THE UNIVERSITY OF HULL

BRAIDING AND CHANNEL MORPHODYNAMICS: THE BRAHMAPUTRA-JAMUNA RIVER, BANGLADESH

being a Thesis submitted for the Degree of Doctor of Philosophy

in the University of Hull

by

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APPENDIX II (cont…)

11. Vegetation types with canopy :

Vegetation types	Canopy(%)
a. *Kaisha* grass	85

12. Relative elevations of the left and right Banks :

Left Bank (East): 10.92 m

Right Bank (West): 9.20 m

13. Nearest gauging station reading : 7.51 m

ABSTRACT

This study investigates the bar morphology, sediment properties and amount of sediment yield in relation to channel dynamics of the Brahmaputra-Jamuna River over a decadal timescale (1987-1997) using digital satellite images and field observations. Two typical reaches were chosen for study, representing the upper widest reach (Bahadurabad Ghat Reach) and the lower narrowest reach (Jamuna Bridge Reach) of the Brahmaputra-Jamuna River.

Erosion and accretion of channel banks appears to be the root of all the processes of braiding. Channel banks of both the study reaches are more severely affected by erosion than accretion and both banks are retreating each year. An increased amount of sediment load in excess of transport competence immediately downstream node of a flow convergence seems to initiate the process of development of a braid bar. The process of braiding and channel expansion appears to be interdependent which reveals 'chicken and egg' relationships between them. Bars are usually diamond or triangular-shaped in plan view and their long axes are oriented parallel to the channel. The bars of the Brahmaputra-Jamuna River are grouped into two types, island and attached according to their morphological characteristics, this classification provides increased functional capability with less ambiguity. Between these two types, island bars are prominent features relative to attached bars. Both forms of bars are characterised by three level successions of topographic features although they constantly change their position with few localities left to be permanently stable. Most of the bars are submerged during high flow and erosion tends to occur at the upstream end of a bar and deposition on its downstream, while during falling stage the upstream end and lateral margins of bars receive sediment deposits and the downstream faces occasional erosion. There are considerable mutual adjustments in bar erosion and deposition between the two forms of bars. During the decadal timescale both the study reaches are accreted by bar deposition and the Brahmaputra-Jamuna River is in a condition of active aggradation.

Sediment size characteristics at both banks and bars are dominated by very fine sand to fine sand particles. Very little discernible variability of particle size parameters and mineralogical compositions between the banks and bars indicate channel bank material as the potential source of bar sediments. There is no evidence of downstream diminution of sediment particle size, indeed the study results reveal a slight trend of downstream coarsening. Estimation of reach-scale sediment balance using cross-sections and satellite images provides information of quality comparable to that of measured cross-sections or a sediment continuity approach, and demonstrates a preferred method for sediment balance estimations in the Brahmaputra-Jamuna River.

These findings suggest that analysis of digital satellite images has an advantage over the traditional field-based studies while a very intensive field work program supplements ground truth information that fills in the drawbacks of satellite imagery. Combination of both methods and relevant computer analysis is useful as a means of mapping and quantifying spatial and temporal change of channel morphology, and as a means of measuring some of the variables which promote, sustain and control channel braiding over annual-decadal timescales.

ACKNOWLEDGEMENTS

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CHAPTER I: INTRODUCTION

1.1. Introduction

The fluvial system is a non-linear complex geomorphic system that is influenced by both past (various timescales) and present (short timespans) conditions (Schumm, 1977; Simons & Li, 1982; Knighton, 1998). The channel pattern, or planform, of a fluvial system reflects the dynamics of flow pattern within the channel and the associated processes of sediment transfer and energy dissipation (Richards, 1985; Downs & Priestnall, 1999). Fluvial geomorphology thus demands an understanding of the morphodynamics of the river that modify its behaviour.

As a consequence of many theoretical works on channel processes and dynamics, supplemented by various field studies and flume investigations, a fairly sound knowledge of the processes has been reached, but much of this is concerned with single thread or meandering rivers under steady flow conditions. There is less understanding of braided systems because the hydraulics and sedimentological interrelationships in braided streams are very complicated with substantial feedback (Howard *et al.*, 1970; Miall, 1977; Bristow, 1987; Bristow & Best, 1993; Thorne *et al.*, 1993). Non-uniform flows, mixed-sized bed materials, and the spatial and temporal variability in channel response to flood events result in difficulties in making detailed and representative quantitative measurements even under simplified laboratory conditions (Davoren & Mosely, 1986; Thorne, 1997). In addition, the natural reluctance of engineers to build structures on, or geomorphologists to study, unstable braided rivers has inhibited the development of our understanding of the behaviour of this type of stream.

The past few years have seen an upsurge of research on the dynamics of braided rivers (Warburton *et al.*, 1993; Paola, 1996). Laboratory, field and statistical approaches have all been adopted that have greatly improved our understanding of the basic processes. But these studies are much more compatible with gravel-bed braided rivers, and arguably have not yet led to a comparable advance in understanding of the behaviour of sand-bed braided rivers (Ashworth *et al.*, 2000). Gravel-bed river systems exhibit totally different morphological characteristics and they are less responsive to modest changes in discharge and discharge duration than a sand-bed braided river (Simons & Simons, 1987; Bristow & Best, 1993). Moreover, most hydraulic models that have been developed, are mainly based on gravel-bed braided rivers and it is ambiguous as to whether the models can be applied to sand-bed braided rivers (Bristow & Best, 1993; Ashworth *et al.*, 2000).

Flow hydraulics, sediment transport and evolution of bar and bedforms are closely related; but because of the difficulty of making measurements under the rapidly changing conditions of sand-bed braided rivers, there have been few attempts to make comprehensive quantitative observations of the interrelationships. Most of the work in this area has been either in small channels, short reaches of medium sand-bed rivers or in experimental studies (e.g. Cant & Walker, 1978; Blodgett & Stanley, 1980; Crowley, 1983; Bridge & Gabel, 1992; Bridge *et al.*, 1998). Studies on the interrelations between channel hydraulics and braiding over a large discharge range for sand-bed braided rivers are extremely rare (e.g. Jiongxin, 1997); and this is equally true with the Brahmaputra-Jamuna River which is not only a typically sand-bed braided river but also one of the largest rivers in the world (Best & Ashworth, 1997). Even if recent work has begun to contribute quantitative information on sedimentary processes and braiding in the Brahmaputra-Jamuna River, including bar developments (e.g. Mosselman, *et al.*, 1995; Richardson *et al.*, 1996; EGIS, 1997; McLelland *et al.*, 1999; Ashworth *et al.*, 2000), reach-scale extensive study on the relationship between bar development and channel shifting with morphological and sedimentary evidence is still lacking. The main aims of this study are therefore to examine the growth and development of braid bars and their impacts on channel morphodynamics, to assess sedimentary properties and to estimate sediment budgets over decadal timescales (1987-1997) for selected reaches.

1.2. Rationale of the Study Area Selection

The Brahmaputra-Jamuna, one of the major international rivers flowing through Bangladesh, has profound effects on the land, people and resources along its course. It is well known for its drastic bank-shift with rate of movements as high as 1000 metres a year being very common (Islam, 1990; Mosselman, 1995). The rise and fall of water stages, the change in number and position of major channels, the formation and movement of large bedforms and braid bars, the frequency and intensity of bank erosion are some of the determinants that control bankline shift and channel configuration. In recent years, bank erosion, bar formation and consequent widening of the Brahmaputra-Jamuna channel are reported to have caused serious damage and threat to human occupancy in terms of agriculture, settlement, industry-commerce, and transport networks (EGIS, 1997). Development and engineering plans with regards to bridges, waterways, embankments, irrigation and drainage in and along the river seemed almost impossible while considering the potential cost that may accrue for the cause of bank erosion and channel sedimentation of the Brahmaputra-Jamuna River. The impact of bank erosion and channel sedimentation is well documented (e.g. Hossain, 1993; Thorne *et al.*, 1993; Roden, 1998), but there is still a lack of quantitative knowledge concerning the interacting and interdependent mechanism of bar formation and channel shifting.

The size and multitude of channels of the Brahmaputra-Jamuna create problems for extensive field study over the entire length. Additionally, most historic information and morphological data is limited to relatively small areas. To study morphology and braiding processes, flow patterns, sedimentary properties, sediment budgets, and bankline shifting and channel expansion of the Brahmaputra-Jamuna River it is necessary to select potential discrete, but representative or typical, reaches. In this study, two reaches (widest reach from the upstream and narrowest reach from the downstream) were selected for spatial analysis of morphodynamics over decadal timescales (Fig. 1.1). The widest (Bahadurabad Ghat Reach) and narrowest (Jamuna Bridge Reach) reaches were selected on the basis of width and degree of braiding. The other criteria of such selection were good aerial access to site, locality close to a gauging station, availability of hydraulic records and well-defined banklines.

1.3. Research Objectives

The braided Brahmaputra-Jamuna River is typically unstable and subject to change over short time periods. It is characterised by multiple channels, separated by bars, and migrates frequently in an environment of unrestricted bank erosion. The braided reaches tend to be much wider than non-braided reaches, no matter whether the braided reach is downstream or otherwise. The logical inference from this effect is probably that there is a relationship between braiding process and channel widening. In order to follow up this reasoning it is necessary to consider the mechanism by which channel width is affected. An investigation of the complex process-response relationships of bar formation and channel expansion of the Brahmaputra-Jamuna River may shed light on this mechanism; and therefore, the main objectives of the study are:

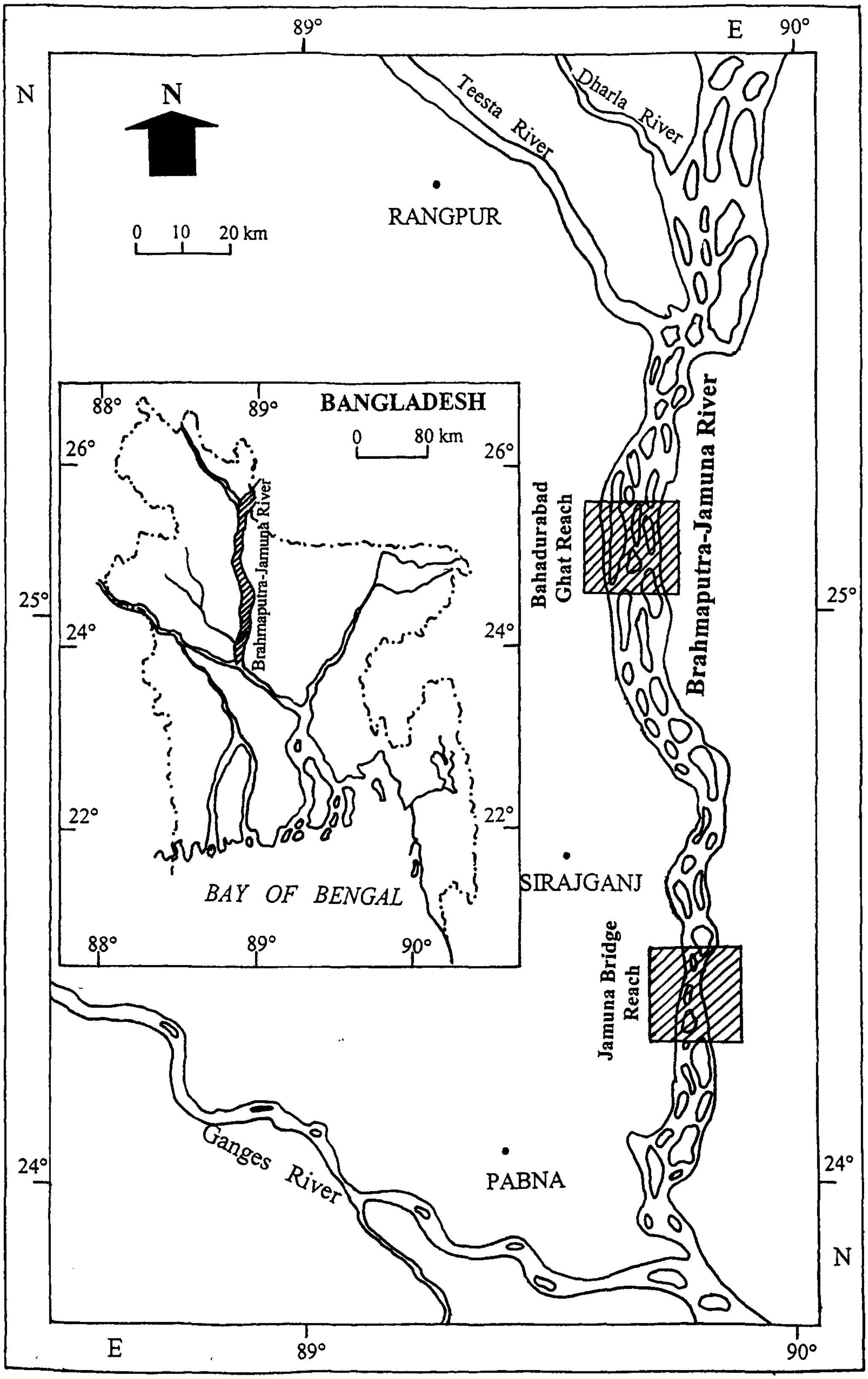

Figure 1.1. Location of the study reaches.

i) To analyse channel morphodynamics over decadal timescales (1987-1997);

ii) To examine spatial and temporal variability of braiding process and its morphological characteristics;

iii) To investigate reach-scale variability in sedimentary properties of braided alluvium;

iv) To assess relationships between bar formation and channel expansion; and

v) To estimate reach-scale morphological changes and sediment balance.

1.4. Research Frameworks

Braided rivers are characterised by a series of channel segments which divide and rejoin around bars in a repeated pattern. Channel geometry, water flow and sediment transport in braided rivers interact and vary in spatial and temporal scale, resulting in erosion and deposition in channel segments; and growth and migration of bars. Quantitative determination of channel dimension in relation to sedimentation and bar formation requires an understanding of interactions among flow hydraulics, bar dynamics and channel migration. The present study is based on detailed field investigation and satellite image interpretation of the Brahmaputra-Jamuna River at selected reaches and the overall research scheme encompasses the following chapters.

Chapter 2 attempts to review the relevant literatures of research on the dynamics of braided rivers and include some insights on the unsolved issues. The background information to the study area is examined in Chapter 3; the location and physiographic settings are identified and the historical perspective of channel change is evaluated. Chapter 4 presents the study methods and data collection, including survey design. Bank erosion and accretion, bankline shifting and channel widening are the primary controls of channel morphology, and in Chapter 5 the rate and magnitude of channel dynamics is discussed.

The rapid bank erosion and channel expansion produces a huge range of in-channel sedimentation features which comprise island and attached bars. Association amongst bar growth, mechanism of bar movement, and sediment characteristics provide the basis for the discussion of bar morphodynamics and bar sedimentology in Chapters 6 and 7, respectively. Estimation of reach-scale morphological change and sediment balance is considered in Chapter 8 with an effort to build a new method. Syntheses of the results of investigations are reported in Chapter 9 and finally, Chapter 10 presents the concluding remarks, which are followed by recommendation for future research.

CHAPTER II: REVIEW OF LITERATURE

2.1. Introduction

Until relatively recently, the process and products of braided rivers have received much less attention compared to meandering fluvial systems as they are characterised by high stream power and width/depth ratio, rapid rates of erosion and deposition, and frequent channel shifting and avulsion (Miall, 1977; Rust, 1978b; Bridge, 1993; Ferguson, 1993). Advances have been made within the recent few decades by several researchers in interpreting channel braiding from small laboratory models to natural braidplain widths of up to 20 kilometres (e.g. Coleman, 1969; Williams & Rust 1969; Rust 1972; Smith 1974; Ashmore, 1982, 1991; Ferguson & Werritty, 1983; Goswami, 1985; Davoren & Mosley, 1986; Bristow, 1987; Dawson, 1988; Ashworth *et al.*, 1994; Thorne *et al.*, 1993; Mosselman *et al.*, 1995). However, most of these studies are either qualitative or restricted to 'before and after' observations (Ashworth, 1996), few exist concerning flow and sedimentary processes and no workers have quantified process-form relationships within large braided rivers (Ashworth *et al.*, 2000). Therefore, a number of unsolved problems remain to be addressed. In this chapter, the key advances are discussed, the current state of knowledge assessed and unsolved issues highlighted.

2.2. Braided Rivers: General Research

Rivers and river processes did not become subjects of specialised study until the late nineteenth century (Miall, 1978). However, it is a difficult task to trace the various ideas that lead to our present understanding of braided rivers. Davis (1898) was the first to recognise clearly that there is a distinctive type of channel pattern which he called braided (Miall, 1978). He illustrated this type using the Platte River, Nebraska which is characterised by the formation of bars and islands of gravel and sand, splitting its current into many shifting channels. Chamberlin and Salisbury (1909) were also aware of the depositional activity of the Platte River, however, they described the river as an example of an anastomosing stream. They stated that streams which are actively aggrading their valleys are likely to anastomose. A detailed study on the same river by Smith (1970, 1971) confirmed the early recognition of the distinctiveness, although he recommended this river be termed a braided one. He suggested that the term anastomosing be restricted to rivers characterised by a network of stable, highly sinuous channels, as opposed to unstable braided channels.

However, actual study on processes of channel division and bar formation began with the work of Rubey (1952). He attempted to explain the division of the channel of the Illinois River by islands, however, he was unable to explain clearly the changes in width, depth and slope caused by island development from the maps available to him. Rubey's work was continued by Leopold and Wolman (1957), who used both field and flume experiments and demonstrated that channel patterns form a continuum resulting from variations in discharge, sediment load and slope, and provided the relationships between these parameters for sand-bed rivers in Mid West USA. Leopold and Wolman mentioned that the changes in width, depth, and slope in the flume-river are of the same order of magnitude as comparable changes in the natural river. They also defined a threshold between meandering and braiding on the basis of slope and discharge ($S=0.06Q^{-0.44}$, where S is slope and Q is discharge), and postulated that for a given slope a braided channel will have higher discharge than a meandering one. This contradicts their statement that channel planform patterns form a continuum.

The distinctiveness of the braided channel pattern was recognised in the late nineteenth century but quantitative analysis of this pattern and study of depositional behaviour, were not attempted until the 1960s (Miall, 1978). Doeglas (1962) published the first important work on the sedimentary structures and pebble orientation of two braided tributaries of the river Rhone, the Ardeche and Durance. He used aerial photographs to study bar topography and channel patterns at different flow stage and proposed that fluctuations in discharge are a pre-requisite for braiding. This became widely accepted. Later work, notably the flume experiments of Ashmore (1982, 1991), however, suggest that discharge fluctuations may not be an absolute prerequisite.

Brice (1964) continued the work on planform characterisation and attempted to quantify the continuum of channel patterns from single thread channels (straight or meandering) to highly braided. Brice developed a braiding index (BI), defined as follows:

$$BI = 2(\sum L_i)/L_r$$

where, $\sum L_i$ is the total length of bars and (or) islands in the reach, and L_r is the length of the reach measured midway between the banks. In subsequent papers (e.g. Brice *et al.*, 1978; Brice, 1984), Brice modified this definition, and classified the degree of braiding as the proportion of the channel length in a reach that is divided by bars and islands, and the character of braiding in terms of whether the bars or islands are dominant and a function of the planform shape of islands (Bridge, 1993). Brice's BI is the most widely adopted index of braiding and has often been used to measure the braiding intensity of the largest braided rivers (e.g. Goswami, 1985; Jiongxin, 1997; Goswami *et al.*, 1999).

In the late 1960's and 1970's, a number of studies were published on a range of braided rivers demonstrating more widespread distribution than previously assessed. This included works by Coleman (1969), Williams and Rust (1969), Rust (1972) and Smith (1974). The work of Coleman (1969) on Brahmaputra channel processes and sedimentation was the first work of its kind on one of the world's major rivers (Miall, 1978). Coleman studied cross-sectional patterns, change in bedforms and channel bank cutting using maps, aerial photographs and field surveys. He suggested that bank slumping is the main factor responsible for controlling bankline movement and that significant bankline modifications take place during falling river stage. He also suggested that the Brahmaputra River is migrating westward through preferential erosion of the right bank since the early 1800's. Coleman's conclusions have been challenged by recent studies (e.g. JMBA, 1988) which suggest the apparent westward migration was in fact an oscillation in the random shifting of banklines and that it was unlikely to be sustained for long. As the river is known to be highly active at all scales numerous questions concerning the direction of movement of the Brahmaputra-Jamuna River are still unresolved (Thorne *et al.*, 1993).

A detailed study involving investigation of sedimentary textures and facies of surface topography of the proglacial gravel-dominated braided Donjek River, Canada, was conducted by Williams and Rust (1969). The presence of a hierarchy of channels (e.g. first-, second- and third-order channels) within braided rivers was first discussed in their study, which has been brought to a relatively advanced state by Rust (1972). In the channel hierarchy of Williams and Rust (1969), each channel scaled with individual bars within the river and the river changes from a multiple channel at low stage to a single channel at high stage. The hierarchy of channels in large rivers is likely to be very different from the one described in the Donjek River as most of the second-order and occasionally some third-order channels appear to maintain their identity at bankfull stage (Bristow, 1987). However, recently Bridge (1993) has raised questions about the hierarchies of bars and channels at all scales as the existing channel bar ordering schemes are difficult to apply and are not defined consistently. He argued that the segments of first-order bars bounded by the second-order channels are not always second-order bars but they may be partly eroded depositional units associated with episodic deposition on first-order bars. He also demonstrated that second-order bars are those that form within and at the terminations of second-order channels.

Smith (1974) and Hein and Walker (1977) carried out studies on another proglacial stream, the Upper Kicking Horse River, Canada, and documented the formation and movement of gravel bars, sedimentary structures of bar tops and general classification of bars. Smith (1974) classified bars into different types whose forms are mainly associated with falling flow stage, and whose growth depends on characteristics of local flow and channel morphology. Hein and Walker (1977) postulated an initial stage of bar formation from 'diffusive gravel sheets', which develop into longitudinal or diagonal bars with horizontal stratification, or transverse bars with cross-bedding. However, it is not certain that these observations are a suitable model for processes occurring during major floods, which probably form the greater part of bar deposits (Rust, 1978b; Ashworth *et al.*, 2000).

Towards the middle of the 1970s, there was a growing recognition among geologists of the need for understanding of the major lithotypes associated with braided systems as they are critical for interpretation of ancient and modern river deposits, and predicting subsurface geometry and facies. Rust (1978a) was the first to divide braided systems into two major types on the basis of bedload calibre: gravel and sand.

He noted that gravel-dominant braided systems are characterised by framework-supported gravel with no upper grain-size limit whereas the principal lithology of a sand-dominant braided system is sand with little silt or clay, but there do not appear to have been any detailed quantitative estimations. In the same year Cant (1978) made the first attempt to develop a facies model on a sandy braided river. According to his observations, a facies model for a small to moderate sized sandy braided river consists mainly of channel, bar, and sand flat deposits (complex braid bars) interfingering laterally and succeeding one another vertically, and these types of deposits are mainly medium to coarse sand with trough crossbeds generated by dune bedforms. However, Cant emphasised the great variability of morphological characteristics in sand-bed braided rivers, and noted that the model is not a general one and does not extend to very large rivers.

The preceding sections summarised work on braided systems up to the 1970s, most of which came from relatively small and proglacial rivers and the majority of works had a geological focus. After this date several key developments took place. First, important advances in the study of two distinct types of braided rivers began to appear in the early 1980s (after the first International Workshop on Gravel-bed Rivers, Wales, 1980). Second, the study of each type became a specialised branch, with its own body of workers (e.g. geologists, geomorphologists) and its own purposes and applications (e.g. flume experiments, field observations). Third, more integrated approaches were adopted with interdisciplinary collaborations linking results of geological and geomorphological studies. Table 2.1 portrays key experimental studies, and major field investigations of the two main types of braided rivers carried out in both large and small rivers, located in different climatic regions. The succeeding sections present progress since 1980 in understanding processes in gravel- and sand-bed rivers,

Table 2.1: Key studies on braided systems.

Study Type	Author	Area of Investigation	Methods	Temporal Scale	Spatial Scale	Sedimentary Characteristics	Climate and Vegetation
Experimental studies	Ashmore (1982)	Laboratory modelling of gravel braided stream morphology	Constant discharge overflow and adjustable sediment (D_{50}~ 1.2 mm) feed equipment	Several weeks	Flume Size: 11.70 m^2	Downstream and upward fining	Not applicable
	Ashmore (1991)	How do gravel-bed rivers braid	Constant discharge overflow and adjustable sediment (D_{50}~ 1.16 mm) feed equipment	Several hours	Flume Size: 20 m^2	Progressive downstream fining	Not applicable
	Hoey and Sutherland (1991)	Channel morphology and bed load pulses in braided rivers	Constant discharge flow, river sand (D_{50}~0.57 mm), 3 mm beam to survey stream bed	Two weeks	Flume Size: 42.60 m^2	Production of bedload pulses in a braided river is a consequence of the morphology of such river	Not applicable
	Ashworth *et al.* (1994)	Physical modelling of braided rivers and deposition of fine-grained sediments	British Petroleum (BP) flume table, sediment (D_{50}~5.6 mm) feed equipment, point gauge and two colour video cameras	Several weeks	Flume Size: 20.35 m^2	Six fine-grained depositional types are identified and no syste-matic change is observed for the range of sediment sizes	Not applicable
Field investigations on gravel-bed rivers	Werritty and Ferguson (1980)	Pattern changes in a Scottish braided river	Field survey, aerial photographs and large-scale maps	200 years	Reach-scale (5 km) study	No data on sedimentary characteristics	Mountain climate, no data on vegetation
	Bluck (1982)	Texture of gravel bars in braided streams	Repeated measurements and analyses of bar sediments	3 years	Reach-scale (120 m and 700 m) study	Bar surface texture varies little over time; no progressive changes in sorting along the channel	Proglacial climate, no data on vegetation
	Ferguson and Werritty (1983)	Bar development and channel changes in the gravelly River Feshie	Field observations, sediment survey and photographs	5 years	Reach-scale (100 m and 160 m) study	Downstream and lateral fining with some local contrasts	Mountain climate, shrub type vegetation
	Davoren and Mosley (1986)	Observations of bedload movement, bar development and sediment supply in the braided Ohau River	Field observations and sediment sampling	Several months	Reach-scale (300 m) study	Sediment transport is supply limited, not flow limited	Proglacial climate, no data on vegetation
	Dawson (1988)	Sediment size variation in a braided reach of the Sunwapta River	Repeated sediment sampling on a regular basis	Several months	Reach-scale (10 km) study	Reach-scale downstream fining varies in response to differing rates of aggradation and tributary inputs	Proglacial climate, no data on vegetation
	Goff and Ashmore (1994)	Gravel transport and morphological change in braided Sunwapta River	Repeated daily morphometric surveys and discharge data	4 weeks	Reach-scale (60 m) study	Bedload transport rates depend on discharge, and responsible for major morphological change	Proglacial climate, no data on vegetation

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Table 2.1: Key studies on braided systems.

Study Type	Author	Area of Investigation	Methods	Temporal Scale	Spatial Scale	Sedimentary Characteristics	Climate and Vegetation
Field investigations on gravel-bed rivers	Martin and Church (1995)	Bed-material transport estimated from channel surveys: Vedder River	Repeated cross-sections survey data and surveys occurred 3 years apart	9 years	Reach-scale (8 km) study	Bedload transport rates vary with summer and winter floods for a given peak flow	Proglacial climate, no data on vegetation
	Nicholas and Smith (1998)	Relationships between flow hydraulics, sediment supply, bedload transport and channel stability in the Virkisa River	Field survey using a quick set level and radio tracer technique	2 weeks	Reach-scale (250 m) study	Sediment transport is supply limited and characterised by coarse-grained poorly sorted and well imbricated sediments	Proglacial climate, no data on vegetation
Field investigations on sand-bed rivers	Goswami (1985)	Brahmaputra, Assam, India: physiography, basin denudation and channel aggradation	Sediment budget and measured cross-section approaches	8 years	Channel-scale (645 km and 145km) study	Sediment transport is supply limited, upward fining, downstream fining varies in response to tributary inputs	Tropical climate, no data on vegetation
	Bristow (1987)	Brahmaputra River: channel migration and deposition	Field work, historical maps and Landsat image interpretation	200 years	Channel-scale (200 km) study	Temporal bedload grain size fining during low flow and coarsening during peak flow	Tropical climate, no data on vegetation
	Bristow (1993)	Sedimentary structures exposed in bar tops in the Brahmaputra River	Field observations	4 weeks	Bar-scale study	Vertical and lateral changes in bar sedimentary structures are ubiquitous which include upper plane bed lamination, trough-cross stratification and current ripple lamination	Tropical climate, no data on vegetation
	Thorne *et al.* (1993)	Planform pattern and channel evolution of the Brahmaputra River	Discharge data, cross-section information and satellite image interpretation	40 years	Channel-scale (220 km) study	Bank material is 60% sand and 40% silt, bar material is 60% sand and 40% silt	Tropical climate, vegetation pattern is influenced by bar elevation
	EGIS (1997)	Morphological dynamics of the Brahmaputra-Jamuna River	Satellite image, cross-section information and historical maps	165 years	Channel-scale (240 km) study	No data on sedimentary characteristics	Tropical climate, no data on vegetation
	Jiongxin (1997)	Study of sedimentation zones of the braided Hanjiang River, China	Field work, cross-section information and large-scale map comparison	35 years	Reach-scale (115km) study	Bedload movement is highly discontinuous and not large enough (<30%) compared with suspended load (>70%)	Sub-tropical climate, no data on vegetation
	McLelland *et al.* (1999)	Flow structure and transport of suspended sediment around a braid bar, Jamuna River	Bathymetric and flow survey data	27 months	Bar-scale study	Bar widening is associated with high suspended sediment concentrations and bar extension accompanies increased suspended sediment transport over the bar top	Tropical climate, no data on vegetation
	Ashworth *et al.* (2000)	Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River	Bathymetric and flow survey data	28 months	Bar-scale study	Vertical aggradation takes place during high flood stage with lateral accretion at low flow	Tropical climate, no data on vegetation

highlighting in particular research on braiding and channel dynamics, flow patterns and sedimentary characteristics, and bar inundation frequency and vegetation pattern.

2.3. Gravel-bed Braided Rivers

2.3.1. Flume Experiments

Laboratory models offer the potential to investigate the processes and products of fluvial deposition, and were widely adopted for studying meandering systems. In comparison, models of braided systems have received much less attention as the hydraulic and sedimentological interrelationships in braided streams are very complicated with substantial feedback (Ashworth & Ferguson, 1986). Moreover, the spatial and temporal variability in channel response to flood events result in difficulties in making detailed and representative quantitative measurements even under simplified laboratory conditions (Ashworth *et al.*, 1994). Despite these difficulties, during the last two decades various simulation models have been developed in an attempt to isolate the mechanisms of deposition and erosion in gravel-bed braided environments (Goedhart & Smith, 1998). A brief review of key experimental studies with spatial and temporal scales is presented in table 2.1.

In his pioneering work, Ashmore (1982) reports on the result of an extensive series of flume experiments, key findings of which include the observations that braiding occurs due to a rapid decrease in sediment transport capacity associated with local scour of the bed; and channel pattern changes are a response to scour, bar deposition and resultant channel migration. Ashmore observed that alternating bars are responsible for the initiation of braiding, a conclusion which differs from the mid-channel bar forming mechanisms described by Leopold and Wolman (1957). Ashworth (1996), on the other hand, used a Froude-scale mobile-bed model of a mid-channel bar to quantify the change in surface flow speed and direction as the bar became emergent, and argued that his model is comparable with the results of the flume experiments of Leopold and Wolman (1957).

In a further paper, Ashmore (1991) modified his earlier observations suggesting that bedload pulses are associated with bar creation, dissection and reworking in braided rivers. He noted that initial deposition is through the stalling of a thin bedload pulse, which may be transported down one of the tributaries as a discrete morphological unit. Hoey and Sutherland (1991) observed similar mechanisms in their flume experiments on bed-load pulses in a braided environment. However, flume experiments by Ashworth (1996) on mid-channel bar growth showed that bars do not owe their origin to bedload pulses or the local sorting of the bedload but instead to local exceedence of the transport capacity and sediment accumulation in the channel centre by the strongly convergent flow.

In their flume experiments, Ashworth *et al.* (1994) investigated the depositional sites of fine-grained sediments and compared with field prototypes. They identified six different depositional features (e.g. confluence scours, bar-top hollows, thalweg scours, abandoned channels, splays, backwater bar leeside) each have their own morphological and geometric characteristics. They also noted that the degree of braiding is very similar between flume and field. Diplas and Parker (1992) investigated the process of deposition and removal of fines in a gravel-bed flume under conditions similar to those encountered in natural systems, and noted that deposition of fines is higher at the bar tail and in the pool area. They also found that the depth of fines penetration is proportional to the shear stress on the bed and level of exchange depends on the permeability of the bed material and the topography of the streambed.

Another aspect of braiding examined in laboratory experiments is that of anabranch confluence kinetics, channel changes and bar sedimentation processes, most notably by Ashmore (1993). On the basis of observations from model streams, Ashmore suggested that confluence scours play the key role in sedimentation patterns and processes in gravel-bed braided streams. He illustrated the optimal site for medial bar growth as downstream of a confluence scour and argued that confluence zones are extremely dynamic and energetic, and constantly changing, causing rapid and complex adjustments in confluence geometry.

