower reach of the Jamuna River, the Padma and the Lower Meghna both actually narrowed immediately prior to the onset of rapid widening (Figure 6.9 A&B). Narrowing occurred in both reaches of the Padma during the 1970s and during the 1980s in the Lower Meghna. The dates of the onset of both narrowing and widening in these rivers and the equivalent behaviour in the lower reach of the Jamuna display a phase lag that is consistent with the downstream passage of a disturbance and a morphological response in the fluvial system.

It should also be noted that the upper reach of the Jamuna River, however, shows a different pattern of width adjustment. Rather than narrowing, it maintained a constant width during the period 1967-1973 prior to beginning its phase of rapid widening in the late-1970s. Of course, its width may have decreased earlier than 1973, but no satellite imagery is available. Based on cartographic analysis of maps published in 1955, the average width of the Jamuna River in the early 1950s was about 9.5 km, which is close to the average width of 9.3 km observed in 1967. This suggests that any reduction in the width of the upper reach that did occur was quite small.

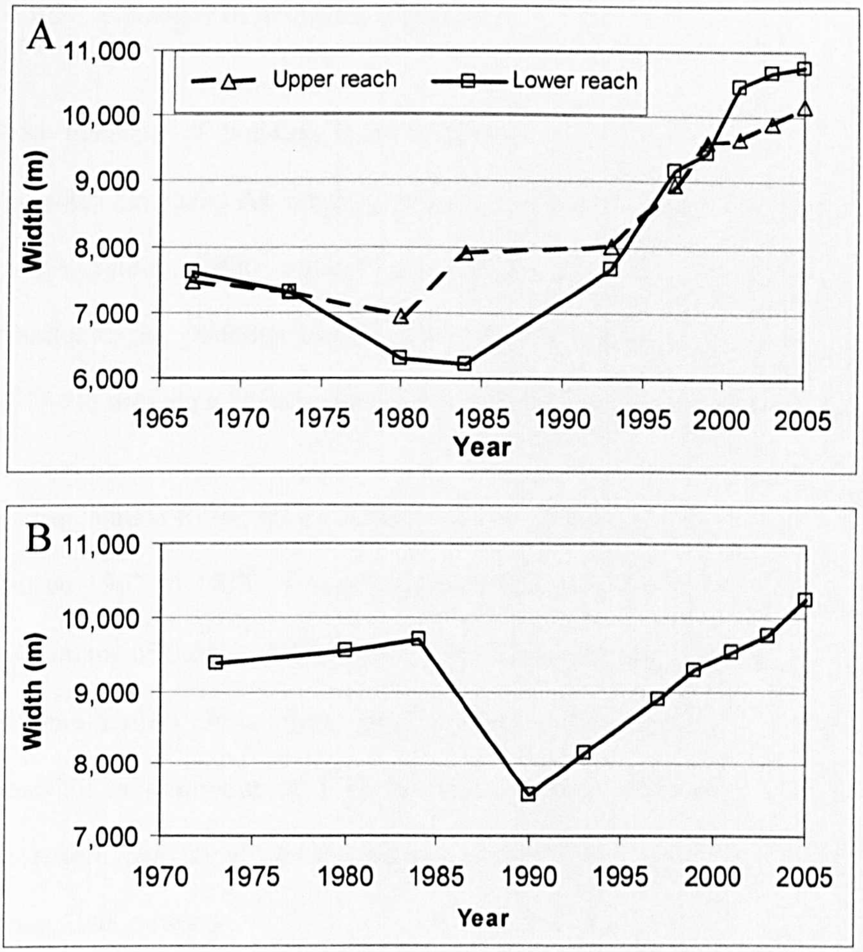


Figure 6.9. Changes in width of (A) Padma and (B) Lower Meghna Rivers

Similarly, the width response of the upper reach during the period when the sediment supply to it was increasing occurred prior to the availability of satellite imagery, although cross-sectional data and specific gauge analysis for the late-1960s, during the peak in sediment transport, both suggest that the width was nearly constant while the bed elevation was aggrading. During the late-1970s, in response to the decrease in sediment supply, the width of the upper reach increased at a very high rate while the bed was degrading. If it is assumed that sediment load in the lower reach peaked a few years later than in the upper reach, it could be inferred that as the sediment supply increased the river narrowed, while as the sediment supply subsequently returned to its pre-disturbance level, the river widened rapidly.

6.4.3 Changes in braiding intensity

The intensity of braiding is an important morphological parameter in rivers with multi-threaded channels. As braiding intensity is strongly stage-dependent (Bridge, 1993; Nanson and Knighton, 1996), indices for different dates can only be compared if they represent similar stages. Satellite images of the rivers at similar stages were used in this study (Figure 6.7A) to provide a reliable record of morphological changes through time.

In the Jamuna River, the braiding intensity of the upper reach was constant at 2.42 during the period 1967 to 1973. It then increased throughout the early 1970s and 1980s, reaching a maximum of 3.08 in 1992, before declining markedly through the remainder of the 1990s (Figure 6.10A). In contrast, braiding intensity declined in the lower reach during the 1970s, reaching a minimum of 1.73 in 1980. After that braiding intensity in the lower reach increased, peaking at 2.64 in 1992 and oscillated around 2.5 before starting to fall consistently from 1996 onwards.

The braiding intensity of the upper reach of the Jamuna River started to increase in 1973, while it started to increase in 1980 in the lower reach of the river showing a seven-year phase lag equivalent to a downstream propagation speed of about 15 kmy^{-1}. Braiding intensity started to decrease substantially in both reaches of the Jamuna River within an interval of four years, indicating a downstream propagation speed of 25 kmy^{-1}.

The Padma and Lower Meghna rivers are much less intensively braided than the Jamuna (Figure 10B and C). Typical braiding indices for the Jamuna lie in the range of 2 to 3, while those for the Padma and Lower Meghna very rarely exceed 2, and both rivers have approached a straight, single-channel planform configuration on one occasion during the last three decades. The Padma River concentrated in a single channel in 1984, while adoption of this pattern in the Lower Meghna was lagged by six years to 1990. The minimum braiding intensities of the Padma and Lower Meghna River were 1.2 and 1, respectively. The braiding intensity of the Padma reached its maximum of 2 in 1999, while the braiding intensity of the Lower Meghna River is still increasing at present.

The record of change in the Padma is similar to that in the lower reach of the Jamuna, with braiding intensity first decreasing and then increasing (Figure 6.10B). Like the lower reach of the Jamuna River, the braiding intensity of the Padma River finally decreased in the late 1990s. Increasing and later decreasing of braiding intensity of these rivers show a clear phase lags of four and three years respectively. The pattern of changing braiding intensity in the Lower Meghna is also similar to that of the Padma River, but features a downstream phase lag of six years (Figure 6.10C).

Comparison of the changes in braiding intensity with available records for sediment supply and bed level changes suggests that when the sediment load started to decrease the braiding intensity of the river started to increase. This is in line with Figure 3.5, according to which braiding decreases in response to an increase in sediment load and increases as the sediment load decreases.

In many braided rivers, changes in braiding intensity are positively correlated with the changes in width. This is also the case in the Padma and Lower Meghna Rivers, which have relatively simple planforms. It is interesting to note, however, that the high intensity of braiding and great complexity of the planform of the Jamuna River results in situations where the braiding index *decreases* while the width is increasing (compare Figures 6.8 and 6.10A), suggesting that in reality braiding intensity need not always be associated with the changes in width.

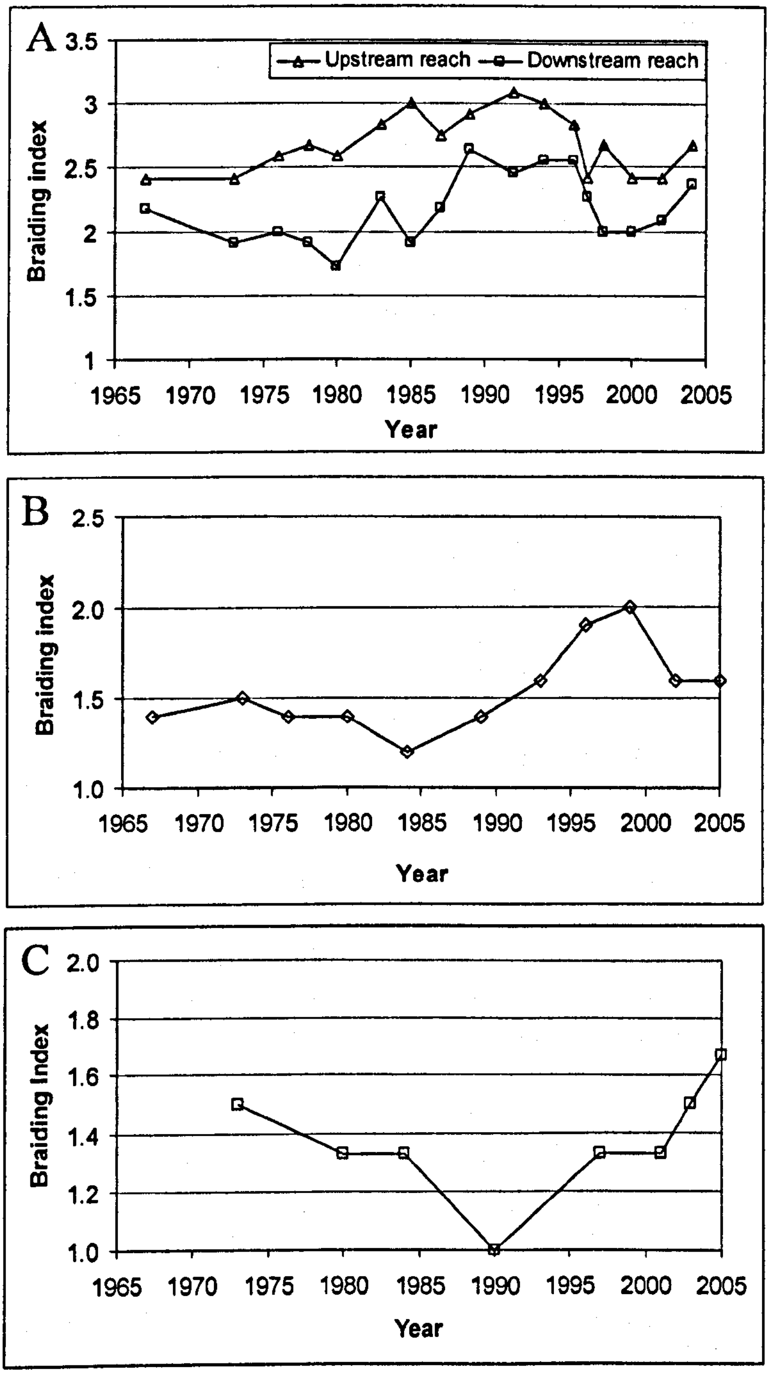


Figure 6.10. Changes in braiding intensity for (A) Jamuna, (B) Padma and (C) Lower Meghna rivers

6.4.4 Phase lags in the observed morphological changes

The records of observed morphological changes in the river system recounted above allow estimation of downstream phase lags in the turning points in trends of morphological response to disturbance involving bed level change, width adjustment and braiding index. The results are summarised in Table 6.2 for different reaches of the Brahmaputra-Jamuna-Padma-Lower Meghna system. Unfortunately, estimation of the celerity in the sediment wave is limited to the reach between the Brahmaputra and the Jamuna as the only measurements of sediment load are for Pandu and Bahadurabad.

Observed values of phase lag indicate that the propagation speed of different morphological changes vary from about 50 kmy^{-1} at the upstream limit of the system to 10 kmy^{-1} further downstream, being highest for the Brahmaputra, Jamuna and Padma rivers and much lower for the Lower Meghna River. These results are consistent with the estimated celerity of a bed sediment wave in these rivers in that the observed average phase lags for the Brahmaputra and Jamuna rivers (38 kmy^{-1}) and the Padma and Lower Meghna (17 kmy^{-1}) are of the same order of magnitude as the wave celerities calculated from the theory of river mechanics (32 kmy^{-1} and 10 kmy^{-1}).

Table 6.2 Phase lags in observed morphological changes in the river system

Reach	**Phase lag in morphological change (kmy^{-1})**				
	Peaking of bed level	Turning point			
		Increase in widening rate	Decrease in widening rate	B.I. increase	B.I. decrease
Dibrugarh to Pandu	43				
Bessamara to Bahadurabad			37		
Pandu to Bahadurabad	54				
Upper Jamuna to Lower Jamuna			10	15	25
Lower Jamuna to Upper Padma		10			
Lower Jamuna to Padma				25	33
Upper Padma to Lower Padma		12			
Padma to Lower Meghna		10		12	

65 Development of the conceptual process-response model

6.5.1 Background

Based on the available accounts of the volume and timing of sediment introduced to the Brahmaputra River by the Assam earthquake and the observed changes in sediment transport, bed level, width and braiding intensity in the Jamuna River downstream, a conceptual process-response model was constructed to explain how morphological adjustments may be linked to downstream propagation of a sediment wave. The conceptual model presented in Figure 6.11 and described here builds on and extends the approaches of previous authors particularly Lane (1955), Schumm (1969), Bettess and White (1983), Nicholas (1995), Jiongxin (1996), Simon (1989), Lisle *et al.* (2001) and Cui *et al.* (2005).

The Jamuna River has been divided into two reaches each of 100 km in length. The upper reach of the Jamuna River around Bahadurabad provides primarily the basis for model development as it has the most complete record of causal (bed material load) and responsive (channel adjustments) changes (Figures 6.4B, 6.5, 6.6B, 6.8 & 6.10A). The changes in planform parameters of the downstream reach of the river provide supplementary information of use in developing the model.

Slope adjustments are often considered to be a key element of dynamic process-response and have been used to describe why complex response occurs in disturbed fluvial systems (Schumm, 1977). However, in the rivers studied in this project the huge scale of their channel and floodplain systems diminishes the significance of slope adjustment in driving morphological response. Also, Simon and Rinaldi (2006) showed that river response through slope adjustment is insignificant in rivers like the Jamuna that can adjust their width and planform very easily due to their erodible, non-cohesive, sandy banks. Thus, the valley slope was not considered as an independent variable in the conceptual process-response model and neither was the channel slope considered as a dependent variable.

Similarly, changes in the characteristic size of the bed material are often found to be significant in influencing process-response mechanisms in disturbed rivers (Chien, 1985; Simon and Thorne, 1996). During downstream propagation of the sediment wave, the size of the transported sediment was found to be finer during the aggradation phase and coarser during the degradation phase (Miller and Benda, 2000; Bartley and Rutherfurd, 2005). While the temporal resolution of the measurements was not ideal, observations of bed material grain size in the Jamuna River between the 1960s and the 1990s indicate that changes are insignificant (Figure 6.3) and certainly would not significantly alter the hydraulic roughness or the mobility of the bed material. Consequently, it was concluded that changes in bed material size should not be considered in the conceptual model.

In line with current thinking (Biedenharn *et al.* 2006), the contribution of the wash load to promoting morphological channel change is also neglected, and it is variation in the supply of bed material load to a reach that is considered to drive stream processes and trigger morphological adjustments. As recognised by Knighton (1998), morphological response is not instantaneous and a reaction time is included between the time that the input bed material load changes and the time that channel adjustments become detectable. Based on the observations of Simon (1989, 1992), a secondary oscillation both for independent and dependent variables has been assumed during the development of the conceptual model.

6.5.2 Adjustments in the upstream reach of the Jamuna River

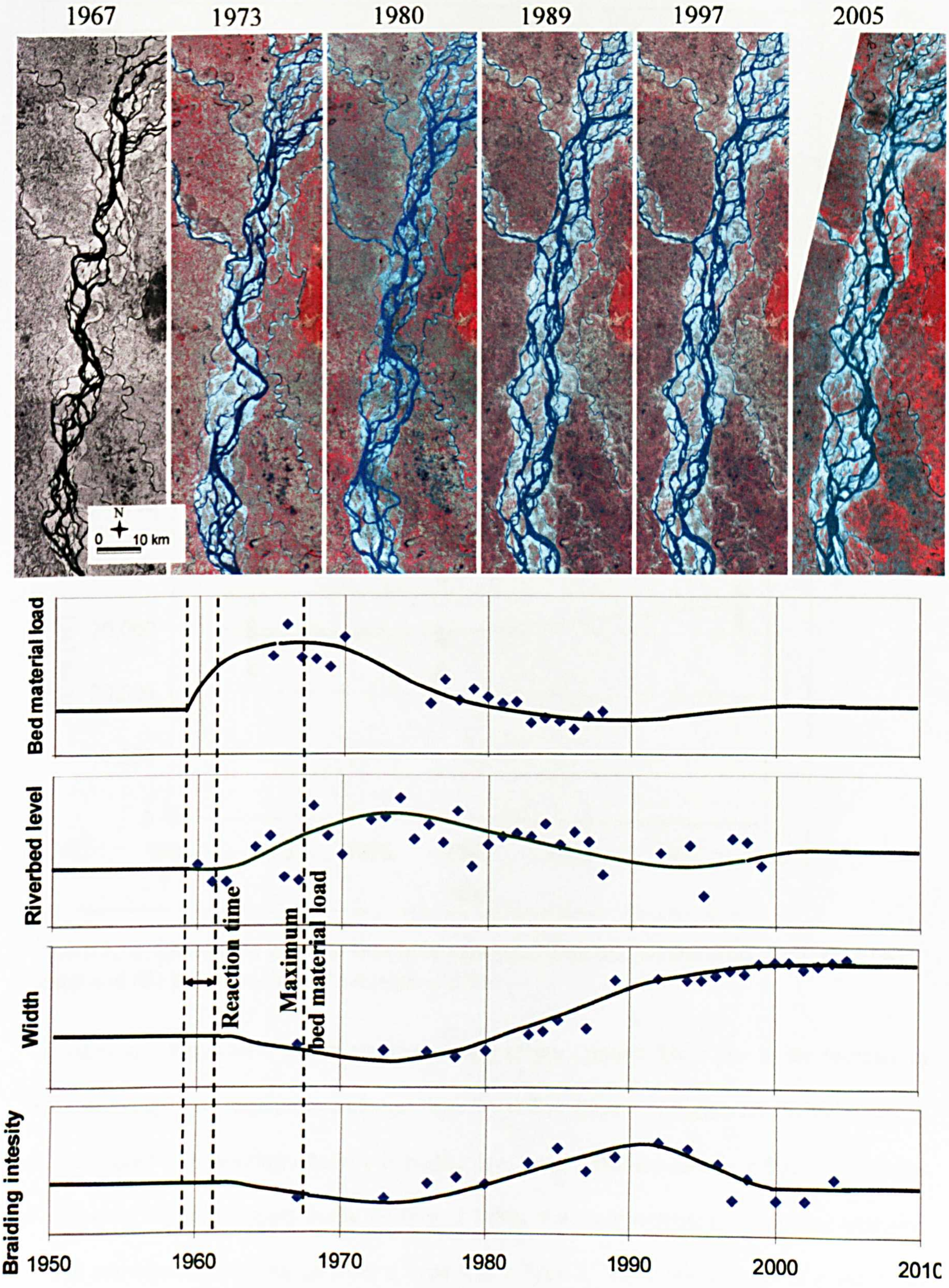
Unfortunately, the sediment transport record at Bahadurabad does not extend back beyond 1966, by which time the input of bed material load was already high (Figures 6.4B and 6.5). Consequently, there is no hard evidence from measurements or observations that can be used to indicate exactly when the bed material load entering the upstream reach of the Jamuna started to increase, or the amount by which it increased prior to 1966. Hence, it is necessary to infer a date for the arrival of the leading edge of the wave of bed material load at Bahadurabad as being sometime around 1960 (Figure 6.11). It follows that this part of the conceptual model, which shows the bed material load entering into the Jamuna River rising during the early to mid-1960s and which indicates a secondary oscillation in bed material load during the 1990s, must be considered as hypothetical. The available data does, however, establish that the suspended bed material load peaked in the late-1960s and then decreased until the end of the 1980s.

The specific gauge analysis at Bahadurabad (Figure 6.6B) indicates that the effective bed level started to rise in the early-1960s because the increased supply of bed material load was greater than the local transport capacity. While the sediment load was increasing, the river bed was aggrading as well and this continued until the mid-1970s, by which time the sediment supply had started to decrease and reached a condition where local bed material load transport capacity matched the supply of bed material load from upstream. From the mid-1970s to the late-1980s, the bed level decreased as the supply of bed material load continued to fall further below the local transport capacity.

The upstream reach of the Jamuna maintained a nearly constant width during the late-1960s and early-1970s. The channel widened rapidly throughout the period 1978 to 1989, but since then the rate of increase in the width of the upstream reach has decreased dramatically (Figure 6.8). The braiding intensity of the upstream reach increased throughout the 1970s and 1980s, before declining markedly after 1992 (Figure 6.9A). On the other hand, a lower braiding index can be assumed prior to the onset of the increasing trend in the 1970s, with sometime between 1967 and 1973 (Figure 6.11). It is necessary to mention here that both width and the braiding intensity of the downstream reach of the Jamuna River decreased during the late-1960s and 1970s, prior to rapid increases in both parameters during the 1980s. The rapid increase in braiding intensity during the 1980s was associated with rapid widening at a time when the bed material supply was decreasing and the bed was degrading.

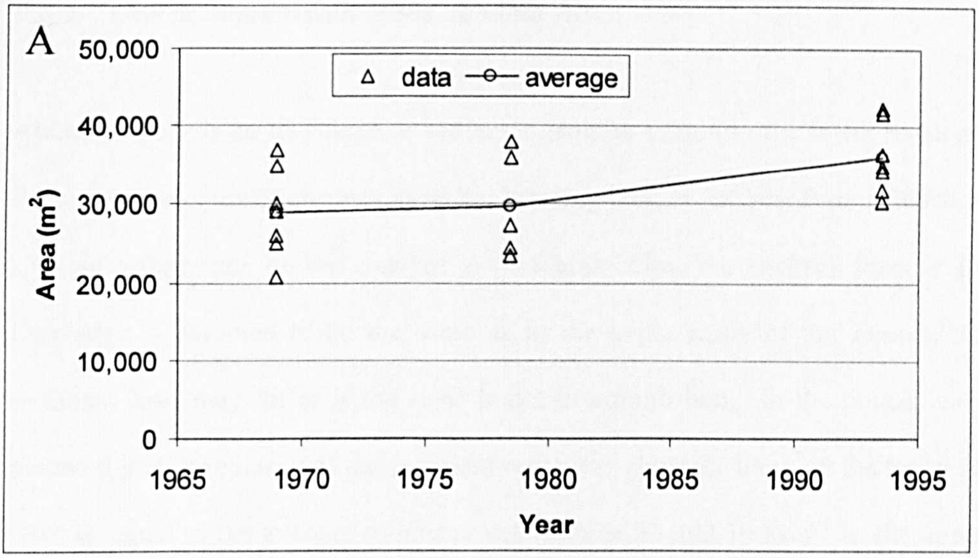
Changes in bed level, width and braiding intensity over time indicate that the bankfull flow area should have been higher in the 1990s than it was in the 1960s and 1970s. Analysis of reliable cross-sections in the upstream reach of the Jamuna River shows that the bankfull flow area was nearly constant during the 1960s and 1970s, but that it had increased by about 20% by the early-1990s (Figure 6.12A).

Increasing braiding intensities are generally thought to occur concurrently with increasing width. However, the records of channel change in the upper reach of the Jamuna show that the braiding intensity began to increase in 1973, 5 years before the widening trend became apparent, in 1978. In the conceptual model, it is degradation of the bed that is taken to trigger first, then braiding intensity and width. During this time the sediment supply is lower than the local sediment transport capacity of the river. In the early 1990s, the decreasing trend in sediment supply ceased and the sediment input probably increased slightly due to a secondary oscillation in the sediment wave (Simon, 1989 and 1992). Consequently, the braiding intensity was reduced during the early 1990s. In the conceptual model, the width increases, but at a lower rate. Hence, although a positive association between braiding intensity and width is widely reported in the literature, the conceptual model indicates that this is not true for all types of morphological adjustment associated with dynamic process-response.



Note:Data points shown in this figure were presented in Figures 6.5, 6.6, 6.8 and 6.10.

Figure 6.11. Conceptual model of morphological process-response developed for the upper reach of the Jamuna River



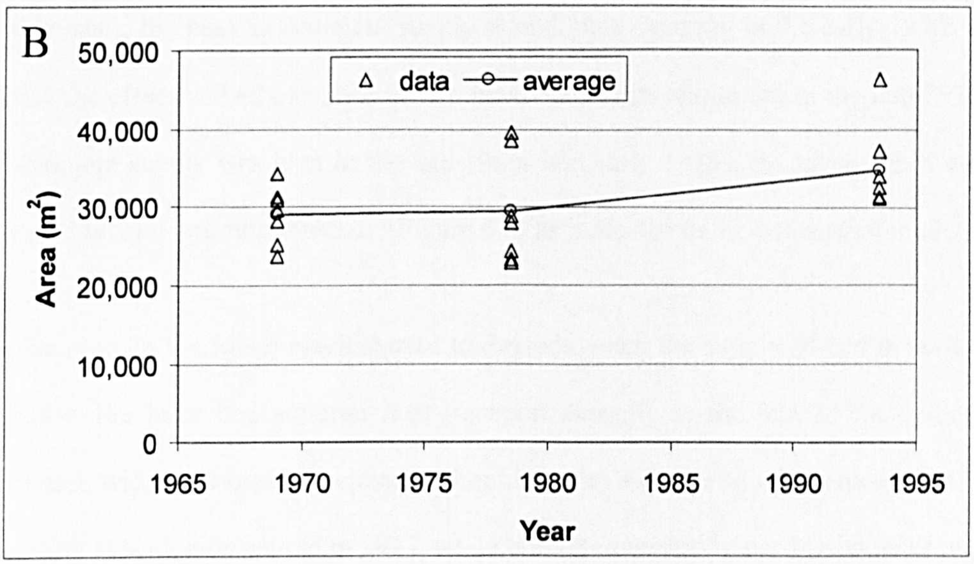


Figure 6.12. Changes in bankfull flow area measured from the reliable cross-sections in (A) upper and (B) lower reaches of the Jamuna River

Changes in the planform of the upstream reach of the Jamuna River due to the increase in sediment supply correspond to a change from Type 5 to Type 4 in Figure 3.5. In the model, it is considered that braiding intensity is higher in a Type 5 channel than in a Type 4. With the decrease of sediment supply in the 1970s and 1980s, the river increased its braiding intensity, which corresponds to a change from a Type 4 to a Type 5. Thus, the changes of planform in the conceptual model developed from observations made in the upper Jamuna match with the patterns indicated in Figure 3.5.

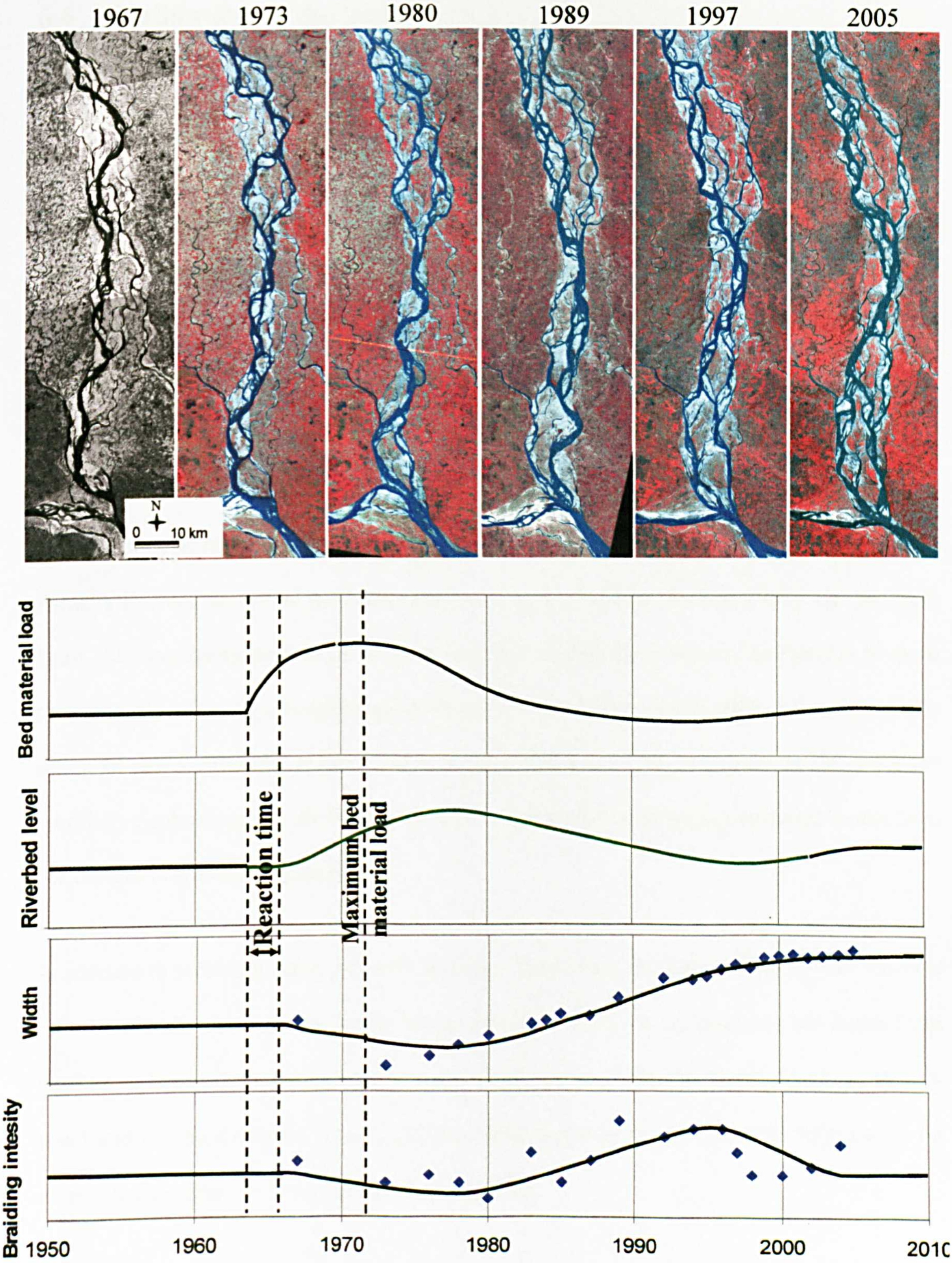
6.5.3 Downstream reach of the Jamuna River

Although there is no discharge or sediment gauging station in the lower reach of the Jamuna River, good records of changes in width, braiding indices and planform patterns are available. Limited information on the changes in flow area below the bankfull level is also available. Discharge is assumed to be the same as in the upper reach of the Jamuna River, but the sediment load may differ if the river is not in equilibrium. In the conceptual model, it is assumed that the celerity of the sediment wave was about 21 kmy^{-1} in the lower Jamuna River (that is, equal to the average estimated celerities of 32 and 10 kmy^{-1} in the upper reach). On this basis, the peak in sediment supply would have occurred in the early-1970s (Figure 6.13) and the effective bed elevation would have been at its maximum in the late-1970s. When the sediment supply was high in the late 1960s and early 1970s, the lower reach was decreasing its width and braiding intensity (Figure 6.8) as indicated in the conceptual model.

The river in the lower reach started to degrade when the supply of bed material load dipped below the local bed material load transport capacity in the late 1970s. According to the model, width and braiding intensity should start to increase simultaneously. But this differs in reality as widening started in 1973, while braiding intensity started to increase in 1980 (Figure 6.8 and 6.10A). As explained earlier, this occurs because of the complexity of the river and the definitions of width and braiding intensity. Analysis of reliable cross-sections in the lower reach shows that the bankfull flow area was higher in the 1990s than it had been in the 1960s and 1970s (Figure 6.12B). This result supports the validity of the changes in bed level, width and braiding intensity indicated by the conceptual model for this reach for the period between the mid-1970s to the 1990s (Figure 6.13).

Processes driving widening and an increasing braiding intensity continued until the supply of bed material load stopped decreasing in the mid-1990s, as reflected in reality (Figures 6.8 and 6.10A) and also in the conceptual model (Figure 6.13). Once the supply of bed material load to the lower reach stabilised, the braiding intensity started to decrease again and the rate of widening was reduced. Figure 6.13 nicely demonstrates how, in the conceptual model, changes in planform are associated with changes in the sediment supply.

In 1967, when the supply of sediment was increasing, the aerial photographs showed that through a reduction in braiding intensity, the river was developing a meandering planform (Type 3 in Figure 3.5). Further increases in the sediment supply then caused the river to develop a Type 1 braided channel due to sediment over-loading. By 1973, the planform of the lower reach of the Jamuna was almost straight and braided. In the late-1970s, 1980s and 1990s, as the sediment supply decreased, the river planform evolved through straight (Type 2), to meandering (Type 3) and later to an equilibrium, braided planform (Type 4). Hence, the sequence of planform changes in the lower reach of the Jamuna between 1967 and 2005 may be explained by the changes in sediment supply envisaged in the conceptual model and also demonstrate good agreement with the scheme presented in Figure 3.5.



Note: Data points shown in this figure were presented in Figures 6.8 and 6.10.

Figure 6.13. Conceptual model of morphological process-response in the lower reach of the Jamuna River

6.6 Validation of the model

6.6.1 Approach

The morphological changes observed in the Padma and Lower Meghna rivers were used to validate the conceptual model. In using these downstream rivers to validate a conceptual model developed for the Jamuna, it is important to remember that the Jamuna River is not the only the source of water and sediment entering the downstream rivers, as the Ganges also feeds into the Padma (Figure 1.1). Records of sediment transport in the Ganges River at Hardinge Bridge, about 100 km upstream of the confluence with the Jamuna, show a decreasing trend in the sediment load during the 1980s. Temporary storage at the upstream of Farakka Barrage would be the main reason for such reduction (Sarker, 2004). On the other hand, this decreasing amount of sediment is much smaller than those in the Jamuna River at that time. Consequently, morphological changes in the Padma can be attributed to changes in sediment supply from the Jamuna River during validation of the conceptual model using the morphological changes in the Padma and any influence due to changing sediment inputs from the Ganges is ignored (Figure 6.14).

In addition to receiving water and sediment from the Padma, the Lower Meghna also receives runoff and sediment from the Upper Meghna River. However, compared to the inputs from the Padma River, the contributions of water and sediment from the Upper Meghna are very small and can be neglected when validating the conceptual model using the information on morphological changes in the Lower Meghna River.

For validation, interrelationships between the sediment supply, bed elevation, width and braiding intensity are assumed to be the same as in the Jamuna, and allowance is made for a downstream phase lag and a degree of attenuation in the propagation of the sediment wave. The celerity of the sediment wave is estimated from the observed phase lag of morphological responses downstream in the Jamuna and Padma rivers. There is no measured sediment load or bed level measurement data for the Padma and Lower Meghna Rivers. Validation is then based on comparing predictions of morphological changes based on the conceptual model to the morphological changes (width, braiding intensity and in some cases bed level) actually observed in the Padma and Lower Meghna Rivers.

6.6.2 Padma River

According to the conceptual model in the lower reach of the Jamuna River sediment load peaked in 1972. The propagation speed of the different morphological responses between the lower reach of the Jamuna and Padma varied from 10 to 33 kmy^{-1} (Table 6.1), the average of which is 23 kmy^{-1}. If this average value is assumed as the celerity of the sediment wave moving from the Jamuna to the Padma, sediment load should have peaked in 1977 in the Padma River (Figure 6.14).

Measured bed material loads at Baruria, just downstream of the Ganges-Jamuna confluence, showed that input to the Padma was high in 1968/69 and 1976/77, but was much reduced during the 1980s and early-1990s (Figure 6.15). Bearing in mind that Baruria is located at the upstream end of the 100 km long Padma River, it would be expected that a similar pattern of change in sediment load at the mid-point of the river would be lagged by a few years. The measured value agrees with the time of peak sediment load considered in the conceptual model for the Padma River (Figure 6.14).

The conceptual model suggests that the sediment wave should have arrived in the Padma River at the end of 1960s and in response to the increasing sediment load, bed level should have started to rise in the early 1970s, leaving some interval for reaction time. At the same time the width and braiding intensity of the Padma River should have started decreasing. These processes should have continued until the sediment supply dropped below the local transport capacity of the river. From 1980, the riverbed should have started to degrade, and the width and braiding intensity should have started to increase, with these processes continuing till the arrival of the secondary oscillation of the sediment wave. From 2000, the width should have continued to increase but at a slower rate. In response to the secondary oscillation, the braiding intensity should have started to decrease.