It is evident from the flume models that all of these studies have tried to explain different aspects of braiding of gravel-bed braided rivers and inferred that it is possible to provide useful information about the nature and short-term evolution of braided rivers. However, questions remain about the extent to which these small-scale models do correspond with small- or large-scale natural braided systems. Bridge (1993) mentioned that these models are significant in a general understanding of the process involved, but may be inappropriate for large-scale braided systems. Bristow and Best (1993) suggested that more observations and field data are needed to substantiate or refute apparent similarities of models with natural braidplains. Indeed, many flume researchers themselves recommended caution in interpreting observations. Ashmore (1982, 1991) advised that direct application of model information to natural rivers must be treated with caution in view of simplified experimental conditions and scaling considerations. Hoey and Sutherland (1991) also urged caution in the application of their model results to field conditions. Ashworth (1996) mentioned that most of the flume model heavily depends on qualitative observations and ignores many of the local hydraulic factors. 'Scaling issues' are particularly significant for the extrapolation of these models across a range of braided channels, and it is essential to know which attributes are scale invariant or scale dependent (Bristow & Best, 1993). In this way, it is not possible to make comparative assessments on bar permanency, bank stability and channel migration, and flood frequency from flume models as these are more temporal- and spatial-scale dependent.

2.3.2. Field Investigations

A basic understanding of the process-form relationships operating in braided systems is a prerequisite to elucidate their dynamic nature. In this context, there was a great deal of developments in the study of gravel-bed braided rivers (see Table2.1) after the first international workshop on gravel-bed rivers, held in Wales in 1980. Since then geomorphologists have emphasized understanding of how river morphology changes and evolves, and focused on study of the process-form relationships between sediment supply and bar development. Attention was initially focused on the planform of bars and their classification. A comprehensive survey of the different types of bars and their external geometry is included in Church and Jones' (1982) paper. They made a distinction between bedforms and bars, and classified different types of bars (e.g. attached or detached bars, lateral or longitudinal bars) according to their functional and morphological criteria. However, there is much disagreement over such classification as there has been a considerable lack of clarity and overlapping embodied in much of the terminology. Ashmore (1982) noted that the nomenclature of bars alluded to by Church and Jones arises from an incomplete understanding of bar development and it is caused by the problems of observation and measurement of bar forming flows in the field. Ashmore also considered that small-scale flume models might be considered for generic classification of bars. Ferguson (1993) stated that classifications by looking only at planform bar may be inappropriate as visible bars not only appear to change as stage varies, they also change as sediment erodes and accretes.

The nature of channel migration is critical in understanding the nature of channel bars (Bridge, 1993). There have been many studies of the patterns of channel migration for single curved channels but fewer for braided rivers (Bridge *et al.*, 1986). An important advance came in this respect by Werritty and Ferguson (1980), who examined the behaviour of the River Feshie, Scotland and discussed the variability of its channel pattern over timescales from a year to two centuries as revealed by field survey, aerial photographs, and large-scale maps. According to Werritty and Ferguson, events of high magnitude and low frequency (e.g., floods) are responsible for substantial bank erosion and channel change, and ultimate reworking of the bar and bed materials. In a further study, Ferguson and Werritty (1983) reiterated this view based on field observations on the River Feshie and pointed out that channel migration by bar erosion and accretion in gravel-bed braided rivers is much more common than by channel switching (avulsion). They also suggested that short-term channel switching is, therefore, not influenced by bank erosion but by local aggradation and scour. In their study on the North Ashburton River, New Zealand, Laronne and Duncan (1992) reinforced previous suggestions that flow events rework bars but may also bring about some large changes such as cut-offs, avulsion of the main anabranch and channel switching. Additionally, they argued, it is apparent that new bars may be formed by small flow events and the lack of very coarse armour in the bed and banks of the inner-channels in their alternate bar reach enabled large channel changes to occur during small events. Their observation contradicts Werritty and Ferguson's (1980) postulation of a direct relationship between channel pattern and the incidence of high-magnitude events. Therefore, it is important to be aware of the history of rare events when assessing the channel changes of braided systems.

The generalisations in the previous paragraph about flow events, braiding and channel changes are based almost entirely on qualitative observations. Such observations are instructive and indeed vital, but there has been increasing interest in supplementing these qualitative approaches by making quantitative measurements. What has been attempted is integrated field measurement of flow hydraulics, bedload transport and channel change. The first attempt to apply this approach in braided rivers was made by Davoren and Mosley (1986) using a jetboat as a measuring platform in the Ohau River in New Zealand. Davoren and Mosley showed the extent of convergence and divergence of both the flow and the bedload transport in an X-pattern reach, and the formation of a mid-channel bar which induce lateral channel migration. They observed a big difference in bedload transport rates found in the same reach on two different dates and demonstrated that the sediment transport in the Ohau River is dependent upon the availability of sediment to be transported, indeed, sediment transport is supply limited. Recently, Nicholas and Smith (1998) in their study on the Virkisa River, Iceland, also indicated that bedload transport of the Virkisa River is supply limited and that braidplain morphology is controlled by low frequency, high magnitude flood events. Ashworth and Ferguson (1986) in their study on another proglacial river, the Lyngsdalselva River in Norway, found that the spatial patterns of shear stress and of channel erosion or deposition can alter dramatically with an increase in discharge through a reach, causing drastic channel change or even avulsion. They also argued that the same reach can change in essentially opposite ways according to peak flow bedload transport due to local differences of sediment inputs. Therefore, it suggests that channel change in braided rivers is dependent on the availability and addition of bedload and flow magnitude, but this also depends on bed material characteristics (Bridge, 1993). There is, however, much more to be researched about the sorting of sediment by size within braided systems, both locally within reaches and at a more extended scale along braidplains to reveal channel dynamics.

Many studies have shown that braided channel pattern varies with bed material size, which is controlled by both the flow conditions and the available sediments (Henderson, 1966; Osterkamp, 1978; Carson, 1984). Changes in bed material characteristics represent an element of the sediment transport process which is of geomorphological significance (Clifford *et al.*, 1993). From observations on gravel bars, Bluck (1982) noted that bar surface texture varies little over time and speculated that sorting occurs during deposition, with the initial surface texture of a bar acting as a template which traps similar-sized particles but allows coarser ones to overpass or to infiltrate beneath the surface. Ashworth *et al.* (1992) provide a notable supplement, dealing with both flume and field study (on the Sunwapta River, Canada), in an examination of the spatial distribution of bedload transport rate and grain size sorting in a mid-channel bar as it evolved. They suggested that the coarse bedload tends to be deposited on the bar head whereas finer sediment is deflected around the bar where it may be deposited in the tail. Both observations, however, concentrated mainly on the texture of gravels in the bar head and there have been no detailed, quantitative studies of downstream changes of sediment size parameters.

Downstream fining implies an eventual change from gravel to sand facies, and is likely to be associated with progressive changes in channel patterns and bar types (Ferguson, 1993). In the proglacial Sunwapta River, Canada, Dawson (1988) attempted to quantify and discuss downstream sediment size variation. The grain size variation showed a distinct downstream diminution from cobbles and boulders to fine gravel and sand. Dawson also mentioned that the patterns of sediment size decline and diminution rates are often very irregular with variation occurring both at a local scale and through the effect of tributary inputs. Bluck (1987) suggested that bars are the primary loci of downstream size change; as coarser material is temporarily trapped during bar head aggradation, finer bar tail material is more readily transported and progressively downstream units are starved of coarser material. There is, however, an ongoing debate as to whether sediment transport is sufficiently selective to account for rapid downstream fining, and what the role is of local sediment supply in producing the discontinuities and variations in the decline of grain-size. Moreover, downstream changes in bar types and sedimentary facies along braided rivers remain a priority of future research.

There inevitably exists a relationship between changes in channel morphology and sediment transport, yet very few studies have investigated the possibility of using the relationship to evaluate sediment transport; this is due to problems associated with sediment transport estimation (Martin & Church, 1995). However, the estimation of bedload transport in braided systems and the interaction between transport of material and the morphology of the river have been the focus of much recent research (e.g. Goff & Ashmore, 1994; Lane *et al.*, 1994, 1995; Martin & Church, 1995; Milne & Sear, 1997; Brasington *et al.*, 2000). Goff and Ashmore (1994) quantified the variations of bedload transport and related them to morphological changes from the results of field surveys in a 60 m reach of the braided Sunwapta River, Canada. They estimated bedload transport rates from volumetric morphological data using different approaches (e.g. step length, sediment budget), and specified that major morphological change occur during periods of high discharge due to destruction and reconstruction of large bar complexes. However, Goff and Ashmore concluded that the estimated results differ explicitly between methods and further testing is required in order to reliably investigate the process-form relationships. In a similar study, Martin and Church (1995) investigated bed material transfer by analysing morphological changes along the length of an 8 km reach of the proglacial Vedder River, Canada. They used repeated cross-section survey data and their estimation was based on a continuity approach. From their observations, Martin and Church inferred that estimation of bed material transport from channel morphology provides information of quality comparable to that of direct measurements. Although their methodological approach claimed the potential for constructing reach-scale sediment budgets (Brasington *et al.*, 2000), there remains a question whether this approach can be applicable for large braided rivers or for longer timescales.

Recent advances in analytical photogrammetry and survey technology permit the acquisition of three-dimensional topographic data of high resolution and present the opportunity to evaluate morphological change in a more detailed manner over the traditional cross-section survey methods. Lane *et al.* (1994) described the methodological background to the combination of analytical photogrammetry and tacheometry used to acquire three-dimensional coordinates of a dynamic river channel and to construct a series of digital terrain models (DTMs). They mentioned that DTMs have the potential to reconcile deterministic process based modelling approaches and can be extended to temporal assessment of river channel change. Lane *et al.* (1995) illustrated the potential of estimating reach-scale bedload transport rates using information on the rate of bed material transfer and information on sediment supply from a 50 m length of actively braiding proglacial stream in Switzerland. They used DTMs to determine both the total volumes and the distributed volumes of erosion and deposition. Lane *et al.* also mentioned that the total volumes could be combined with upstream information on sediment supply to assess the contribution of a particular reach to the total bedload transport. The photogrammetric approach to topographic surveying is, however, restricted to observable areas of the channel and is thus of limited use in the turbid subaqueous zones. More recently, Brasington *et al.* (2000) presented an alternative approach to the study of three-dimensional morphodynamics of a divided reach of the gravel-bedded River Feshie, Scotland, using high resolution Global Positioning System (GPS) survey techniques. They argued that GPS survey, in combination with DEM differencing, has major potential advantages that enables high resolution ground-based capture of terrain data in complex fluvial systems at speeds and scales previously unattainable. Brasington *et al.* also demonstrated that their methodology can be used to infer form-process relationships directly and the information they provided may be a reliable baseline for further research. However, the major problem with a DEM approach is that it is time consuming and requires high resolution topographic data. Therefore, this approach is restricted to small-scale study and may not be feasible for large rivers.

2.3.3. Summary

The preceding paragraphs review research progress in gravel-bed braided rivers over the last two decades and reveal that a good number of published works are now available on different aspects of braiding. The overriding trends of these research efforts are reach-scale study with relatively short timescales (see Table 2.1), and the following are the most specific themes that have been focused:

i) Bar development and channel change,

ii) Flow hydraulics and bedload transport,

iii) Sediment size variation and downstream fining, and

iv) Bedload transport and morphological change.

Much of these reach-scale works come from small proglacial rivers (e.g. Ashburton and Ohau River of New Zealand; Lyngsdalselva River of Norway; Virkisa River of Iceland; Sunwapta and Vedder Rivers of Canada) and few studies undertaken in upland environments (e.g. River Feshie of Scotland). Their climatic conditions are almost similar, and these rivers are associated with high rates of bedload movement, within channel deposition, bar growth and bank erosion (Nicholas & Smith, 1998). This similarity across scales of braiding may shed light upon the processes inherent in causing braiding, bar formation, bed material transport and channel change in proglacial environment. However, it is essential to know how to extrapolate these reach-scale findings to a completely different type of system (e.g. sand-bed braided rivers) in different climates or even in the same river. As within a single reach, discharge remains almost uniform and measurements taken at a particular reach along the river need not reflect the overall pattern of sediment transport at all (Petts & Foster, 1985; Martin & Church, 1995). Therefore, the scaling issue is a major concern, and much remains to be known about braiding processes and scale dependence.

In braided systems, bank erosion by flows around growing braid bars is a primary cause of widening (Leopold & Wolman, 1957; Bristow & Best, 1993; Thorne *et al.*, 1993; Simon & Thorne, 1996). Widening not only encompasses a variety of timescales, it is also accomplished by a wide range of fluvial processes associated with discharge fluctuation, climatic variability and influence of vegetation (ASCE, 1998a). Unfortunately, these process-form relationships in gravel-bed braided rivers are yet to be fully understood, across a wide range of temporal and spatial sequences. Thus, identification of the dominant erosion processes, channel sedimentation and widening mechanisms in respect to discharge variation and vegetation influence remains to be studied over a longer spatial and temporal scales.

2.4. Sand-bed Braided Rivers

Compared to gravel-bed braided rivers, research on sand-bed braided river is surprisingly limited, and until relatively recently, there have been few studies on different aspects of braiding in this type of system. Earlier works on sand-bed braided rivers were undertaken in proglacial environments with individual anabranches less than 100 m wide (e.g. Collinson, 1970; Smith, 1971; Cant & Walker, 1978; Blodgett & Stanley, 1980), however, questions remain as to whether these rivers are entirely sand-bed braided or not. Moreover, to date nobody has attempted to investigate braided river flume models with sand-grade sediments (except the flume experiments of Leopold & Wolman (1957)). Reasons behind this hindrance are possibly due to the highly unstable nature of sand-bed braided rivers and relatively sparsity of these systems in comparison with its counterpart. This reasoning becomes clear when it appears that during the last two decades most of the works on sand-bed braided systems have been based on a limited number of rivers. More specifically, it is evident from the summary of literature survey that studies of sand-bed braided systems are mainly confined to the Brahmaputra-Jamuna River system in Bangladesh (see Table 2.1).

The summary of key studies shows that there is no specific theme that has been followed in the study of sand-bed braided systems. However, investigations can be divided into a number of areas, and accordingly, the available literature are grouped into four sub-themes and they are reviewed below:

i) Planform morphology and channel movement,

ii) Secondary flow and morphological change,

iii) Facies models of channel morphology, and

iv) Other research on spatial and temporal scales of braiding.

i) Planform morphology and channel movement

The early pioneer work on the Brahmaputra River was made by Coleman (1969), who used aerial photographs and maps to show bar migration in response to channel movement and large-scale river migration. Eighteen years after Coleman's study, Bristow (1987) published a similar work on the Brahmaputra River. He reviewed much of the previous work on the Brahmaputra River, and monitored channel planform and migration since 1787 using Landsat imagery and historical maps. He observed that channel movement is dominated by lateral migration with some minor channel switching and this is mainly controlled by very high or prolonged high discharges. Bristow supplements Coleman's (1969) findings on multiple channel morphology by identifying three-levels of channel hierarchy (e.g. first-, second- and third-order channels) in the Brahmaputra River, but his channel ordering schemes are not defined consistently (Bridge, 1993, p. 20). Moreover, Bristow's hierarchy of channels is difficult to extrapolate as second- or third-order channel shifting is quite common in the Brahmaputra-Jamuna River. Based on analysis of cross-section survey data and Landsat imageries, Burger *et al.* (1988) examined the possible causes of channel movement. They concluded that channel movement in the Brahmaputra-Jamuna River is not primarily caused by bank erosion but, sometimes channels are 'pushed-away' by the formation and consequent movements of braid bars, and widening continues by trimming the edge of the channel until a stable width has been attained. By interpreting satellite imageries, they also mentioned that bank erosion along the main channels seems to occur after a catastrophic flood has passed, which contradicts Bristow's (1987) observation that very high or prolonged high discharge accelerates channel bank erosion. However, Burger *et al.*'s observations are qualitative and there is no strong evidence behind the stated inferences. Recently, the EGIS (1997) developed a computer based data analysis program using satellite images, historical maps and hydraulic data to study the channel-scale morphology of the Brahmaputra-Jamuna with particular emphasis on planform change. The study reported that the river has widened since 1830 and over the past three decades this has occurred through retreat of both west and east banks; and much of the eroded land is going into the creation of new braid bars. This study supports Bristow's (1987) notion that high magnitude and prolonged monsoon floods accelerate bank retreat. The study also concludes that satellite images and cartographic evidence can provide general information on historical channel evolution and flood hazard mapping, but traditional 'ground-based' survey techniques are needed for detailed morphological analysis.

Thorne *et al.* (1993) analysed planform morphology and channel evolution of the Brahmaputra-Jamuna River since 1950 in a simplified and generalised way with the help of cross-sections, aerial photographs, and SPOT and Landsat images. They observed sustained right (west) bank erosion compared with a left (east) bank that shows both erosion and accretion. They also postulated that the river may be changing in form from braided to meandering. However, other recent studies on channel planform changes found no evidence to supports this, indeed they suggest an increase of braiding (e.g. EGIS, 1997, 1999). Thorne *et al.* further developed the concepts of island and nodal reaches originally developed by Coleman (1969), and observed that bank erosion is slower in nodal reaches than in island reaches probably due to the occurrence of erosion resistant materials. Jiongxin (1997) expressed similar views in his study on a Chinese sand-bed braided river, the Hanjiang, where he used a large-scale channel map, cross-section data and field investigation. His study revealed that channel widths and width-depth ratios of sedimentation zones (island reaches) are larger than those of transportation zones (nodal reaches), and they are due to higher stream power, flow shear stress, and bank erosion. His investigation also showed that bank erosion supplies large quantities of sediment to the channel, leading to the formation of mid-channel bars, and that bank erosion rates in sedimentation zones are very high compared to transportation zones.

ii) Secondary flow and morphological change

There have been few field measurements of flow hydraulics around bars in gravel-bed braided systems (Bridge & Gabel, 1992) and this is equally true with sand-bed braided rivers. Recent work emphasised that secondary flow around a braid bar may consist of helical flow cells, which transport sediment towards the bar from the outer bank (e.g. Ashworth *et al.*, 1992), and could be responsible for significant morphological changes (Thorne *et al.*, 1993). The importance of secondary flow for sediment concentration and channel changes in sand-bed braided rivers has primarily been investigated by Richardson *et al.* (1996). They undertook a bar-scale study on secondary flow and channel morphology in the Brahmaputra-Jamuna River, using secondary information (from FAP 24, 1996a) and field data (Acoustic Doppler Current Profiler for velocity measurement) to observe the three-dimensional flow structure around a large compound braid bar which had undergone several stages of growth and migration. Richardson *et al.* also developed a model of flow structure around a braid bar, with helical circulation in the thalweg, outward flow near the surface and inward flow at depth driving strong welling at the bar face. Richardson and Thorne (1998) carried their previous studies further, contextualising the observation at the study site in terms of large-scale medium term planform changes. Both of their synonymous studies indicated that flow structures in bends of braided rivers share common features (e.g. inward and outward flows) with patterns observed in meander bends of single thread rivers and the current understanding of process-form interaction in meandering rivers may be transferable to braided rivers. McLelland *et al.* (1999) presented a detailed study of the development and evolution of a kilometre-scale mid-channel sand bar in the Brahmaputra-Jamuna River using the same sorts of methods adopted by Richardson *et al.* (1996) and Richardson and Thorne (1998). McLelland *et al.* showed that the majority of the braid bar is composed of large sand dunes, which are linked to high concentrations of suspended sand-grade sediments. Their study also identified a rapid increase in suspended sediment concentration on to the bar head and very low suspended sediment concentration on the bar lee-side at both high and low flow stages. They disagreed with Richardson *et al.* (1996) and Richardson and Thorne (1998) about the coherent helical flow around a braid bar. According to their study, there is no evidence for channel-scale, coherent helical flow cells in either anabranch channel around the braid bar or over the bar top at any flow stage (Ashworth *et al.* (2000) supported this view). Instead, they suggest the structure of flow is dominated by a simpler flow divergence over the bar head, flow convergence at the bar tail and flow that is usually parallel to the thalweg in each distributary.

iii) Facies models of channel morphology

Depositional models of bars and channel fills in braided rivers are relatively rare and most of the models are purely qualitative (Bridge, 1993). Morphological elements may be useful tools for the recognition and interpretation of braided river deposits, and the relative proportions of morphological elements may be derived from depositional models (Bristow & Best, 1993). In this context, sedimentary structures exposed in a bar top in the Brahmaputra River and their vertical and lateral arrangement were described by Bristow (1993) on the basis of a field study in a particular reach. According to his study, vertical and lateral changes in facies are extremely abundant with many changes in sedimentary structures and reactivation surfaces within each depositional sequence. Bristow also presented a generalised facies model for bar top sedimentation which shows occasional upstream accretion with trough cross-stratification due to waning flow regime, vertical and lateral accretion with current ripple lamination on the central section during falling flow and an accretionary platform on the downstream margin probably because of high stage flow. However, Bristow's inferences on bar top sedimentary structures are observed at low flow stages and it is not clear what bar top sedimentary structures are associated with high flow stages when most erosional and depositional activity takes place in the Brahmaputra-Jamuna River. Moreover, his facies model did not attempt to use observations of grain sizes on bar surfaces to predict the distribution of grain sizes and sedimentary structures and this is common practice in building fluvial facies models (e.g. Bluck, 1971; Jackson, 1976).

A review of literature on confluence morphology from flume and field studies (on the Brahmaputra-Jamuna River) has been presented by Bristow *et al.* (1993), who introduced a tentative Y-shape facies model which suggests that channel junctions may be represented by a unique assemblage of bedforms and sedimentary structures. Bristow *et al.* have identified four morphological elements within channel junctions: tributary mouth-bars, deep confluence scour, bars within areas of flow separation and post-confluence mid-channel bars. They observed that morphological elements are formed mainly at high flow stages, and at low flow stages partial confluence scour fill occurred and mouth-bars and mid-channel bars are modified as flow is diverted around them. They also suggested that sedimentation at channel junctions is particularly important in multichannel braided or anastomosed rivers where channel confluences are most abundant. However, channel confluence morphology is highly variable and seldom resembles the classic Y-shape configuration, due to the strong influence of several variables including upstream erosion and sediment transfer, particle size distribution and changing discharge of the confluent channels (Mosley, 1976; Ashmore, 1982; Ashmore & Parker, 1983; Best, 1988). Bristow *et al.*, in their study on channel confluence morphology, have not considered many of these variables which should be included in a general model.

iv) Other research on spatial and temporal scales of braiding

Since 1969, when Coleman published his pioneer work on the Brahmaputra River, there were few attempts made to study the sand-bed braided rivers at a large spatial scale, up until mid-1980s. The next large-scale investigation on sand-bed braided river was carried out by Goswami (1985), who dealt with the upper part of the Brahmaputra River in Assam (India). Goswami attempted to evaluate the rates of basin denudation and channel aggradation of the two long reaches (645 km and 145 km, respectively) of the Brahmaputra using measured cross-section and suspended sediment budget approaches. His observations indicated an overall channel aggradation of both reaches from 16 cm to 21 cm during the period of 1971-1979. Goswami also estimated the denudation rates of the eastern Himalayas (drainage area~10,000 km^2) assuming uniform removal of suspended sediment load over the basin, which is 0.73 mm yr^{-1}. However, his observations are fully qualitative and seriously flawed by the assumption of uniform removal of sediment from the entire watershed. Moreover, his methods of estimation of channel aggradation from widely spaced cross-sections or computation from simple equations may not be representative of conditions in a long reach as it involves a huge percentage of measurement error (14% to 139%).

Recently, Hassan *et al.* (1999) tried to determine the age and relative elevation of bars, and to monitor bar planform morphology at different flow stages using remote sensing and GIS technology. They used land cover maps created from satellite images for the 1973-1996 period of the Brahmaputra-Jamuna River. Hassan *et al.* suggested that sand bars (newly formed bars) are lower than island bars and older bars are higher than younger bars. They also noted that rate of elevation growth is initially high in younger bars but that the rate of growth decreases as the bar matures. Although Hassan *et al.*'s methodology of bar elevation measurement is somewhat different from some other corresponding studies, their stated inferences are not new. Bristow (1987) mentioned the existence of a three-level hierarchy of bar morphological features in the Brahmaputra-Jamuna River and Thorne *et al.* (1993) identified three levels of bars in terms of bar elevation, landuse and vegetation, although their studies were based on qualitative observations. Moreover, the techniques Hassan *et al.* suggested are largely based on satellite images and channel cross-sections, hence, in order to validate and extend their techniques as a preferred method for large-scale study it is necessary to acquire extensive field information (cf. EGIS, 1997).

Very recently Ashworth *et al.* (2000), in a study on the Brahmaputra-Jamuna River, described the initiation, growth and evolution of a kilometre-scale braid bar during a

28-month period of observation using 100 m interval bathymetric and land survey data. They examined the time and flow-stage dependency of bar growth and its impact on local channel change, and developed a model for mid-channel bar growth. Ashworth *et al.* observed that mid-channel bar growth occurred downstream of a major flow convergence, receiving large-scale sediment input from bank erosion immediately upstream of the zone of bar deposition. According to their study the principal mechanism of bar growth is through an amalgamation of large dunes that form a central bar nucleus, and bar widening continues through lateral accretion. Although Ashworth *et al.* used a good range of field data in developing their mid-channel bar growth model, it is not very different from Bristow *et al.*'s (1993) observations on post confluence mid-channel bar in the Brahmaputra-Jamuna River. Bristow *et al.* noted that post confluence mid-channel bar deposition occurs as flow expands and velocities decrease downstream from the confluence scour. They also describe that development of the mid-channel may be accelerated by the accumulation of material eroded from the scours and either side of the confluence. However, the general similarity of bar formation and growth between the two studies suggests that mid-channel bars initiate immediate downstream of a flow convergence due to flow expansion and velocity deceleration, and their growth and development accelerated by bed scour, dune amalgamation and channel bank erosion (cf. Cant & Walker, 1978).

In the preceding section, a review of literature on sand-bed braided rivers reveals that very little work has been undertaken on this type of system, other than that on the Brahmaputra-Jamuna River. It is also evident that some progress has been achieved in channel-scale study of planform morphology and channel movement, bar-scale study of secondary flow and morphological change, and in a few investigations, on facies models in bar tops and channel confluences. In addition, some studies have considered channel-scale sediment transport and channel aggradation and bar topography mapping, and formation and evolution of a single bar. Though all of these studies highlight different aspects of sand-bed braided systems, some important areas have yet to be addressed that could have important morphological (e.g. bank erosion, floodplain destruction) and social (e.g. human life and settlement) implications. The followings are therefore the potential areas of further research:

i) Quantitative investigation of the braiding process in relation to bank erosion with sedimentary evidence,

ii) Study of sediment size parameters and downstream sorting in connection to flow patterns,

iii) Impact of inundation frequency on bar permanence, human settlement and vegetation pattern, and

iv) Estimation of morphological changes to ascertain sediment transfer and balance.

2.5. Concluding Discussion

Studies of braided rivers upon which this review is based reflect a research effort carried out on both gravel- and sand-bed braided rivers, located in a variety of climatic and geologic settings. However, the majority of the previous work is restricted to gravel-bed braided rivers and most studies have concentrated either on small rivers and flume experiments or on proglacial braided streams. Contrarily, research works on sand-bed braided rivers are very limited and they are mainly based on the Brahmaputra-Jamuna River. Nevertheless, this literature review indicates some progress in some specific areas in both types of rivers, namely bar development and planform channel evolution, and flow hydraulics and bedload and suspended sediment transport. Hence, several important areas remain to be investigated, specifically quantification of the braiding process in relation to bank erosion and channel expansion, downstream sorting of sediment size in connection to flow patterns, and morphological changes and sediment balance. More importantly, research efforts should extend to the impact of flooding on bar instability and human settlement, and floodplain loss and vegetation pattern. This aspect of braiding has not been studied yet, and it is specifically vital for the Brahmaputra-Jamuna River, Bangladesh, which is frequently inundated by monsoon floods that affect more than 1.8 million bar dwellers.

Apart from the research themes that have been addressed or are yet to be addressed, one most important issue remains unsettled that is what should be the spatial and temporal scales of any particular geomorphological study. Previous studies on braided systems ranged across from small laboratory models to channel-scale studies, from a few weeks to 200-year time-scales (see Table 2.1). The issue of scaling across this range of braided channel sizes is rarely addressed and this issue is particularly relevant when attempting to link the results of geological and geomorphological studies. Furthermore, some difficulties are encountered when comparing results from one channel size to a system of a completely different magnitude (Bristow & Best, 1993). First, channel-scale or large reach-scale study over a long time period is usually based on secondary information (e.g. Werritty & Ferguson, 19980; Goswami, 1985; Thorne *et al.*, 1993; Jiongxin, 1997) which probably is of less utility when studying the process-form interactions of braiding. Second, studies of the morphological impact on the short period bar-scale or small-scale are limited (e.g. Davoren & Mosley, 1986; Goff & Ashmore, 1994; Nicholas & Smith, 1998), and their results may not be representative for the whole river system due to spatial and temporal variation of flow patterns and sediment movements (Petts & Foster, 1985; Martin & church, 1995). The question therefore remains as to what the most appropriate scale of study is. Obviously scale dependence is related to the aims and objectives of the respective study and the availability of improved methodologies. However, selection of spatial and temporal scales should be undertaken on the basis of linking the research results with other small- or large-scale studies at different geological or geomorphological perspectives.

The research framework of this study is therefore selected using the status of recent methodological advancement and progress of studies in braided systems, and in an attempt to address some of the issues yet to be resolved. The main aims of this study are to examine the braiding process and its impacts on bank erosion and channel morphodynamics, to assess sedimentary properties and downstream sorting of sediment size classes in connection with flow patterns, and to estimate morphological changes and sediment balance for the two selected reaches (approximate length of each reach is 30 km) of the Brahmaputra-Jamuna River over decadal timescales (1987-1997). In addition, impact of flooding on bar instability and human settlements, agricultural lands and natural vegetation will also be considered. The rationale behind the selection of two reaches for this study are twofold: first, to make up the previous shortcomings about the application of channel-scale studies or reach-scale studies with single bars and to compare the results of one reach to the other for the representation of the whole channel; and second, due to the strategic and geomorphological importance of these two reaches (see Section 1.2). Two main reasons also lie behind the selection of a decadal time-scale: first, a catastrophic flood occurred in 1988 which was the largest flood in Bangladesh ever recorded that had substantial social and morphological impact. Secondly, use of digital Landsat images and improved technologies (e.g. ERDAS Imagine and ArcView GIS techniques, Coulter laser sediment size analyser) permitted to consider a 10-year scale study.

CHAPTER III: BACKGROUND TO THE STUDY AREA

3.1. Introduction

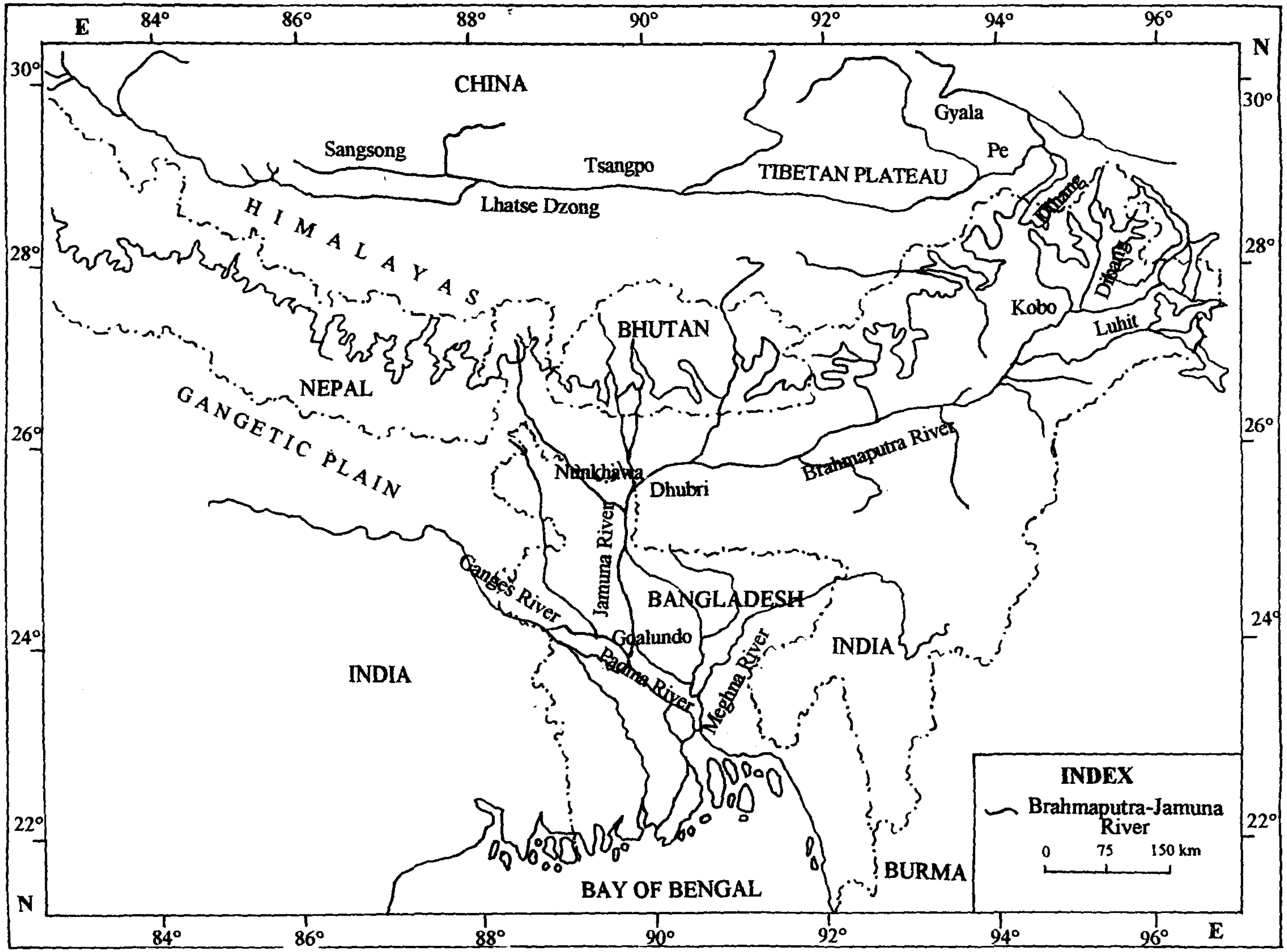
Bangladesh is situated astride the intersection of the Tropic of Cancer and longitude 90°E and at the confluence of the three mighty rivers, the Ganges-Padma, the Brahmaputra-Jamuna and the Meghna. The combined drainage area of the Ganges-Brahmaputra-Meghna is about 1.65 million km^2 of which 7.5 percent lies within Bangladesh. Stream flow varies from a maximum of 102,000 m^3s^{-1} in August to a minimum of 7,030 m^3s^{-1} in February (Bhuiya & Chowdhury, 1986). These rivers together discharge water exceeding 113,000 m^3s^{-1} at the peak period, and carry about 2.4 billion tons of sediment annually into the Bay of Bengal (Bhuiya *et al.*, 1991). The annual mean suspended sediment transport is greater than 1.3 million tons day^{-1}, and during flood the maximum load may exceed 15 million tons day^{-1} (Coleman, 1969). The large volume of water and sediment discharge causes the rivers to be extremely unstable and migratory. Rapid bank erosion and channel migration at rates varying from 60 to over 1,600 metre $year^{-1}$ are reported in a number of studies (Coleman, 1969; Siddiquey, 1988; Islam, 1990). The great catchment area of the Ganges, Brahmaputra and the Meghna has a tropical monsoon climate. The region experiences most of its precipitation in five months, May through September. Mean annual rainfall ranges from 1,110 mm in the centre-west to a maximum of 5,690 mm in the extreme north-east corner.

Bangladesh is predominantly a large alluvial basin floored with recent sediments deposited by the Ganges, Brahmaputra and the Meghna river systems. It has three discernible physiographies. The *alluvial plains,* constituting about 80 percent of the land surface, have a general lay sloping (23 cm km^{-1}) from north to south; and 65 percent of the alluvial plain is below 7.5 metre with respect to mean sea level (Bhuiya *et al.*, 1991). The remaining 20 percent of land are occupied by the *Pleistocene terraces* (8 percent), and the *hill* areas (12 percent) formed during the Miocene and the Pleistocene periods. The countries population of about 118 million (1994) has doubled since 1961 and is projected to double again by 2025. Over 80 percent of the population are rural, living in a flood prone environment and their primary occupation is agriculture.

3.2. The Brahmaputra-Jamuna River

The Brahmaputra-Jamuna is a major river system of the world, ranking fifth in terms of discharge and eleventh in terms of drainage area (Thorne *et al.*, 1993). The Brahmaputra-Jamuna, originating from the *Chema-yung-dung* glaciers of the Himalayas in south-west Tibet, flows through a distance of about 2,900 kilometres to its confluence with the Ganges-Padma in Bangladesh (Desai, 1968; Pranavananda, 1968; Vij & Shenoy, 1968). The main channel of the river system is known as the Brahmaputra River but it is given different local names along its length.

The Brahmaputra River drains a large area (600,000 km^2) of China, Tibet, Nepal, India, Bhutan, and Bangladesh from its source to its confluence (Fig. 3.1). The river basin of the Brahmaputra in its upper course is separated from those of the great rivers the Indus and the Sutlej by *Mariam La* pass in the Himalayan *Kailash* range at an elevation of 5,150 metres (ECAFE, 1966; Desai, 1968). The river flows in an eastward direction parallel to the Himalayan range, under its Tibetan name Tsangpo, and runs a length of about 1,000 kilometres (Coleman, 1969; Goswami, 1985). The Tsangpo has a wide channel (600 metre wide) from *Lhatse Dzong* with a unique inland waterway for 640 kilometres with an elevation of 3,650 metres above sea level



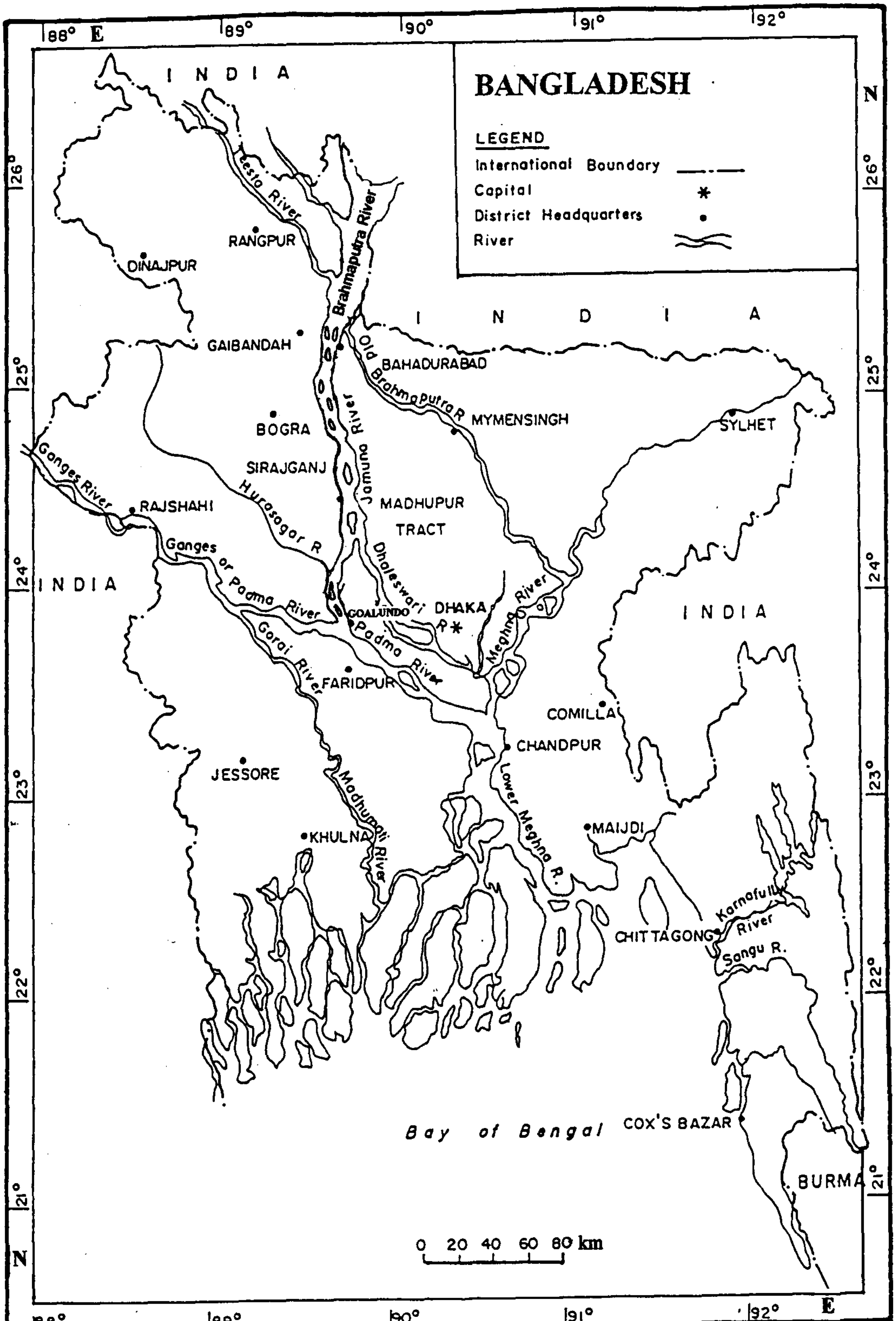
Source: Choudhury *et al.*, 1983.

Figure 3.1: The Brahmaputra-Jamuna River from its headwater to confluence.

(ECAFE, 1966). The river remains wide further east at *Pe* which has an elevation of 3,000 metres. Here the river turns the north-east and runs through many gorges. The river again makes a steep turn and follows a southward route in India for 226 kilometres with a new name, the Dihang (Anand, 1968; Goswami, 1985). Two large tributaries, the Dibang and the Luhit Rivers meet the Dihang near Kobo; and their combined flow, known as the Brahmaputra, flows a westward route for 725 kilometres upto Dhubri (ECAFE, 1966; Anand, 1968; Khan & Miah, 1983; Goswami, 1985). The Brahmaputra River continues to flow through Assam towards south-west before entering Bangladesh from the north.

The lower reach of the Brahmaputra River enters Bangladesh at *Nunkhawa* by taking an abrupt south turn and flows a down stream distance of 258 kilometres to its confluence with the Ganges-Padma river near Goalundo. From the entrance point to a few kilometres down stream of Bahadurabad where the old channel of the Brahmaputra branches off to the left, the river keeps the same name. The name 'Jamuna' is given to the reaches between Bahadurabad and Goalundo (Chowdhury, 1973; Rashid, 1977; Khan & Miah, 1983). At Goalundo, the Brahmaputra-Jamuna meets with the Ganges river and then flows south-east under a new name, the Padma (Fig. 3.2).

The Brahmaputra-Jamuna River is characterised by a network of interlacing channels with numerous sand bars. The channel bars in the Brahmaputra-Jamuna are transient in nature and changing their geometry and location from time to time. The Brahmaputra-Jamuna is a very wide river. During the rainy season, it is about 8 to 20 kilometres from bank to bank (Islam, 1990), and individual channels within its braid belt are up to 2 kilometres wide (Mosselman, 1995). Even during the dry season, the



Source: Thorne *et al*, 1993.

Figure 3.2: The major river systems of Bangladesh.

breadth is hardly less than 3 to 5 kilometres. The river is heavily charged with sediments and water. The physiography, geology, hydrography, soil and climate, and vegetation and landuse of the region around the Brahmaputra-Jamuna as it passes through Bangladesh are discussed in the following sections.

3.2.1. Physiography

The physiography of the Brahmaputra-Jamuna is finely attuned to its seasonal flooding and associated water regime. It has five sub-regions: (i) Brahmaputra floodplain, (ii) Teesta floodplain, (iii) Karatoya-Bangali floodplain, (iv) Ganges river floodplain, and (v) old alluvial terraces (Fig. 3.3). The Brahmaputra floodplain includes three units: the Active floodplain; Young Brahmaputra-Jamuna floodplain; and the old Brahmaputra floodplain. The Teesta floodplain includes the Active Teesta floodplain and Teesta Meander floodplain. The Karatoya-Bangali floodplain is a part of bigger floodplain of the Brahmaputra with different relief. Another physiographic region along the course of the Brahmaputra-Jamuna is the active Ganges floodplain, which can be divided into a western and an eastern unit. The eastern unit lies along right bank and the western unit lies along the left bank of the Brahmaputra-Jamuna River. The river course of the Brahmaputra-Jamuna is bounded by two major areas of Pleistocene sediments with alluvial origin (Coleman, 1969). These are the Barind and Madhupur Tract. The Barind Tract is located in the west and the Madhupur Tract in the east of the Brahmaputra-Jamuna, and are more elevated than the other regions. The elevation of the Barind Tract ranges from 6 to 40 metres from the east to west; and, on the other hand, the elevation of the Madhupur Tract ranges from 15 to 30 metres. Apart from these two Pleistocene terraces, the immediate surrounding regions of the Brahmaputra-Jamuna River are level plains. The elevation of these

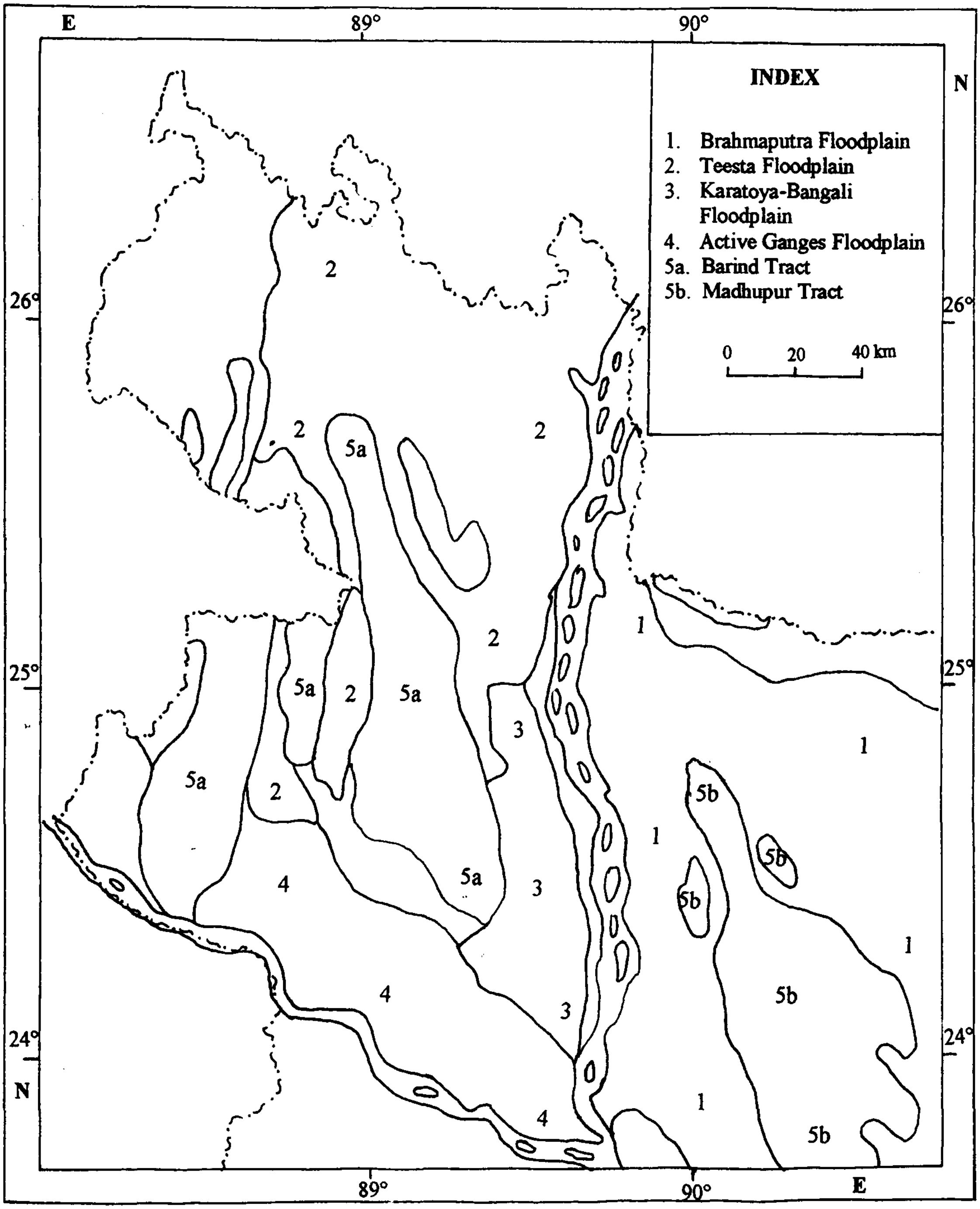


Figure 3.3: Surrounding physiographic regions of the Brahmaputra-Jamuna River
(after Land Resources Appraisal of Bangladesh).

physiographic regions ranges from 25 metres in the north to 7 metres to the south. The physiographic sub-regions are given below (Table 3.1) with their approximate areas and inundation land types.

Table 3.1: Physiographic units and sub-units with their approximate areas, and inundation land types.

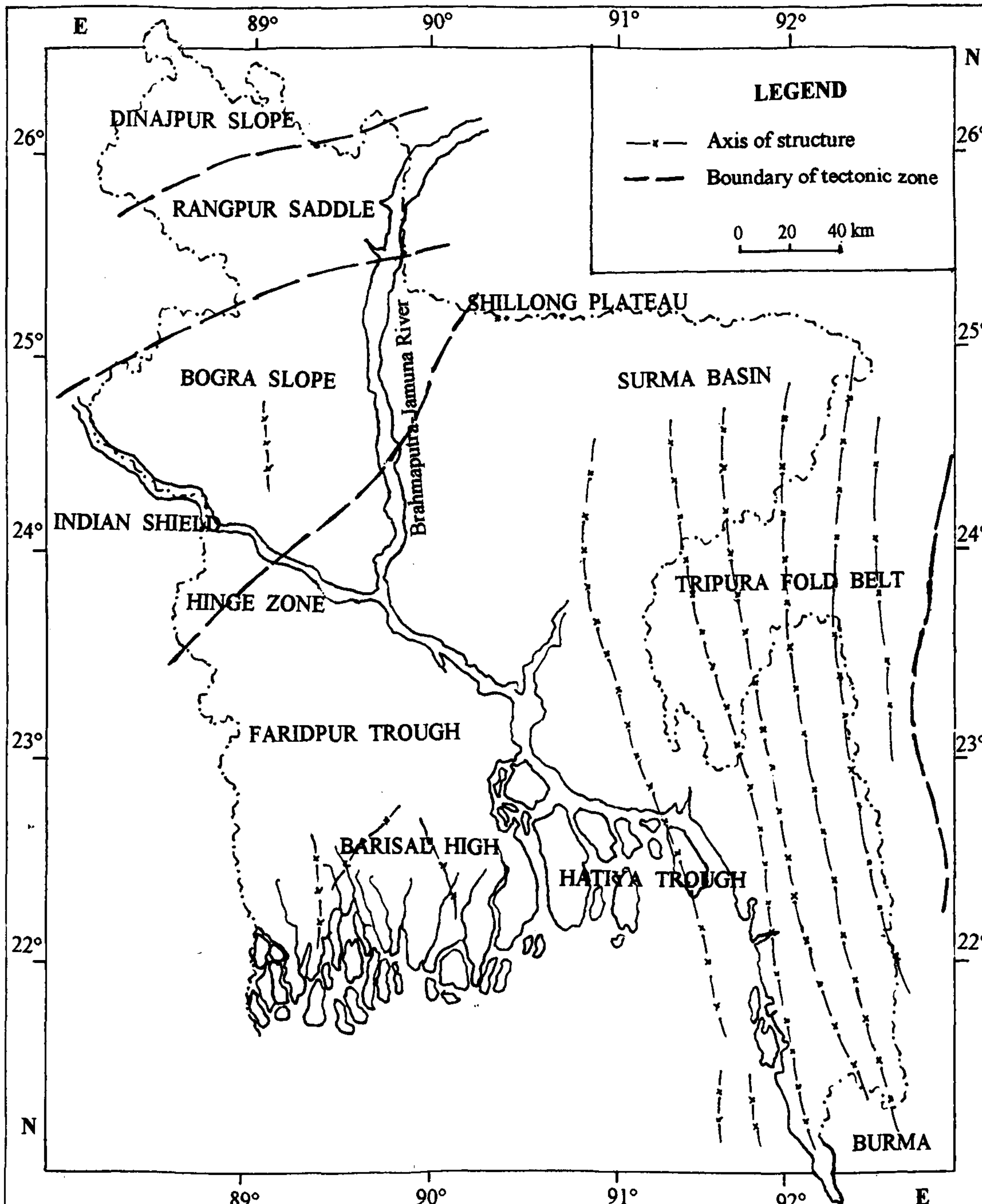
Physiographic Units and Sub-units			Area (km^2)	Area in Inundation Land Type (Ha)					
Unit	Sub Unit	Name		High Land	Medium Highland	Medium Lowland	Low Land	Very Low Land	Total
1		Brahmaputra Floodplain	16,344	323,925	614,274	321,527	133,444	91	**1,074,292**
	1a	Active Brahmaputra Floodplain	(3,190)	16,924	117,287	63,324	26,155	0	**223,690**
	1b	Young Brahmaputra-Jamuna Floodplain	(5,924)	105,500	245,206	114,732	53,123	0	**51,861**
	1c	Old Brahmaputra Floodplain	(7,230)	201,501	251,781	143,471	54,166	91	**651,010**
2		Teesta Floodplain	10,304	331,726	543,459	40,358	5,131	0	**920,674**
	2a	Active Teesta Floodplain	(836)	1,968	59,750	0	0	0	**61,718**
	2b	Teesta Meander Floodplain	(9,468)	329,758	483,709	40,358	5,131	0	**858,956**
3		Karatoya-Bangali Floodplain	2,572	59,940	113,382	34,903	11,509	1,447	**221,181**
4		Active Ganges Floodplain	3,335	39,183	109,467	61,064	14,036	0	**223,750**
5	5a	Barind Tract	7,727	337,451	337,994	22,735	10,834	0	**709,014**
	5a.1	Level Barind Tract	(5,048)	149,590	276,076	21,907	10,179	0	**455,752**
	5a.2	North-eastern Barind Tract	(1,079)	38,922	60,766	719	0	0	**100,407**
	5a.3	High Barind Tract	(1,600)	148,939	1,152	109	655	0	**150,855**
	5b	Madhupur Tract	4,244	233,945	76,416	31,568	39,583	0	**381,512**

Source: Land Resources Appraisal (LRA) of Bangladesh, 1988.

3.2.2. Geologic Setting

Geologically, Bangladesh is a part of the Bengal Basin, and tectonically this is an active zone formed as part of the Himalayan Orogeny. The Bengal Basin is affected by anticlinal folds and faults (Mithal, 1968) and comprises ~100,000 km^2 of lowland floodplain and delta plain (Goodbred & Kuehl, 2000). It is bounded to the north by the Cretaceous Shillong Massif, to the west by the shelf area of the pre-Cambrian Indian Shield and to the east by the folded belt of Tripura (Fig. 3.4).

The subsurface geology and tectonic features of the Bengal Basin vary considerably from one area to another. The Brahmaputra-Jamuna River lies within seismically



Source: MPO, 1987.

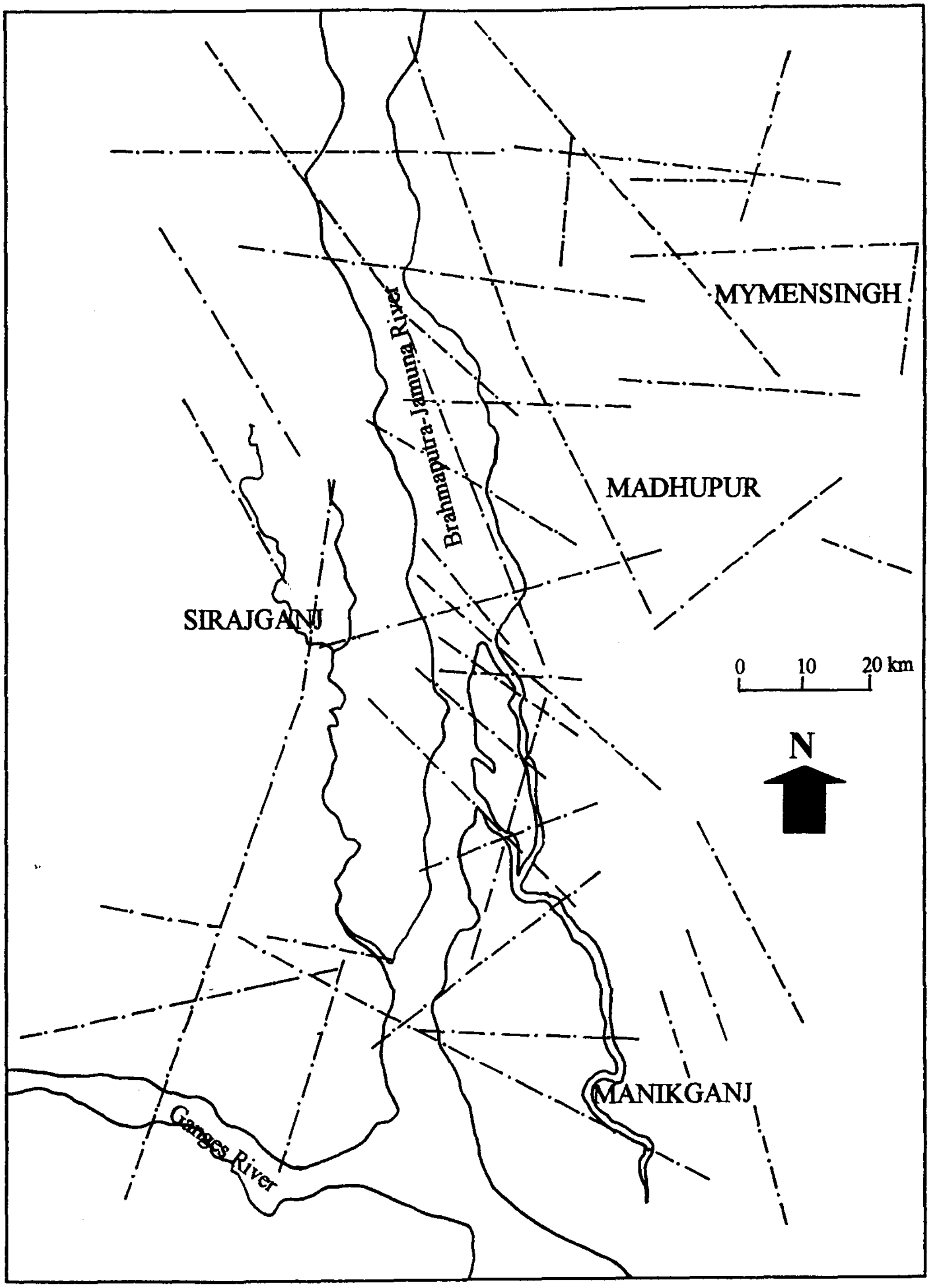
Figure 3.4: The major tectonic framework of the Bengal Basin.

active zone of the Bengal Basin (Seijmonsbergen, 1998). The river valley is underlain by Quaternary sediments (fluviatile deposits) approximately 200-300 metres thick and consisting of clay, silt, sand and pebbles (O'Malley, 1917; Wadia, 1953; Goswami, 1985). The prevailing sediment is a sandy micaceous and calcareous clay (O'Malley, 1917). The depth of the pre-Cambrian basement rock over which Quaternary sediment lies, is about 4 kilometres at Bahadurabad, 6 kilometres at Serajgonj, and more than 10 kilometres at the confluence of the Ganges-Brahmaputra near Goalundo (Gupta, 1976; Tappin *et al.*, 1998).

There are elevated terraces (the Madhupur and the Barind Tract) on either side of the river Brahmaputra-Jamuna that have been uplifted during the Pleistocene age (Morgan & McIntire, 1959). These uplifted terraces partition the lowland into sub-basins and in part control channel migration and course avulsion (Goodbred & Kuehl, 2000). Tilting of the Indian plate towards the Himalayan collision zone and shearing have caused fault lines to develop, many of which are approximately parallel to the present course of the Brahmaputra-Jamuna (JBS, 1988; Seijmonsbergen, 1998) (Fig. 3.5). The south of Bahadurabad, which is across the Eocene hinge zone, exhibits a series of faults (Mosselman *et al.*, 1995). It is believed that the north-south aligned fault zone along which the Brahmaputra-Jamuna River flows is a Gondwanic weak zone (Fergusson, 1863; Hirst, 1916; Krishnnan 1953; Morgan & McIntire, 1959) that might have been reactivated recently due to tectonic activity (Mosselman *et al.*, 1995).

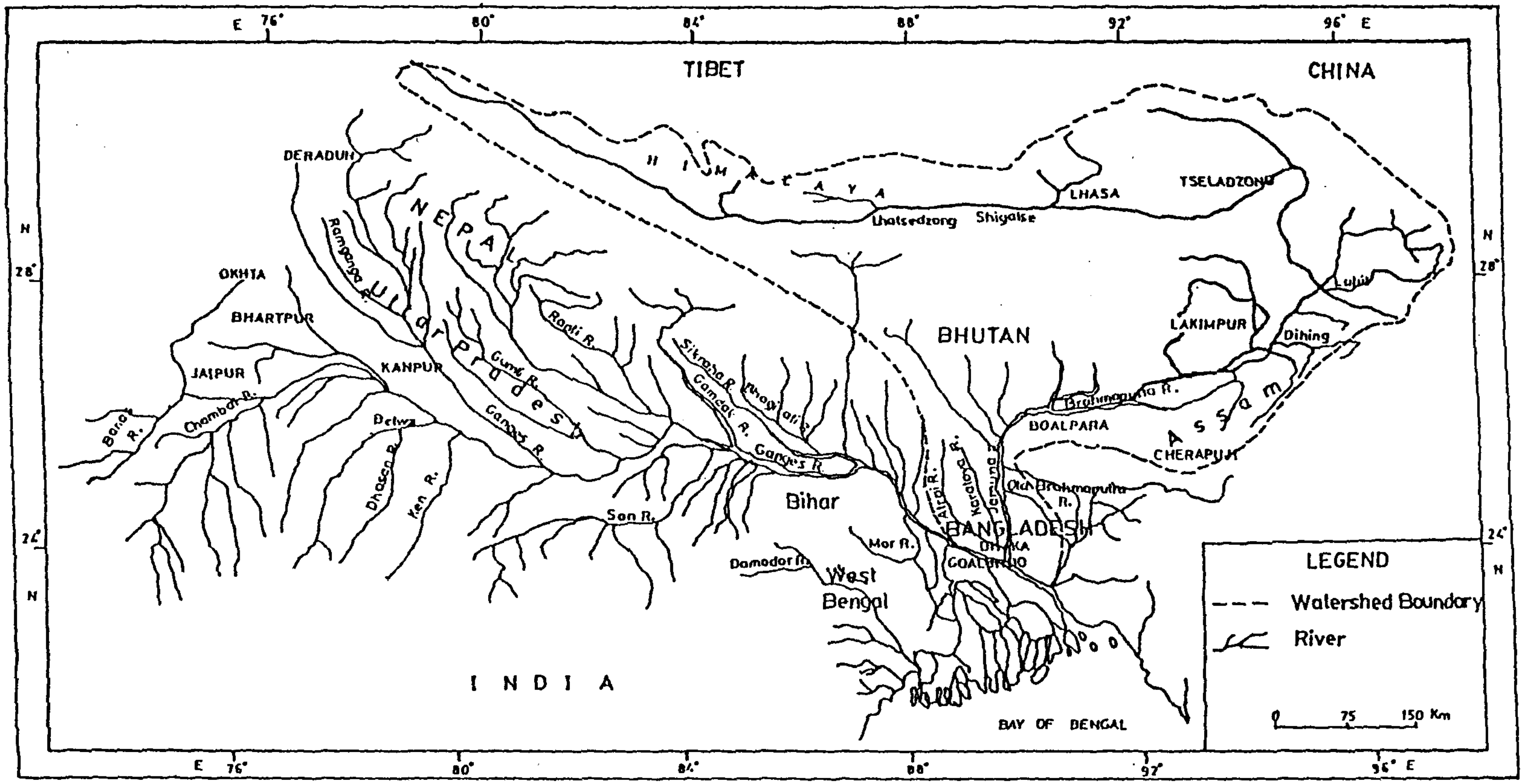
3.2.3. Drainage Basin and Hydrology

The total drainage area of the Brahmaputra-Jamuna River from its source to confluence is approximately 600,000 km^2 out of which 47,000 km^2 lies in Bangladesh (Vij & Shenoy, 1968; Goswami, 1985; Thorne *et al.*, 1993) (Fig. 3.6). The drainage



Source: Mosselman *et al.*, 1995.

Figure 3.5: Major faults along the Brahmaputra-Jamuna River.



Source: Khan *et al*, 1983.

Figure 3.6: The catchment of the Brahmaputra-Jamuna River.