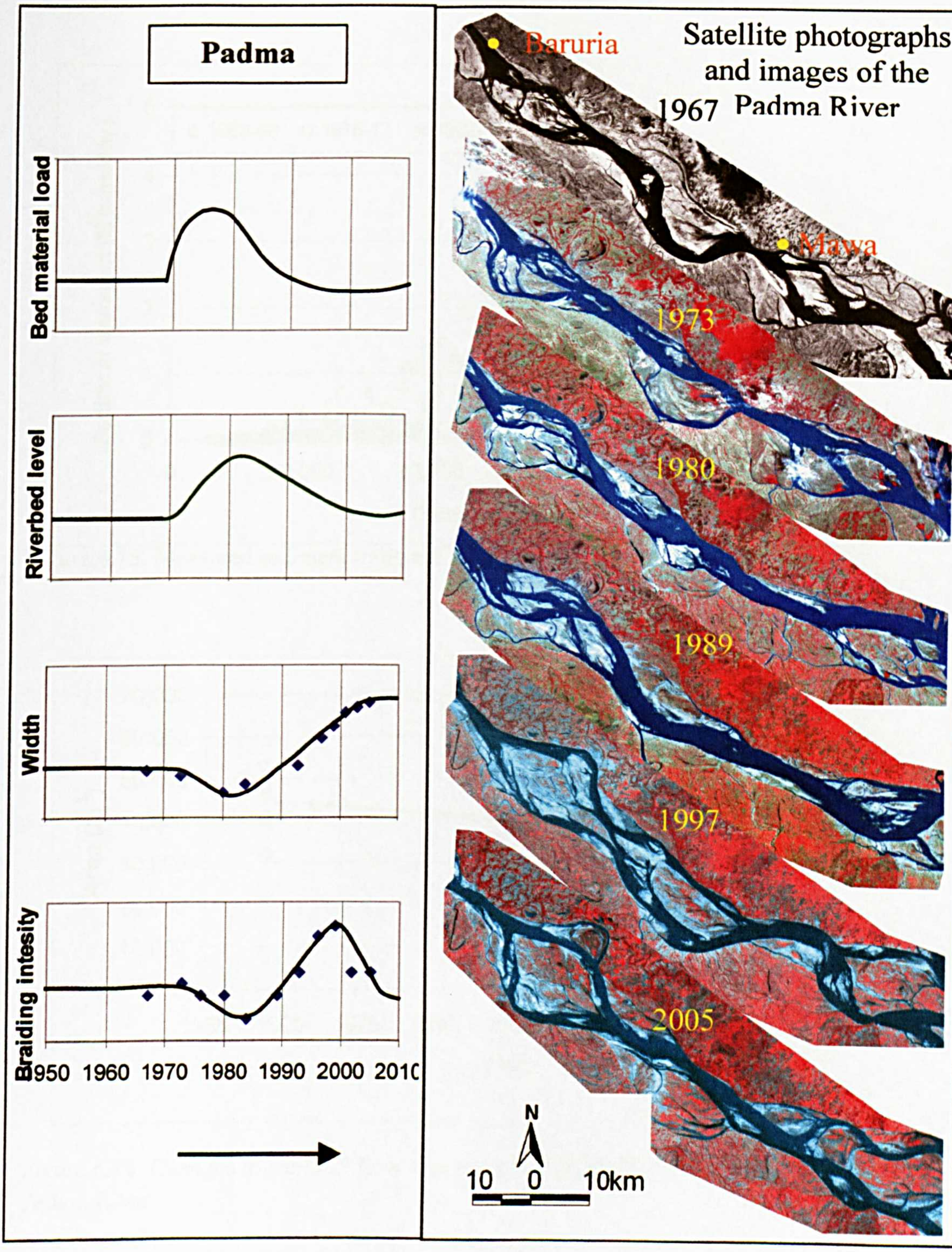
For the Padma River, information on the flow area has been extracted from reliable BWDB cross-sectional survey data, and accurate records of changes in channel width and braiding intensity are available from satellite imagery. Although the flow area is not the direct measure of bed level change, it can be considered as a good indicator. In the late 1960s, the average flow area of the Padma below the bank level was about 45,000 m^2 (Figure 6.16), when according to the conceptual model the riverbed should have been in an undisturbed condition (Figure 6.14). The flow area dropped to about 40,000 m^2 in the early 1980s, when the bed level rise should have peaked according to the conceptual model. Later in 2000, the flow area was again close to 45,000 m^2 and according to the model, the bed level at that time should have been close to that of 1960s. The changes in average flow area in bankfull condition of the Padma River matches with the changes of the bed level as shown in the conceptual model (Figures 6.14 and 6.16).

Changes in the planform of the Padma River as observed in 1967 and 1973 indicate that the river responded to the increase in the supply of bed material by narrowing and reducing its braiding intensity (Figures 6.9A and 6.10B) in a manner similar to the response of the lower reach of the Jamuna River. The width of the upstream reach of the Padma River had been decreasing till 1980 as suggested by the conceptual model. The lower reach of the river, however, continued to decrease its width until 1984. Satellite images of 1980 show that the river had adopted a straight course and reached close to its minimum width (Figure 6.14). Unlike the width, the braiding intensity of the river did not decrease monotonically, from 1967 to 1973 it increased slightly, then it decreased until 1984. Although the braiding intensity decreased as suggested by the model, there was a time lag of four years between the conceptual model and the observed changes in braiding intensity.

Since the early 1980s and 1990s, the width has increased in association with intensified braiding along the whole of the Padma. The satellite image of 1997 (Figure 6.14) shows that the Padma had appeared as a fully developed braided river. The rate of widening started to decrease in 1999 at the upper reach of the Padma, while it occurred in 2001 at the lower reach (Figure 6.9A). On the other hand, braiding intensity of the Padma started to decrease in 1999 (Figure 6.10B). The timeframe of both of these processes matches nicely with that of the conceptual model (Figure 6.14). In 2005, both the conceptual model and observations suggest that the rate of widening and braiding intensity of the Padma River had decreased markedly.

The planform changes observed in the Padma River in response to changes in the supply of bed material match the sequence presented in Figure 3.5. The initial increase in sediment supply caused the mixed braided (Type 4) and meandering river (Type 3) that was present in 1967 to change into a straight river (Type 2) by 1973 and to remain in this configuration until the sediment supply decreased below local transport capacity in 1980. Response to the decreasing sediment supply then drove transformation of the straight river (Type 2) into a meandering (Type 3) and later into a braided (Type 4) channel in the late-1980s and 1990s.

The sequence of the morphological adjustments and their corresponding timeframe as observed in the Padma River in response to the changes in sediment load showed a good agreement with that suggested by the conceptual model. Like the Jamuna River, changes in the planform of the Padma River in response to disturbance caused by downstream propagation of the wave of bed material load were also in good agreement with the scheme developed in Chapter 3 (Figure 3.5).



Note:Data points shown in this figure were presented in Figures 6.9 and 6.10.

Figure 6.14. Conceptual model of morphological process-response in the Padma River

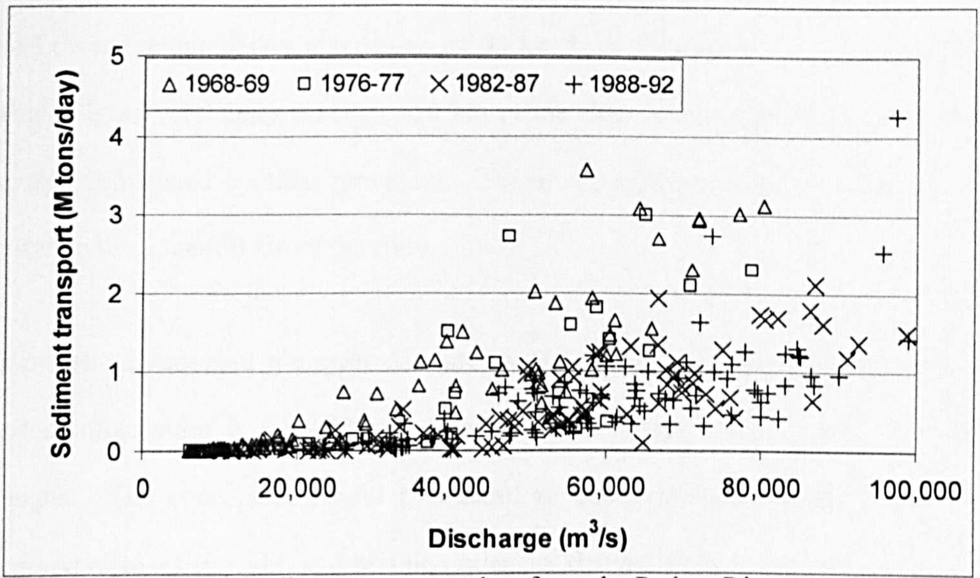


Figure 6.15. Measured sediment transport data from the Padma River at Baruria

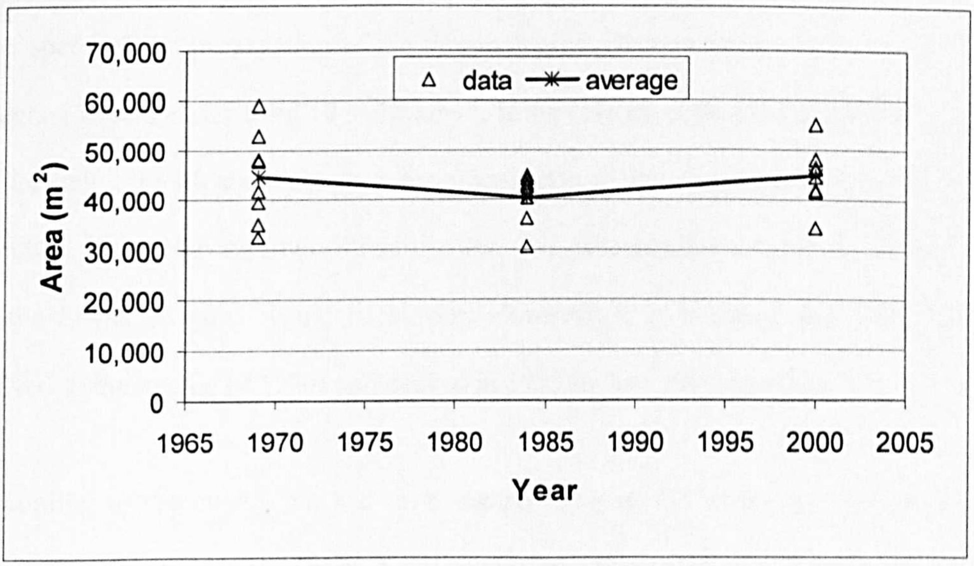


Figure 6.16. Changes in bankfull flow area measured from reliable cross-sections in the Padma River

6.6.3 Lower Meghna River

The Lower Meghna River extends about 90 km from Chandpur to the northern tip of Hatia Island (Figure 1.1). Only the upper 50 km of the river is truly fluvial as the lower 40 km is strongly influenced by tidal processes. Therefore, application of the conceptual model is limited to the upper 50 km of the river.

No measured sediment transport data are available for the Lower Meghna River and only limited information is available from the Meghna Estuary Study (MES II) on bed level changes. The conceptual model has therefore been validated primarily on the basis of observed changes in width and braiding intensity derived from time series of satellite images (Figure 6.17).

The speed of the propagation of the morphological changes between the Padma and Lower Meghna Rivers varies from 10 to 12 kmy^{-1}. If the celerity of the sediment wave is assumed to be 12 kmy^{-1}, it took about six years for propagation of the wave from the Padma to the Lower Meghna. Due to having lower stream power, it is expected that celerity of the sediment wave in the Lower Meghna would be slower. However, it is assumed that the sediment wave arrived in the middle of 1970s and peaked in 1983 in the Lower Meghna.

According to the model, the bed level should have started to rise at the end of the 1970s leaving some interval for reaction time. At the same time, width and braiding intensity should have started to decrease in response to the increased sediment load. The bed level should have started to rise until the end of the 1980s, when the sediment load was balanced by the local transport capacity of the river. During the same period, width and braiding intensity should have continued to decrease. Since 1988, the riverbed should have started to degrade, and width and braiding intensity should have started to increase with these processes continuing till the arrival of secondary oscillation of the sediment wave. From 2005, the width should have continued to increase but at a slower rate. In response to the secondary oscillation of the sediment wave, the braiding intensity should have started to decrease.

There are very few observations (Table 6.3) to support or refute the changes in bed level of the Lower Meghna River as suggested by the conceptual model. Erosion/accretion in the Lower Meghna River between Bhola and Gajaria (in the tidal reach immediately downstream of the reach shown in Figure 6.17) does show a net accumulation of 140 million m^3 of sediment, indicating bed accretion at about 20 cmy^{-1} around from 1986 to 1992 (Table 6.3). Based on the assumed celerity, the sediment wave would take 3 to 4 years to travel from the study reach to the Bhola-Gazaria reach. Thus, the observed period of bed accretion would correspond to the rising of bed level as suggested in the conceptual model.

Bathymetric surveys of the Lower Meghna River between Chandpur to north of Hatia Island in 1997 and 2000 show that a net erosion of 400 million m^3 occurred in the 90 km long reach during a 3-year period, indicating degradation at 12 cmy^{-1} during the period 1997-2000. The conceptual model also shows the degradation of the bed level during the same period.

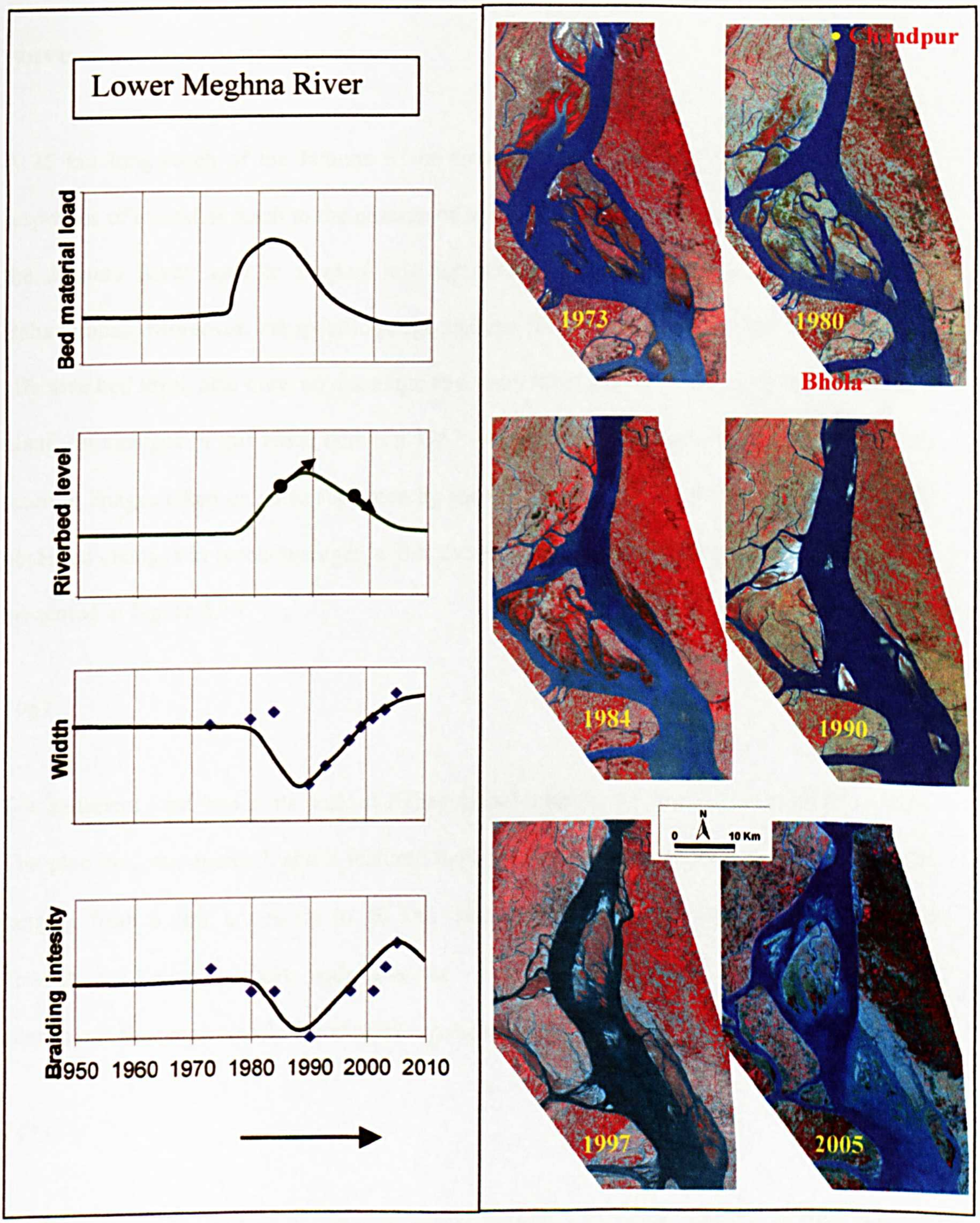
The 1973 image shows a relatively narrow, single-threaded pattern immediately downstream of Chandpur, followed by a braided reach (Figure 6.17). Both major anabranches in the braided reach have well-defined channels at this time, suggesting a degree of stability. However, the 1980 image shows that left bank anabranch had enlarged at the expense of the right bank anabranch. Figures 6.9B and 6.10C show that width had started to decrease in the mid 1980s and braiding intensity had started to decrease in the early 1970s. The complex processes of response of the braided river might be one of the causes for these time differences. However, the average time of reaction of decreasing width and braiding intensity corresponds to the time suggested by the conceptual model.

By 1990, the channel had become single-threaded throughout its length, reducing its width and braiding intensity to minimum values (Figures 6.9B and 6.10C). This matches very well with the conceptual model. The widening associated with the increasing of braiding intensity in 1990s also corresponds to the conceptual model. Like the Padma River, changes in bed level, width and braiding intensity of the Lower Meghna River show good agreement with the conceptual model.

Like the lower reaches of the Jamuna and Padma rivers, the planform changes of the Lower Meghna River also show very good agreement with the scheme presented in Figure 3.5. During the period when the sediment supply was decreasing, planform changes in all the reaches of the Jamuna, Padma and Lower Meghna rivers show a similar sequence of changes to that observed by Jiongxin (1996) in the Lower Yongdinghe, Lower Yellow and Hanjiang rivers in China.