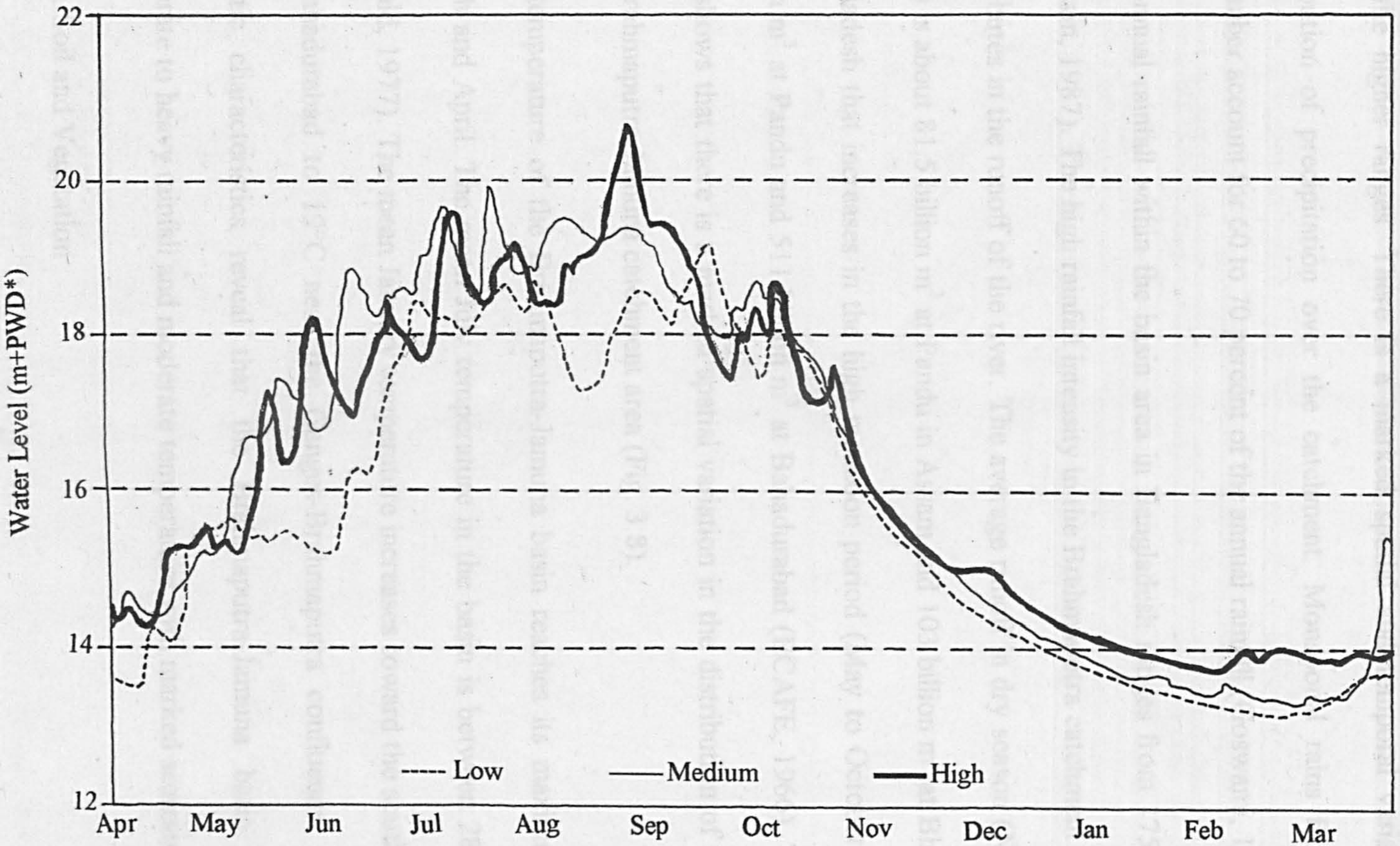
basin of Brahmaputra-Jamuna mainly includes the snow covered mountainous region of Himalayas and its foothill regions. The mountain chain acts as a rain barrier and intensifies monsoon rainfall which adds to river discharge.

Within Bangladesh, the main tributaries of the Brahmaputra-Jamuna are the Teesta and Karatoya-Hurasagar on the right bank; and the distributaries are old Brahmaputra and Dhaleswari on the left (see Fig. 3.2). The annual hydrograph of the Brahmaputra-Jamuna shows high seasonal fluctuations in discharge (Fig. 3.7). The river is characterised by low flows during the winter dry season and high flows during the summer due to snowmelt and heavy local rainfall. Maximum discharge of the Brahmaputra-Jamuna at Bahadurabad is 100,244 m^3s^{-1}, whereas minimum and average flows are 2,427 m^3s^{-1} and 20,177 m^3s^{-1}, respectively (FAP 25, 1992). The bankful discharge of the river varies from 45,000 m^3s^{-1} to 60,000 m^3s^{-1}, corresponding to a range of about 0.75 metres in water level (EGIS, 1997).

The Brahmaputra-Jamuna River carries a huge amount of sediment from its catchment areas. The sediment yield from the catchment is around 500 million tons annually (Thorne *et al.*, 1993). The average annual suspended sediment transport of the Brahmaputra-Jamuna in Bangladesh has been estimated at 600 million tons (JBAS, 1986). Monthly sediment transport in the river varies between less than 1 million tons (at low flow stage) and more than 250 million tons (during the floods) (Islam, 1990). Data on bed load material of the Brahmaputra-Jamuna is not available, but some estimates have been made based on measurements of 15 to 25 percent of total suspended sediment discharge (Coleman, 1969; Goswami, 1985).

3.2.4. Climate

The catchment area of the Brahmaputra-Jamuna, excluding the Tibetan portion, forms an integral part of the monsoonal regime of south-east Asia. The whole catchment



*A horizontal datum applied by Public Works Department (PWD), Bangladesh.

Source: EGIS, 1997.

Figure 3.7: Representative water level hydrograph at Bahadurabad Ghat in the Brahmaputra-Jamuna River.

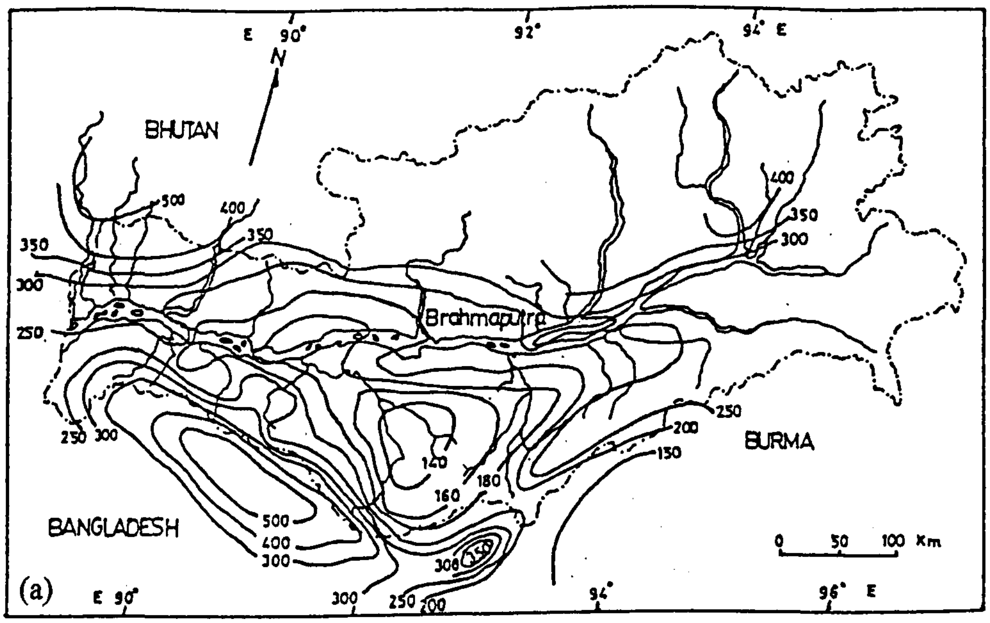
area receives intense precipitation in the form of snow and rain. The mountains of Assam are one of the heaviest rainfall-receiving zones of the world. The Himalayan ranges receive 500 cm of rainfall per year but the lower ranges receive more rainfall than the higher ranges. There is a marked spatial and temporal variation in the distribution of precipitation over the catchment. Monsoonal rains from June to September account for 60 to 70 percent of the annual rainfall (Goswami, 1985).

The annual rainfall within the basin area in Bangladesh ranges from 175 to 225 cm (Hossain, 1987). The high rainfall intensity in the Brahmaputra catchment area greatly contributes in the runoff of the river. The average runoff in dry season (November to April) is about 81.5 billion m^3 at Pandu in Assam and 103 billion m^3 at Bhadurabad in Bangladesh that increases in the high monsoon period (May to October) up to 431 billion m^3 at Pandu and 511 billion m^3 at Bahadurabad (ECAFE, 1966). The isohytal map shows that there is a marked spatial variation in the distribution of rainfall over the Brahmaputra-Jamuna catchment area (Fig. 3.8).

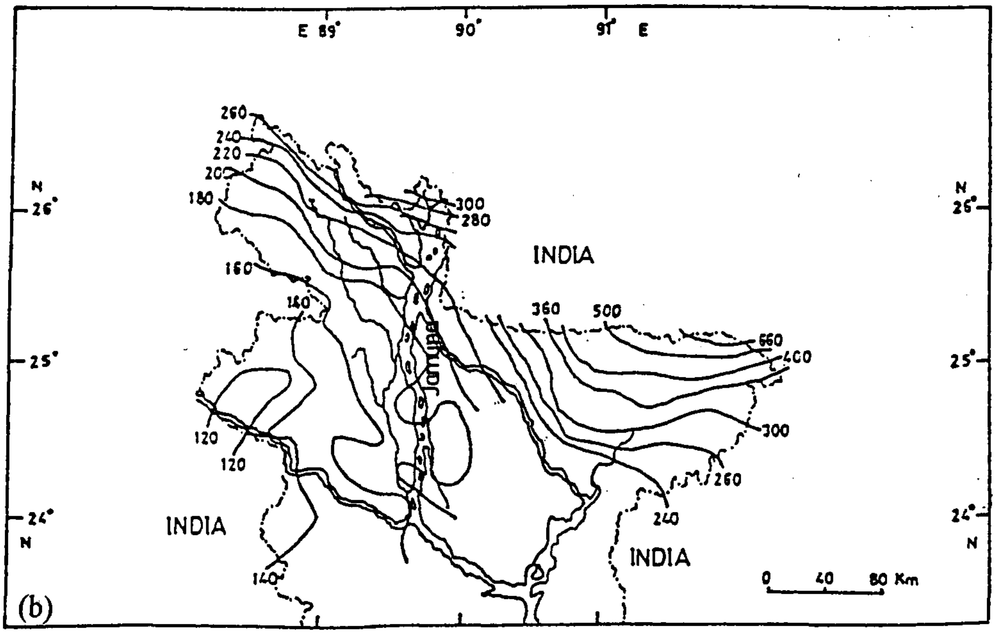
The temperature of the Brahmaputra-Jamuna basin reaches its maximum between March and April. The mean July temperature in the basin is between 28°C to 29°C (Rashid, 1977). The mean January temperature increases toward the south from 17°C at Bahadurabad to 19°C near the Ganges-Brahmaputra confluence. The overall climatic characteristics reveal that the Brahmaputra-Jamuna basin experiences moderate to heavy rainfall and moderate temperature with marked seasonal variation.

3.2.5. Soil and Vegetation

From the headwater of the Brahmaputra River to its junction with the Ganges, the increase in temperature and variation of rainfall is reflected in the soils. Soils in the sub-Himalayan region developed on the Tertiary sandstones are shallow and consist



Source: Goswami, 1985.



Source: Hossain, 1987.

Figure 3.8: The isohytal map (in cm yr^{-1}) of (a) the Brahmaputra valley and (b) the Jamuna valley.

primarily of sands with admixtures of cobbles and boulders (Goswami, 1985). The Brahmaputra valley in Assam and the Jamuna valley in Bangladesh contain soils of alluvial origin with some scattered areas of deeply weathered old alluvium.

The Brahmaputra-Jamuna River plain in Bangladesh is composed of grey-brown soils formed on fine to medium grained alluvium, silty and clayey sediments, and relatively unweathered alluvial and aeolian deposits. Both the distributions of these deposits and the soil types are controlled by the fluvial depositional patterns of river plain. The Brahmaputra-Jamuna floodplain soils are characterised by: i) non-calcareous grey floodplain soils, ii) non-calcareous alluvium, iii) non-calcareous dark grey floodplain soils, iv) shallow and deep grey terrace soils, v) deep red brown terrace soils, and vi) calcareous dark grey floodplain soils (Fig. 3.9). The soils are mainly developed due to horizontal alluvial accretion, which results from migration of the channel and redistribution of the eroded materials (Coleman, 1969).

As the Brahmaputra-Jamuna River flows from the highlands towards the plains, it proceeds through several soil and vegetational zones. In the highland areas natural vegetation varies from tropical evergreen, mixed deciduous to alpine meadows. Permanent vegetation types are less evident in the Brahmaputra-Jamuna basin in Bangladesh, as the region is subjected to yearly inundation and intensive agricultural practices. All types of native crops are grown on the braiding islands and floodplains as the soils are very fertile. The principal crop types are paddy, jute, wheat and peanuts; and the vegetation is dominated by trees and bushes, catkin and *kaisha* grass.

3.2.6. Landuse Pattern

The landuse and settlement patterns of the Brahmaputra-Jamuna floodplain are determined by the dynamism of the river; and monsoon dominates the agriculture of

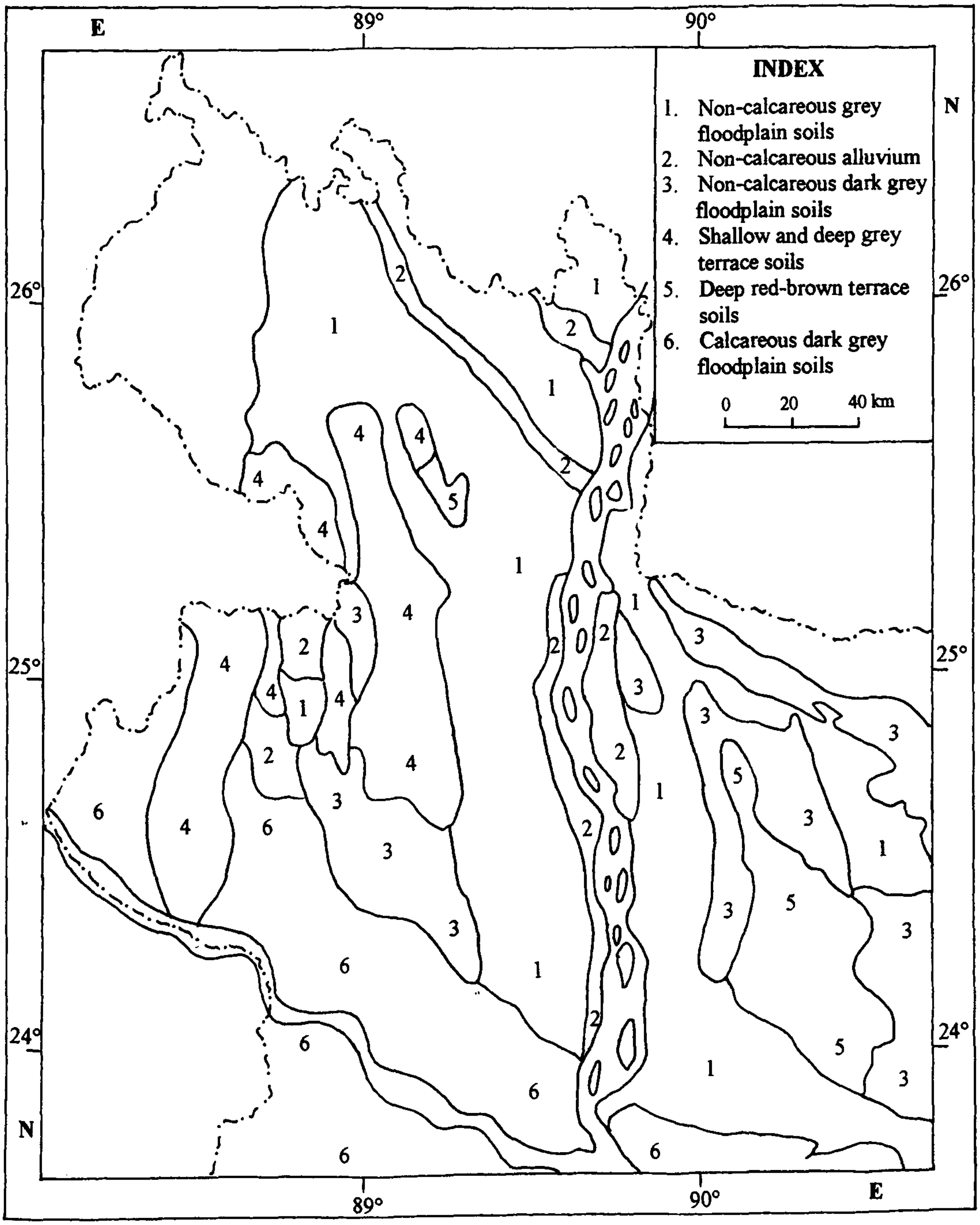


Figure 3.9: The soil types of the Brahmaputra-Jamuna floodplain (after Land Resources Appraisal of Bangladesh.

the region. Natural overflow of the periodic inundation is sufficient to supply a soil that receives, in addition, a heavy rainfall; and this natural overflow is allowed to find variety of landuse patterns. The island and attached bars are comparatively less intensively cultivated than the surrounding floodplains. The fertile alluvium of the Brahmaputra-Jamuna active floodplain and some older braid bars is well suited to the paddy and jute from May to October when vast areas go under water. Dry season cultivation in the floodplain is relatively more important than in the hazardous monsoon as these areas face some of the highest flood risk in the country. The dry period cropping systems predominate and appear to be concentrated mainly on the older braid bars; and include millets, peanuts, oilseeds, and the several other seasonal crops. Some areas characterised as sand grow catkin grass, an important resource for cattle grazing, fuel, and building material for house construction and homestead flood protection.

The unprotected mainland generally is reported to be 70 to 80 percent cultivated (FAP19, 1995). The lighter higher soils are easier to cultivate than those of the braid bars are. Close to the homesteads, for which sites are selected on the highest parts of the active floodplain in order to avoid most floods, vegetables and spices are grown in kitchen fields all the year round. Fruit trees, mangoes, jackfruit, and betel nut provide a supplement to the farmers diet and to their income.

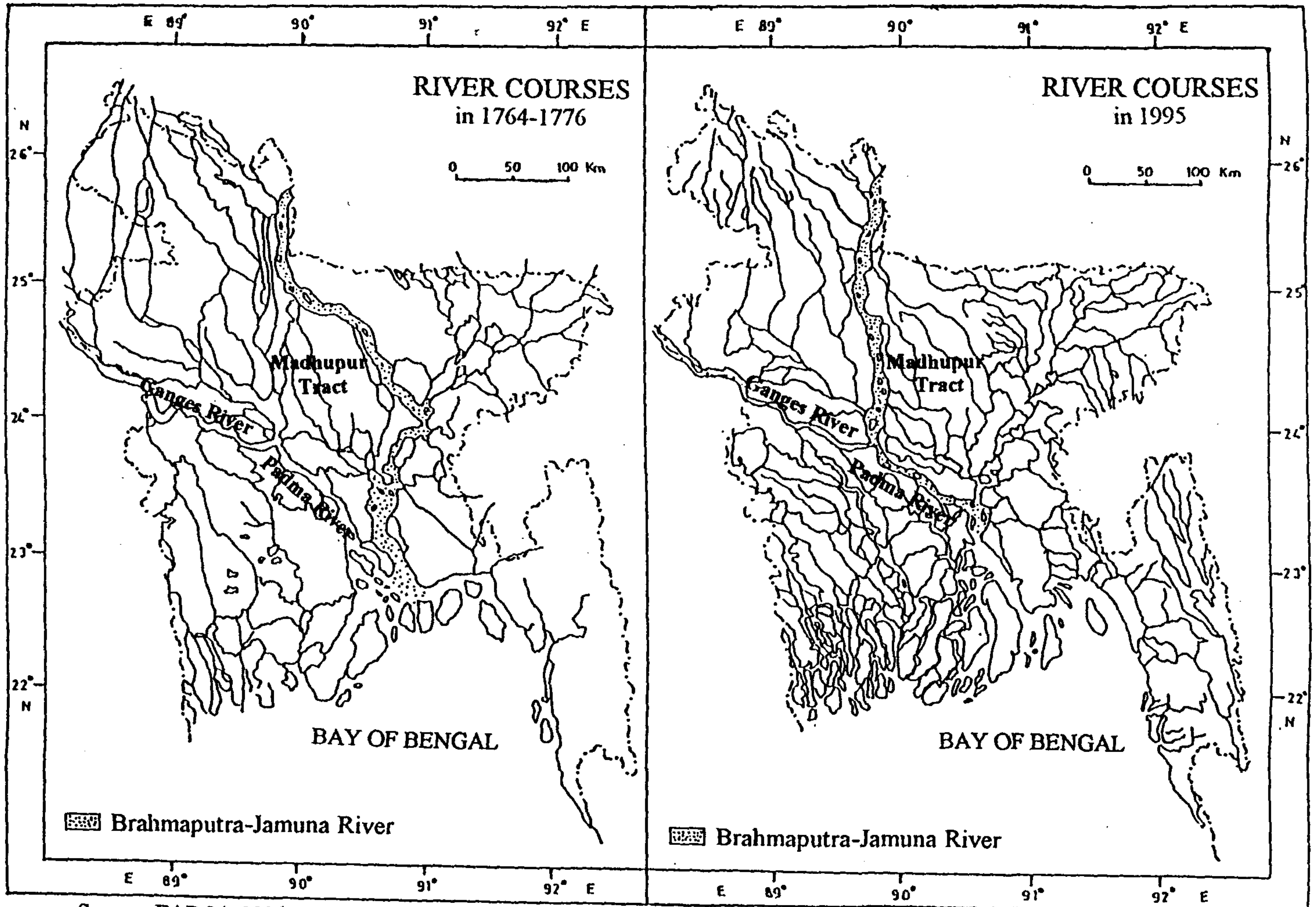
3.3. Historic Channel Change

The diversion of the old Brahmaputra River to the new course Brahmaputra-Jamuna in the early nineteenth century are well recorded events, and a discussion of change and its effect on the fluvial system of Bangladesh is deemed necessary. The available evidences of the change consists of records of banklines and surveys of the channel bed, surveys of land levels throughout the lower river basin, geological studies of subsurface deposits, deep borings, seismic studies and earth satellite studies (e.g. Wilcox, 1830; Fergusson, 1863; Hirst, 1916; Gales, 1918; La Touche, 1919; Wadia, 1953; Morgan & McIntire, 1959; Coleman, 1969; JBAS, 1986; Mosselman *et al.*, 1995; Seijmonsbergen, 1998). It is hardly possible to produce reliable documentary evidence on the Brahmaputra-Jamuna River before the survey carried out by Rennell (1781) between 1764 and 1776. Studies on the Brahmaputra-Jamuna could be said to have begun with Rennell on the basis of his statement:

> "...... and, till the year 1765, the Burrampooter, as a capital river, was unknown in Europe."

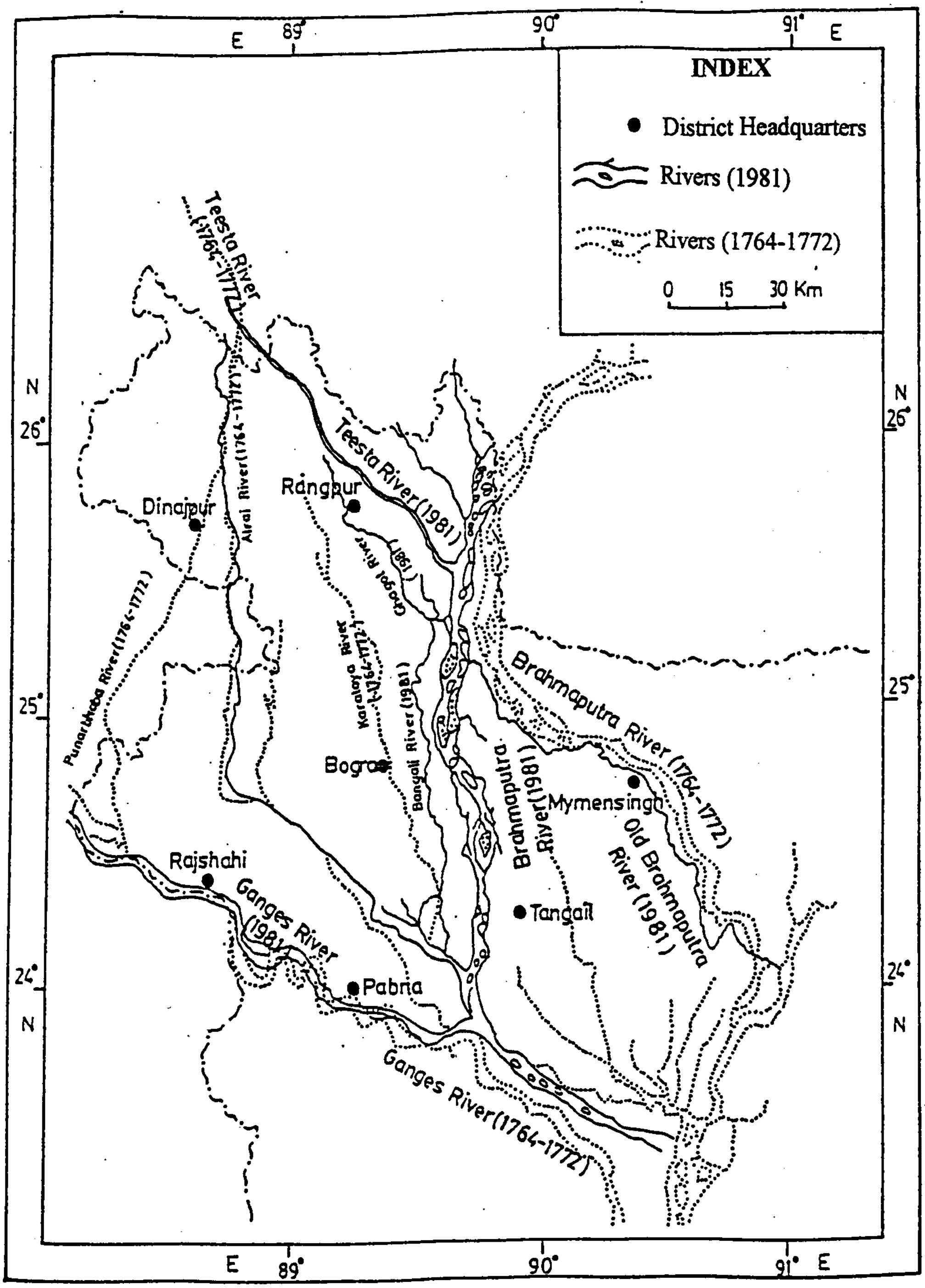
At the time of James Rennell (1764-1776), the Brahmaputra used to flow through its old course lying to the east of the old alluvial terraces, the Madhupur Tract (Fig. 3.10). The present course was then occupied by three independent channels, known as the Jhenai, the Jamuna, and the Teesta Creek (Rennell, 1781); and the then Teesta River was used to flow through north Bengal in several branches like the Purnabhaba, Atrai, Karatoya, and the Jamuneswari (Fig. 3.11). These streams used to flow southward and ultimately discharged into the Ganges.

It appears from Rennell's maps that there were relatively small spill rivers flowing from the right bank of the old Brahmaputra and the largest of these, the Jhenai, followed a path close to that of the present river (Fig. 3.12). Only a few years after Rennell's mapping, possibly in 1787, the Teesta diverted its main flow towards the relatively less important south-east flowing stream, called the Teesta Creek and through it, began to discharge into the Brahmaputra, instead of the Ganges River Wadia, 1953; Chowdhury, 1973). The diversion of the Teesta increased the discharge of the Brahmaputra which exceeded the rivers capacity, causing catastrophic floods



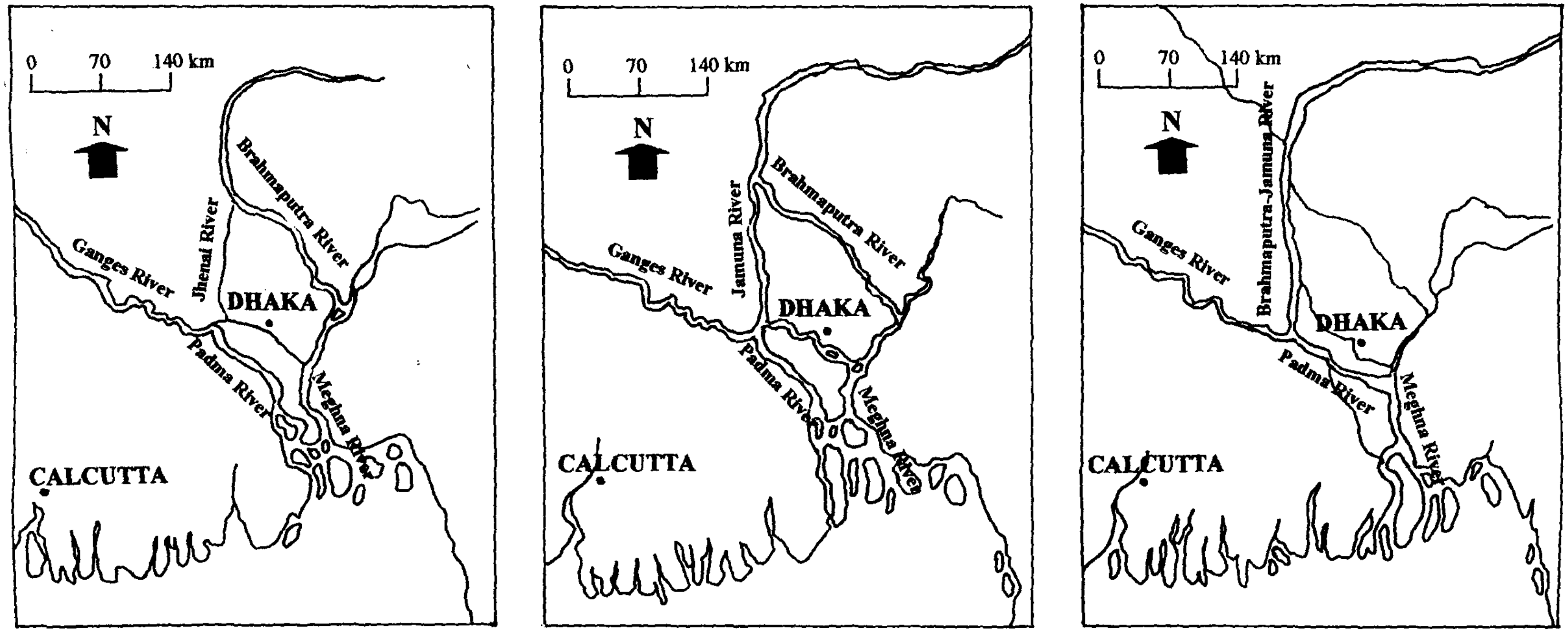
Source: FAP 24, 1996.

Figure 3.10: Change in the courses of the of the Brahmaputra-Jamuna River (1764-1995).



Source: Islam, 1990.

Figure 3.11: Rennell's map showing the old Brahmaputra River course.



(a) End of 18th Century (after Rennell's map of 1776). (b) 1821–1834 (after Wilcox's map of 1840). (c) 1991 (after ISPAN, 1993).

Figure 3.12: Historical evolution of the Brahmaputra-Jamuna River.

near the confluence (Coleman, 1969). Some of the excess discharge passed through the Jhenai and this distributary of the Brahmaputra gradually enlarged itself, and its discharge increased from year to year until it became the main channel of the Brahmaputra.

Fergusson (1863) postulated that this kind of widespread morphological change might not have been accomplished in a single flood, and this shifting of the course of the Brahmaputra might have been due to the uplift of the Madhupur Tract. According to Hirst (1916) the diversion of Jamuna from its old course to the present course was completed by 1830, that is approximately fifty years after Rennell's mapping (Fig. 12b). Hirst attributed the diversion of the Brahmaputra to tectonic activity and he believes that the present course of the river lies directly along the line of subsidence. Morgan and McIntire (1959) support his views and state that the diversion of the Brahmaputra has been caused in part by gradual tilting of the alluvial terrace Madhupur Tract.

La Touche (1919), however, produced a different explanation and he supposed that the increase of volume of water in the Brahmaputra resulted from the beheading of the Tsangpo river of Tibet by the Dihang, causing a part of its volume to flow to the Brahmaputra through Teesta Creek. This opened a passage through the Jhenai, and gradually began to increase the width of the channel, resulting in the present form of the Brahmaputra-Jamuna River. Chowdhury (1959) emphasised that the most remarkable change that has occurred since the time of Rennell, is the avulsion of the eastern course through Mymensingh and its pursuit of the narrow channel of the river Jhenai. On the other hand, Gales (1918) suggested that channel switching of the Brahmaputra amounted to rejuvenation of an old channel. He assumes that the present bed of Issamuti river through Pabna and Bogra was the earlier course of the

Brahmaputra. However, regarding the map published in 1840 after the abandonment of the old Brahmaputra, Coleman (1969) concludes that the new course was a typical meandering stream with a very broad and low curvature meander loop (Fig. 12b).

The diversion of the old Brahmaputra River to the new Brahmaputra-Jamuna is an event of considerable significance in the recent history of many rivers of Bangladesh. But there is no agreement among the researchers regarding the cause as well as time of the shifting of the Brahmaputra-Jamuna from east to west. It is believed that the evolution of the Brahmaputra-Jamuna river during the past two centuries is a combination of long-term effects of faults; and either a major seismic event, an increased flood discharge, or a catastrophic flood in 1787 that triggered the shifting.

3.4. Summary

The river Brahmaputra-Jamuna is extensively braided, bars and other bedforms are transient in nature and change their location frequently. The lands within the river-belt are prone to flood hazard and erosion, which destroy crops, homesteads and livestock, and bring death and suffering to the people. The socio-economic lives of the Brahmaputra-Jamuna basin dwellers are largely influenced by the ever-changing nature of lands upon which they live. To improve socio-economic conditions and to ensure sustainable development, in-channel environment must be taken into consideration in terms of its dynamism that is linked with channel behaviour, flooding, soil and vegetal characteristics, and land resource appraisal. So, there is an urgent need for better understanding of the processes involved in the formation and change of bar morphology in order to interpret channel dynamics that can help to construct both qualitative and quantitative depositional models for the large braided river environments.

CHAPTER IV: METHODS OF RESEARCH AND DATABASE DEVELOPMENT

4.1. Introduction

The ability to measure and quantify morphological behaviour successfully is central to any geomorphological investigation. The role of a 'method' is to allow the variables involved to be quantified in a consistent, rigorous and precise manner. In attaining the objectives of morphological study within a fluvial system the key requirements are to develop database and analysis capability for storing, analysing and presenting remote sensing images, historical maps and diagrams, hydrological and sedimentological data, river morphology and other information about the river. In addition, data should be obtained following good practise guidelines using appropriate equipment and for a reasonable length of time to allow long-term trends to be evaluated.

It is difficult logistically and quantitatively to provide a comprehensive, long-term channel-scale study of the Brahmaputra-Jamuna River which has braidplain widths of up to 20 kilometres and individual channel widths of several kilometres. Therefore, the main objectives of the study are to examine reach-scale variability of bar growth and impacts on channel morphodynamics, and to estimate sediment budgets over decadal timescales. Integration of remote sensing images and GIS analysis techniques with extensive field data can provide better understanding of processes involved in braiding and channel morphodynamics (EGIS, 1997; Hassan *et al.*, 1999). In this context, for the present study attention has been focussed on satellite image analysis, sediment size analysis and microscopic analysis of the mineralogical compositions of sediments. This chapter presents an overview of the methods and techniques used for this study, with more detailed analytical methods given in the later analysis chapters (see Chapters 5, 6, 7 and 8).

4.2. Remote Sensing Data Acquisition and Analysis

4.2.1. Remote Sensing Data

In order to apply geostatistical methods in the analysis of channel morphodynamics, the basic need is for numerical data. The size, multitude and inaccessibility of channels within the Brahmaputra-Jamuna system create problems for field survey and the collection of representative sediment samples. Consequently, continuous measurement and monitoring of the variables involves much time, effort, resource, and thus, cost; and most secondary information is limited to a relatively short stretch of a river adjacent to a locality. Hence the need to utilise alternative reconnaissance methods capable of providing this type of morphological information over large areas in a short time and a reasonable cost (Maior, 1973).

Remote sensing provides an enormous global source of data, particularly for unstable fluvial environments, and where ground survey is very difficult (Broers *et al.*, 1990; Roberts *et al.*, 1993; Browne, 1995; Hassan *et al.*, 1999). The use of satellites to monitor land surface features has increased with the near daily coverage of most earth locations by different satellites. Synoptic scenes repetitively covered in computer processable format offer a range of data, as well as providing means for testing predictive models. Additionally, archived satellite data provide a means of retrospective assessment of landscape conditions, which would be otherwise extremely difficult to achieve, particularly for inhospitable and remote environments (Walsh *et al.*, 1998). Chronologies constructed on an annual or seasonal basis can be developed from archived satellite data, covering the last 30 years.

More recently, digital satellite data has been used to detect and map change and as a means of measuring some of the physical variables which promote, sustain and control change in the fluvial environment (e.g. Milton, *et al.*, 1995; Nellis *et al.*, 1998; Walsh *et al.*, 1998; Goswami *et al.*, 1999; Wright *et al.*, 2000). The advent and rapid progress in remote sensing and geographical information technologies have advanced the field of fluvial geomorphology (Vitek *et al.*, 1996). Nevertheless, the latest generation of remote sensing does not seek to replace the traditional field-based investigations and technologically advanced data collection techniques, but to complement them by allowing the results and interpretations of such studies to be extended across wider areas, from the cross-section to the reach and thence to the channel segment and the catchment scale (Walsh *et al.*, 1998).

4.2.2. Data Acquisition

Landsat acquire images of large areas in the water-penetrating visible wavelength region at good spatial resolution and thus are potentially useful in studying large-scale fluvial environments (Harris & Kowalik, 1994). There have been many efforts to evaluate the use of Landsat Multispectral Scanner (MSS) and Landsat Thematic Mapper (TM) data to digitally delineate geomorphic features. In that way, Salo & Kalliola (1986) used multi-date Landsat MSS images of the meandering and anastomosing reaches of the Ucayali and Amazon rivers to quantify lateral migration rates. Haack *et al.* (1987) used the MSS and TM (Thematic Mapper) data for an assessment of urban and near-urban landcover classification. Landsat MSS and TM data of the Ganges River were also used by Philip *et al.* (1989) to reconstruct palaeochannel patterns. There have also been applications of the MSS and TM data for estimation of suspended sediment (Ritchie *et al.*, 1987), differences in vegetation indices (Gallo & Daughtry, 1987), and estimation of water depth (Harris & Kowalik, 1994). In most cases the relatively coarse spatial resolution with difficult geomorphic discrimination of MSS satellite sensors limits their application to the studies. That difficulty is generally attributed to the MSS 80×80-m pixel size which is considered to be too coarse for morphological environments and to a lesser degree attributes to having only four spectral bands. The inclusion of the Landsat TM sensor in 1982 improved radiometric (four fold), spectral (7 bands instead of 4) and geometric (2.6 times) sensitivity relative to the Landsat MSS (Mather, 1989, 1999; De Jong, 1994; Lillesand & Kiefer, 2000). Major differences between the two generations of Landsat sensor are given in Table 4.1. The higher resolution of simulated TM data compared to MSS allows for discrimination of geomorphic features which effect landscape stability (Nellis *et al.*, 1998; Walsh *et al.*, 1998). Surfaces with different landcover types, areas experiencing high rates of river bank erosion, and active sedimentation can be analysed with this improved spatial resolution data set (EGIS, 1999).

Table 4.1: Differences between Landsat MSS and TM observation function.

Sensor	Launching Date	Band	Nominal Spectral Location	Wavelength (μm)	Reso-lution	Data Trans-mission Rate	Orbital Cycle	Altitude
MSS	July 23, 1972	4	Green	0.50~0.60	80×80-m	15 megabits sec^{-1}	18-day	880 to 940 km
		5	Red	0.60~0.70				
		6	Near IR	0.70~0.80				
		7	Near IR	0.80~1.10				
TM	July 16, 1982	1	Blue	0.45~0.52	30×30-m	85 megabits sec^{-1}	8-day	700 to 900 km
		2	Green	0.52~0.60				
		3	Red	0.63~0.69				
		4	Near IR	0.76~0.90				
		5	Mid IR	1.55~1.75				
		6	Thermal IR	10.40~12.50				
		7	Mid IR	2.08~2.35				

Source: Lillesand & Kiefer, 2000.

The ability to digitally identify geomorphic characteristics provides increased opportunities for automated derivation of hydrologic and sediment transport model parameters. Nevertheless, the development of Geographical Information Systems (GIS) offered a means of extracting parameters that would be impracticable to attempt manually, and so provides a flexible means of exploration (Downs & Priestnall, 1999). A substantial portion of the geostatistical database for this study was derived from a time series of Landsat images. The Landsat images consist of 14 image frames for the two reaches (Bahadurabad Ghat and Jamuna Bridge), acquired for 7 years between 1987 and 1997. Of the image frames, two frames taken in 1987 are Landsat MSS and the remaining 12 images were Landsat TM. It is to be noted here that no suitable dry-period cloud free image was available for the years 1988, 1990, 1991, and 1993 in Space Research and Remote Sensing Organisation (SPARRSO), Bangladesh, who are authorised for data storing and supply for public use. The Landsat images were obtained from EGIS (Environment and GIS Support Project for Water Sector Planning, Ministry of Water Resources, Bangladesh), where they had been digitally processed, georeferenced and transformed into the Bangladesh Transverse Mercator (BTM) projection. They were supplemented with field survey, hydrometric data, historic maps and results of other studies. Figure 4.1 shows the flowchart of the image acquisition and analysis procedures.

Choice of the timing and frequency of image sensing was determined by minimising geometric distortion that may be introduced by the sensor. Although each cloud-free satellite image in the time series was collected during the dry season when water levels were relatively low, the effect of water level variations in the images was investigated (see Chapters 5 and 6) to minimise the affect on morphological interpretations. Water level and discharge data for each image acquisition date are presented in Table 4.2.

Table 4.2. Water levels and discharge data for dates of image acquisition.

Image Year	Type of Sensor	Image Date	Water Level (m+PWD*) at Bahadurabad Ghat	Water Level (m+PWD) at Serajgonj (near to Jamuna Bridge)	Discharge (m^3/sec) at Bahadurabad
1987	MSS	Feb 07	13.30	6.94	4000
1989	TM	Feb 28	13.94	7.67	6070
1992	TM	Mar 08	13.76	7.60	4660
1994	TM	Jan 25	13.61	7.76	5070
1995	TM	Jan 28	13.07	7.77	3562
1996	TM	Jan 31	13.53	7.33	4965
1997	TM	Feb 18	13.26	6.74	4460

*A horizontal datum applied by Public Works Department (PWD), Bangladesh.

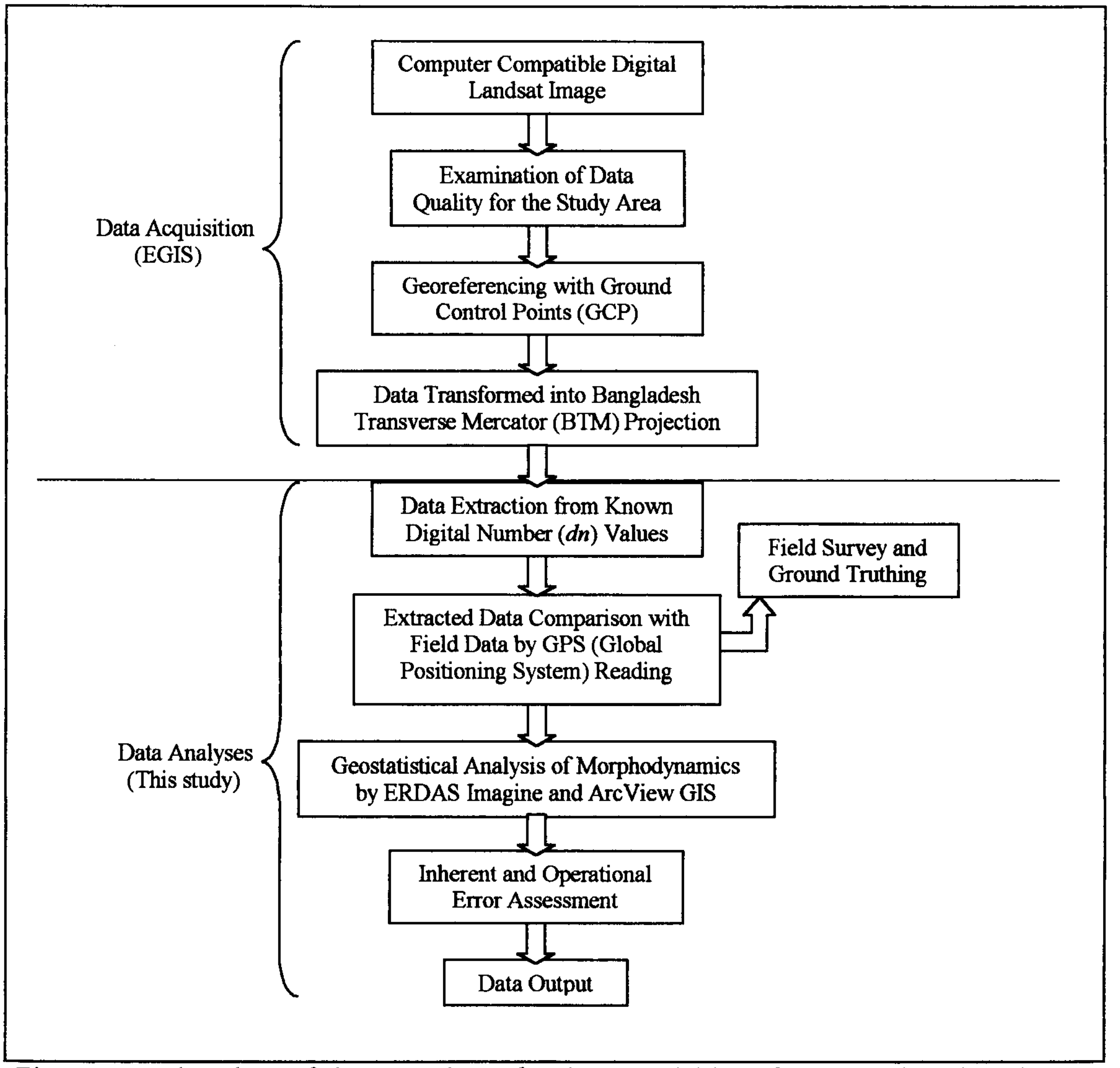


Figure 4.1: Flowchart of the procedures for data acquisition (from EGIS) and analyses (adopted by this study).

4.2.3. Analysis Approaches

The ideal image processing system for monitoring change in fluvial systems does not exist, but a number of operational and forthcoming systems have much to offer the fluvial geomorphologist (Milton *et al.*, 1995). Digital image processing provides the opportunity to apply techniques of geostatistics and spatial analyses to images of the fluvial environment.

A GIS is often described as an information system that uses geographically referenced data, and it can be viewed as a chain of operations involving data collection, input storage, analysis and display, within the framework of defining an objective and ultimate use of that analysis for some decision-making purpose (Neil, 1987; Lane *et al.*, 1994; Browne, 1995; Martin & Church, 1995; Milne & Sear, 1997). GIS also have the power to integrate data from many sources; and field based topographic surveys can be overlaid with other remotely sensed grids. The scales of satellite images are appropriate to reach surveys and this can provide information on sedimentation process, channel change and water depth (Acornley *et al.*, 1995).

Many GIS based models have been developed for small rivers (e.g. Johnson *et al.*, 1995; Townsend *et al.*, 1995; Walsh & Townsend, 1995); but often these are much smaller than the size of rivers requiring management decision. Recent developments in information technology have enabled progress in morphological modelling to study spatial patterns as well as processes (Downs & Priestnall, 1999). The raster GIS is becoming increasingly popular through modern display technologies and because of the relative computational advantages of using raster rather than vector data (Johnston, 1998). Recent hydrological literature indicates that ArcView GIS and ERDAS Imagine are arguably the two most widely used analysis tools and they also have PC-based implementation (e.g. Weatherbee, 1994; Browne, 1995).

To visualise, classify and analyse morphological change for the selected reaches of the Brahmaputra-Jamuna river, the latest version of ERDAS Imagine (version 8.3.1) and ArcView GIS (version 3.1) was used. A series of analyses were performed to delineate, edit and assess banklines and bar dynamics with the ArcView GIS program (detailed analyses techniques are described in Chapters 5 and 6). A second series of analyses involved a supervised maximum likelihood classification of land cover types using ERDAS Imagine.

Assessment of the accuracy of interpretation and analyses was based on comparison of actual ground conditions with those interpreted from the image at 122 sites (corresponding to the locations of the sediment samples) along selected reaches of the Brahmaputra-Jamuna River. Waterways and water depths, land cover, and agronomic practices were observed and documented extensively in the field, then compared with spectral signatures from *dn* (digital number) [The numbers defining the radiation intensity of red, green and blue colour of a pixel are referred to as *digital number* (Rees, 1990). More specifically, the value represented or every pixel is called the *digital number*] values at the truthing locations from the Landsat images. Identification of ground position was determined using a Global Positioning System (GPS) [Magellan GPS NAV DLX-10™/1996] (cf. Golledge *et al.*, 1998; Walsh *et al.*, 1998; Higgitt & Warburton, 1999). The GPS receiver was configured to transmit position based on 30-reading average and thereby location of ground features (X & Y co-ordinates) was obtained with an error of generally under 10-m.

4.3. Field Work and Survey Design

Satellite image analysis refers to the process of determining or making educated guesses about the significance of features recognised in an image (Harris & Kowalik, 1994). Field techniques should be combined with the techniques of satellite image analyses in order to utilise the best of both data collection methods, because, field surveyed evidence can complement considerably the understanding of documentary evidence that may escape if only image analyses techniques are employed (Walsh *et al.*, 1998). With braided channels there has therefore been much greater emphasis on field observation and measurement because of the more dynamic nature of the channels (Ferguson, 1993; Hooke, 1997; Milne & Sear, 1997). Moreover, field studies play a vital part in the sedimentological investigation that is linked to the remote sensing database (Brown *et al.*, 1998).

In order to assess reach-scale morphodynamics and sedimentary structures of the Brahmaputra-Jamuna River, a base map was prepared for field survey from the Landsat TM image at a scale of 1:500,000 taken on the middle of December, 1997. The base map covers the two selected reaches (Bahadurabad Ghat and Jamuna Bridge) of the Brahmaputra-Jamuna River, each having an approximate length of 30 kilometres. The base map was also used to choose locations for sediment samples along longitudinal, lateral and vertical co-ordinates as well as to record morphological features for the selected bars and reaches.

To delineate reaches and to sample sediments from the pre-designed locations on the maps, two surveys were undertaken. In the first, a reconnaissance survey was carried out in the low flow periods between October and December 1997 for the selected reaches. The purposes of survey were first, to acquire enough knowledge of the reaches to design sampling locations; and second, to gain experience on ground control points (GCPs) that would be required for interpretation of the satellite images.

In the second survey (between January and April 1998), samples of sediment from 4 selected braid bars of the Brahmaputra-Jamuna were collected at different locations to assess the reach-scale variability in sedimentary properties. Two braid bars, Harindhara (smallest, 2.59 km^2) and Kulkandi (largest, 5.57 km^2) along the reach of Bahadurabad Ghat; and two bars, Belutia (smallest, 0.77 km^2) and Chatpier (largest, 15.74 km^2) along the Jamuna Bridge Reach, a downstream distance of about 70 kilometres from Bahadurabad Ghat, were chosen for sediment sampling. Sediment samples from each bar were collected along longitudinal (Y-axis), lateral (X-axis) and vertical (Z-axis) co-ordinates. It is notably that two different size braid bars from each reach were considered in order to compare morphological behaviour and sedimentological characteristics between the bars. Samples of sediment from both banks of the selected reaches were collected at different locations. Sampling locations along longitudinal, lateral and vertical directions were marked as Y1, Y2, Y3, ...Yn; X1, X2, X3, ...Xn and Z1, Z2, Z3 ...Zn, respectively (Fig. 4.2). The positions of the sampling locations were chosen using stratified random sampling techniques and marked on the surface with the help of GPS, keeping an approximate constant distance along a particular co-ordinate, and relative height of each position was measured using Optical Reading Clinometer (Version PM-5/360 PC).

To obtain representative sediment samples, approximately 500 grams of sediment was collected from each of the chosen locations and put into polythene bags. The polythene bags were marked with a suitable code reference for identification. In addition to surface sampling, at each location samples were also collected at a depth of 3.0 metre, using a manually operated soil auger. It was not possible to bore more than 3.0 m by a manually operated auger because of two reasons; first, it was very difficult to put in the soil auger manually into the bar deposit beyond the approximate depth of 3.0 m and second, there was rapid collapsing of loose sediments from the sides of auger as soon as the auger was withdrawn to make clear. However, there was no significant grain-size variation discovered within the limit of 3.0 m depth. A total of 122 sediment samples were collected from both bars and banks of the two selected reaches of the Brahmaputra-Jamuna River.

To undertake detailed topographic survey of the bars of each reach and to assess the accuracy of change detection procedures from the satellite images a checklist was used. Information collected from the field studies consisted of geomorphological characteristics, crop and vegetation types, erosional and depositional features, settlement patterns, and sediment outcrop orientations.

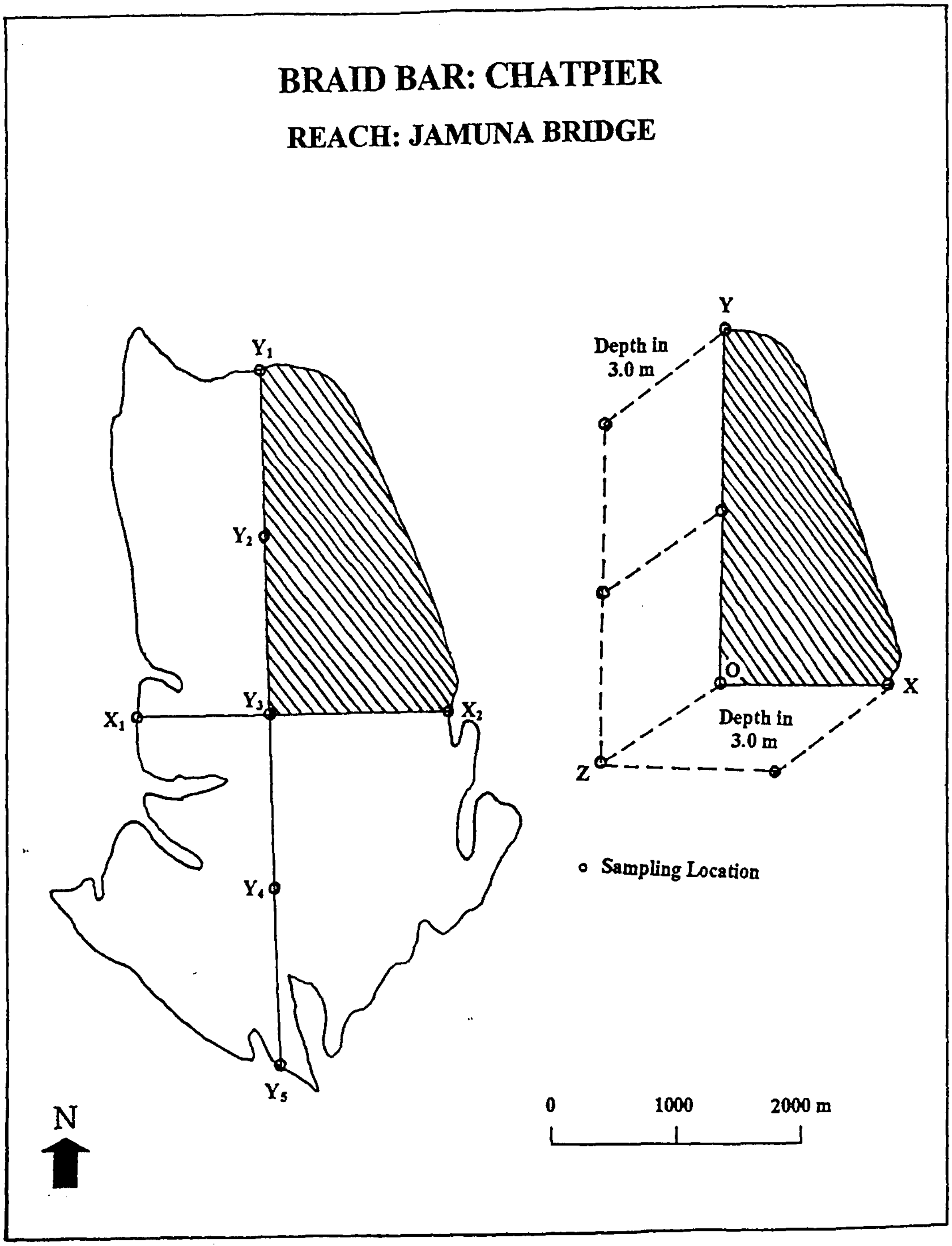


Figure 4.2: Diagrammatic representation of longitudinal (Y), lateral (X) and vertical (Z) co-ordinates with sampling locations.

4.4. Sediment Sample Studies

Sediment grain size is the primary basis on which lithostratigraphic units are defined, and changes in grain size are among the most fundamental and readily observed features of sedimentary sequences (McCave & Syvitski, 1991; Paola *et al.*, 1992). The distribution of grain sizes is one of the most elementary properties of sedimentary deposits that can supply valuable clues to the environment of deposition; and the mineralogical composition of a sediment sample is often closely controlled by the sources of the detrital particles (Blatt, 1992).

A large and continually expanding range of laboratory methods has been developed over the decades to analyse loose sediment samples (Lewis, 1984; Tucker, 1988; McCave & Syvitski, 1991; Blatt, 1992; Lieberman, 1996), including sieving and electron microscopy. Choice of the best methods depends on the objective of the research and sediment size of the samples.

Several methods are generally used for detecting sediment particles and characterising particle size and size distribution. The size of fluvial sediments is mainly determined by either a nest of sieves, a settling tube or opto-electric detectors (Azzopardi, 1992; Robinson & Slingerland, 1998). Each method has some advantages but, unfortunately, they are too time consuming and it is not possible to insert the data directly into the computer for further analysis.

Recently, some new techniques have come into use – laser diffraction and light scattering analysers for the determination of grain size of detrital sediments (Figueiredo *et al.*, 1992; McCave & Syvtiski, 1996). But very few of them yield data well into the sub-micron range. The COULTER LS™ Laser Diffraction Particle Size Analyser, through its various models, has become an established and well evaluated method of sizing sediment particles (Konert & Vandenberghe, 1997). The main advantage of this method is that it can measure the size of sediment particles in the range of 0.04 μm to 2000 μm. This sophistication is partly due to the way precise measurement can be made quickly and easily using a computer program. And, it also stems from the flexibility of the technique, particularly the way it can be adapted to measure samples presented in various forms. Moreover, this technique can analyse grain size mathematically and that can produce an accurate, reproducible diagram of the size distribution.

The latest version of Coulter laser diffraction particle size analyser (LS230) was used to analyse the sediment samples collected in the field. 88 samples have been analysed to specify different statistical parameters and to identify the morphodynamic environment prevailing at the time of sediment accumulation. The primary software used was LS Control Program Version 2.11 for statistical parameters and sediment size trend analysis.

The mineralogical compositions of bar sediment deposits generally reflect the geology and landuse over which a watercourse flows, but very little standardised procedure has been introduced for these source studies (Merefield, 1995). The sources of sediment are difficult to trace and there is no accurate base on which to ascertain either from where or when the sediment load is being derived (Campbell, 1992). Likewise, sources of sediment in the development of braid bars in the Brahmaputra-Jamuna are difficult to trace, since large areas and many natural aspects are involved in depositional processes. However, information on the mineralogical composition that reflects the parent materials on which a river flows, can be used to trace sediment movement and to determine the place of sediment origin (Bogardi, 1974; Loughran & Campbell, 1995; Merefield, 1995). The present consideration is, therefore, confined to the study of the mineralogy of individual sediment samples and their characteristics, because they may be indicators of the nature of the source from which they were derived. Twenty-two representative samples were subjected to sediment mineralogy analysis. A comprehensive qualitative and quantitative analysis was carried out using a polarising petrographic microscope. The mode of occurrence of each individual detrital and authigenic components, and their relative abundance were carefully examined from standard thin sections of indurated sediment samples. The mineral contents of each slide were determined by particle counting.

4.5. Conclusion

Fluvial geomorphological research requires intensive monitoring of the study site and the collation of a large volume of data. For these data to become useful information, tools are needed to process the database in various ways. Indeed, Downs and Priestnall (1999) argued that remote sensing and geographic information systems offer the ideal framework to allow the integration and standardisation of fluvial parameters. These efficient tools allow geomorphologists to examine spatial relationships at a variety of timescales that would not be feasible using only fieldwork or traditional aerial photography. However, fieldwork is an integral part of the discipline (Walsh *et al.*, 1998).

The preceding sections outline the methods of data acquisition and analyses concerning braiding and channel morphodynamics of the Brahmaputra-Jamuna River. The main aim has been to maintain the quality of all methods consistent with accomplishing an end in a logical way.

CHAPTER V: CHANNEL BANK MORPHOLOGY AND DYNAMICS

5.1. Introduction

Understanding of controls on channel morphology and channel instability through time is critical to many geomorphological and river engineering problems (Milton *et al.*, 1995). A detailed knowledge of channel change of rivers is essential for the management of the river banks (e.g. river regulation, bank protection, bankline abandonment) and adjacent environments (e.g. floodplain dwellers, riverside structures, riparian ecosystems) (ASCE, 1998a). Moreover, by analysis of the changes in the pasts insight is developed to help understand the potential course of channel changes in the future (FAP 24, 1996b). This chapter considers the processes and extent of bank erosion and accretion, bankline shifting, and rate and magnitude of channel width change to gain a more comprehensive understanding of the channel bank morphodynamics of the Brahmaputra-Jamuna River.

5.2. Bankline Dynamics

5.2.1. Methodology

Satellite remote sensing and geographic information systems are emerging tools in geomorphological studies. Yet, there is no universally applicable satellite image processing system for monitoring and analysing change in the fluvial environment (Milton *et al.*, 1995). A large range of methods has evolved, reflecting, amongst other things, different research aims, logistical constraints, site characteristics, disciplinary backgrounds of workers and, especially, timescale of interest (Lawler, 1993; Lawler *et al.*, 1997). However, a GIS for fluvial geomorphology uses accurate and efficient remote sensing data holding, extraction and processing functions to provide the best practicable approach (Downs & Priestnall, 1999). Also, the interrelationships of scale, pattern, and processes of the fluvial systems can be explored within a spatial domain afforded through GIS and field data (Walsh *et al.*, 1998).

ArcView GIS has been a widely adopted tool in geomorphological studies. At the most advanced, the ArcView GIS program is the latest extension of integration between satellite image and field based data analysis (Johnston, 1998). It allows use of the best format for the data and provides functionality to enable data sets to be integrated with ease. ArcView can load any data that is linked to geographic locations and display it graphically as maps, charts and tables. It allows the user to edit the data, change the way it is displayed, append additional data, create data of its own, perform queries to answer specific questions or meet specific criteria and analyse the information statistically as well as spatially. The reach-scale bankline dynamics study of the Brahmaputra-Jamuna was based on analysis of digital Landsat images. Processing and analysis of the Landsat images were performed using the ArcView GIS (version 3.1) program.

5.2.2. Bankline Delimitation

Channel planform in braided rivers is highly stage dependent, as well as altering over time through erosion and accretion (Bristow, 1987; Ferguson & Ashworth, 1992; Bridge, 1993; Bristow & Best, 1993). Delimitation of active channel perimeters at different flow stages is not a simple basis for the quantification of channel configuration and change because braided channels show different planform patterns at different stages. It is, therefore, essential to define the channel planform pattern on a certain flow stage that has significant impact on the drainage network and infrastructure development. The other aspect of the channel configuration that must be considered is the morphologically 'effective' discharge which provides a working approximation for generalising the channel behaviour.

To delimit the banklines of the two reaches of the Brahmaputra-Jamuna River, dry period georeferenced Landsat imageries have been considered. The basis of selection of this particular period is twofold. Firstly, the dry period satellite imagery is required to analyse its exposed morphological features (floodplains, bars, banklines, etc.) because at the time of high flow stage most of the features are submerged and the river course exhibits almost straight patterns, and it is not possible to assess erosional and depositional modification of morphological features. Secondly, only dry period cloud-free georefenced imageries and hydrological information are available for the selected study reaches. It is to be noted here that the range of flow stage variations on geomorphic features on the different dates of image acquisition (see Table 4.1) was insignificant (0.87 m at Bahadurabad Ghat Reach and 1.03 m at Jamuna Bridge Reach) compared to annual low flow and high flow stage differences (8.92 m and 9.07 m, respectively).

To delimit the river banks, digital images were firstly displayed and visually interpreted on a computer monitor, and provisional banklines (that encompassed active river channels, island bars and attached bars, and separated floodplains) were delineated using the ArcView line theme algorithm (see Appendix I). The provisional banklines were then retested with the field-registered GPS readings by locating a ground value of GPS at its correct position on the image. These iterative processes yielded the most consistent delineated banks for the image of 1997 (Fig. 5.1) that correspond to the in-situ field observations.