Table 6.3. Estimated erosion/accretion in the Lower Meghna River (source: DHV Consultants BV, 2001)

Period	**Reach**	Reach Length (km)	Data Source	Accretion (+) or Erosion (-) (M m^3)	Accretion/Erosion Rate (cmy^{-1})
1986-92	North Bhola to Gazaria	20	LRP	140	20
1997-00	Chandpur to north of Hatia	90	MES and MES II	- 400	-12



Note:Data points shown in this figure were presented in Figures 6.9 and 6.10 and Table 6.2

Figure 6.17. Conceptual model of morphological process-response in the Lower Meghna River

6.7 Local morphological responses during passage of the sediment wave

A 25 km long reach of the Jamuna River around Bahadurabad was selected to assess the responses of a smaller reach to the passage of sediment wave. The sediment transport data for the Jamuna River used to support this assessment came from the measuring station at Bahadurabad. Moreover, the specific gauge analysis (Figure 6.6B) used to indicate changes in effective bed level, also drew on discharge and water level data from that gauging station. The planform changes in this reach between 1967 and 2001 can be assessed from a series of six satellite images taken on dates separated by equal intervals of seven years (Figure 6.18). The observed changes in reach-averaged width and braiding intensity during the study period are presented in Figure 6.19.

1967

The sediment load was at its peak at Bahadurabad (Figures 6.5 and 6.11) in the late-1960s. The planform was braided, and it featured multiple, small, sand-covered islands with lengths ranging from a few km to up to 10 km. The braided reach was bounded at its up and downstream limits by short, nodal reaches. The braiding index based on the secondary channels in the reach was 2.25 and reach-averaged width was 8.2 km.

1973

By 1973, the sediment load at Bahadurabad had started to decrease and the effective level of the river bed was close to its highest elevation. Flow in the Jamuna River was concentrated in a major meandering channel flowing along the left bank at Bahadurabad (Figure 6.6B). There were also two remnant channels, which were active during the summer monsoon hydrograph. The planform can be seen to have transitioned from braided to a predominantly single threaded channel. The short nodal reaches have remained at same positions observed in 1967.

During the early 1970s, braiding intensity decreased to 2 and it may be surmised that width would also have decreased, although due to the definition of bank line derived from satellite images, it would take few more years for this to be apparent in the satellite imagery.

1980

By 1980, the sediment load had decreased considerably and the elevation of the river bed had been lowered. The river again displayed a braided planform, this time featuring large, well vegetated islands. The two main islands were 12 and 21 km long, respectively. The secondary channels surrounding these large islands maintained planforms that varied between meandering and braided, with the left bank anabranch remaining dominant. The nodal reaches remained at their previous locations. The braiding intensity increased to 2.75 and reach-averaged width increased to 9.4 km.

1987

At this time, the sediment load had decreased further and was close to its minimum. The planform featured two anabranches of which the larger, left anabranch was braided, while the right anabranch varied between meandering and braided. The lengths of the two main islands had grown to about 30 km. Multi-channeled planforms had appeared at both the up and downstream, nodal reaches. The braiding intensity decreased slightly to 2.5 and reach-averaged width increased to 10.1 km.

1994

The sediment load was close to its minimum and two anabranches separated by a very long, wide, well-vegetated island continued to dominate the channel planform, as in 1987. However, the up and downstream nodal reaches disappeared during this period. The flow was more concentrated to the left anabranch which featured a meandering channel with a series of mid-channel bars. In contrast, the planform of the right anabranch varied between single-threaded and braided. The braided intensity increased slightly to 2.75 and reach-averaged width increased to 11.2 km.

2001

During this period, the sediment load did not change much from that measured during the 1990s. Flow in the right anabranch declined significantly while that in the left anabranch developed to make it the dominant channel. The large island between these anabranches remained intact, although its length was shortened. The planform of the left anabranch became more braided, although the overall braiding intensity of the reach was reduced to 2.5. The width continued to increase, but at a slower rate (Figure 6.19A).

Overview

During the peak of the sediment load, the planform of the reach was braided, with multiple mid-channel bars that were small and non-vegetated. The braided reach was bounded by two short, nodal reaches. As the sediment load decreased, the planform was transformed from braided to a predominantly meandering pattern. However, as the sediment load further decreased, the planform of the reach metamorphosised from meandering to braided with two large, vegetated islands separating two major anabranches. A pattern featuring these two anabranches and a large, meta-stable island then dominated the planform for several years. The planforms of these anabranches varied between single-threaded meandering and braided. There were two other reaches in the Jamuna River where the planforms were dominated by two large anabranches starting in the 1980s. In line with overall planform changes of the Jamuna River, this reach initially decreased its width but then, in response to the decreasing sediment load, the river started to increase its width and also its braiding intensity.

The response of the planform in this reach to changes in the sediment load showed somewhat a similar pattern to that indicated in Figure 3.5. On this basis, it may be concluded that the planform during the period of high sediment load was probably similar to Type 1 braided, and that it subsequently transformed itself into a Type 4 or 5 braided planform as the sediment load decreased. The planform was close to a single-threaded, meandering pattern during a short, transitional period between the two types of braiding.

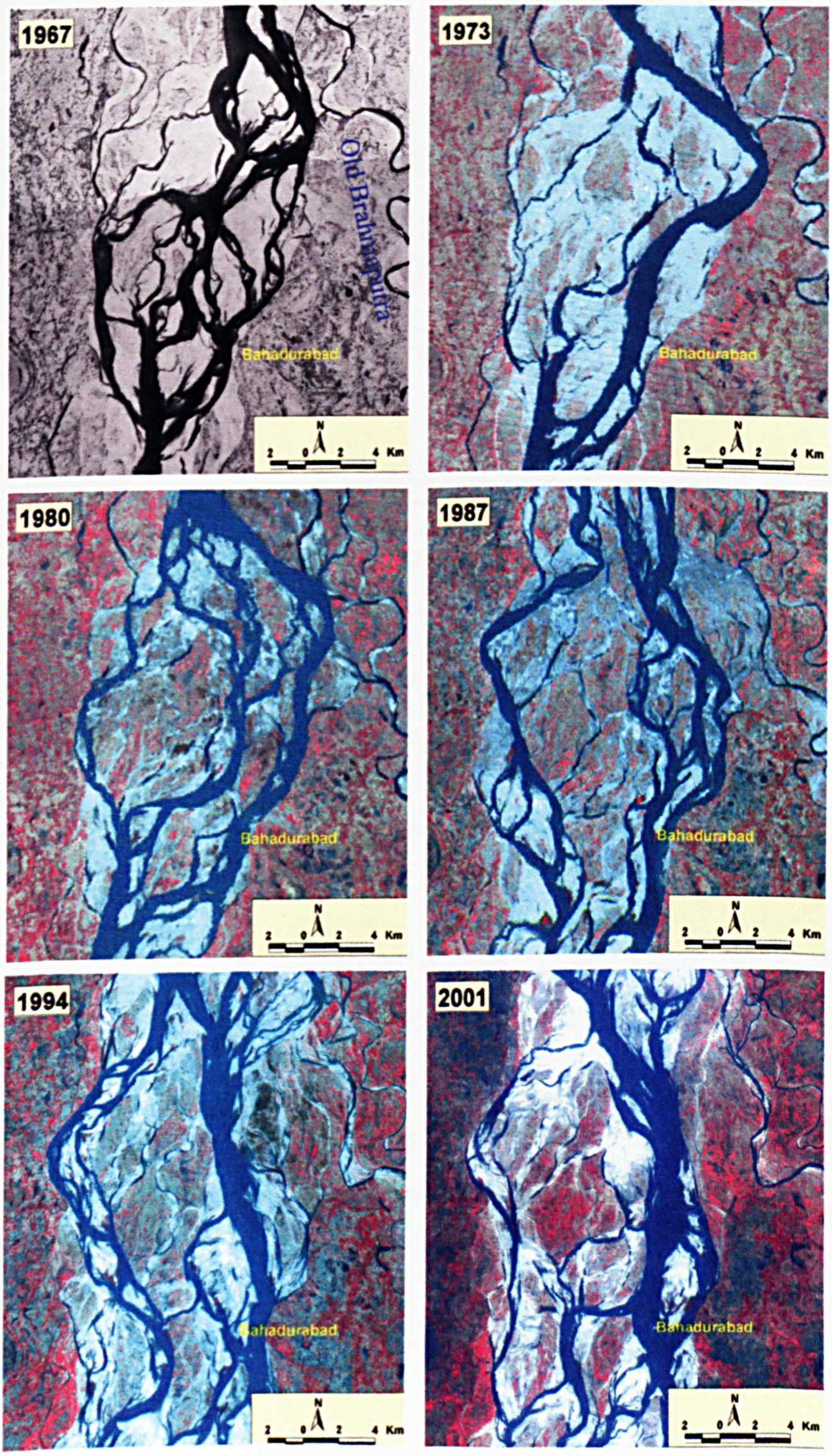
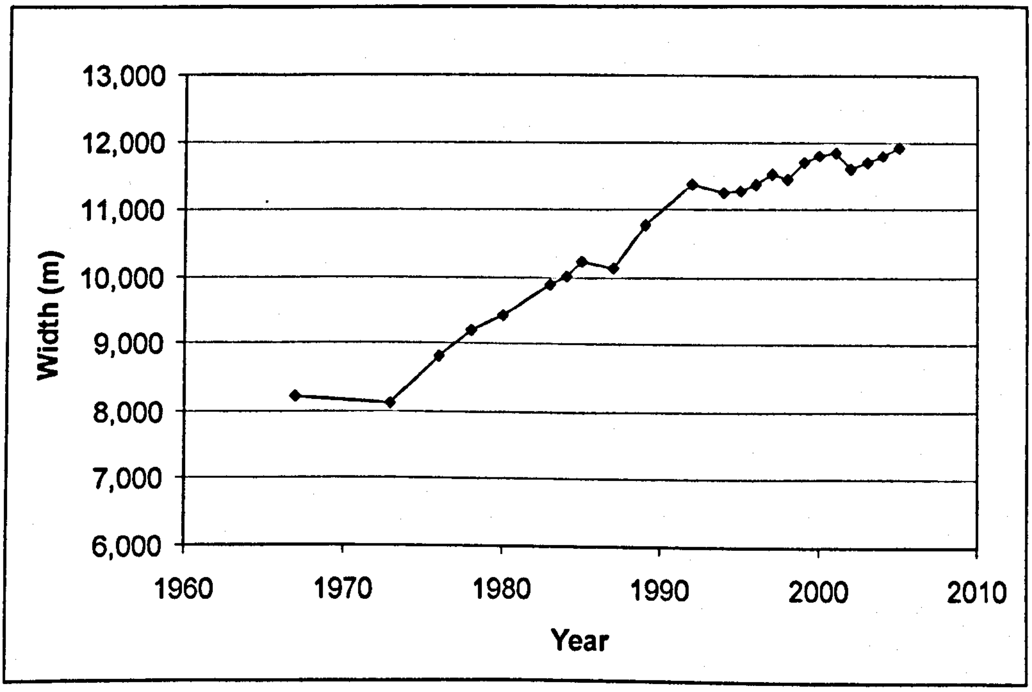


Figure 6.18. Changes in planform of the Jamuna River at Bahadurabad over time



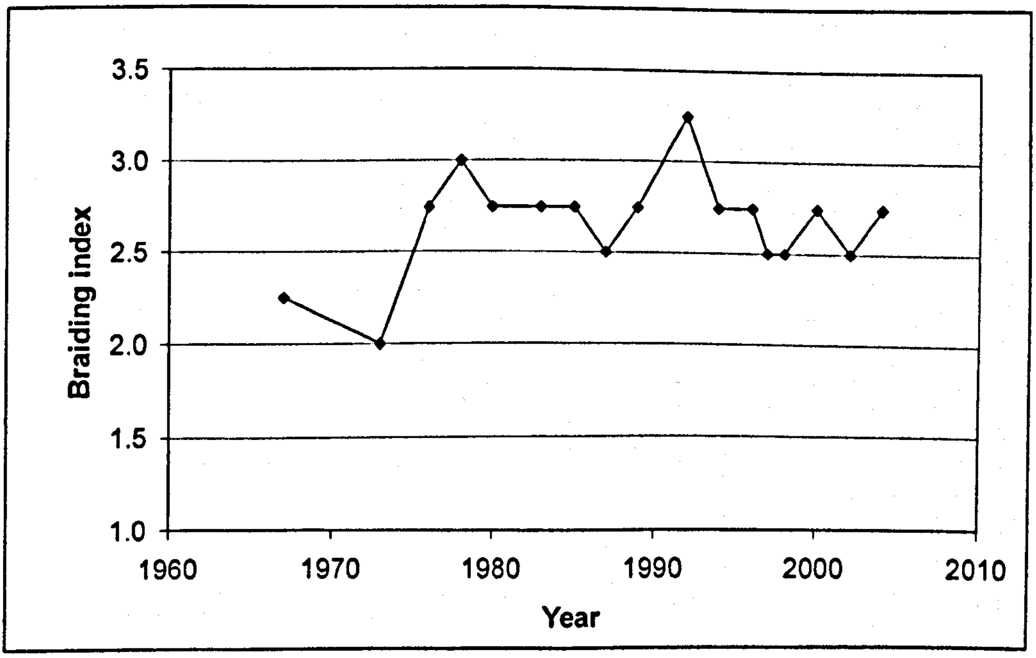


Figure 6.19. Changes in reach-averaged (A) width and (B) braiding intensity of the Jamuna River at Bahadurabad

6.8 Propagation of the river response through the system

During development and validation of the conceptual model, graphical forms of the expected temporal variation in morphological responses to the passage of the sediment wave were shown for different locations. The spatial distribution of morphological responses to the propagation of the sediment wave represented by changes in bed elevation and width for selected dates, are shown in Figure 6.20. This figure is mainly based on phase lags for morphological changes inferred from Figures 6.11, 6.13, 6.14 and 6.17, and also estimated changes in the celerity of the sediment wave as it propagated downstream through the system at a progressively slower rate. In considering the spatial representation of channel changes, it must be borne in mind that there is little information on morphological response in the Brahmaputra River in Assam, except that provided by Krug (1957), Goswami (1985) and Verghese (1999). These sources only provide a basis for guessing the spatial variation of the morphological changes in the Brahmaputra River in Assam. If the characteristics of the Brahmaputra River in Assam are actually similar to those of the Jamuna River, the guesses will be close to reality, but if not then they could be far from what actually occurred.

1950

The earthquake occurred on August 15, causing huge landslides in the Himalayas. The sediment input generated by the landslides can be divided into two fractions: fine (silt and clay) and coarse (sand) sized sediment. A major part of the fine sediment passed quickly through the system, moving as wash load and not affecting the river morphology. On the other hand, the coarse sediment entered into the Brahmaputra along a length of several hundred kilometres and through tributaries including the Debang, Dehang, Lohit, Subansiri and numerous other rivers. It moved more slowly as bed material load, forming a moving sand wave that started at around the Debang and Dehang confluences and had probably reached Dibrugarh on the Brahmaputra River by the end of 1950 (Figure 6.18). At this time, the remainder of the river system downstream was in a state of dynamic equilibrium.

1960

In 1960, the leading edge of the coarse sediment wave entered the Jamuna River in Bangladesh and was probably just downstream of Bahadurabad. At this time, the crest of the sand wave was still in Assam, being located around Pandu. In response to the change in the sediment regime (with the supply of bed material load exceeding the local transport capacity), the bed started to aggrade in the braided Brahmaputra River in Assam, the braiding intensity started to decrease and the width started to narrow along a reach extending for several hundred kilometres upstream of Pandu. Further upstream still, the sediment supply started to decrease as the stock of material released by the earthquake became exhausted in some of the tributaries. The channels responded through bed degradation, increasing braiding intensity and widening. This implies that the entire Brahmaputra River in Assam was unstable in 1960, though there were no noticeable changes in the morphologies of the Jamuna in Bangladesh and the rivers further downstream in the system.

1970

By 1970 the leading edge of the wave of coarse sediment had reached the confluence of the Padma River with the Upper Meghna. At this time, the crest of the sediment wave was near Bahadurabad and the trailing edge was still in the Brahmaputra near Bessamara. Channel response through a rising of bed level, reduction in braiding intensity and narrowing had started to occur in the Padma River in response to increasing sediment supply associated with the passage of the leading half of the sediment wave through the river (Figures 6.9A and 6.14). At this time, the Lower Meghna was still in a state of dynamic equilibrium. The processes of narrowing and decreasing of braiding intensity in the Jamuna River were continuing (Figures 6.8, 6.10A and 6.11). In the Brahmaputra River upstream of the international border, bed level started to decrease, and width and braiding intensity started to increase where local sediment transport just exceeded the sediment supply. The processes of widening and increasing braiding intensity were continuing thoughout the entire upstream reach of the Brahmaputra River.

1980

In 1980 the leading edge of the coarse sediment wave had reached the Bay of Bengal, while the crest was in the upper reach of the Lower Meghna River and the trailing edge was downstream of Pandu. At the furthest upstream point in the Brahmaputra River, the rate of widening was reduced and the increase in braiding intensity decreased or ceased in response to the secondary oscillation of the sediment wave. In both the upper and lower reaches of the Jamuna River, the braiding intensity was increasing and the channel was widening at a very high rate in response to the decrease in sediment supply (Figures 6.8, 6.9 & 6.10). The bed elevation was at its maximum at this time in the upper reach of the Padma and the channels of the Padma and Lower Meghna rivers both displayed decreasing braiding intensities and narrowing in response to the excess supply of bed material load over the local transport capacity.

1990

In 1990, the crest of the coarse sediment wave had already reached the Bay of Bengal, while the trailing edge was in the Padma River. At this time the bed of the Lower Meghna River reached its maximum elevation and the width and braiding intensity of the river were at minimum (Figure 6.9B and 6.10C). In response to the decreased sediment load less being than the local transport capacity, the Padma and downstream reach of the Jamuna River was widening at a very high rate associated with the increasing of braiding intensity (Figures 6.8, 6.9 and 6.10). The Jamuna and Brahmaputra, upstream of the trailing end of the sediment wave, started widening with a slower rate and reducing the braiding intensity. These processes might be the result of the secondary oscillation of the sediment wave. The Brahmaputra River further upstream was approaching new equilibrium.