However, for the other years' images, it was not be possible to retest demarcated banklines as no ground truth information was available. Active river channels are

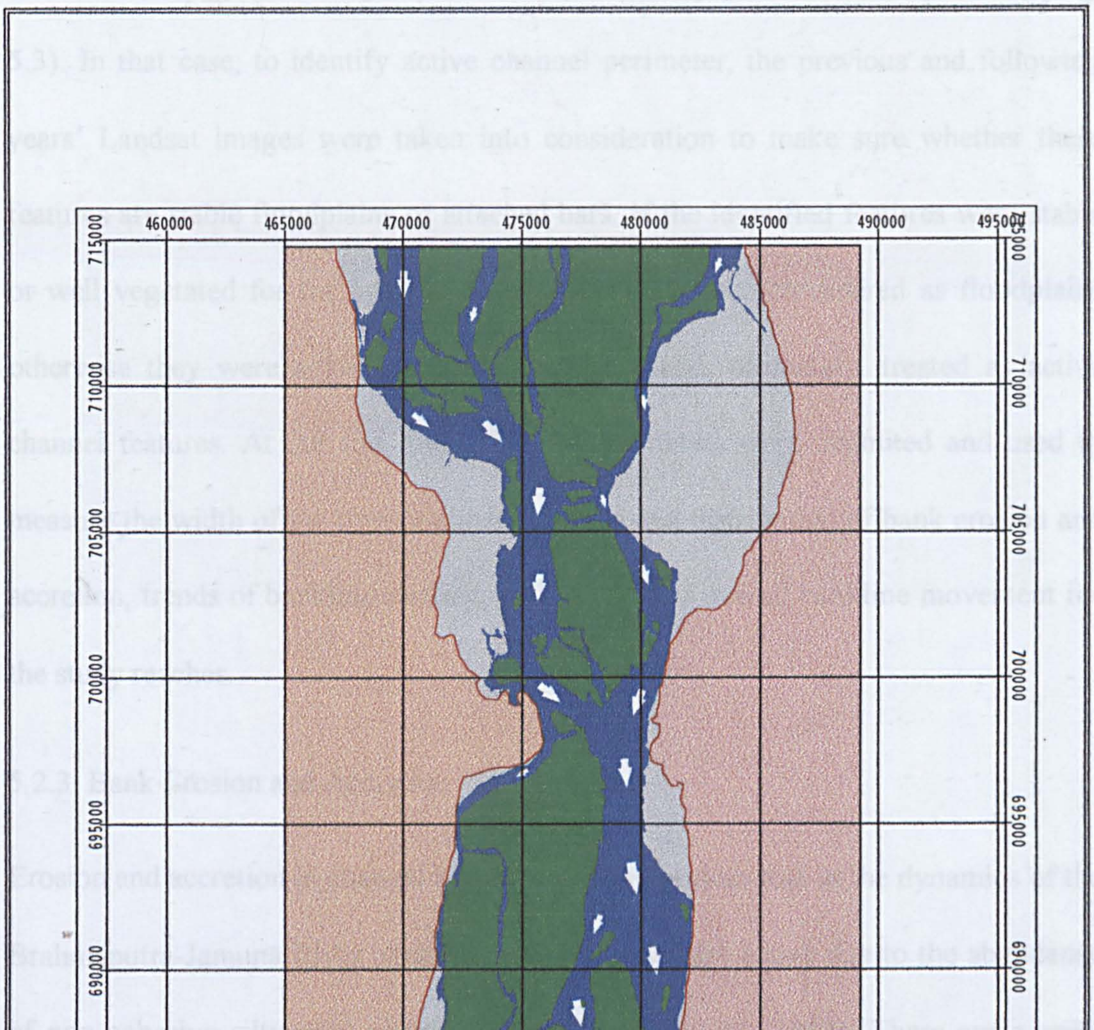


Figure 5.1: Delimited channel perimeter on 1997 Landsat imagery at Jamuna Bridge Reach.

characterised by both erosional and depositional features. Erosive channel banks were easy to recognise (Fig.5.2), but accretionary channel banks were somewhat difficult to separate from floodplain because of the presence of attached bars (Fig. 5.3). In that case, to identify active channel perimeter, the previous and following years' Landsat images were taken into consideration to make sure whether these features are stable floodplains or attached bars. If the identified features were stable or well vegetated for the last few years, then they were considered as floodplains otherwise they were adjudged as attached bars and, ultimately, treated as active channel features. At the end, final channel perimeters were delimited and used to measure the width of the river, estimate the rate and distribution of bank erosion and accretion, trends of bankline shifting, and patterns of overall bankline movement for the study reaches.

5.2.3. Bank Erosion and Accretion

Erosion and accretion in channel banks have an important role in the dynamics of the Brahmaputra-Jamuna River because these processes are active due to the abundance of non-cohesive silty-sand in both banks (Thorne *et al.*, 1993). There are a good number of studies on bank erosion and rates of bankline migration along the entire course of the Brahmaputra-Jamuna (e.g. Klaassen & Massenlink, 1992; Thorne *et al.*, 1993; FAP 19, 1995; Mosselman *et al.*, 1995; FAP 24, 1996b). These studies have been mainly qualitative and most lack a quantitative estimation. Moreover, all of these studies were primarily concerned with channel bank erosion and no attempt has been made to measure reach-scale bank accretion. This section of the thesis attempts to quantify the actual rates of annual bank erosion and accretion along the two selected reaches based on satellite images and field studies.

Figure 5.2: Left bank erosion by slab failure at Jamuna Bridge Reach.

Figure 5.3: Right bank accretion by merging attached bar at Jamuna Bridge Reach.

5.2.3.1. Estimation of Bank Erosion and Accretion

Bank erosion and accretion processes were observed and estimated from the delimited banklines on Landsat imageries at both reaches. Estimation of the total area of the east and west banks were performed within ArcView GIS. As the total area of each year's image frame is exactly similar to each other for a particular reach (total area of each year's image frame for the Bahadurabad Ghat and Jamuna Bridge reaches are 582.06 km^2 and 592.92 km^2, respectively), and as there was no significant influence of flow stages on the river banks, the measured area of bank erosion and accretion was thought to be more accurate than ground survey methods for such a large river. Year-wise measured bank area (in hectares) at two selected sites are given in tabular form (Table 5.1) with explanations in the following.

Table 5.1: Year-wise measured bank area (in ha) for the two reaches.

Year	Bahadurabad Ghat Reach		Jamuna Bridge Reach	
	East Bank	West Bank	East Bank	West Bank
1987	15973	13604	18262	15986
1989	14810	12384	16521	15237
1992	14708	11878	15599	14317
1994	14245	11953	15489	14287
1995	14228	11821	14663	14269
1996	13695	11835	14824	13977
1997	13606	11496	14740	14635

5.2.3.2. Rates of Bank Erosion and Accretion at Bahadurabad Ghat Reach

Erosion and accretion of the east and west banks between 1987 and 1997 have been calculated from the measurements (Table 5.1) of total bank area. The surface area of the two banks between two successive years was compared and overall rates of erosion and accretion are given in Table 5.2. The net distribution of bank erosion and accretion between 1987 and 1997 is mapped in Figure 5.4.

The result show that over the entire study reach bank erosion during the period was severe compared to bank accretion. The rate of bank erosion during 1987-1989 was

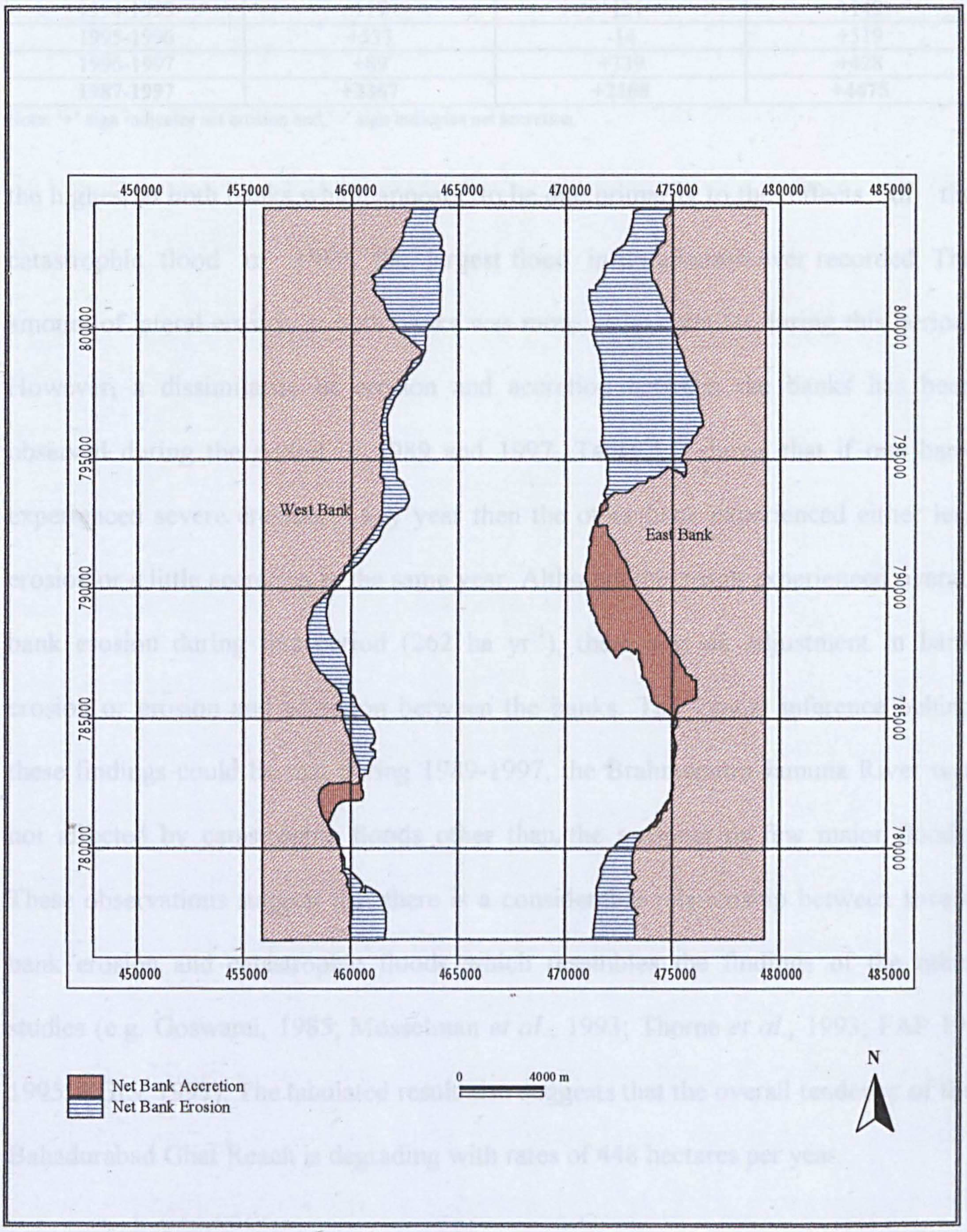


Figure 5.4: Bank accretion and erosion at Bahadurabad Ghat Reach during 1987-1997.

Table 5.2: Rates of bank erosion and accretion at Bahadurabad Ghat Reach (in ha).

Period	East Bank	West Bank	Total
1987-1989	+1163	+1220	+2383
1989-1992	+102	+506	+608
1992-1994	+463	-74	+389
1994-1995	+17	+131	+148
1995-1996	+533	-14	+519
1996-1997	+89	+339	+428
1987-1997	**+2367**	**+2108**	**+4475**

Note: '+' sign indicates net erosion and '–' sign indicates net accretion.

the highest at both banks which appears to be due primarily to the effects of the catastrophic flood of 1988, the largest flood in Bangladesh ever recorded. The amount of lateral erosion at both banks was more or less similar during this period. However, a dissimilarity of erosion and accretion between the banks has been observed during the period of 1989 and 1997. Table 5.2 shows that if one bank experienced severe erosion in any year then the other bank experienced either less erosion or a little accretion in the same year. Although this reach experienced overall bank erosion during this period (262 ha yr^{-1}), there was an adjustment in bank erosion or erosion and accretion between the banks. The logical inference behind these findings could be that during 1989-1997, the Brahmaputra-Jamuna River was not affected by catastrophic floods other than the seasonal or few major floods. These observations suggest that there is a considerable relationship between severe bank erosion and catastrophic floods which resembles the findings of the other studies (e.g. Goswami, 1985; Mosselman *et al.*, 1993; Thorne *et al.*, 1993; FAP 19, 1995; EGIS, 1997). The tabulated result also suggests that the overall tendency of the Bahadurabad Ghat Reach is degrading with rates of 448 hectares per year.

5.2.3.3. Rates of Bank Erosion and Accretion at Jamuna Bridge Reach

The Jamuna Bridge Reach is the narrowest reach (nodal reach) within the entire length of the Brahmaputra-Jamuna River and is located a distance of about 70 km downstream from the Bahadurabad Ghat Reach. Historical evidence suggests that this was the most stable reach over the centuries on the river and it has been chosen for the construction of the world's 11th largest bridge (JBAS, 1986; JBS, 1988). Up until 1989 this reach had been remarkably stable, although the upper and lower parts of the reach were regularly affected by bank erosion (Thorne *et al.*, 1993). This study reach showed severe bank erosion during the 1987-1989 period at both banks (Table 5.3) because of the 1988 catastrophic flood which was followed by considerable erosion over the 1989-1992 period.

Table 5.3: Rates of bank erosion and accretion at Jamuna Bridge Reach (in ha).

Period	East Bank	West Bank	Total
1987-1989	+1741	+749	+2490
1989-1992	+922	+920	+1842
1992-1994	+110	+30	+140
1994-1995	+826	+18	+844
1995-1996	-161	+292	+131
1996-1997	+84	-658	-574
1987-1997	**+3522**	**+1351**	**+4873**

Note: '+' sign indicates net erosion and '–' sign indicates net accretion.

The rate of bank erosion during 1992-1997 was not uniform and balanced between the banks. This inconsistent behaviour was due to the engineering works prior to the construction of the Jamuna Multipurpose Bridge. It is evident from the studies of the Jamuna Multipurpose Bridge Authority (JMBA, 1996) that after the inception of the bridge project, the most stable middle stretch of this reach has begun to expand by severe bank erosion (JMBP Survey Report, 1997). To restrict bank erosion, JMBA constructed *Guide Bunds* (concrete structures) at both banks to maintain constant width. As a result the upper and lower part of the bridge site outside of the *Guide Bunds*, experienced sustained bank erosion (272 ha yr^{-1}); however, moderate accretion was observed (819 ha during 1995-1997 period) around the *Guide Bunds* (Fig. 5.5). These imbalanced rates of erosion and accretion at both banks are apparently due to river training works and they do indicate the future unpredictability of the Jamuna Bridge Reach (JMBP Survey Report, 1997).

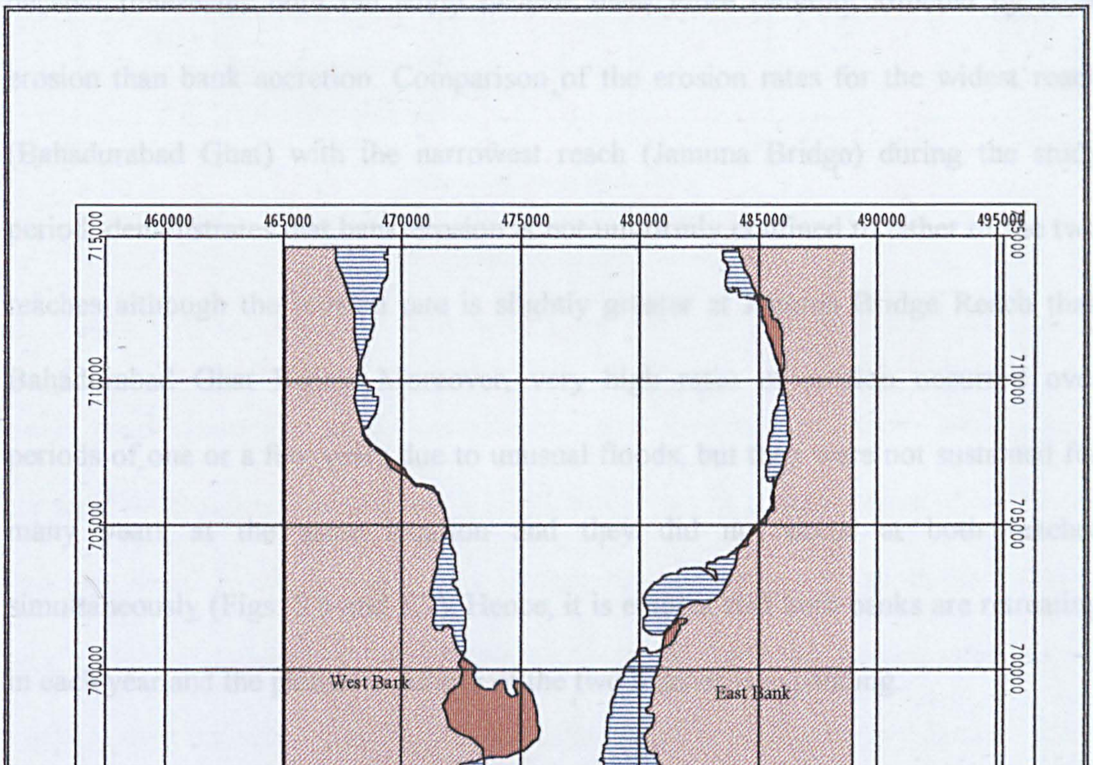


Figure 5.5: Bank accretion and erosion at Jamuna Bridge Reach during 1987-1997.

5.2.3.4. Comparison of Bank Erosion and Accretion between the Reaches

The figures and tables presented in the previous sections indicate that over the decadal timescales both the study reaches were more severely affected by bank erosion than bank accretion. Comparison of the erosion rates for the widest reach (Bahadurabad Ghat) with the narrowest reach (Jamuna Bridge) during the study period, demonstrates that bank erosion is not uniformly confined to either of the two reaches although the erosion rate is slightly greater at Jamuna Bridge Reach than Bahadurabad Ghat Reach. Moreover, very high rates of erosion occurred over periods of one or a few years due to unusual floods, but they were not sustained for many years at the same location and they did not occur at both reaches simultaneously (Figs. 5.6 and 5.7). Hence, it is evident that both banks are retreating in each year and the planform pattern of the two reaches is expanding.

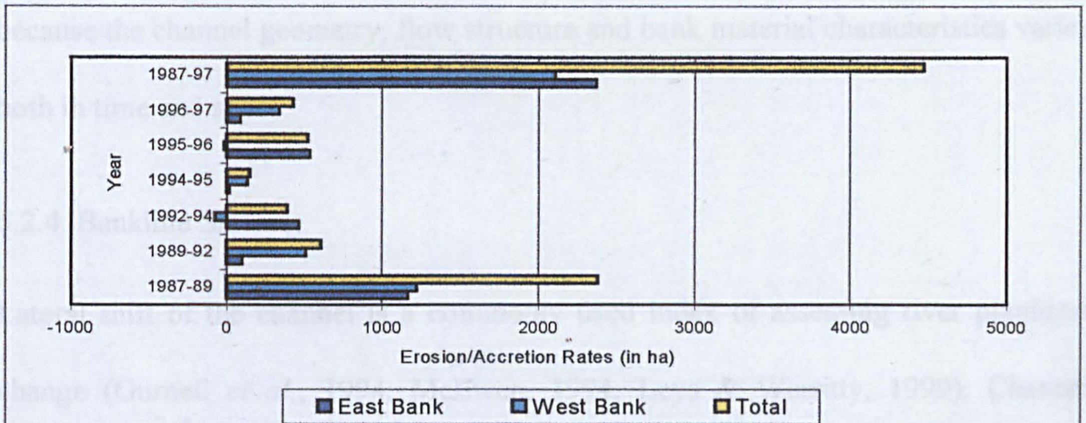


Figure 5.6: Distribution of bank erosion and accretion at Bahadurabad Ghat Reach.

References to earlier studies carried out on the Brahmaputra-Jamuna riverbank erosion (e.g. Thorne *et al.*, 1993; FAP 19, 1995) indicates that overall bank erosion rates are more severe (90 to 100 myr^{-1}) on the west bank than the east bank (40 to 50 myr^{-1}), and the river has moved westward during the last three decades. The present findings disagree with the earlier postulations as the latter estimations were based on

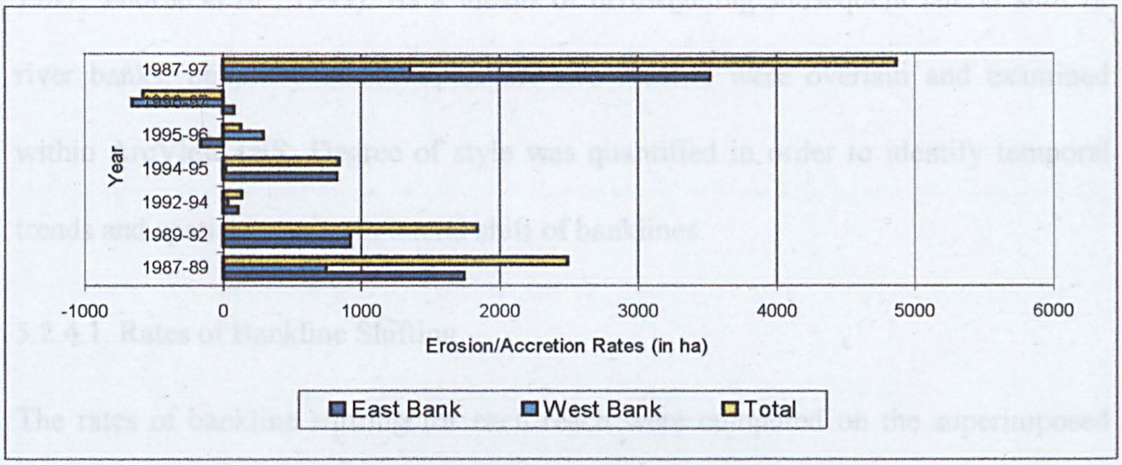


Figure 5.7: Distribution of bank erosion and accretion at Jamuna Bridge Reach.

linear measurements at single locations and thus involved uncertainty arising from the fact that erosion or accretion at a location may not be representative of conditions in a long reach. However, the present findings are consistent with some other studies (e.g. Coleman, 1969; FAP 24, 1996b), and indicate that bank erosion rates are not uniform over the entire length between the banks of the Brahmaputra-Jamuna River because the channel geometry, flow structure and bank material characteristics varies both in time and space.

5.2.4. Bankline Shifting

Lateral shift of the channel is a commonly used index of assessing river planform change (Gurnell *et al*., 1994; McEwen, 1994; Leys & Werritty, 1999). Channel shifting is essentially a vector property, with channels moving both laterally and vertically through processes such as bank erosion, accretion, avulsion and bend migration (Leys & Werritty, 1999). The flexibility of the satellite image processing techniques is such that they enable monitoring of bank shifting in a large river such as the Brahmaputra-Jamuna (Bristow, 1987). Channel moving in the Brahmaputra-Jamuna River occurs frequently at a variety of magnitudes (Coleman, 1969; Bristow, 1987; Thorne *et al.*, 1993). As a means of investigating subsequent lateral shift of river banks, delimited banklines of the two reaches were overlain and examined within ArcView GIS. Degree of style was quantified in order to identify temporal trends and spatial patterns in lateral shift of banklines.

5.2.4.1. Rates of Bankline Shifting

The rates of bankline shifting for each reach were computed on the superimposed outlines of the image series. In order to obtain an overall pattern of the bankline shifting, every single image for each reach was divided into 4 equal cross-sections approximately 10 kilometres apart (Figs. 5.8 and 5.9). Cross-sections were positioned by their northings and eastings (in metre) and their values were then tabulated (Tables 5.4 and 5.5).

Table 5.4: Measured northing and easting (in m) at Bahadurabad Ghat Reach.

North -ing	Easting													
	1987		1989		1992		1994		1995		1996		1997	
	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank
804790	463184	471708	462962	472230	462810	472384	462582	472372	462430	472382	462356	472534	462348	472840
795218	461512	470122	461368	471088	461292	471776	461286	473142	461216	473144	461220	473218	461140	473446
785644	460092	473798	459772	473674	459680	472460	459620	472384	459392	472232	459544	472080	459620	472088
776072	462600	469620	461290	469952	460076	470788	460000	470864	459998	471092	460076	471086	459924	471420

Table 5.5: Measured northing and easting (in m) at Jamuna Bridge Reach.

North -ing	Easting													
	1987		1989		1992		1994		1995		1996		1997	
	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank	West Bank	East Bank
714824	469765	481256	469416	482456	468496	482446	468266	482378	468036	482480	467958	482500	467966	482402
705134	472126	483617	471946	483376	472024	483298	472022	483222	471948	483376	472022	483682	472030	482452
695440	473700	477635	473558	478542	472638	479330	472484	480154	472402	480308	472408	480232	472310	480460
685750	470945	478973	470872	479632	470950	479618	470744	479310	470644	479318	470642	479694	470636	480002

Bankline shifting was computed on each northing at both banks by subtracting one year's easting from the previous year's easting. Westward shifting is indicated by 'W' sign and eastward shifting by 'E' sign. Comparative rates of bankline movement for the measured reaches are given in tabular form (Tables 5.6 and 5.7) and the explanations are summarised below.

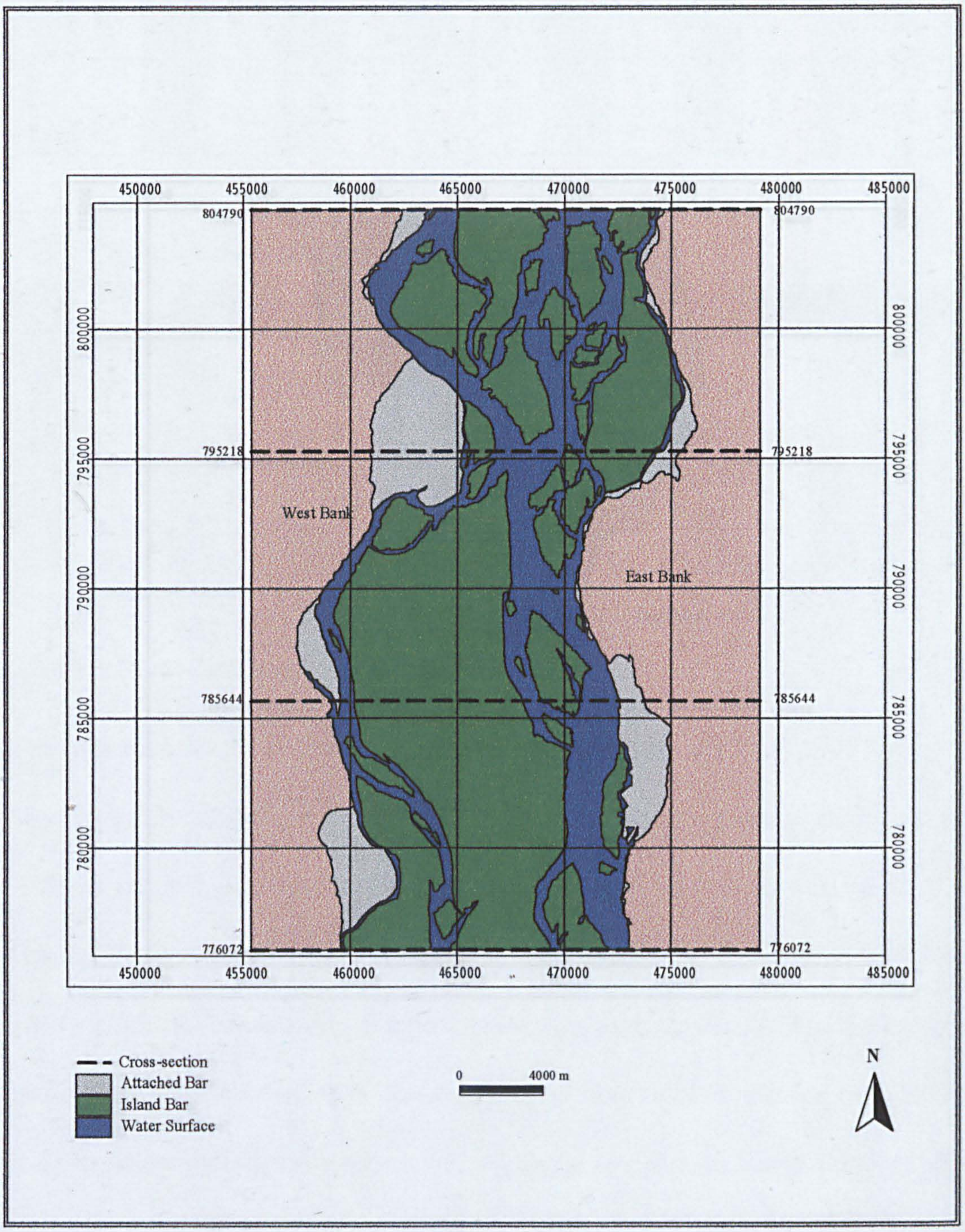


Figure 5.8: Map showing 4 cross-section locations at Bahadurabad Ghat Reach.

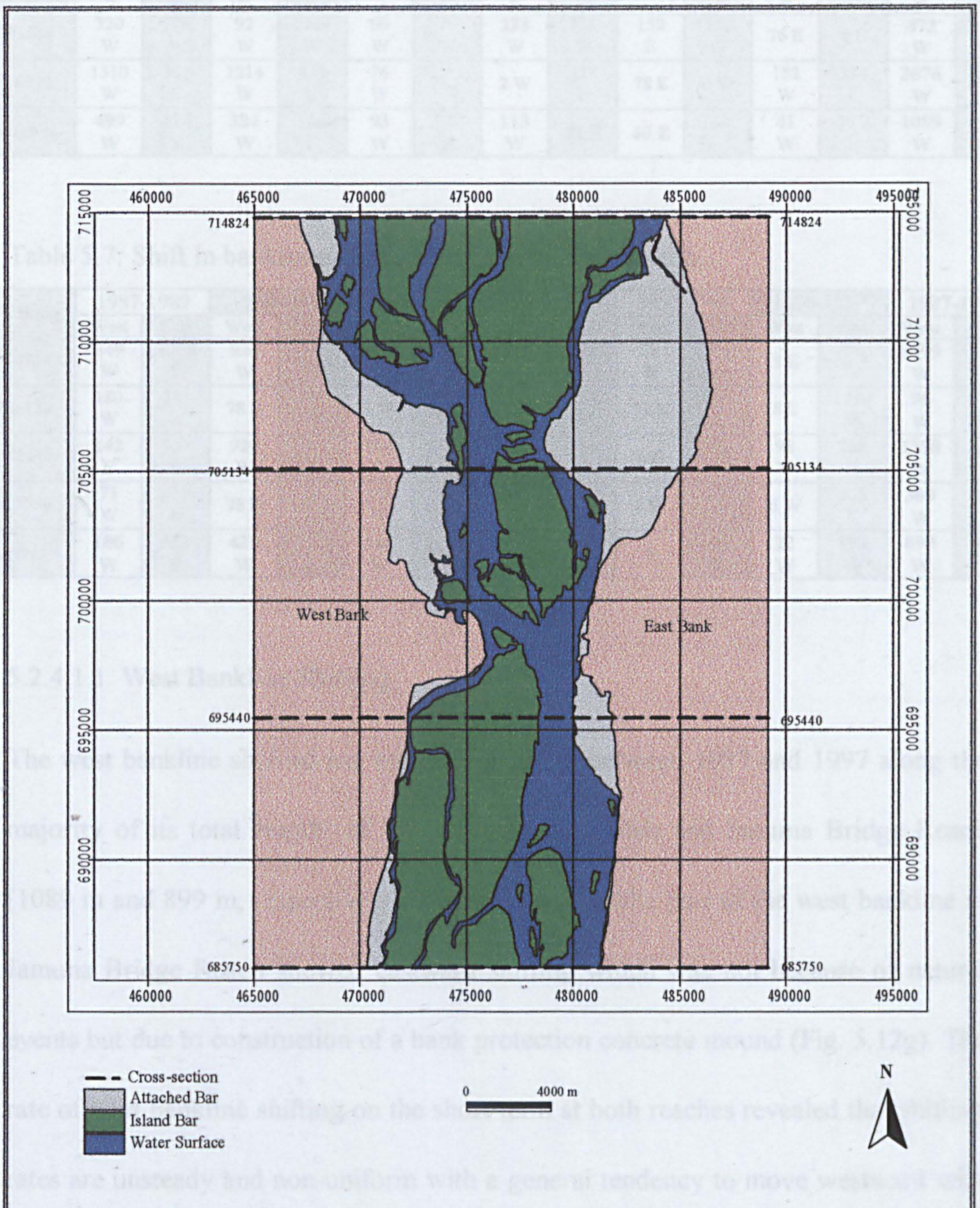


Figure 5.9: Map showing 4 cross-section locations at Jamuna Bridge Reach.

Table 5.6: Shift in banklines (in m) at Bahadurabad Ghat Reach.

Northing	1987-1989		1989-1992		1992-1994		1994-1995		1995-1996		1996-1997		**1987-1997**	
	West	East	West	East	West	East	West	East	West	East	West	East	**West**	**East**
804790	222 W	522 E	152 W	154 E	228 W	12W	152 W	10 E	74 W	152 E	8 W	306 E	**836 W**	**1132 E**
795218	144 W	966 E	76 W	688 E	6 W	1366 E	70 W	2 E	4 E	74 E	80 W	228 E	**372 W**	**3324 E**
785644	320 W	124 W	92 W	1214 W	60 W	76 W	228 W	152 W	152 E	152 W	76 E	8 E	**472 W**	**1710 W**
776072	1310 W	322 E	1214 W	836 E	76 W	76 E	2 W	228 E	78 E	6 W	152 W	334 E	**2676 W**	**1800 E**
Average	**499 W**	**424 E**	**384 W**	**116 E**	**93 W**	**339 E**	**113 W**	**22 E**	**40 E**	**17 E**	**41 W**	**219 E**	**1089 W**	**1137 E**

Table 5.7: Shift in banklines (in m) at Jamuna Bridge Reach.