2000

By 2000, almost the entire sediment wave had entered into the Bay of Bengal. The trailing end was in the Padma River. With the decreased sediment load lower than the local transport capacity, the Lower Meghna and Padma were widening with a very high rate associated with the increasing braiding intensity (Figures 6.9 and 6.10). The rate of widening slowed down and the braiding intensity was reduced in the Jamuna River. These processes resulted from the secondary oscillation of the sediment wave. The Brahmaputra River in Assam had recovered its condition of dynamic equilibrium, but it does not imply that the planform or channel dimensions of the river would be exactly the same as it was in the pre-earthquake period.

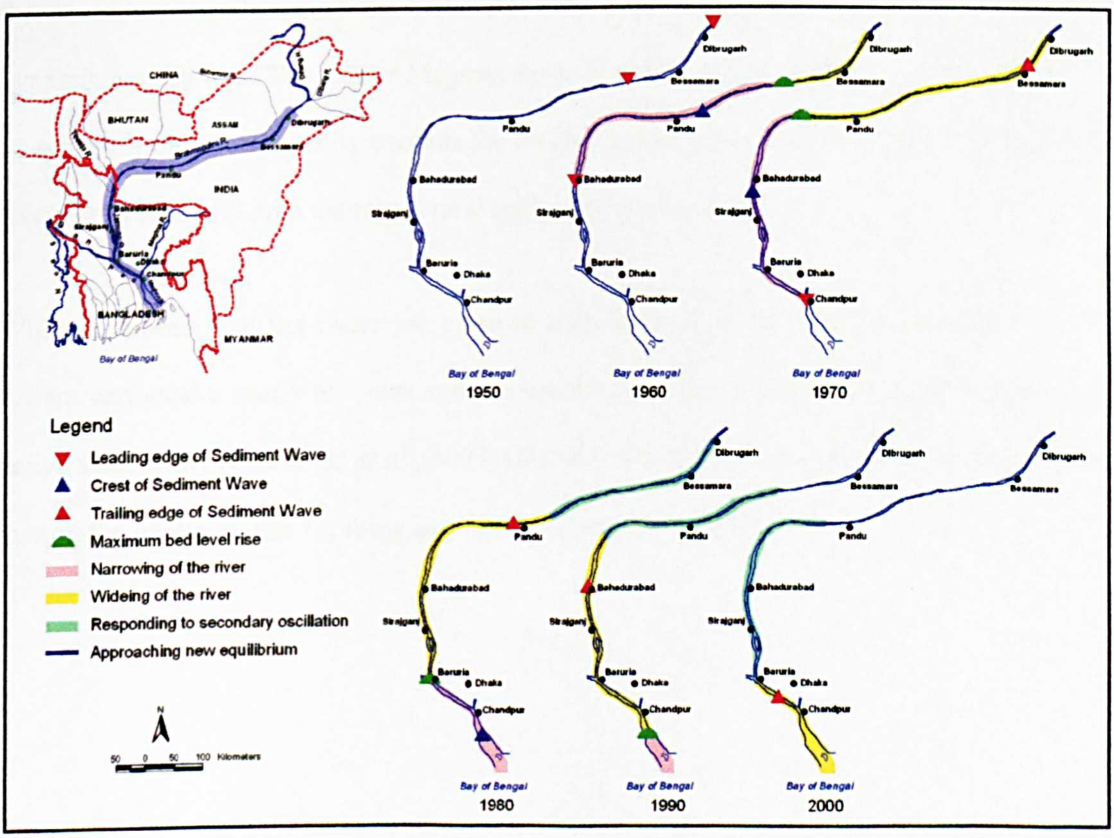


Figure 6.20: Propagation of the coarse sediment wave through the Brahmaputra-Jamuna-Padma-Lower Meghna river system.

6.9 Conclusion

Based on the conceptual model, measured sediment transport rates at three stations and the morphological responses observed throughout the river system, it may be deduced that a wave of coarse sediment, moving as bed material load that was generated by the 1950 Assam Earthquake, travelled through the Brahmaputra-Jamuna-Padma-Lower Meghna system and started to enter into the Bay of Bengal in the late 1970s. By 1990, all the excess coarse sediment had entered the Bay. However, the morphological responses to downstream propagation of the sediment wave continued in the rivers upstream throughout the 1990s and into the early 21st century.

At present, the stability of the Brahmaputra is unknown due to a lack of information, though probably it is maintaining its post-disturbance condition of dynamic equilibrium. The Jamuna and Padma are still widening slowly with reduced braiding intensity as they are responding to the secondary oscillation of the sediment wave and are approaching a new condition of dynamic equilibrium. The Lower Meghna River is continuing to widen at a very high rate as its sediment transport capacity exceeds the diminished supply of sediment from the stabilising rivers upstream, although the rate is now beginning to decrease.

While it appears that the rivers are close to recovering from the disturbance caused by the Assam earthquake nearly 60 years ago, it must be remembered that this region remains very active seismically (Goodbred *et al.*, 2003) so that at any time another seismic event may again disturb the whole system resulting in a return to unstable conditions.

Chapter 7

Discussion: The wider implications of Stream Energy, Channel Adjustment and Braiding Types for Process-Response Models of Alluvial Rivers

7.1 Introduction

The main research outcome reported in this thesis is a conceptual model of channel evolution following disturbance. The model was developed from established models of process-response in alluvial streams, using information from the Jamuna River as it responded to the downstream progression of a wave of relatively coarse sediment generated by the Assam earthquake of 1950 and it was validated for the Padma and Lower Meghna Rivers. During the course of this research, a number of interesting issues emerged concerning dynamic processes-response, morphological adjustments, stream energy dissipation and the comparability and limitations of the conceptual model. While these issues were not on the critical research path in terms of achieving the aims and objectives for the thesis that were established when the studentship supporting it was awarded, they are nevertheless of considerable interest and so they are discussed at some length in this chapter.

The following sections present exploratory attempts to account for the observed changes in river planform through consideration of energy expenditure arguments. These arguments cannot be considered as validating the conceptual model, rather they represent a series of 'thought exercises'. Their purpose is, then, to follow lines of thought triggered by the conceptual model, investigate the implications for dynamic process-response mechanisms in alluvial rivers that are subject to disturbance and identify new lines of enquiry that could shed further light on this important topic.

The first issue to be discussed centres on the expenditure of stream energy required to transport sediment through the river system. Energy dissipation due to sediment transport is not considered in the hydrodynamic calculations conventionally used for assessing the channel roughness. The assumption implicit to neglecting this factor is that the amount of energy so expended is insignificant compared to that consumed by other mechanisms of energy dissipation (Mackin, 1948, Richards, 1982). This assumption is revisited in the discussion presented here. There is a great deal of evidence from the literature that an

imbalance between the sediment supply from upstream and the local sediment transport capacity will trigger marked changes in river morphology (Lane, 1955; Schumm, 1969; Galay, 1983; Chien, 1985; Zhou and Pan, 1994; Lagasse, 1994; Jiongxin, 1996; Kondolf et al. 2002; Richard and Julien, 2003; Simon and Rinaldi, 2006) and this is the basis for the conceptual model developed in this thesis. However, in the model, no consideration was given to the amount of energy available to transport sediment and how this change in comparison to the energy required to transport the sediment supplied, as the channel adjusts. In this chapter, an attempt is made to assess the energy required to transport the bed material load moving both in suspension and as bed load in the Jamuna River. The significance of energy dissipation associated with changes in the sediment load and the morphological responses so generated, especially involving changes in the planform pattern of the river, are then examined and discussed.

The conceptual model was based on, and may be compared to, longer established process-response models. It was pointed out in Chapter 3 that there are apparent contradictions between some of the existing models, while it emerged in Chapter 6 that there also appear to be differences between the conceptual model and the previously established process-response models. To identify the reasons for these contradictions and differences and resolve them, a scheme was developed and described in Chapter 3. The scheme revealed that the apparent contradictions could be resolved by recognising that there are two types of braided rivers that differ markedly in their morphological responses to a change in upstream sediment supply. It was concluded that process-response mechanisms and morphological adjustments to the changes in the sediment load in braided rivers are strongly dependent on the type of braiding, but the wider implications of this finding were not deeply investigated. Hence, some of the issues raised by recognition that there are different types of braiding are further addressed in this discussion chapter.

7.2 Sediment transport, energy dissipation and channel adjustment

The mass of water flowing along the river 'm' possesses two kinds of energy. Expressed in terms of 'head' with units of metres, the first is potential energy = h and the second is kinetic energy = $^1/_{2g}\, u^2$, where g = acceleration due to gravity, h = vertical distance above a reference point (either sea level or the confluence with a larger river) and u = the mean velocity of the fluid. According to Bernoulli's equation for the conservation of energy:

$$h+\frac{1}{2g}u^2+h_L=\text{constant} \qquad (7.1)$$

where, h_L = head loss due to energy dissipation. In uniform, steady flow, kinetic energy does not change significantly in time or space and so the head loss per unit channel length balances the vertical fall in the water surface and the bed, with the water surface and energy slopes being identical (Figure 7.1). The loss of energy mainly occurs through internal losses due to viscosity and turbulence, frictional and drag losses at the channel boundary, and the energy expended in transporting sediment, with any excess energy being used either to accelerate the flow (transforming it into kinetic energy) or erode the channel boundaries and so increase the rate of sediment transport (Mackin, 1948; Richards, 1982; Knighton, 1998; Harmar *et al.*, 2005).

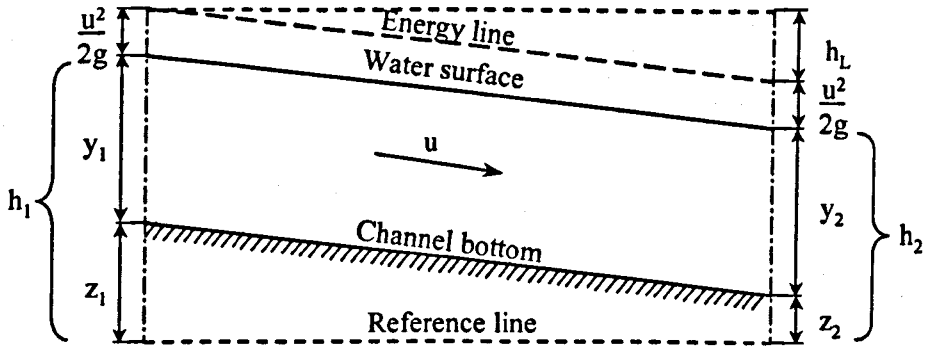


Figure 7.1: Potential energy head, kinetic energy head and head loss due to energy dissipation in uniform and steady flow.

It has generally been assumed that the proportion of energy expended in transporting sediment is very small, being of the order of 3% to 4% (Mackin, 1948 and Richards, 1982). On this basis, flow resistance computations routinely consider that all energy losses may be attributed to friction and drag effects at the channel boundaries, though a few equations account for losses due to internal distortion as well. This is despite the fact that experimental studies have shown measurable increases in the friction factor due to the bed load transport in both pipes and open channel flows (Song *et al.,* 1998; Gao and Abrahams, 2004).

Quantitative expressions are, in fact, available for computing the energy loss due to sediment transport for material moving as both suspended and bed loads (Einstein and Chien, 1954; Bagnold, 1966; Yang, 1996).

According to Einstein and Chien (1954), the energy expended in supporting the suspended sediment load per unit weight of fluid, per unit time is defined by:

$$E = \sum \frac{\overline{C}\omega}{ui} \frac{\rho_s - \rho}{\rho} \tag{7.2}$$

where, E = ratio of the power required for suspending the sediment to the available unit stream power, C = average concentration by weight for a given grain size, ω = fall velocity of the sediment particles, and ρ_s and ρ = densities of suspended sediment and water, respectively. Bagnold (1966) provided an expression for estimating the stream power needed to transport the suspended load per unit width of the channel:

$$\phi = \frac{\gamma_s - \gamma}{\gamma} s \frac{\omega}{\bar{u}_s} \tag{7.3}$$

where, ϕ = stream power required to transport the suspended sediment load per unit width of the channel, s = sediment load per unit width of the channel, and $\bar{u}_s$ = mean transport velocity of the suspended load.

If it is assumed that the mean velocity of the water is roughly equal to the mean velocity of the suspended sediment, equations 7.2 and 7.3 result exactly the same identity, ($C^* \omega^* \frac{\gamma_s - \gamma}{\gamma}$), to define the stream power required to support a given rate of suspended sediment transport.

Bagnold (1966) also developed a sediment transport function from the stream power concept. He related the rate of energy dissipation by the stream in transporting bed load to the amount of energy available. The resulting relation is:

$$\frac{\gamma_s - \gamma}{\gamma} s_b \tan\alpha = \tau v e_b \tag{7.4}$$

where, s_b = bed load transport rate expressed as sediment weight per unit width of the channel, tan α = ratio of tangential to normal fluid forces, τ = bed shear stress, v = mean velocity, e_b = an efficiency coefficient and γ and γ_s = unit weights of water and sediment, respectively. Equation 7.4 can be expressed as the ratio of stream power required for transporting bed load to available stream power, as follows:

$$e_b = \frac{\gamma_s - \gamma}{\gamma} \frac{s_b \tan\alpha}{\tau v} \tag{7.5}$$

Song *et al.* (1998) and Gao and Abrahams (2004) investigated the flow resistance (energy dissipation) caused by bed load movement in flumes under plane bed conditions with no suspended sediment transport. They found that flow resistance increased as either sediment concentration or sediment size increased and demonstrated that the contribution of bed load transport to overall flow resistance could be as great as that due to grain roughness. However, as their experiments were performed with a plane bed condition and with no suspended sediment transport, their results are not directly applicable to estimating the amount of energy lost through bed load transport in the Jamuna River.

Conversely, it is reasonable to apply equations 7.3 and 7.5 in estimating the ratios of stream power required to transport the suspended and bed loads, respectively, to the total stream power available in the Jamuna River.

The measurements performed at the main hydrometric station at Bahadurabad demonstrate that bed material transport in the Jamuna River has varied by about a factor of three during the last few decades (Table 5.4). Measurements for two different periods, 1966-70 and 1982-88, may be considered in estimating how the proportion of stream power dissipated through bed material transport has varied. To estimate the proportion of stream power expended in transporting the suspended bed material load, bankfull discharge was taken as the reference discharge on the basis that this is a good representative of morphologically significant or 'channel forming' flows. According to Delft Hydraulics and DHI (1996a), the bankfull discharge of the Jamuna River lies within the range of 45,000 m^3s^{-1} to 50,000 m^3s^{-1}. Hence, for illustrative purposes, the bankfull discharge may be taken to be 50,000 m^3s^{-1}. According to the sediment rating curves derived from BWDB measurements for the periods 1966-70 and 1983-88, sediment concentrations at bankfull stage are 381 mgl^{-1} and 112 mgl^{-1}, respectively. The median size of the bed material at Bahadurabad is 0.2 mm, fall velocity of which is about 2.75 cms^{-1}. According to equation 7.3, for a slope of 7.5 cm per km, the proportions of available stream power energy required to transport the measured suspended bed material loads are 15% and 4% in late-1960s and mid-1980s, respectively.

Unlike the suspended sediment transport, bed load transport has not been measured in the Jamuna River. However, assuming a higher value from a wide range of bed load as mentioned in the literature, Alam and Hossain (1988) considered that the bed load of the Jamuna River would be ~25% of the measured suspended sediment load. On the other hand, on the basis of dune tracking, Klaassen et al. (1988) suggested that the bed load would be ~10% of the suspended bed material load.

For reasonable approximations of an average active bed width = 4500 m and an average depth = 7 m at bankfull stage, the proportions of overall stream power required for bed load transport in the 1960s, are 47% and 6%, respectively, based on the estimated bed loads of Alam and Hossain (1998), and Klaassen et al. (1988) (Table 7.1). The equivalent figures in the 1980s would be 15% and 2%. Clearly, these two estimates of bed load as a proportion of measured suspended loads yield wildly different values for the proportion of stream power expended in transporting the bed load. However, as the estimate of bed load of Alam and Hossain was based on the assumption of a higher value can be disregarded while assessing the morphological response of the Jamuna to the changes in energy dissipation.

Table 7.1: Estimates of bed load and energy required to transport

Literature	**1966-70**		**1983-88**	
	Bed load (million $ton y^{-1}$)	Energy required	Bed load (million $ton y^{-1}$)	Energy required
Alam and Hossain (1988)	144	47%	46	15%
Klaassen *et al.* (1988)	20	6%	6.5	2%

This implies that, under 'channel forming' conditions, when the river is at the bankfull stage, the proportion of overall stream power required for transporting the suspended bed material and bed loads was ~20% during the late-1960s, but only ~5% during the mid-1980s. That is, during the period when the sediment wave was passing through the Jamuna River, there was a about a 15% increase in the proportion of stream energy expended in transporting the bed material load. As the amount of bed load estimated by Klaassen et al. (1988) is probably conservative, the difference may in fact be larger. The point is that, for a very large river like the Jamuna, expenditure of 20% of stream energy on bed material transport represents a huge amount of energy loss, while a change of 15% represents a massive shift in the distribution of energy dissipation between sediment transport and boundary friction, equivalent to nearly 1,200 mega-watts. Recognising this, it is little wonder that changes through time in the supply of bed material load should trigger profound morphological responses in the channel. The nature of the morphological responses displayed by the Jamuna River to the changes in the distribution of stream energy dissipation associated with changes in the rate of sediment transport are discussed in the remainder of this section.

Unfortunately, no measurements of sediment load were made in the Jamuna during the 1950s, prior to the arrival of the sand wave in Bangladesh. Based on records from Assam, it can reasonably be assumed that sediment load at that time was much lower than that measured at Bahadurabad in 1960s when the sediment load in the Jamuna was at its peak.

Based on the calculations presented earlier, if there had been no change in channel dimensions, geometry or planform, the arrival of the sand wave in the early-1960s would have produced a deficit of energy equivalent to about 15% of the available stream power of the Jamuna River. After the sand wave moved through the Jamuna, bed material loads measured in the 1980s reduced significantly. This decrease in bed material load would have reduced the loss of energy due to bed material transport by about 15% of the total available. Viewed in this way, it is possible to compare the morphological implications of changes in the supply of bed material load directly to the increases or decreases in stream energy produced by changing the valley slope or through human interventions in the river system through, for example channelisation.

The valley slope usually decreases in the downstream direction in a manner inversely proportional to the downstream increase in discharge, though it may vary locally along the course of a river due to valley geology, neo-tectonics or artificial controls on the local base level. In such cases it is often observed that the river planform varies as a function of spatial change in the valley slope. For example, Schumm et al. (1994) found that the sinuosity of the Mississippi River is higher where valley slope is steeper (making available additional stream power) and *vice versa*. Similarly, Schumm and Galley (1994) detected adjustments in the River Nile that were related to local changes in valley slope. Interestingly, it was noted that the Nile does not only increase its sinuosity in response to an increase in energy where the valley slope is higher, it also increases its width. Conversely, Harbor et al. (1994) found a different morphological response in the Sindh River in Pakistan, which becomes braided where the valley slope steepens and available energy increases. This was also the case for Bogue Homo Creek in the USA: the planform changes from meandering to braided in a reach where the slope is relatively high downstream of the Wiggins uplift (Burnet and Schumm, 1983).

These case examples demonstrate that where the valley steepened, alluvial rivers either increase their sinuosity or switch their planform from meandering to braided. This planform response may be explained in terms of a response to the increased availability of stream power in the steeper valley reach. It seems that, if discharge, bed sediment size and channel boundary conditions remain the same, the addition of stream power causes an alluvial river adjust its morphology in ways that reduce the rate at which energy is supplied to the channel and/or increase flow resistance so that the rate of energy loss to friction balances the higher rate at which potential energy is being supplied to the flow. For example, in sinuous and meandering rivers, increasing planform sinuosity reduces the channel slope, decreasing the rate at which potential energy is input to the flow, while also lengthening the channel to increase frictional losses and introducing additional energy losses at the tighter bends associated with the more sinuous planform. If the increase in available energy is particularly marked, increasing the width/depth ratio and/or changing the planform into a braided pattern that is either dynamically stable or incising will act to further increase the rate at which energy is lost to friction. The adjustments that occur in response to a decrease in valley slope have the opposite effects, typically involving the river decreasing its sinuosity in order to increase its channel slope or switching from a dynamically stable, braided planform to meandering to increase the rate of frictional loss. Under these circumstances, further lowering of valley slope would be likely to trigger metamorphosis from a meandering to an aggrading, braided planform. However, the braided planform so produced does not represent a new equilibrium condition, but a transition towards equilibrium through an increase in channel slope that is achieved through aggradation. These considerations illustrate that it is the imbalance between available energy (a function of valley slope) and the rate of energy dissipation (flow resistance, channel slope) that determines the type of cross-sectional and planform changes that occur in an alluvial channel in response to a change in valley slope.

The importance of energy availability and dissipation in disturbed alluvial channels was investigated by Simon (1989; 1992), Simon and Thorne (1996), and Simon and Rinaldi (2006). Simon (1989; 1992) studied energy dissipation in two dissimilar, disturbed fluvial systems. The North Fork, Toutle River flows through the Cascade Mountains of Washington State and was disturbed by the 1981 eruption of Mount St Helens. Obion Creek is located in the loess plains of West Tennessee and was disturbed by post-war channelisation and straightening. Simon (1989; 1992) found that both systems initially responded to the great increases in energy availability due to disturbance by evolving so that the rate of energy dissipation also increased to very high levels. However, subsequent channel changes caused the rates of energy supply and dissipation to decay with time back towards pre-disturbance levels. He also found that all the metrics of stream energy including unit stream power, total mechanical energy and specific energy declined to a minimum during the process of morphological adjustment. In this respect, widening associated with bank instability following degradation in channels with cohesive banks was shown to be highly effective in minimising all components of stream energy. In contrast, widening without incision was the dominant form of channel adjustment in high energy environments where the bank materials were noncohesive.

Wide support for Simon's findings may be found in the literature. For example, experience has shown that excessive availability of energy following channel straightening may lead to increased energy dissipation through both widening and channel changes that increase boundary roughness (Winkley, 1994; Biedenharn *et al.*, 2000, Harmar *et al.* 2005). For example, following a series of artificial bend cut-offs in the Lower Mississippi River, the river returned its stream power towards the pre-disturbance level through degradation upstream of the cut-offs and aggradation downstream while simultaneously increasing the rate of energy dissipation through widening, increasing the amplitude of pool-crossing depth variation and shortening the spacing in the crossing-pool sequence (Biedenharn et al., 2000; Harmar *et al.* 2005). However, Winkley (1994) also noted a response in the sediment dynamics of the Mississippi River, with the rate of energy consumption through erosion and sediment transport increasing in reaches where more energy became available.

A reduction in sediment supply also produces excess energy availability, but often the morphological response of the river that would decrease the energy availability to a pre-disturbance level through degradation is limited by armouring of the riverbed (Galay, 1983; Chien, 1985; Zhou and Pan, 1994; Lagasse, 1994; Kondolf et al. 2002; Richard and Julien, 2003; Simon and Rinaldi, 2006). While armouring also increases bed friction (Simon and Thorne, 1996), this may be insufficient to counter balance the increase in energy availability. In such cases, the planform may change from braided to a single threaded, meandering channel (Galay, 1983; Chien, 1985). Widening or the formation of a braided channel is another mode of river adjustment to excessive energy availability produced by natural or human disturbance.

It should be remembered though that the types and sequences of morphological adjustments that occur in disturbed systems and not solely controlled by energy imbalance. For example, Simon and Rinaldi (2006) used a numerical model to simulate channel response to a 50% reduction in sediment load in channels with banks formed in clay, silt and sand. They found that channels with clay banks incised without widening, channels with silt banks incised and then widened, and channels with sand banks widened with insignificant incision. This demonstrates that the characteristics of the bank materials are thus another factor that conditions the types and sequences of adjustments that occur in response to a particular destabilising phenomenon.

Similarly, Jiongxin (1990 and 1996) reported that the Yongdinghe River in China widened and became braided following a reduction in sediment load downstream of Guanting Reservoir, but that while the Lower Yellow and Hanjiang rivers of China initially incised and increased in sinuosity immediate after operation of reservoirs at upstream, at a certain stage the rivers widened and became braided (Jiongxin, 1996). The experimental study by Jiongxin (1990) also supported the findings from the Yongdinghe, Lower Yellow and Hanjiang rivers.

The examples reported above provide evidence that, in response to the creation of a condition of excess stream energy availability due to an increase in valley slope or channelisation, a river may respond in multiple ways including increasing its bed roughness by armouring, increasing its width by bank erosion, increasing its sinuosity by meandering more intensively, or transforming itself from a single-thread to a braided planform. The common thread that links these adjustments is that they all tend to restore the balance between energy availability and dissipation.

In the case of the Jamuna River, morphological changes occurred in response to an increase in the supply of relatively coarse sediment (sand) that travelled through the reach as a moving wave of bed material load. When the sand wave entered the Jamuna River, additional energy was required to transport the excess bed material load. To adjust to this imbalance between energy availability and demand, the Jamuna reduced the width and braiding intensity of its dynamically-stable, braided channel, during the 1960s and early-1970s. In nature, examples of other types of adjustment have been reported, often involving increases in braiding intensity in response to an increase in sediment load. However, it should be noted that not all of the responses reported would adjust the channel towards a configuration that achieves a stable balance between energy availability and expenditure. For example, increasing the width and braiding intensity in response to an increase in sediment supply may be a transitional morphological adjustment because it balances energy availability and dissipation by increasing the channel slope through aggradation – which produces an unstable channel configuration. However, this type of adjustment occurs under different circumstances to those found in the Jamuna River, as indicated by Figure 3.5.

After the crest of the sand wave progressed through the Jamuna in the mid-1970s, the supply of bed material load began to decrease and it continued to do so throughout the late-1970s and 1980s, reducing the amount of stream power required for sediment transport and generating excess available energy. To deal with this energy imbalance, the river responded by increasing its width and braiding intensity, increasing flow resistance in order to dissipate the excess energy that was available. The energy balance was achieved using these mechanisms because the Jamuna River could not use the other options to dissipate its excess energy such as bed armouring to increase its bed friction, or incising or transforming into a meandering river to reduce its channel slope. Armouring is not an option because a sand-bed river has a very little scope to coarsen its bed through selective entrainment. Incision of a very large river like the Jamuna requires the displacement of tremendous amount of sediment, which would take a long period even given the transport capacity of the Jamuna – making it a longer-term response. Moreover, the banks of the Jamuna are mainly non-cohesive and highly erodible and experience shows that in these circumstances an alluvial river tends to widen in response to a reduced sediment load (excess energy availability) rather than incising (Simon and Rinaldi, 2006).

With respect to planform changes, Bettess and White's (1983) investigation suggested that for same sediment concentration braiding is the more likely planform adjustment in rivers with higher discharges and coarser bed materials. On the other hand, for the same bed material size, braiding is more likely for rivers with higher discharges and sediment concentrations.

This explains why large, highly sinuous, gravel-bed rivers and small, braided, sand-bed rivers are rare in nature. It follows that the geomorphological setting and boundary material characteristics of the Jamuna River conditioned the morphological responses to disturbance, favouring adjustments through increasing width and braiding intensity to dissipate the excess energy generated due to a decrease in the bed material load.

According to the conceptual model, an increase in bed material supply caused the bed of the channel to rise (aggrade) and the width and braiding intensity to decrease at the same time. The upper reach of the Jamuna River did display these types of response, and also the width and braiding intensity of the lower reach of the Jamuna, the Padma and the Lower Meghna rivers all decreased in response to an increase in the supply of bed material load. This type of response is not in line with Equation 3.14 or the models of Schumm (1969), Chang (1979 & 1986) and White *et al.* (1982). Rather equations 3.3 and 3.4, as derived by Klaassen (1995), support the observed responses of the rivers. It appears that, by decreasing their braiding intensity and width, these rivers saved enough energy through reduced friction losses to make available the additional energy required to transport the increased bed material load. As a result the Jamuna, Padma and Lower Meghna transformed their planforms from higher to lower types, as shown in Figure 3.5.

In a meandering river, the term 'width' represents the width of the water surface. However, in a braided river, 'width' represents the width of the braid belt. It includes not only the flow width but also the width of the islands - which are not inundated at the bankfull stage. As a result, the width of a braided river generally increases as the braiding intensity of the river increases and decreases if the braiding intensity is reduced, though this may not be true in all cases. For example, if a new braided channel occupies the width of an island or bar, the width of the river may not increase with an increase in braiding intensity (Figure 7.5). The opposite is also true, in that a braided river may continue widening, even when the river is reducing its braiding intensity.

An increase in the width of a single-thread channel generally indicates an increase in energy dissipation due to enlarging of the wetted perimeter and losses to boundary friction. In this respect, an increase in the width of a braided river does not mean anything. In braided rivers, it is the flow width that is the important parameter. Enlargement of flow width occurs when the width increases together with an increase in braiding intensity. It may therefore be deduced that during the 1980s, when the widths and braiding intensities of the rivers both increased together, energy dissipation due to boundary friction increased massively to compensate for the decreasing amount of energy required to transport sediment. Conversely, the increase in width of the Jamuna River that occurred without an increase in braiding intensity during the 1990s probably did not result in additional energy dissipation.

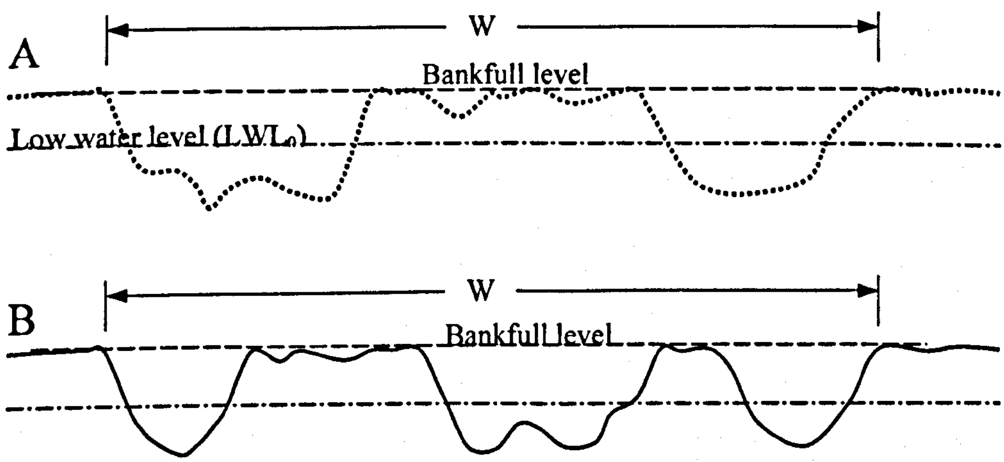


Figure 7.2: Diagram to illustrate how a river cross-section (A) with a width W and braiding index of 2 might be converted into a cross-section (B) with the same width W but a braiding index of 3.

Bank erosion was found to increase along the Mekong River as a result of the trapping of sediment due to the construction of a reservoir (Kummu and Varis, 2007; Kummu *et al.*, 2008). During the 1980s, the bank erosion rate along the Jamuna River was very high when the sediment supply dropped from its peak. In the 1970s it was less than 4,000 hay^{-1}, but it increased to 5,000 hay^{-1} in the 1980s (Figure 7.3). Recently, the annual average rate of erosion was found to be 2,000 hay^{-1}. This value is two and a half times lower than the rate of erosion that occurred in 1980s. It follows that the high rate of bank erosion in 1980s indicated a high rate of energy dissipation.

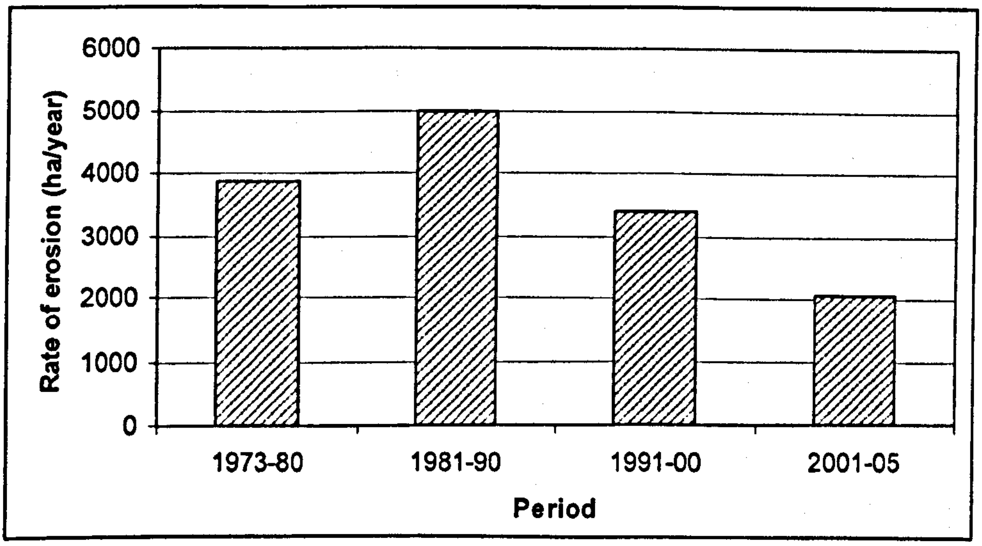


Figure 7.3: Rates of annual erosion along the Jamuna River for different periods

7.3 Reconciliation of the conceptual model with previously established process-response models

The conceptual model developed in this thesis displays both points of agreement and apparent disagreement with previously established process-response models presented in Chapter 3. These models address the morphologies of rivers in dynamic equilibrium and their responses to disturbance in different ways. Some of them take a one-dimensional approach, such as Lane (1955) and Simon (1989). Lane (1955) dealt with the relations between discharge, sediment load, sediment calibre and slope, while Simon (1989) dealt with morphological response to a sediment wave moving through the fluvial system and modifying the bed elevation. Schumm (1969) took a qualitative approach, developing relations showing how the independent variables of discharge and sediment load control several dependent variables of channel morphology including width, depth, slope, sinuosity and meander wave length.

Bettess and White (1983) developed a theoretical framework for determining the equilibrium planform based on the relative values of valley slope and stable channel slope. The stable

channel slope was taken to be a function of discharge, sediment load and sediment size. Jiongxin (1996) also developed a descriptive model, but his was empirical, having been based on observations on the response of rivers downstream of reservoirs in China. His model describes how a river may adjust its planform when the supply of sediment from upstream is cut-off due to the construction of a reservoir.

The conceptual model presented here stems from these established models but has been developed primarily from the observed behaviour of the Jamuna River – a very large, sand-bedded, braided river system. It deals particularly with the morphological response of this river to disruption by changes to the sediment load that involve adjustments to bed elevation, depth, width, braiding intensity and planform. This does not deny that changes in other independent variables (such as discharge and bed material size) can trigger morphological responses, or that there are other dependent parameters (such as channel slope) that might be affected by changes in the sediment load. However, as the available data indicate that changes in these other independent and dependent variables during the last 50 years were not significant, they were not included in the conceptual model. Exclusion of these parameters should not be taken to suggest that Lane's relation (1955) is unimportant. Rather it represents confirmation that, while channel slope and bed material size are very important parameters, in very large alluvial rivers with highly erodible banks, morphological adjustments take place primarily through changes in width, braiding intensity or sinuosity, and planform pattern. However, the driving mechanism remains the same, i.e. the requirement to decrease the dissipation of stream energy by reducing flow resistance due to an increase in the proportion of the available energy expended in transporting the sediment load that results from an increase in sediment supply. This is demonstrated by the fact that equations 3.3 and 3.4 (derived on the basis of Lane's (1955) relation) show that a river may decrease its width and braiding intensity instead of increasing its channel slope and decreasing its bed material size in response to an increase in sediment load.

In the Jamuna, an increase in the sediment supply to a reach due to arrival of a moving wave of excess bed material load from upstream was shown to lead first to a rise in bed elevation that could be recognized from specific gauge analysis. The available data are consistent with the model of Simon (1989) in that the magnitude of bed level rise diminishes with distance downstream from the area of maximum disturbance. Unfortunately, due to data limitations, it could not be ascertained whether attenuation in the bed wave followed an exponential function in the downstream direction, as envisaged by Simon (1989).

According to the model proposed here, an increase in the supply of bed material load generated by the Assam earthquake caused bed aggradation, width *reduction* and a *decrease* in braiding intensity. This proposal contrasts to that of Schumm (1969; 1977), in which an increase in sediment load generates *increases* in width and braiding intensity. Chang (1979 & 1986), White *et al.* (1982), Germanoski and Schumm (1993) and Bridge (2003) have all expressed support for the model of Schumm.