Northing	1987-1989		1989-1992		1992-1994		1994-1995		1995-1996		1996-1997		**1987-1997**	
	West	East	West	East	West	East	West	East	West	East	West	East	**West**	**East**
714824	349 W	1200 E	920 W	10 W	230 W	68 W	230 W	102 E	78 W	20 E	8 E	98 W	**1799 W**	**1146 E**
705134	180 W	241 W	78 E	78 W	2 W	76 W	74 W	154 E	74 E	306 E	8 E	1230 W	**96 W**	**1165 W**
695440	142 E	907 E	920 W	788 E	154 W	824 E	82 W	154 E	6 E	76 W	98 W	228 E	**1390 W**	**2825 E**
685750	73 W	659 E	78 E	14 W	206 W	308 W	100 W	8 E	2 W	376 E	6 W	308 E	**309 W**	**1029 E**
Average	**186 W**	**631 E**	**421 W**	**172 E**	**148 W**	**93 E**	**122 W**	**105 E**	**0**	**157 E**	**22 W**	**198 W**	**899 W**	**959 E**

5.2.4.1.1. West Bankline Shifting

The west bankline showed net westward shifting between 1987 and 1997 along the majority of its total length of the Bahadurabad Ghat and Jamuna Bridge Reach (1089 m and 899 m, respectively). Although the middle part of the west bankline at Jamuna Bridge Reach showed eastward shifting which was not because of natural events but due to construction of a bank protection concrete mound (Fig. 5.12g). The rate of west bankline shifting on the short-term at both reaches revealed that shifting rates are unsteady and non-uniform with a general tendency to move westward with few exceptions (Figs. 5.10 and 5.12). During the 1995-1996 period, the west banklines of Jamuna Bridge Reach appeared almost stable (Fig. 5.12e), while the Bahadurabad Ghat Reach showed little eastward movement (40 m) due to embayment aggradation (Fig. 5.10e).

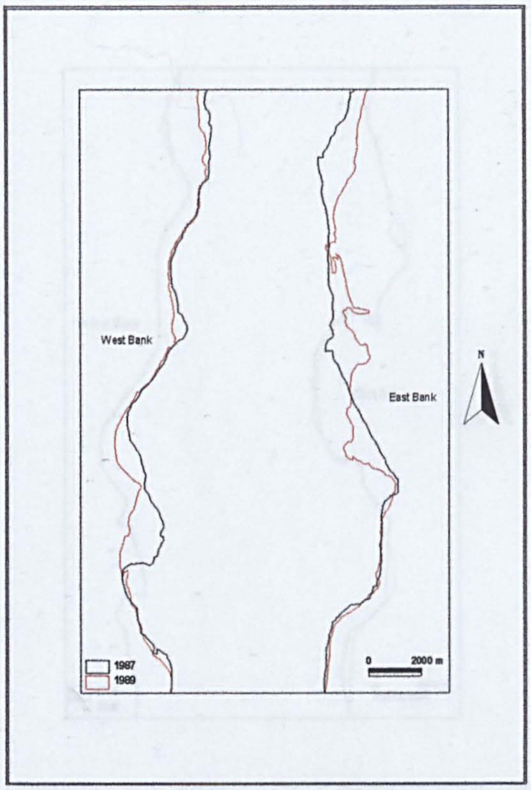


Figure 5.10a: Overlay map showing bankline shifting of Bahadurabad Ghat Reach during 1987-1989.

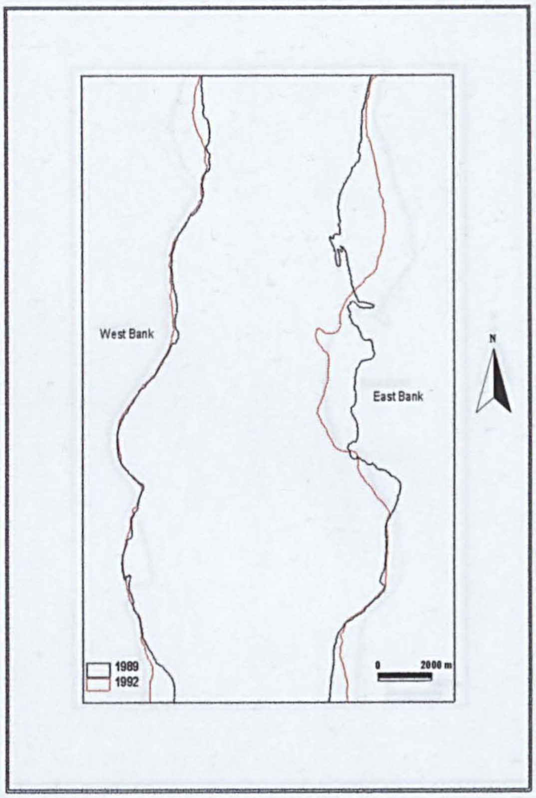


Figure 5.10b: Overlay map showing bankline shifting of Bahadurabad Ghat Reach during 1989-1992.

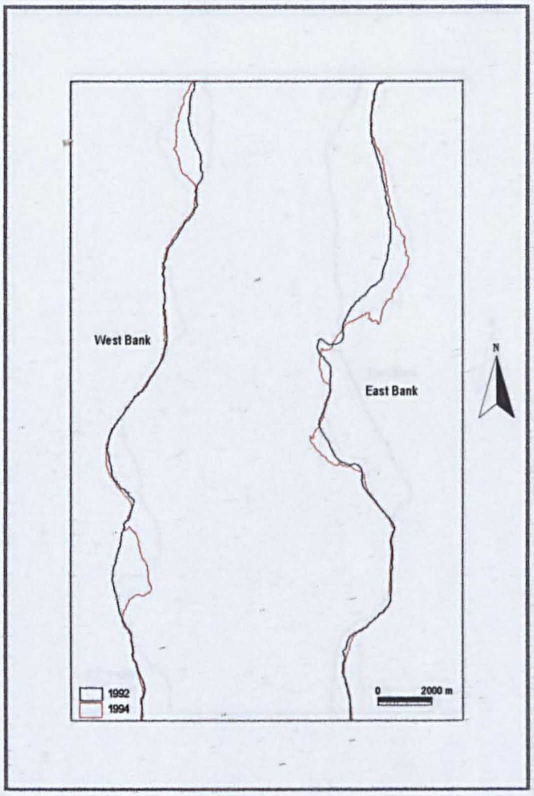


Figure 5.10c: Overlay map showing bankline shifting of Bahadurabad Ghat Reach during 1992- 1994.

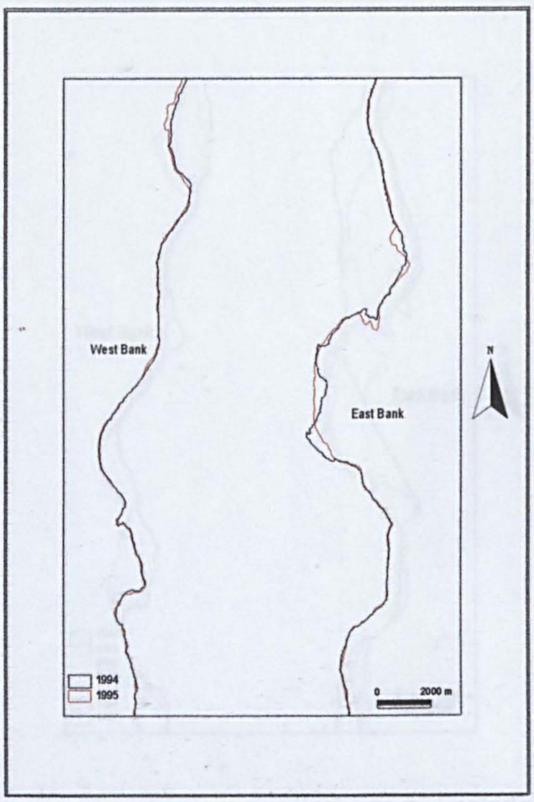


Figure 5.10d: Overlay map showing bankline shifting of Bahadurabad Ghat Reach during 1994-1995.

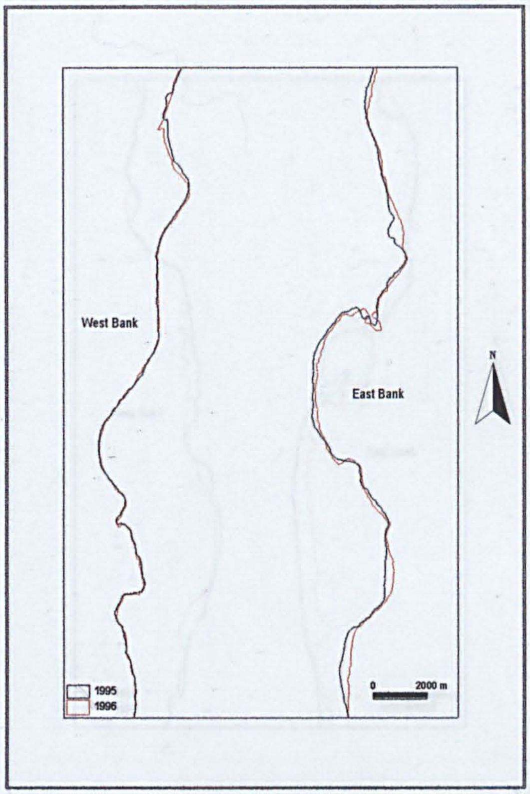


Figure 5.10e: Overlay map showing bankline shifting of Bahadurabad Ghat Reach during 1995-1996.

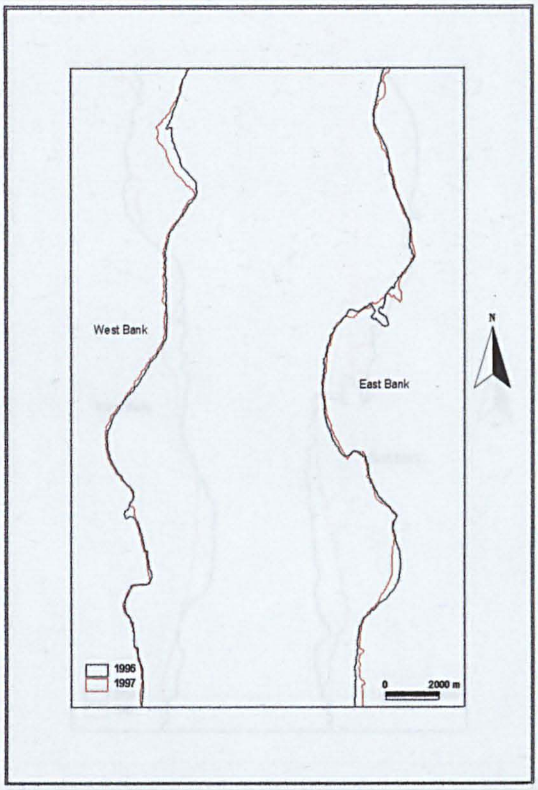


Figure 5.10f: Overlay map showing bankline shifting of Bahadurabad Ghat Reach during 1996-1997.

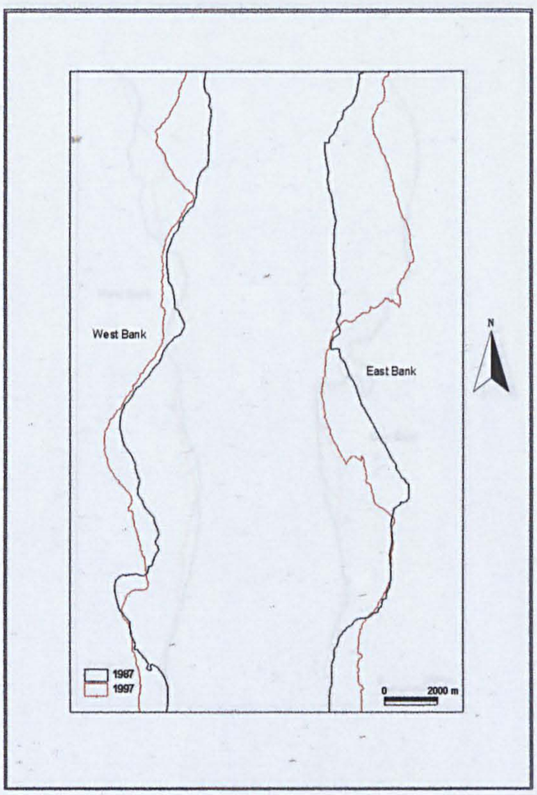


Figure 5.10g: Overlay map showing bankline shifting of Bahadurabad Ghat Reach for the years 1987 and 1997.

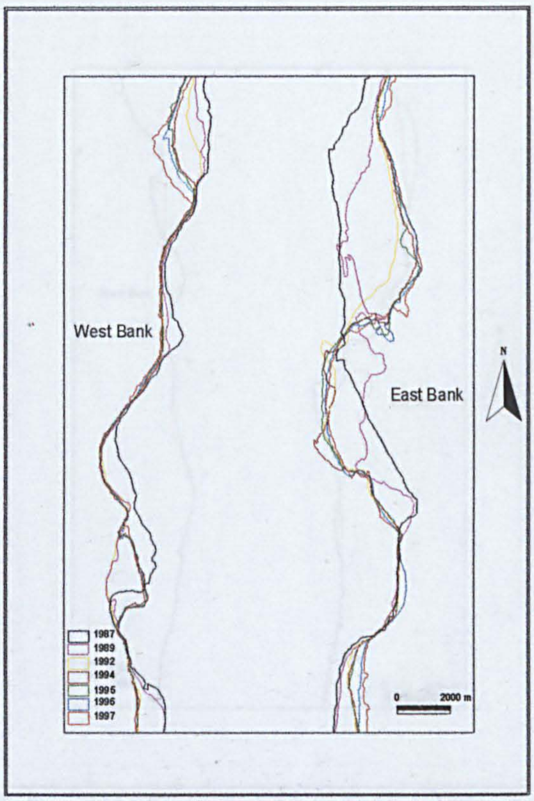


Figure 5.11: Overlay map showing bankline shifting of Bahadurabad Ghat Reach during 1987-1997.

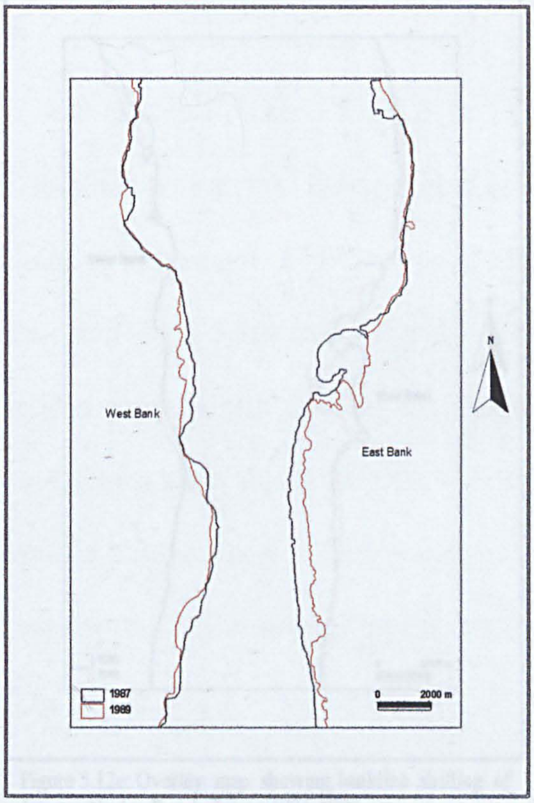


Figure 5.12a: Overlay map s howing bankline shifting of Jamuna Bridge Reach during 1987-1989.

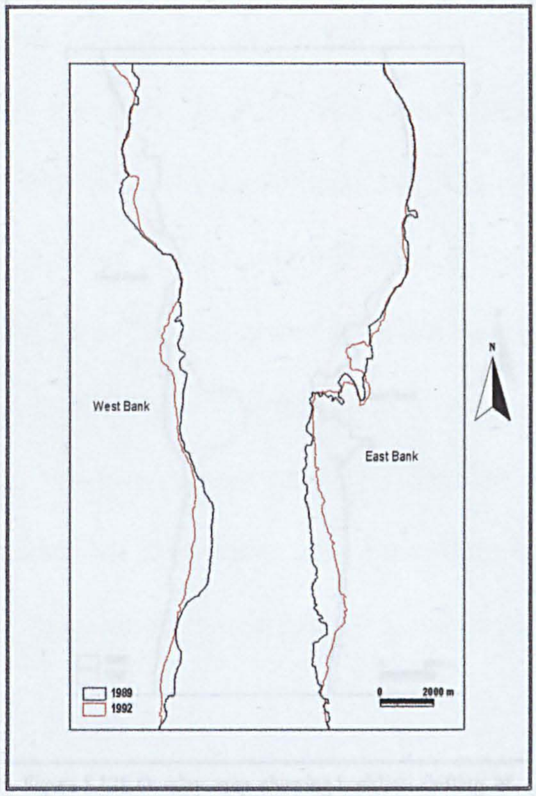


Figure 5.12b: Overlay map showing bankline shifting of Jamuna Bridge Reach during 1989-1992.

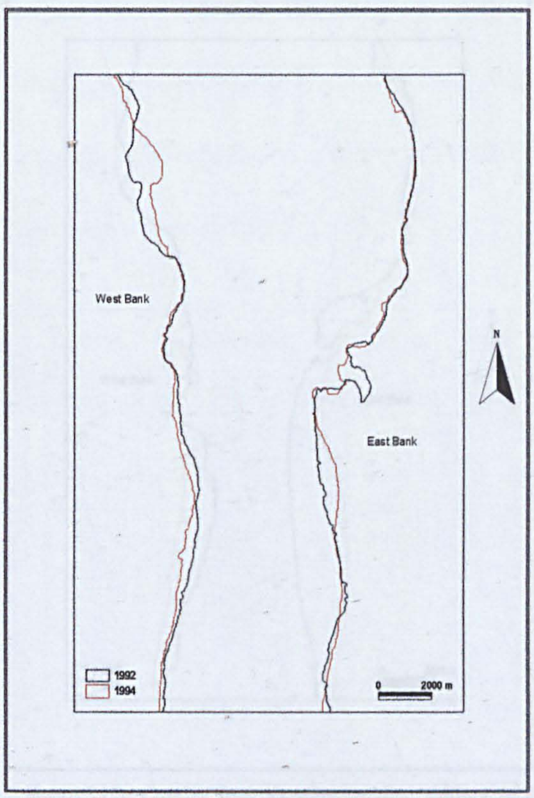


Figure 5.12c: Overlay map showing bankline shifting of Jamuna Bridge Reach during 1992-1994.

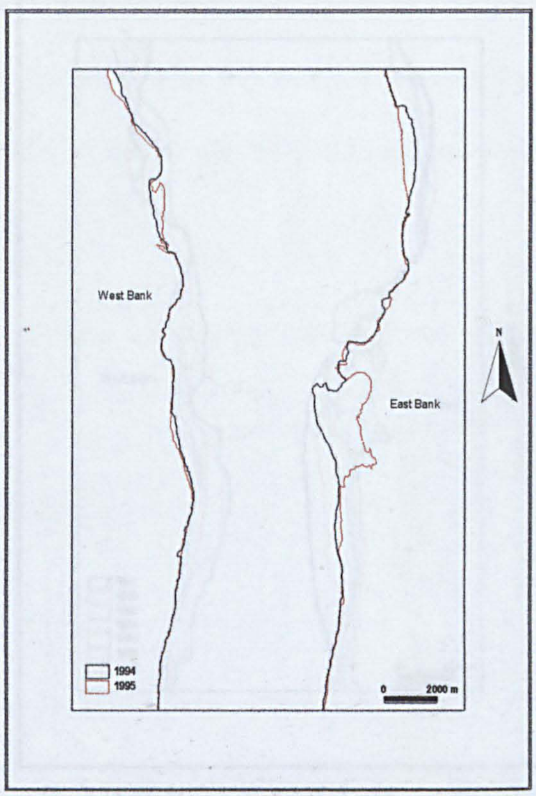


Figure 5.12d: Overlay map showing bankline shifting of Jamuna Bridge Reach during 1994-1995.

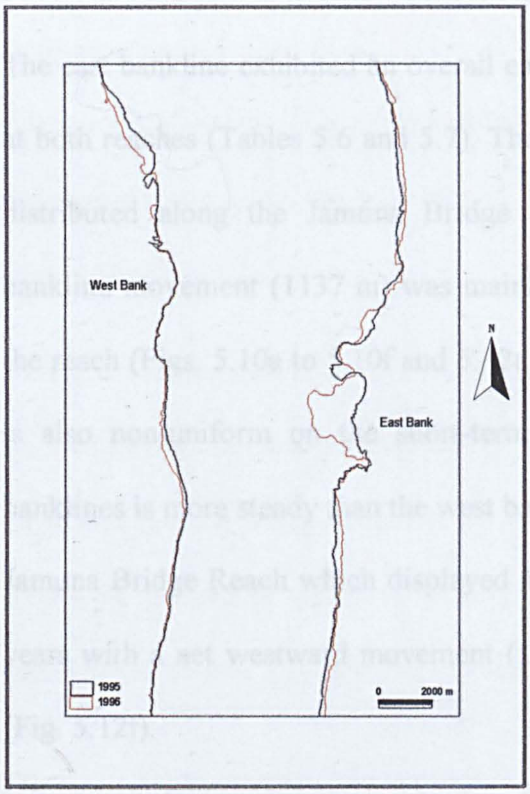


Figure 5.12e: Overlay map showing bankline shifting of Jamuna Bridge Reach during 1995-1996.

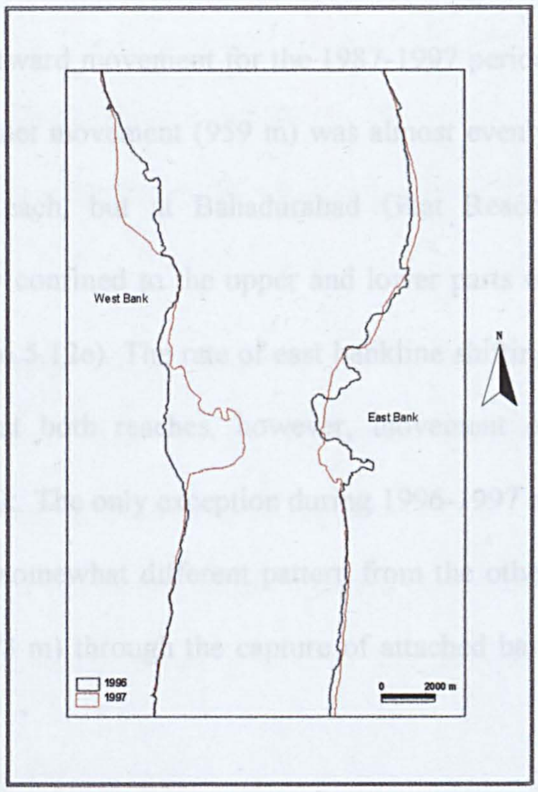


Figure 5.12f: Overlay map showing bankline shifting of Jamuna Bridge Reach during 1996-1997.

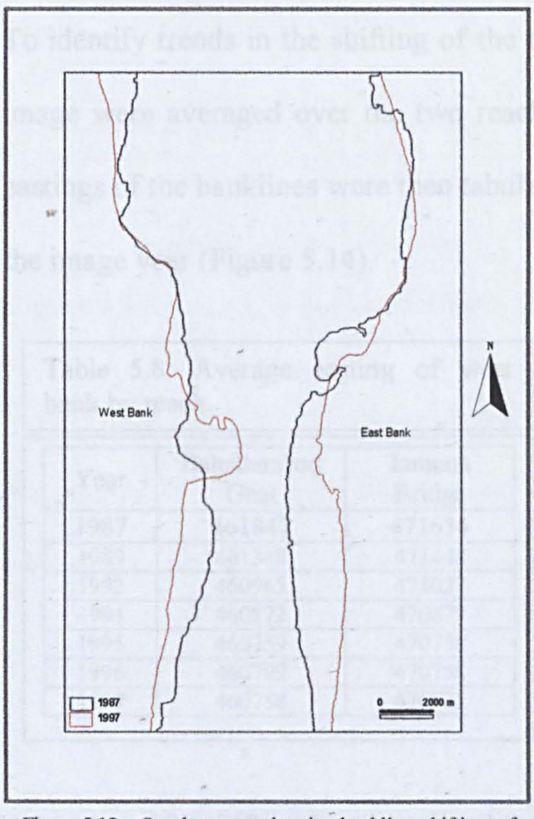


Figure 5.12g: Overlay map showing bankline shifting of Jamuna Bridge Reach for the years 1987 and 1997.

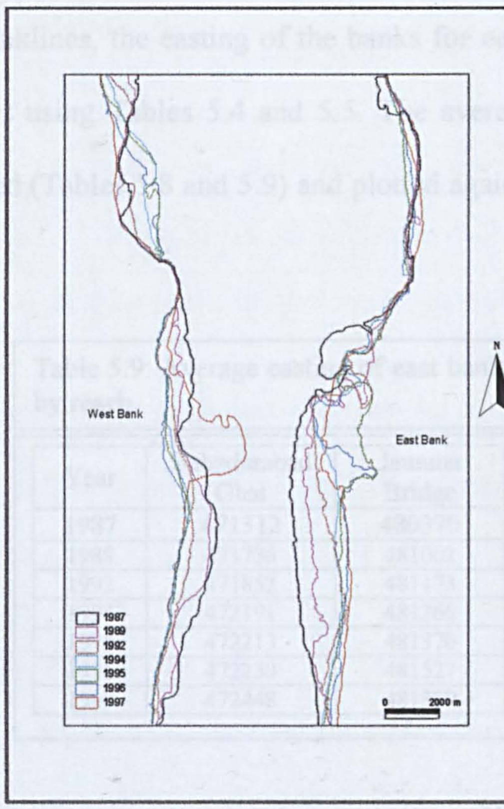


Figure 13: Overlay map showing bankline shifting of Jamuna Bridge Reach during 1987-1997.

5.2.4.1.2. East Bankline Shifting

The east bankline exhibited an overall eastward movement for the 1987-1997 period at both reaches (Tables 5.6 and 5.7). The net movement (959 m) was almost evenly distributed along the Jamuna Bridge Reach, but at Bahadurabad Ghat Reach, bankline movement (1137 m) was mainly confined to the upper and lower parts of the reach (Figs. 5.10a to 5.10f and 5.12a to 5.12e). The rate of east bankline shifting is also non-uniform on the short-term at both reaches, however, movement of banklines is more steady than the west bank. The only exception during 1996-1997 at Jamuna Bridge Reach which displayed a somewhat different pattern from the other years with a net westward movement (198 m) through the capture of attached bars (Fig. 5.12f).

5.2.4.2. Trend of Bankline Shifting

To identify trends in the shifting of the banklines, the easting of the banks for each image were averaged over the two reaches using Tables 5.4 and 5.5. The average eastings of the banklines were then tabulated (Tables 5.8 and 5.9) and plotted against the image year (Figure 5.14).

Table 5.8: Average easting of west bank by reach.

Year	Bahadurabad Ghat	Jamuna Bridge
1987	461847	471634
1989	461348	471448
1992	460965	471027
1994	460872	470879
1995	460759	470758
1996	460799	470758
1997	460758	470735

Table 5.9: Average easting of east bank by reach.

Year	Bahadurabad Ghat	Jamuna Bridge
1987	471312	480370
1989	471736	481002
1992	471852	481173
1994	472191	481266
1995	472213	481370
1996	472230	481527
1997	472448	481329

Average easting for the west bankline shifted westward about 109 myr^{-1} at Bahadurabad Ghat Reach and about 90 myr^{-1} at Jamuna Bridge Reach during 1987-

1997, while the shifting of west banklines of both reaches varies for the two- or three-year periods (see Figs. 5.11 and 5.13). These variations are probably due to extreme flood events (e.g. 499 m at Bahadurabad Ghat Reach during 1987-1989) or major river training works (e.g. 421 m at Jamuna Bridge Reach during 1989-1992) (Fig. 5.14a).

Along the east bank (Fig. 5.14b) the average rate of bankline shifting for both reaches showed eastward movement (114 myr^{-1} and 96 myr^{-1} for the Bahadurabad Ghat and Jamuna Bridge reaches, respectively). Both reaches experienced two- to three-year periods of eastward shifting with fluctuating trends between the periods (see Tables 5.6 and 5.7). The only exception was observed at Jamuna Bridge Reach

(a) (b)

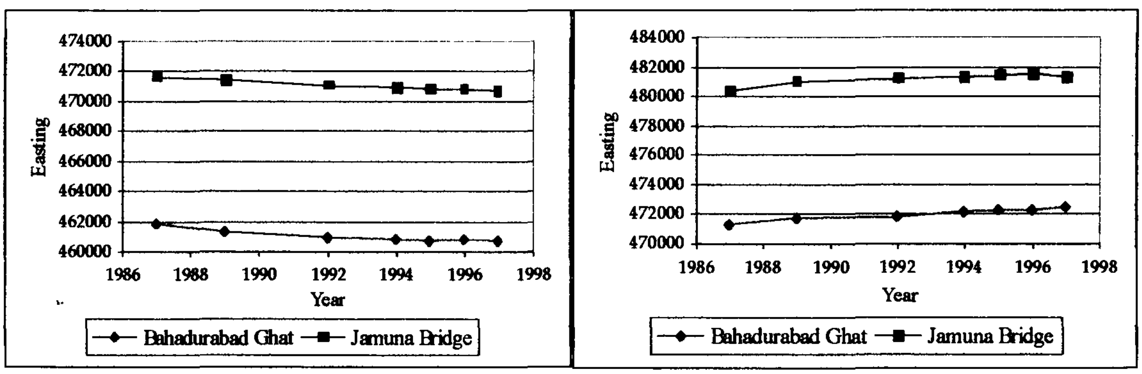


Figure 5.14: Trends in bankline shifting of (a) west bank and (b) east bank by reach.

during the 1996-1997 period due to the abandonment of second-order channels, and amalgamation between floodplains and bars. The overall unsettled shifting patterns of the east bank are also due to the same reasons as observed in the west bank.

It is evident from the previous discussions that the impact of the 1988 flood on bankline movement was widespread at both banks. It is also observed from Tables (5.6, 5.7, 5.8 and 5.9) and Figures (5.10, 5.11, 5.12, 5.13 and 5.14) that there is a uniformity of bankline movement between the west and east banks of the two reaches with overall bank retreat, and 10-year average bankline movement rates are different to those often quoted in the literature concerning the trend of westward movement of the Brahmaputra-Jamuna River (e.g. Coleman, 1969; Thorne *et al.*, 1993; FAP 19, 1995; FAP 24, 1996; EGIS, 1997, 1999). This result suggests that the Brahmaputra-Jamuna River is not migrating westward but expanding by the outward retreating of both banks (Bahadurabad Ghat Reach is about 2226 m wider in 1997 than it was in 1987 while the Jamuna Bridge Reach widened 1858 m in the same period).

5.3. Channel Width Change

5.3.1. Methodology

The delimited banklines of the two reaches were used to estimate the width of the river channel within ArcView GIS. Each-year image at both reaches was divided into 30 east-west transects approximately 1 km apart, and channel width was measured on each transect by subtracting the easting for the west bankline from that for the east bankline (Tables 5.10 and 5.11). Maximum, minimum, mean and standard deviation of channel width for each reach were then calculated to find out the rate and magnitude of channel width change.

5.3.2. Channel Width Assessment

Decadal changes in channel width at both reaches are summarised in Tables 5.12 and 5.13. Mean widening data serve to provide a point of reference as to the magnitude and variability of width changes. Minimum and maximum values of channel widening reflect a realistic range of width changes throughout the reach lengths studied while the standard deviation measures how widely channel widths were dispersed from the mean value.

Table 5.10: Transect-wise channel width at Bahadurabad Ghat Reach.

Transect (upstream to downstream)	Channel Width (m)						
	1987	1989	1992	1994	1995	1996	1997
1	8072	9320	9690	9650	9856	10054	10412
2	7716	8948	9448	9738	9876	10252	10576
3	6776	8470	9396	10018	10354	10414	10540
4	6218	8290	9138	10454	10514	10738	11356
5	6066	8096	9276	10772	10528	10792	11320
6	6700	7768	9760	9912	10022	10216	10884
7	7182	7544	10120	10436	10500	10756	10866
8	8042	8560	11052	11868	11426	12074	12102
9	8852	8812	11414	12600	12484	12562	12792
10	8654	9710	11070	12198	12426	12454	12574
11	8578	9770	9898	11432	11542	11514	12210
12	8172	9486	9104	9878	11252	10790	10012
13	8166	10024	7846	8604	9152	8500	8704
14	8388	11308	9086	8552	8472	8810	8958
15	10812	11144	9776	9808	9138	9368	9576
16	12208	12130	10294	10402	10108	10378	10412
17	13174	12906	11138	10608	10962	11190	11448
18	13452	12622	11828	11380	11842	11822	12048
19	13502	13796	12704	12910	13020	13048	13084
20	13984	14020	12620	12724	12700	12562	12538
21	12474	14012	13950	13910	13718	13896	13356
22	12108	13846	14104	12968	13042	13050	13084
23	12212	14348	14380	12514	12598	13012	12664
24	13590	13736	14224	12548	12352	12760	12374
25	13656	13346	13346	13264	13204	13266	13156
26	11370	12010	11276	11466	11890	11750	11884
27	10356	10635	10884	10890	11182	11460	11666
28	9114	9814	10432	10594	10588	10972	11266
29	8446	8694	10724	10784	10720	10956	11448
30	8426	8500	10758	10908	10984	11044	11430

Table 5.11: Transect-wise channel width at Jamuna Bridge Reach.