This apparent paradox may be resolved by considering differences in the pre-disturbance planform configurations of the channel and the mechanism by which the morphology responds. In the Brahmaputra-Jamuna-Padma-Lower Meghna system, the sediment wave entered rivers that were already braided and, in the case of the Brahmaputra and upper reach of the Jamuna, intensely so. Aggradation, narrowing and a decrease in braiding intensity were achieved through siltation and abandonment of the smaller anabranches that raised the average elevation of the bed, narrowed the width and reduced the number of anabranch channels (Figure 7.4). In contrast, the starting situation conceptualised in Schumm's model is quite different, envisaging an initially single-threaded or weakly braided channel that responds to an increase in sediment supply by building additional medial bars and so aggrading, eroding its banks, widening and becoming more intensely braided. That situation is very similar to the changes that occur when a river switches from Type 2 to Type 1 in Figure 3.5 or remains in Type 1 but becomes more strongly braided. The morphological

response to an increase in sediment supply in this type of river can be illustrated by the response of the Toutle and Cowlitz Rivers to the massive sediment input associated with the eruption of Mount St. Helens (Bradley, 1983, Simon, 1992). Prior to the eruption, the Toutle and Cowlitz were dynamically stable rivers with planforms that displayed meandering and weakly braided reaches, and they responded by aggrading, widening and braiding intensely. However, the upper reach of the Jamuna was already intensely braided (similar to Type 5 in Figure 3.5) prior to the arrival of the sand wave and it responded by silting its smaller anabranches, aggrading, narrowing and becoming less intensely braided – that is similar to a Type 4 river (Figure 3.5). The important point here is that Figure 3.5 clearly demonstrates that there are two types of braided river in terms of morphological response to a change in sediment supply. This explains why it is possible for apparently similar rivers react almost in opposite ways to a change in sediment supply.

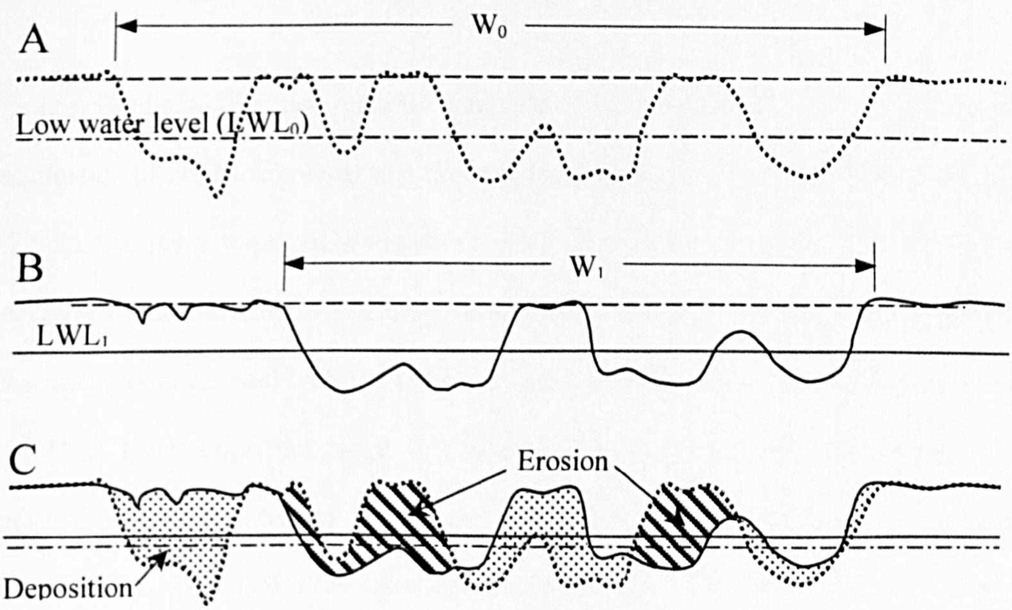


Figure 7.4. Adjustment of a hypothetical cross-section to an increase the the supply of bed material load: (A) cross-section prior to the arrival of the sediment wave, (B) cross-section during the high supply period of high bed material load ($W_0 > W_1$ and $LWL_1 > LWL_0$) and

(C) sediment deposition and erosion during adjustment (deposition > erosion). The process reverses when the bed material load decreases following its peak.

There is then no conflict between the conceptual model proposed here and that of Schumm (1969; 1977). In the scheme proposed in Figure 3.5, Schumm's braided rivers are similar to Type 1 or the higher order of braided river. These rivers increase their width and braiding intensity in response to an increase in sediment supply. On the other hand, the Jamuna River is represented by a Type 5 or Type 4 planform and these rivers decrease in width and braiding intensity in response to an increase in sediment supply.

In the conceptual model, it is proposed that channel narrowing and reduced division of discharge as the flow concentrates into fewer, larger anabranches leads to an increase sediment transport capacity. This is consistent with the well-established rule that sediment transport capacity increases as a non-linear function of discharge. For example, bed material transport capacity is often found to vary as a power function of discharge in the form:

$$S = aQ^b \qquad (7.6)$$

where, Q = discharge, S = bed material load, and a and b are empirically-derived constants. Measurements of sand load reveal that the exponent, b, in Equation (7.6) varies between 1.3 and 2.5 in the main rivers of Bangladesh (Deft Hydraulics and DHI, 1996h). Taking a conservative assumption that b = 1.5, conversion of a braided channel with two anabranches into a single-thread channel with the same discharge would increase the capacity to transport sand by 40%. If b = 2.0, which is not unreasonable, the transport capacity of the single-thread channel is double that of the two anabranches put together. Although these calculations are purely indicative, Equation (7.6) provides a rational basis for proposing that sediment transport increases with decreasing braiding intensity and so provides support for prediction of that response to an increase in sediment supply in the conceptual model.

Bettess and White (1983) showed how the dynamically stable planform of a river varies as a function of changes in valley slope. Using the concept of Bettess and White (1983) in developing the scheme presented here for predicting planform response to disturbance, provides further support for the proposal that increasing the sediment supply to an intensely braided river causes a decrease in its braiding intensity and that the reverse is also true – decreasing the sediment supply causes braided intensity to increase. Bettess and White's (1983) framework and the scheme developed in Chapter 3 are supplementary to each other. One shows the changes in planform of a river as a function of valley slope, while the other shows it as a function of sediment load. Both of these models indicate that the processes of energy dissipation are the main driver of planform change. In order to dissipate the excess energy generated due to the increase of valley slope, a straight channel starts to meander and then braid (Figure 3.4). The scheme (Figure 3.5) shows similar sequence of planform change to that of Bettess and White (1983), the driver again being the need to dissipate the excess energy made available due to the decrease of sediment load. Thus, the relations between the dependent and independent variables as proposed in the conceptual model match well the energy dissipation concept.

Joingxin (1996) developed a descriptive model for how the planform of a river changes in response to the reduction in sediment supply associated with dam closure. The planform changes observed in the Jamuna-Padma-Lower Meghna system as the sediment load decreased following passage of the crest of the sediment wave and predicted by the conceptual model fully agree with Jiongxin's model. However, the conceptual model developed here represents an advance over Jiongxin's in that it also predicts changes in planform due to an increase in sediment supply. The observation by Jiongxin (1996) concerning the occurrence of very high rates of bank erosion during transformation of a meandering or straight river to a braided form and a rapid reduction in bank erosion as the stable stage (Stage III) is approached agrees well with the history of bank erosion and planform evolution observed along the Jamuna River (Figure 7.3).

7.4 Complex response in the latter-stage of the conceptual model

In the conceptual model, a further phase of morphological adjustment is proposed, due to a second increase in coarse sediment supply. This proposal stems from theories and observations put forward by (amongst others) Hey (1978), Simon (1989, 1992), and Richards and Lane (1997) that, following a single major disturbance, instability in the fluvial system does not decay monotonically, but follows a damped oscillation.

Evidence to support complex response of the type envisioned by Schumm (1977) in the rivers studied here comes from the marked reduction in the braiding intensity observed in the upper Jamuna during the 1990s (Fig. 6.10A), which shows that adjustments are not unidirectional and is consistent with morphological response to a secondary increase in the sand load supplied from upstream. In the model, it is hypothesized that this second pulse of sand is much smaller than the first wave of earthquake-derived sediment, and it originates from secondary phases of morphological response in the tributaries and main stream of the Brahmaputra in Assam. If this is so, then it is likely that the crest of the second sand wave would have reached the Jamuna at about the turn of the millennium.

In predicting future cross-sectional change and planform evolution in the upper Jamuna, it must be borne in mind that the intensity and extent of morphological adjustments associated with this second, damped, oscillation in sand load will be much smaller than those driven by the first wave. In practice, morphological responses to the waning impact of the Assam earthquake are likely to be subsumed within responses to more recent and current drivers of channel change including neo-tectonics (warping, subsidence, lineament development) that may be altering the valley slope, direct engineering interventions in channel morphology such as the Jamuna Multi-purpose Bridge, and changes in the flood regime during the last few decades due to climate change and the decline of the Old Brahmaputra and Dhaleswari distributaries. The effects of these current drivers are not considered in the conceptual model presented here. However, the model and also the planform change scheme could be used to predict the morphological response of the river to such disturbances in the near future when these rivers would be again close to the dynamic equilibrium.

The planform scheme can be used to predict adjustments to the planform qualitatively as a function of changes in the bed material supply, although it does not indicate the time frame over which the planform will respond. On the other hand, the conceptual model does provide a tentative time frame for the sequences of change, based on the celerity of a bed wave and it could be used to make qualitative predictions of changes in bed level, width and braiding intensity. Changes in these parameters are good indicators of the associated changes in other aspects of river behaviour that bear directly on people's lives such as flood frequency and rates of annual bank erosion or accretion. Hence, the capability to make such predictions would be very useful for policy makers, water resources planners and river engineers attempting to minimize the national loses and reduce the suffering of the hundred of thousands of people who live in and along these great rivers.

The scheme could also be used outside Bangladesh for predicting morphological changes in rivers that are known to be responding to the changes in sediment supply. In applying the conceptual model and planform scheme, particular attention would have to be paid to the finding that a river may respond to a decrease in sediment supply either by transforming its planform from meandering to braided (Type 3 to Type 4 of Figure 3.5), or by increasing its sinuosity depending on its geomorphological setting and the nature of its boundary materials. In this context, it should be borne in mind that the conceptual model is mainly applicable to braided rivers and particularly those like the Jamuna (Type 4 or 5 in Figure 3.5). The conceptual model should only be applied to similar types of braided rivers elsewhere in the world with some allowance being made for the different time frame for response associated with rivers of different physical scales.

7.5 Channel patterns and morphological responses

The apparent paradox between the conceptual model and earlier process-response models draws attention to the pre-disturbance planform pattern of the river as being crucial in determining the style and sequence of morphological responses triggered by an increase in the supply of bed material load. This highlights the need to be both accurate and comprehensive when defining channel planform. Early planform definitions, such as those of Leopold and Wolman (1957), classified all multi-threaded rivers as 'braided'. Subsequently, Schumm (1977) differentiated between multi-thread streams that were braided (unstable, bed load dominated) and anastomosing or anabranching (more stable, suspended sediment dominated).

Lane (1957) divided braided rivers into five sub-divisions (see p. 83). A scheme has been developed (see Figure 3.5), based on the work of Bettess and White (1983) and assuming that the Jamuna is a braided river similar to that of Lane's Sub-division 2: *braiding due to steep slope with approximate equilibrium* (Lane, 1957, p 83). It has also been assumed that Schumm's or Bridge's braided rivers are similar to Lane's Subdivisions 3 and 4, which are of *steep to moderate slope but aggrading*. According to the scheme developed here, a braided river could be transformed from Sub-division 2 to Sub-division 3 or 4 if the sediment input is increased and exceeds the local transport capacity (Figure 7.5). The reverse is also possible in response to a decrease in sediment input. It should, however, be borne in mind that transformation from one type of braiding to the other may not be a direct process, as straight and meandering planforms may lie in between (see Figure 3.5). In the case of Lower Yongdinghe River in China, transformation from Type 1 to Type 4 braiding occurred without the appearance of meandering or straight planforms as intermediate planforms. On the other hand, the Lower Yellow and Hanjiang Rivers in China did adopt meandering planforms during their transitions from Type 1 to Type 2 braiding. Clearly, the straight and/or meandering planforms that develop are transitory in nature rather than representing potentially stable forms, as is illustrated by the sequence of planform changes observed in some reaches of the Jamuna, Padma and Lower Meghna system during the last 40 years.

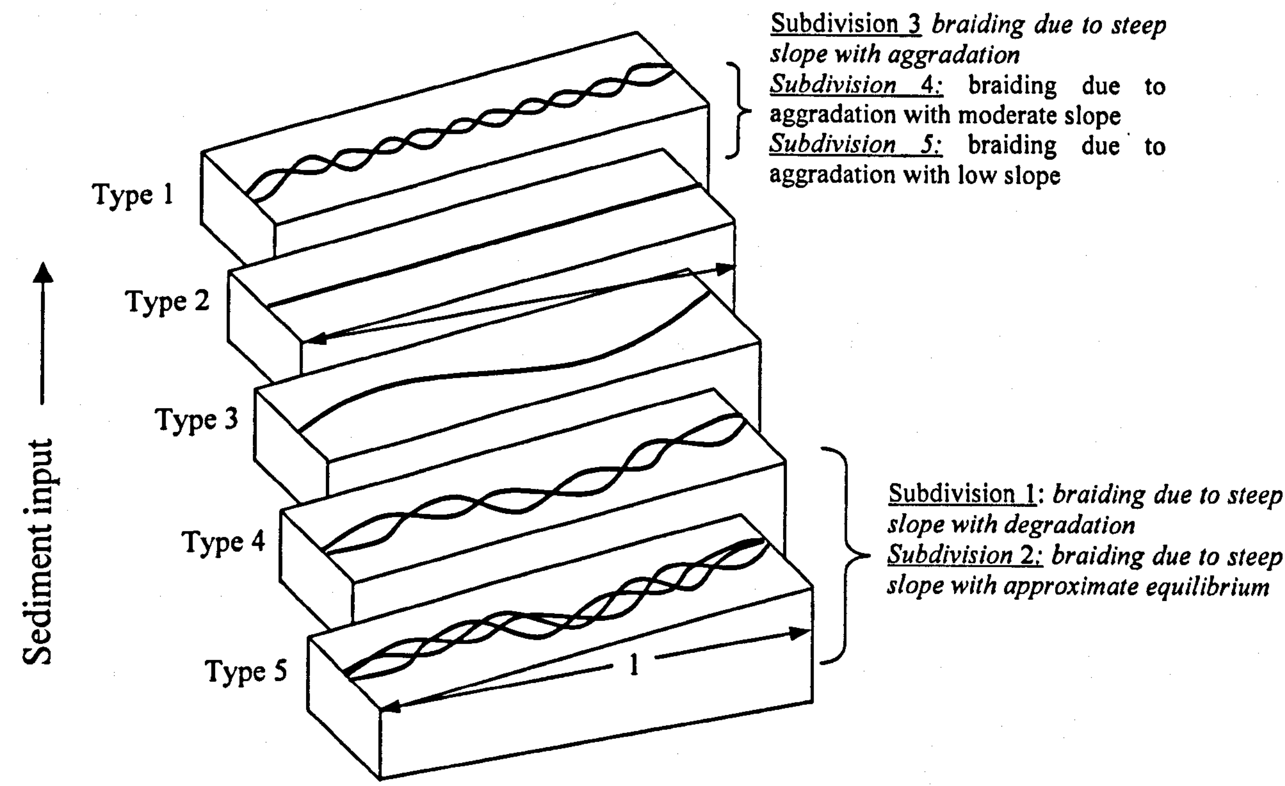


Figure 7.5 Relation between the braided rivers as defined in the scheme and subdivisions of braided rivers as suggested by Lane (1957)

The observed responses of the upstream and downstream reaches of the Jamuna, Padma and Lower Meghna rivers in changing their planforms in response to first an increase and then a decrease in sand (bed material) load are presented in Figures 6.11, 6.13, 6.14 & 6.17. The time-series of satellite images of a reach the lower reach of the Jamuna River (covering only 70 km length) are presented in Figure 7.6. Satellite images taken in 1967 show a combination of braided and single-threaded meandering planforms, though numerous, recently abandoned anabranches can be distinguished. This pattern is consistent with aggradation, width reduction and reduced braiding due to siltation in the second and third order channels in response to sediment overloading when the bed material wave entered this reach in the early to mid-1960s. This situation is somewhat similar to that in the Padma in 1973 (Figure 6.14).

As the bed material load in the lower Jamuna peaked in the early-1970s, a braided pattern gradually replaced the meandering planform. This pattern of braiding was similar to the braided rivers envisaged by Schumm or Bridge and was equivalent to Type 1 in Figure 3.5. In contrast, instead of braiding, the Padma and Lower Meghna rivers developed nearly straight to meandering planforms in 1980 and 1990, during their periods of peak supply of bed material load (Figures 6.14 & 6.17). These rivers were probably in need of more sediment than they were supplied with to transform into type 1 braided rivers.

The reduction in the supply of bed material to the lower reach of the Jamuna River from its peak value in the early 1970s resulted in the lower 40 km of the reach initially reverting to a meandering planform during the 1980s, but by the 1990s the entire length of the lower reach of the Jamuna had again become braided (Figure 7.6). This braided planform was dominated by secondary anabranching, with the shape and size of the islands being significantly different to what was observed in 1973. The Padma and Lower Meghna rivers showed similar transformations from meandering to braiding in response to their periods of decreasing supply of bed material load.

These observations reveal a propensity for reaches with planforms between Type 4 and Type 3 in Figure 3.5 to transform themselves into Type 1 braided patterns in response to an increase in the supply of bed material load. On the other hand, Type 1 braided reaches usually transform themselves first into meandering patterns and then into Type 4 braided rivers in response to a reduction in the supply of bed material load. These sequences of planform metamorphosis have both been displayed clearly by the lower Jamuna, the Padma and the Lower Meghna rivers. They are most probably related to the fact that it is relatively easy for flow to re-entrain sediment that was only recently deposited in abandoned anabranches and so re-occupy them, compared to the more difficult task of increasing sinuosity through eroding banks formed in older, more consolidated floodplain sediments. Also, the high stream power (unit weight of water*discharge*slope) of these rivers restricts the tendency for incision and meandering unless the channel banks are highly resistant to erosion (Simon and Rinaldi 2006). If the banks are erodible, a reduction in sediment load is much more likely to trigger widening and a tendency to braid rather than incision and meandering.

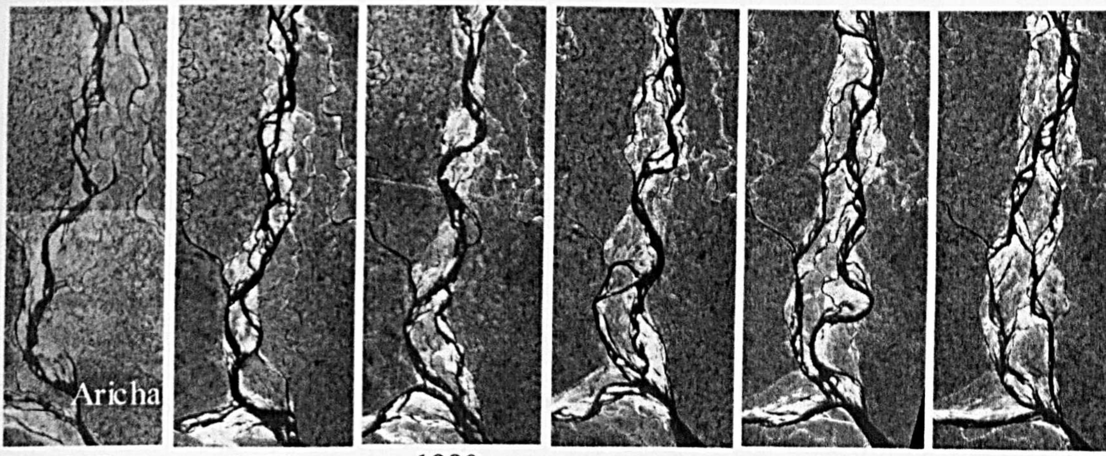


Figure 7.6: Time-series of satellite images covering the 70 km long lower reach of the Jamuna River

7.6 Summary

The main rivers of Bangladesh expend a significant proportion of their stream energy in transporting their bed material loads. Changes in the supply of sediment that constitutes bed material load create excesses or deficiencies of available energy which trigger changes in channel dimensions, geometries and planforms. In adjusting to an energy deficit, braided rivers decrease the amount of energy lost to boundary friction by decreasing their flow width and braiding intensity. Under similar circumstances, a meandering river might decrease its sinuosity. When adjusting to an excess in stream energy, a river will change its morphology so as to increase the rate of energy dissipation due to boundary friction.

The interrelationships between the independent and dependent variables proposed in the conceptual model can be logically explained on the basis that changes in the fluvial processes responsible for energy dissipation are the process-drivers of changes in channel morphology. The planform prediction scheme developed here also supports the concept that energy dissipation is the process-driver responsible for channel adjustments.

The conceptual model apparently shows disagreements with existing process-response models. The disagreements can be resolved if it is considered that there are two types of braided rivers as shown in Figure 3.5, which differ from each other in responding to changes in sediment load.

The scheme and the conceptual model can be used to make qualitative predictions of changes in the planforms and channel dimensions of the rivers of Bangladesh that occur in response to changes in flow and sediment regimes due to climate change, seismic disturbances and large-scale human interventions. The scheme and model may also be used for the rivers elsewhere in the world that display similar types of braiding to that of the Jamuna, Padma and Lower Meghna rivers.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The geomorphological characteristics and dynamics of the Brahmaputra-Jamuna-Padma-Lower Meghna river system were the basis for the research reported in this thesis. The main focus of the work was the sequence of morphological changes observed in the rivers during the last 50 years and a working hypothesis was put forward that these changes resulted from the operation of dynamic process-response mechanisms in the fluvial system triggered by a huge influx of sediment following the Assam earthquake of 1950. The research reported here used a time-series of remotely-sensed imagery together with hydrological, hydraulic, sedimentary and morphometric data to study dynamic process-response and morphological changes in the Jamuna-Padma-Lower Meghna river system within Bangladesh.

To address the issues raised by the working hypothesis it was decided to conduct research with the aim of achieving a new and improved understanding of how the dynamic process-response mechanisms operate within the Brahmaputra-Jamuna-Padma-Lower Meghna braided river system to drive morphological changes through time and space. It was intended from the outset that this understanding should be expressed in the form of a conceptual model and that the utility of the conceptual model should not be limited to explaining past channel changes, but also offer the capability to predict the future behaviour of a river in terms of the morphological responses that might be expected to climate change, future seismic events or human interventions in the fluvial system. Within the context of this aim, the specific objectives were stated to be:

1. to examine the variables responsible for driving morphological changes in alluvial rivers and identify which of these driving variables was causally involved in

producing the changes in channel morphology observed in the Brahmaputra-Jamuna-Padma-Lower Meghna river system since 1950;

2. to assemble and analyse the evidence available to support the working hypothesis outlined above concerning the downstream propagation of a sediment wave generated by the 1950 Assam earthquake;

3. to develop and validate a conceptual process-response model that represents the relationships between changes in the driving variables and responses of the river system through changes to different morphological parameters; and

4. to compare the observed morphological responses and conceptual model of the Brahmaputra-Jamuna-Padma-Lower Meghna river system to the morphological behaviour of other large alluvial rivers elsewhere in the world.

While recent morphological changes and their causes were the focus of the study, the literature and unpublished consultancy reports were reviewed to develop a broader understanding of the geological and tectonic history of the Bengal Basin, the development of the major river systems during the Quaternary and Holocene, and the more recent evolution of the Brahmaputra, Jamuna, Padma and Lower Meghna Rivers as described by scientists and engineers studying the region.

The Bengal Delta is the largest modern alluvial delta in the World. At the regional scale, delta building processes are governed by the huge discharges of the rivers due to snowmelt and monsoonal runoff and the abundant supply of sediment from the Himalayas, coupled with the active tectonics of the Bengal Basin. This combination of great rivers heavily charged with sediment, together with a low relief landscape that is subject to neo-tectonics makes the channel-floodplain system highly dynamic. The risks associated with life in such a dynamic environment are compounded by the very high density and poverty of the population. Millions of people living in the floodplains and on islands in the channels of the great rivers understand the natural hazards they face, of which flooding and erosion are the most severe, but they must continue to live there and suffer the consequences due to lack of any alternative.

The great rivers of Bangladesh are very large on a world scale and they remain mostly uncontrolled by engineering stabilisation. Consequently, the scales of flood events and channel changes are also large. For example, major floods displace millions of people every few years while almost every year, river bank erosion directly affects the lives of nearly a million people (Elahi and Rogge, 1990). More specifically, episodes of sustained and rapid widening of the Jamuna, Padma and Lower Meghna Rivers during the late-20th century made on the order of 800,000 people homeless and landless. Clearly, understanding the causes of such channel changes and being able to predict them in future in order to manage their impacts on people, property and infrastructure is of much more than academic interest to Bangladesh.

To address the aims and objectives, the study began by eliciting information from secondary sources on the immediate effects of the Assam earthquake in 1950 and the consequent changes in the tributaries and channel of the Brahmaputra River in India. It was established that the great earthquake produced huge landslides in the Himalayas amounting to several billion cubic metres. A large proportion of the sediment generated by the landslides was transported to the Brahmaputra River by its numerous tributaries in the Assam Valley. Clearly, the ultimate destination of these sediments was the Bay of Bengal, although a percentage of the material was destined to go into long-term storage in the floodplains and flood basins of Assam and Bangladesh. Contemporary accounts and current sediment transport theory indicate that the fine fraction of the sediment supplied to the river system (silt and clay) constituted wash load that moved quickly through the system without interacting strongly with the morphology of the bed, being instead transported to the Bay of Bengal or deposited in the flood basins. However, contemporary accounts also indicate that downstream movement of the coarser fraction of the sediment (sand) moving as bed material load was much slower, as it was transport-limited rather than supply-limited. This coarser material appears to have formed a sediment wave or pulse moving as a disturbance in the bed that took approximately 50 years to move through the system, triggering the changes observed in the morphology of the channels in each reach sequentially as it travelled from Assam to the Bay of Bengal.

Other possible causes of the channel adjustments observed in the Jamuna-Padma-Lower Meghna river system, such as the changes in flow regime or the characteristic size of the bed materials were examined. However, it was demonstrated that the changes measured in these parameters during the period of morphological adjustment are insignificant and there is no justification for designating them as driving variables responsible for the channel instability. Conversely, examination of sediment transport records from gauging stations at Pandu in India and Bahadurabad in Bangladesh confirm, (i) that the sediment regime of the river system changed markedly through time, (ii) that the sequences of changes in measured suspended bed material loads at these stations are consistent with the downstream progression of a wave coarse sediment and, (iii) that changes in sediment balance (supply versus local transport capacity) appear to match the trends and timings of morphological responses observed at the reach-scale. Thus, it was concluded that the evidence available from the relevant literature, remote sensing, field measurements and data analysis support the working hypothesis that downstream propagation of a wave of coarse sediment input to the Brahmaputra River following the Assam earthquake was responsible for the morphological changes observed in the river system during the last 50 years.

Having accepted the working hypothesis, the research then moved on to building a conceptual process-response model capable of explaining the causal links between changes in the driving variable (sediment supply), fluvial processes (flow resistance, transport capacity for bed material load) and channel morphology (bed elevation, braiding intensity/sinuosity, width and planform pattern), based on existing theories of dynamic response, measured changes in sediment load at Bahadurabad and observed morphological changes in the Jamuna River. The investigation confirmed that arrival of the coarse sediment wave did increase sediment supply to the upper Jamuna so that it exceeded the local transport capacity and this caused the bed elevation to rise, but the results also indicated that there was a noticeable lag between the arrival of the wave and aggradation of the bed, which reflects the 'reaction time' of this very large river. Even after the crest of the sediment wave had passed Bahadurabad and the supply of bed material load started to decrease, aggradation continued until the input of coarse sediment again equalled the local capacity to transport bed material load. After that, the bed was lowered as the supply of coarse load continued to decline, until the reduction in local bed material load transport capacity again matched the supply of coarse sediment from upstream. In the conceptual model braiding intensity and width react almost simultaneously to changes in the bed elevation. In this intensely braided reach, arrival of the sediment wave, an increase in the supply of bed material load, and associated aggradation, caused both braiding intensity and width to decrease markedly, while the subsequent reduction in the supply of coarse sediment as the wave passed downstream and associated degradation caused braiding intensity to increase and the channel to widen.

The conceptual model developed for the Jamuna was validated using sediment loads measured in the Padma at Baruria and morphological changes observed in the Padma and Lower Meghna rivers. The relationships between changes in the sediment supply and morphological responses at the reach-scale expected from the conceptual model were found to match the observed trends and sequences of changes in bed elevation, braiding intensity, width and planform in these rivers, thus validating the conceptual model.

Examples of morphological response to changes in sediment load may be found in the literature (Lane, 1955; Schumm, 1969; Chang, 1979; White *et al.*, 1981; Galay, 1983; Bettess and White, 1983; Jiongxin, 1996; Petts and Gurnell, 2005). Reviewing the literature reveals that while the types and trends of geomorphic response vary widely between rivers, reports of sequences of morphological response like those modelled and observed in the Jamuna-Padma-Lower Meghna river system are rare. However, the morphological responses to reduced sediment supplies associated with reservoir construction and operation upstream in the Lower Yellow River, Lower Yongdinghe and Hanjiang rivers in China are very similar to the sequences expected from the conceptual model. Each of these rivers widened and increased its braiding intensity when the sediment load was drastically reduced. Unfortunately, these rivers cannot be used to establish whether the conceptual model correctly predicts how they would have responded to an increase in sediment load because no such increase in load occurred in them.

A review of the literature on dynamic process-response models for alluvial rivers formed part of the basis for development of the conceptual model. However, apparent contradictions emerged between the conceptual model and some of the established process-response models. As part of the research, a scheme was developed to resolve these apparent contractions. For example, the conceptual model predicts that the planform of the study rivers should change from braided to meandering, then straight and then to braided in response to a progressive increase in sediment supply and this is consistent with their observed behaviour. A reverse sequence was predicted and observed in response to a progressive decrease in sediment supply. The model also concludes that there are actually two types of braided river and that the morphological responses to a change in sediment supply are radically different in rivers that are initially of different braiding types. One type of braided rivers are the Bangladeshi rivers, in responses to the decreased sediment load they increase their width and braiding intensity. With the increased sediment load, these rivers reduce their width and braiding intensity and the progressive increase of sediment load transforms these rivers into meandering, straight and then the second type of braided river. In response to the increased sediment load, the second type of braided rivers increase their width and braiding intensity, which is opposite of the first type of braided rivers. The scheme thus explains the reasons why Bangladeshi braided rivers exhibited different responses to the changing of sediment load than the established process-response model.

Literature on the responses of channel suggests that stream energy plays an important role in determining the channel form (Richards, 1982; Bettess and White, 1983; Robertson-Rintoul and Richards, 1993; Winkley, 1994; Biedenharn *et al.*, 2000, Harmar *et al.* 2005). Calculations based on literature show that the Jamuna River expends a significant part of its stream energy for transporting its sediment load. This implies that changes in sediment load generate an excess or deficit of stream energy, which triggers the changes in channel form. There are several forms of channel adjustment with the changing of stream energy, such as changing slope, widening and an increase of braiding intensity or armouring of the riverbed. Instead of changing the slope through incising, increasing/decreasing sinuosity or river bed armouring, the geo-morphological settings of the Jamuna, Padma and Lower Meghna rivers drive them to adjust width and braiding intensity in response to the changes in stream energy. All the observed efforts of these rivers in adjusting to the changes in sediment load are aimed to expend or save the excess or deficit of stream energy. The interrelationships between the independent and dependent variables as proposed in the conceptual model and scheme have good agreement with the concept of energy dissipation during the process of channel adjustment. The planform changes of the Chinese rivers as described by Jiongxin (1996) also have a very good agreement with the scheme.

Bangladesh remains vulnerable to seismic events and climate change (Goodbred *et al.*, 2003; Mirza, 2002; Mirza 2003; Ahmed, 2006; CCC, 2006). Hence, it must be expected that impulse or step changes in the flow and/or sediment regimes of the great rivers crossing the nation will again disrupt their condition of metastable dynamic equilibrium – triggering new sequences of morphological adjustment and channel change, with serious implications for people living and working in the floodplain. Moreover, it appears likely that the upstream riparian nation, India, may implement a very large-scale inter-basin transfer scheme moving water from the Brahmaputra to the Ganges basin in the near future (Bandyopadhyay and Perveen, 2003; Gupta and Deshpande, 2004; ICID, 2006). This artificial intervention would also disrupt the flow and sediment regimes of these great rivers, and it is certain that there would be responses in their fluvial processes and channel morphologies. Once the nature of the impacts of possible natural or anthropogenic disruptions to the flow and/or sediment regimes have been identified, the conceptual model developed in this study has the potential to be applied to predict the types, spatial distribution, and timing of morphological responses within Bangladesh. Any foresight so gained would be immensely helpful in planning how to manage the channel changes and mitigate their socio-economic impacts for the benefit of the populace and the Nation.

8.2 Recommendations

This research performed here investigated and established the types and sequences of morphological responses in the Jamuna, Padma and Lower Meghna Rivers to downstream migration of the sediment wave generated by the Assam earthquake. However, the scope to investigate the dynamics of the sediment wave and morphological responses in the Brahmaputra River in the Assam Valley was severely limited by lack of access to data. This is particularly unfortunate because this is the reach of the river system closest to the point of maximum disturbance and hence the one expected to show the strongest and most unequivocal links between disturbance, process-response mechanisms and morphological changes. To improve our understanding of morphological responses to changes in the sediment regimes of braided rivers, it would clearly be valuable to be able to study the responses displayed by the Brahmaputra River in the period immediately following the Assam earthquake. It is therefore recommended that scientists with access to hydrological, sedimentary and morphological data and historical maps and aerial photographs that are known to exist inside India study the responses of the Brahmaputra River in Assam to the 1950 earthquake. In this regard, it should also be pointed out that studying the response of the river would enhance our capability to predict future changes the river morphology not only in Assam but also further downstream in the system and so enhance our capability to adapt to and manage the impacts of imminent drivers of channel change such as climate change, seismic events or anthropogenic interference with the Brahmaputra in India.

The scheme has been developed primarily on the basis of the framework developed by Bettess and White (1982) for classifying channel patterns and their responses to changing valley slope. The logic of the planform change model has been explained and appears to be sound. The scheme's predictions of planform response to a change in sediment supply have been shown to be both consistent with the observed behaviour of the study rivers of Bangladesh and previously established models from the literature. However, the scheme has only been validated against fragmentary data and qualitative information from the field and it has not been tested under controlled conditions in the laboratory. Further, the conceptual model has not been developed or tested numerically. It is therefore recommended that the conceptual model developed in this research project be further tested using physical and numerical modelling to investigate model performance under controlled and idealised conditions to explore the limits to its applicability. While the findings reported here are encouraging, further modification of the conceptual model will certainly be necessary and only after a programme of further research and development will the practical and theoretical validity of the conceptual model be fully established.

Finally, this study has established that while the fine grained fraction (silt and clay) of the huge input of excess sediment generated by the Assam earthquake of 1950 entered into the Bay of Bengal decades ago, the coarser fraction (sand) has only recently completed its journey to the ocean. The arrival of this pulse of sand has certainly boosted the supply of terrestrially-derived sand into the Meghna Estuary, which is currently the centre of active coastal accretion in the Ganges Delta (DHV Consultants BV, 2001; DHV consultants BV and CEGIS, 2002). If it is confirmed that recent sedimentation rates in the Meghna Estuary have been temporarily elevated by the arrival sand derived from the Assam earthquake and verified that this supply of sand is set to wane in the coming years, this will increase the capability of estuarine and coastal geomorphologists and engineers to model and predict how the coastline in this important area will respond to sea-level rise, the dynamics of coastal mangrove forests and current and planned human interventions in the form of coastal embankments and polders. It is therefore recommended that a sedimentation study be performed to explore and establish the historical, current and future impacts of the 1950 Assam earthquake on sediment dynamics and morphological evolution of the Meghna Estuary.

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