Transect (upstream to downstream)	Channel Width (m)						
	1987	1989	1992	1994	1995	1996	1997
1	12574	13030	14010	14162	14440	14474	14502
2	12188	13230	13628	14046	14436	14728	14558
3	14174	14294	14214	14396	13894	14418	14670
4	14826	14812	14740	13930	13578	14276	14810
5	15212	15072	15150	13260	12574	13626	15034
6	14620	14984	14272	13726	12832	12834	15398
7	14440	14754	14184	13376	12746	12862	15380
8	14144	13978	13630	12850	12544	12976	14922
9	12958	13086	12810	12298	12142	12382	13354
10	11950	11878	11904	11890	11942	11902	11870
11	10972	11010	11056	10870	10908	11280	10974
12	9192	10498	11142	11102	11224	11054	10752
13	7220	9866	10792	10840	11052	10686	10444
14	6406	9692	9798	9530	9358	9442	8652
15	6998	9260	10030	9004	8754	9526	7308
16	5812	6946	7868	7480	10190	7378	6552
17	5990	6558	7048	7460	9750	7802	4200
18	5100	6068	6786	7840	9816	9330	3808
19	4300	5550	6346	7752	9962	9554	5390
20	4152	3034	6610	7518	7952	8114	7894
21	3854	5120	6814	7548	7608	8056	8146
22	3944	5234	7312	7898	7980	8340	8428
23	4388	5552	7632	8306	8124	8622	8790
24	4892	5810	7956	8538	8468	8848	8988
25	5456	7130	8658	8568	8756	8876	9072
26	6168	7680	8394	8712	8670	8848	9996
27	6702	6874	8364	8858	8870	8962	9238
28	6968	7536	8424	8830	8898	9130	9406
29	7770	8312	8420	8714	8784	9990	9352
30	8126	8830	8830	8538	8670	9018	9324

Table 5.12: Computed channel width at Bahadurabad Ghat Reach.

Year	Channel Width (m)			
	Max	Min	Mean	S.D. (σ)
1987	13984	6066	9882	2553
1989	14348	7544	10722	2248
1992	14380	7846	10958	1746
1994	13910	8552	11126	1377
1995	13718	8472	11215	1335
1996	13896	8500	11349	1340
1997	13356	8704	11491	1229

Table 5.13: Computed channel width at Jamuna Bridge Reach.

Year	Channel Width (m)			
	Max	Min	Mean	S.D. (σ)
1987	15212	3854	8717	3949
1989	15072	3034	9523	3624
1992	15150	6346	10227	2918
1994	14396	7460	10261	2474
1995	14440	7608	10497	2129
1996	14728	7378	10578	2293
1997	15398	3808	10374	3402

Table 5.12 shows that Bahadurabad Ghat Reach is wider in 1997 than it was in 1987. Although maximum width decreases by about 4.49% (62.8 myr^{-1}), minimum and average widths increase by 43.49% (263.8 myr^{-1}) and 16.28% (160.9 myr^{-1}), respectively. On the other hand, Jamuna Bridge Reach (Table 5.13) exhibits an overall increasing tendency in maximum (1.22%) and average width (19.01%) but decreasing tendency in minimum width (1.19%). There is, of course, much variability in width in between the years 1987 and 1997.

The maximum and minimum width was sporadically distributed in the Bahadurabad Ghat reach but it was mainly confined to two zones at Jamuna Bridge Reach (see Figs. 5.10 and 5.12). The upper part of the Jamuna Bridge Reach achieved maximum width due to sustained bank erosion, and the middle and lower middle parts appeared to be restricted to minimum widths due to the presence of erosion resistant materials (Coleman, 1969). Table 5.13 also revealed that there was sudden widening of the minimum width at Jamuna Bridge Reach from 1992 and this was continued up to 1996, and thereafter the widening ceased. The pattern that appeared is related to the inception of river training works to construct the Jamuna Bridge and eventual restriction of channel widening by construction of bank protection mounds.

5.3.3. Changes in Channel Width

5.3.3.1. Rates and Trend of Changes in Channel Width at Bahadurabad Ghat Reach

The changes in channel width between consecutive satellite images (Table 5.12) were used to calculate rates and trend of width change. The trend lines (Fig. 5.15a) and tabulated results (Table 5.14) indicate net widening (1609 m) at Bahadurabad Ghat Reach during the decadal time scales while the maximum and minimum width shows opposite trends. The maximum width exhibits a narrowing tendency (62.8 myr^{-1}), yet, the minimum width widened at a rate of 263.8 myr^{-1}.

Table 5.14: Changes in channel width (in m) at Bahadurabad Ghat Reach.

Year	Maximum	Minimum	Average
1987-89	-364	-1478	-840
1989-92	-32	-302	-236
1992-94	+470	-706	-168
1994-95	+192	+80	-89
1995-96	-178	-28	-134
1996-97	+540	-204	-142
1987-97	**+628**	**-2638**	**-1609**

Note: '–' sign indicates net widening and '+' sign indicates net narrowing.

Table 5.15: Changes in channel width (in m) at Jamuna Bridge Reach.

Year	Maximum	Minimum	Average
1987-89	+140	+820	-806
1989-92	-78	-3312	-704
1992-94	+754	-1114	-34
1994-95	-44	-148	-236
1995-96	-288	+230	-81
1996-97	-670	+3570	+204
1987-97	**-186**	**+46**	**-1657**

Note: '–' sign indicates net widening and '+' sign indicates net narrowing.

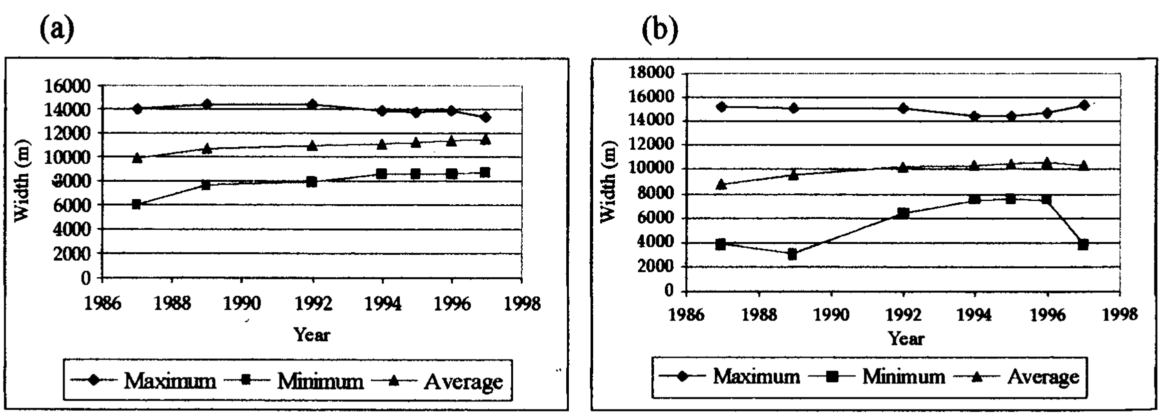


Figure 5.15: Trends in changes of channel width at (a) Bahadurabad Ghat and (b) Jamuna Bridge reaches.

It is observed that short-term maximum and minimum width figures (Table 5.14) show non-uniform nature of change, however, they appeared to be a rectilinear form by narrowing maximum width and expanding minimum width (except 1987- 1989 and 1989-1992 periods) and an overall pattern of straightening, from an earlier more sinuous pattern (see Fig. 5.10). It is also observed that the general expanding nature was reducing during the period 1992-1997 that is believed to be due to reworking between in-channel bars and secondary channels as it was subjected to variable monsoon runoff, while this reach behaved erratically because of the influence of extreme floods during 1987-1992 (as discussed earlier) by widening both maximum and minimum widths. Therefore, it is apparent from the results that channel widening may be associated with a major flood or maintained steady status at the time of lower seasonal runoff (cf. Schumm, 1977; Beschta, 1983; Leys & Werritty, 1999), and narrowing occurs by the processes of bar stabilisation and filling of secondary channels (cf. Allred & Schmidt, 1999).

5.3.3.2. Rates and Trend of Changes in Channel Width at Jamuna Bridge Reach

Channel width at the Jamuna Bridge Reach is highly variable at all areas of measurements (Table 5.15 and Figure 5.15b). During the 1988 flood, the maximum and minimum widths were reduced (140 m and 820 m, respectively) but average width markedly increased (806 m). However, the maximum and minimum channel widths between 1989-1996 period were reduced and enlarged conspicuously (Fig. 5.11b), possibly as a result of the installation and maintenance of engineering works to construct the bridge (as mentioned earlier). During the subsequent period of 1996-1997, there was an evidence for an overall narrowing in width which was possibly due to the construction of bank protection embankments. Although the magnitude of change in channel width during the short-term is found to be variable at different areas of measurements at Jamuna Bridge Reach, the ultimate nature of change is of expansion (165.7 myr^{-1}).

5.4. Error Assessment

No methodology for identifying the character of the geomorphic features from thematic and topographic maps can ever be error free and this error may be incorporated when topographic information is employed to identify river channel planform (Downward, 1995). Errors may be incorporated at each stage of data transcription. If the total sum of *inherent* and *operational* errors (*inherent errors* are those present within the source information prior to analysis, and *operational errors* are those produced by the operational process used to estimate river channel change) involved in any analysis of river channel form exceeds an acceptable level of tolerance then the identified changes have little significance for developing an understanding of the fluvial system (Thapa & Bossler, 1992; Downward, 1995). However, remotely sensed planform information is thus considerably free from inherent errors because the information content of the image conforms to a rationalised set of criteria regarding resolution and scale of presentation (Browne, 1995; Downward, 1995). But, regardless of the precise nature of the techniques employed to identify the character of river planform from remotely sensed images, errors of data generation introduced by the operational procedures may increase the total error (Vitek *et al.*, 1984).

The latest generation of ArcView GIS-approach has been applied in estimating channel planform changes at two study reaches of the Brahmaputra-Jamuna River. Channel boundaries depicting the channel and non-channel interface were identified in digital format with the help of channel delimitation criteria (see section 5.2.2). The precision of delimited boundaries in respect to the real world was evaluated using GPS readings taken in the field (Tables 5.16 and 5.17). The known coordinates of GPS thereby improved the accuracy of delimiting channel boundaries to an error range from 89 m to 2824 m. Therefore, this technique substantially reduces operational errors for all horizontal measurements based on delimited banklines (cf. Walsh *et al.*, 1998; Higgitt & Warburton, 1999). This level of operational error, nevertheless, is justified for the measurement of channel planform of the Brahmaputra-Jamuna River

Table 5.16: Computation of locational errors by comparing the field GPS readings with the satellite image coordinates at Bahadurabad Ghat Reach.

Bank	Locational Coordinates of GPS (m)		Locational Coordinates of Satellite Image (m)		Difference (m)	
	Easting	Northing	Easting	Northing	Easting	Northing
West Bank	460130	796091	461187	796900	1057	809
	460944	792391	460598	791780	346	611
	459094	789504	458605	789334	489	170
	458205	786395	458310	787068	105	673
	458872	784471	459579	784712	707	241
	459908	782917	460258	782288	350	629
East Bank	474193	796091	473955	797086	238	995
	469826	792983	470180	793283	354	300
	469678	789948	469473	789508	205	440
	470344	787950	470560	787253	216	697
	473231	784841	472516	785108	715	267
	473378	782399	472896	782310	482	89

Table 5.17: Computation of locational errors by comparing the field GPS readings with the satellite image coordinates at Jamuna Bridge Reach.

Bank	Locational Coordinates of GPS (m)		Locational Coordinates of Satellite Image (m)		Difference (m)	
	Easting	Northing	Easting	Northing	Easting	Northing
West Bank	469371	707985	468748	708720	623	735
	471090	705743	471281	706385	191	642
	471314	702081	471619	703908	305	1827
	471538	700363	472182	701122	644	759
	473481	698420	475137	698871	1656	451
	472285	696850	475109	697857	2824	1007
	471987	695057	472238	695690	251	633
East Bank	483345	709928	484227	709452	882	476
	484616	706789	483889	706441	727	348
	482822	703875	482285	703317	537	558
	479684	700587	479865	700897	181	310
	479309	698344	479443	698786	134	442
	479684	697075	479189	697576	495	501
	480655	695431	480428	695156	227	275

as its channel width varies between 3.85 km and 14.72 km (cf. Noorbergen, 1993; Gamble & Meentemeyer, 1996); but obviously this resolution may be inappropriate to discriminate boundary changes on the small-scale rivers (cf. Downward, 1995).

5.5. Conclusion

Erosion and accretion of channels is particularly characteristic of braided rivers although this occurs in all rivers to some degree (Bridge, 1993), but these processes are not well understood and no adequate theoretical models are available (ASCE, 1998b). Nevertheless, channel bank dynamics appears to be associated with either flowing water that exerts forces of drag and lift on the boundaries which tend to detach and entrain bank materials (ASCE, 1998a) or deflected flows around growing braid bars (Leopold & Wolman, 1957; Bristow & Best, 1993; Thorne *et al.*, 1993; Jiongxin, 1997; Goswami *et al.*, 1999) or may result when a marginal anabranch in the braided system is abandoned (Schumm & Lichty, 1963; Allred & Schmidt, 1999; Goswami *et al.*, 1999). Moreover, the distribution of sustained bank retreat depends primarily on the distribution of boundary shear stress and erosion-resistance of the channel banks (Ferguson & Werritty, 1983; Jiongxin, 1997; ASCE, 1998a).

The channel banks of the Brahmaputra-Jamuna River are formed in non-cohesive silty-sand (Goswami, 1985: Thorne *et al.*, 1993). The primary process of bank retreat is toe scouring leading to bank failure by high flood discharge (Bristow, 1987; Thorne *et al.*, 1993). An increased amount of sediment load in excess of competency of the river channel due to bank retreat is believed to initiate the process of development of new mid-channel bars, and eventually a greater degree of obstruction to the flow which is then diverted sideways leading to an increase in bank erosion, resulting in channel widening. Rapid bank erosion, however, is evidently due to the high shear stress exerted on non-cohesive bank materials during severe floods (Thorne *et al.*, 1993). By considering these factors, in analysing channel bank dynamics at Bahadurabad Ghat and Jamuna Bridge Reach, this section reveals the spatial and temporal variations in bank erosion and accretion; interprets bankline shifting and channel widening; makes systematic comparison between the reaches; and elucidates the cause and effect of changes. The conclusions of the findings are, however, given in the following paragraphs.

(1) Over a timescale of one decade both the Bahadurabad Ghat and Jamuna Bridge reaches were more severely affected by bank erosion than bank accretion. Very high rates of erosion occurred over periods of one or a few years due to unusual floods, but they were not sustained for many years at the same location and they did not occur on both reaches simultaneously. Both banks are retreating each year but retreat rates are not uniform between the reaches because the channel geometry, flow structure and bank material characteristics varies both in time and space. Occasional channel accretion was observed due to abandonement of secondary-channels by merging attached bars, and construction of concrete structures to protect erected bridge piles.

(2) There is a uniformity of bankline shifting between the west and east bank of the two reaches with opposite direction, and 10-year average bankline movement rates do not correspond with those often quoted in the literature concerning the trend of westward bankline movement of the Brahmaputra-Jamuna River. Short-term unsettled bankline shifting pattern of both banks is thought to have been triggered by severe floods and major river training works to construct one of the largest bridges of the world.

(3) It is observed that both reaches were wider in 1997 than they were in 1987, and the widening trend is expected to continue. Bahadurabad Ghat Reach appeared to be in an equilibrium situation by narrowing maximum width and expanding minimum width and an overall pattern of straightening. But, Jamuna Bridge Reach planform morphology developed an 'hour glass shape' by widening its maximum width and narrowing its minimum width. The magnitude of change in channel width during the short-term at both reaches is found to be variable at different areas of measurements. Widening occurred erratically because of the influence of extreme floods and river training works while narrowing occurred due to secondary channel abandonment and construction of bank protection embankments.

CHAPTER VI: BAR MORPHOLOGY AND DYNAMICS

6.1. Introduction

Bars are distinctive features of braided rivers and they are of great interest to the geomorphologist as the materials constituting the bars and their behaviours are an integral part of the dynamics of river mechanics. It is recognised that the formation of bars that divide channels and divert flow is responsible for the initiation and maintenance of the braided pattern (Leopold & Wolman, 1957; Fahnestock, 1963; Ashmore, 1982; Church & Jones, 1982; Rundle, 1985a, 1985b; Ferguson, 1993; Thorne *et al.*, 1993; Jiongxin, 1997). However, the processes of bar formation and their impact on channel dynamics are inferred from comparatively few studies (e.g. Leopold & Wolman, 1957; Ferguson & Werritty, 1983; Ashworth & Ferguson, 1986; Bristow, 1987; Goff & Ashmore, 1994; Ashworth *et al.*, 2000). The nature of bar dynamics is critical to understanding channel stability as bank erosion and growth and multiplication of braid bars are interrelated, and thus, it has important implications for the explanation of the process-response linkage between bank erosion and braid bar formation (Thorne *et al.*, 1993). Observations on large sand-bed braided rivers are required to evaluate the relational roles of bar morphology and channel instability and to test the hypothesis that the formation and growth of braid bars is fuelled largely by the addition of sediments to the channel through bank erosion. Therefore, the purpose of this chapter is to assess reach-scale spatial and temporal variability of bar formation and growth, bar morphology and dynamics, and its impact on bank erosion and local channel change.

6.2. Channel Braiding and Braiding Index

The planform properties of braided rivers have received considerable attention, especially of their braiding intensity (e.g. Brice, 1964; Howard *et al.*, 1970; Engelund

& Skovgaard, 1973; Rust, 1978a; Hong & Davies, 1979; Mosley, 1981; Richards, 1985; Fujita, 1989; Friend & Sinha; 1993; Robertson-Rintoul & Richards, 1993). Usage of a suitable braiding parameter is an important measure towards better interpretation of braided rivers (Rust, 1978a) as the intensity of braiding varies greatly from river to river (Friend & Sinha, 1993), and even from reach to reach along the course of a particular river under different flow stages (EGIS, 1997). Therefore, an important first step in this study was to select an appropriate method of measuring the degree of braiding in the Brahmaputra-Jamuna River using satellite images. The most appropriate measure that would allow the continuum of the Brahmaputra-Jamuna River braiding to be quantified is the braiding index introduced by Brice (1964). This has often been used to measure the braiding intensity of the largest braided rivers (e.g. Goswami, 1985; Jiongxin, 1997; Goswami *et al.*, 1999). Brice's (1964) braiding index (BI) is defined as follows:

$$\mathrm{BI} = 2(\Sigma L_\mathrm{i})/L_\mathrm{r} \qquad (6.1)$$

where, ΣL_i is the total length of bars and (or) islands in the reach, and L_r is the length of the reach measured midway between the banks. A total braiding index of 1.50 was selected by Brice to differentiate braided from non-braided reaches.

The Brahmaputra-Jamuna flows in a highly braided channel characterised by the presence of numerous lateral as well as mid-channel bars and islands, and its braiding intensity varies significantly from nodal reach to island reach. For each of the two selected reaches of the Brahmaputra-Jamuna, braiding indices were determined on the basis of Landsat imageries using ArcView GIS measuring tools. The average braiding indices are calculated as 6.90 and 5.45 for the Bahadurabad Ghat and Jamuna Bridge reaches, respectively (Tables 6.1 and 6.2).

Table 6.1: Measured braiding parameters at Bahadurabad Ghat Reach.

Year	$2\Sigma L_i$(m)	L_r(m)	BI
1987	216656	29702	7.29
1989	244638	29308	8.35
1992	193290	29654	6.52
1994	217590	30538	7.13
1995	174946	30480	5.74
1996	185164	30356	6.10
1997	217504	30086	7.23
Average	**207112**	**30018**	**6.90**

Table 6.2: Measured braiding parameters at Jamuna Bridge Reach.

Year	$2\Sigma L_i$(m)	L_r(m)	BI
1987	159012	29706	5.35
1989	157456	29762	5.29
1992	167500	29848	5.61
1994	175192	29596	5.92
1995	154092	29618	5.20
1996	167684	29932	5.60
1997	153048	29640	5.16
Average	**161998**	**29729**	**5.45**

Comparison of the braiding indices for the widest reach (Bahadurabad Ghat) with the narrowest reach (Jamuna Bridge) during the study period demonstrates that the degree of braiding varies considerably over the periods of one or a few years and they are more inconsistent in the wider reach than in the narrowest reach (Fig. 6.1).

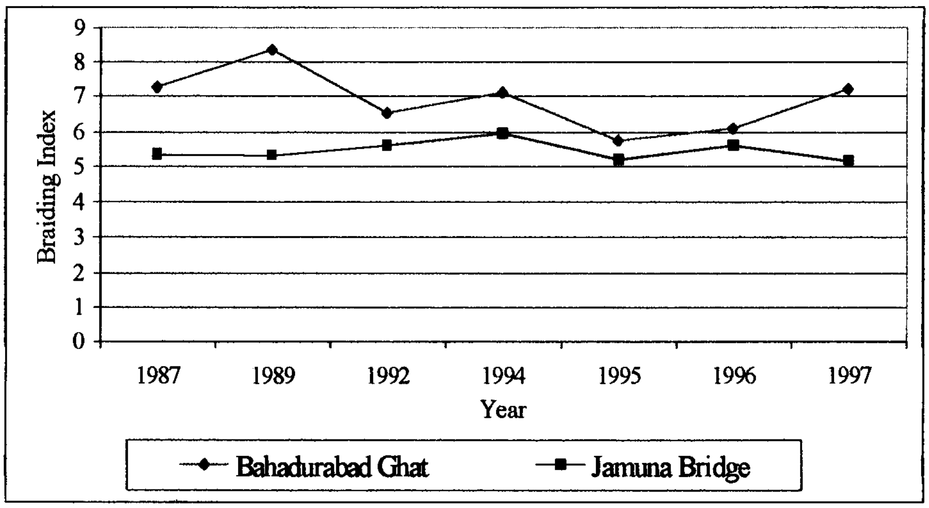


Figure 6.1: Variations of braiding indices by reach.

These short-term variations are thought to be related to morphological response to the magnitude and duration of monsoon flood events (EGIS, 1997). It is also evident from the Tables (Tables 6.1 and 6.2) and Figure (Fig. 6.1) that overall braiding intensity is higher at Bahadurabad Ghat Reach than the Jamuna Bridge Reach, and this is probably due to higher width-depth ratio (Robertson-Rintoul & Richards, 1993) and higher slope values (Klaassen & Vermeer, 1988; Friend & Sinha, 1993) in the wider reach.

6.3. Bar Formation and Pattern of Bar Development

6.3.1. Elementary Features of Braiding

The causes of braiding and bar development have long been the subject of research in fluvial geomorphology, with analyses of data from both flume studies (e.g. Leopold & Wolman, 1957; Ikeda, 1973; Ashmore, 1982, 1991) and field observations (e.g. Fahnestock, 1963; Coleman, 1969; Smith, 1974; Hitchcock, 1977; Werritty & Ferguson, 1980; Ferguson & Werritty, 1983; Ashworth & Ferguson, 1986; Fujita, 1989; Ashworth, 1996). Conditions favouring braiding, for obvious reasons, vary from flume to field and from one reach to another reach for the same river and there can be no single universal model of bar development (Ferguson, 1993). However, the common prerequisites for the initiation, growth and development of braid bars are high-energy fluvial environments with steep valley gradients, large and variable discharges, high bedload transport, and non-cohesive bank materials (Leopold & Wolman, 1957; Coleman, 1969; Howard *et al.*, 1970: Miall, 1978; Osterkamp, 1978; Ashmore, 1982, 1991; Church & Jones, 1982; Ferguson & Werritty, 1983; Richards, 1985; Rundle, 1985a, 1985b; Ashworth & Ferguson, 1986; Bristow, 1987; Laronne & Duncan, 1992; Bridge, 1993; Ferguson, 1993; Thorn *et al.*, 1993; Jiongxin, 1997).

Apart from channel sedimentary structures and hydraulic conditions, explanation of the causes of braiding fall into two general groups. The first is a functional explanation using the central bar braiding mechanism described by Leopold & Wolman (1957). This is considered to be a classic model and has been frequently cited (e.g. Krigstorm, 1962; Fahnestock, 1963; Coleman, 1969; Howard *et al.*, 1970: Miall, 1978; Osterkamp, 1978; Ashmore, 1982, 1991; Church & Jones, 1982;

Ferguson & Werritty, 1983; Richards, 1985; Rundle, 1985a, 1985b; Ashworth & Ferguson, 1986; Bristow, 1987; Laronne & Duncan, 1992; Jiongxin, 1997). The essential feature of this model is the development of a mid-channel bar in a straight and undivided channel by local decline in competence and deposition of the coarsest fraction of bedload with successive accretion at the downstream end and along the margins. The resulting accumulation of sediment in mid-channel bar accelerates progressive bank erosion and channel widening which in turn may lead to the formation of multiple channels over time.

Alternative explanations for the causes of braiding include the chute cutoff of point bars (Krigstorm, 1962; Hickin, 1969; Ikeda, 1973; Hong & Davies, 1979; Ashmore, 1982, 1991; Ferguson & Werritty, 1983; Bridge, 1985; Rundle, 1985a, 1985b; Ferguson *et al.*, 1992) and dissection of transverse unit bars (Krigstorm, 1962; Hein & Walker, 1977; Ashmore, 1982, 1991; Rundle, 1985a, 1985b; Davoren & Mosley, 1986). Although these explanations demonstrate the initiation of braid bars by chute cutoff or dissection of unit bars, these bars are mainly erosional in origin (Ferguson, 1993). Furthermore, they often quote Leopold & Wolman's (1957) classic example of bar formation to justify their findings in one way or the other. Nevertheless, it is evident that chute cutoffs or dissected bars cannot be formed at the initial stage of braiding (Ferguson, 1993). They are features of sand-bed braided rivers at a later stage of their evolutionary sequences (e.g. Miall, 1977; Bristow, 1987; FAP24, 1996a) or laboratory channels (e.g. Ashmore, 1982, 1991) or gravel-bed braided rivers (e.g. Smith, 1974; Hein & Walker, 1977; Church & Jones, 1982). In the Brahmaputra-Jamuna fluvial regime, the formative process of braiding is poorly understood but is generally attributed to Leopold & Wolman's (1957) explanation of bar formation (Coleman, 1969; FAP24, 1996a).

6.3.2. Stages of Bar Development and Planform Evolution

The braiding process of the Brahmaputra-Jamuna River is poorly known and few attempts have been made to identify the causes of bar initiation and growth rather than the flow structure associated with a developing mid-channel bar and its impact on channel morphology (e.g. Richardson *et al.*, 1996; Richardson & Thorne, 1998; McLelland *et al.*, 1999). Recently, a number of studies have considered the morphological development and evolution of mid-channel bars (e.g. FAP 24, 1996a; Ashworth *et al.*, 2000); but these were restricted to a short time span as the bars of the Brahmaputra-Jamuna River are transient in nature; they frequently shift their location, are occasionally washed away by monsoon floods, and change planform pattern by amalgamating with other bars. Moreover, the Brahmaputra-Jamuna River is divided into successive island and nodal reaches with multiple bars and channels (Thorne *et al.*, 1993), and it is almost impossible to find a bar-free reach, even a short nodal stretch, to produce a prototype model of mid-channel bar formation. In the 258 kilometre long Brahmaputra-Jamuna River in Bangladesh, the only reach is Jamuna Bridge which is less braided and comparatively more stable than any other reaches of the river (as discussed in Chapter 5). Keeping all these views in mind, the present section attempts to develop a model of the growth and evolution of a mid-channel braid bar for a decadal timescale at Jamuna Bridge Reach.

The interpretation of bar formation, evolution and consequent findings is based on satellite images, field observations and secondary information. This work provides a prototype model of the formation and development of a mid-channel bar with possible explanations in the light of contemporary and relevant studies. It is to be noted here that the planform evolution of bars were interpreted on satellite images on the basis of Leopold & Wolman's (1957) mid-channel bar formation model as this is considered to be similar in terms of bar initiation and growth to the Brahmaputra-Jamuna River (FAP24, 1996a; Ashworth *et al.*, 2000). The bars that were identified as a model for the growth and development of a mid-channel bar were thought to be linked with the prototype planform bar evolution. Stage-wise growth and development of a mid-channel bar are described in the following section.

Stage I

Braiding begins with the deposition of a short, narrow, central submerged bar at a time of high flow immediately at the downstream node of a flow convergence that was initially unbraided (Fig. 6.2a). The cause of this bar development is not clear, but it was probably due to slack water conditions (Coleman, 1969), convergence of flow and large-scale sediment input (Richardson *et al.*, 1996; Ashworth *et al.*, 2000), less powerful back water (Church & Jones, 1982) or areal and temporal variance in flow conditions and sediment in transport (Leopold & Wolman, 1957; Fahnestock, 1963; Howard *et al.*, 1970). The factors responsible for the local variations that induce braiding are probably so numerous and so rapidly changing that a satisfactory deterministic explanation of bar initiation is difficult to establish (Howard *et al.*, 1970). However, it can be assumed that near-bed flow deceleration with large-scale sediment input from bank and bar erosion may play the pivotal role in the initiation of a mid-channel bar.

Stage II

Once initiated, the central bar emerged further by trapping sediment particles of similar calibre (Miall, 1978; Bluck, 1982), and enlarged (82 ha) by lateral and headwater accretion probably through the amalgamation of large dunes (FAP24, 1996a; McLelland *et al.*, 1999; Ashworth *et al.*, 2000) (Fig. 6.2b) and merging of

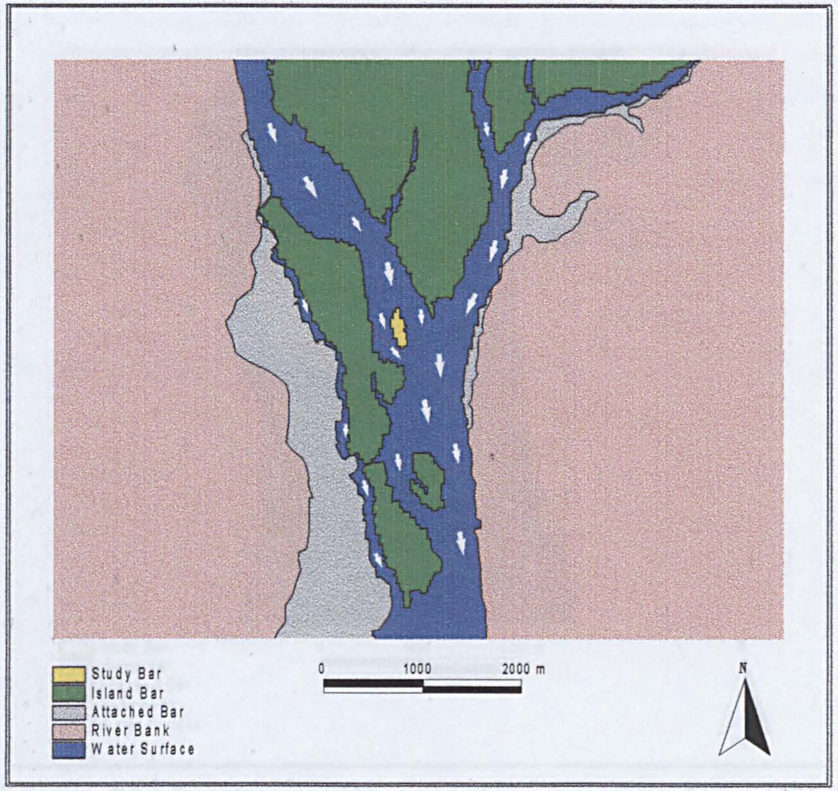


Figure 6.2a: Initial location of a mid-channel sand bar during 1987.

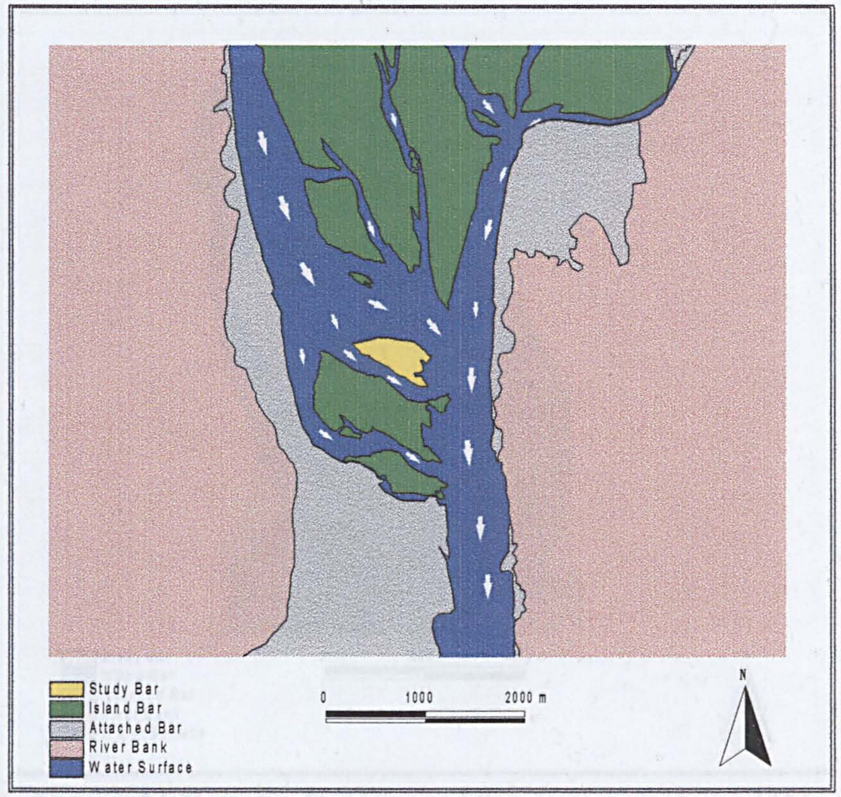


Figure 6.2b: Growth of sand bar by lateral and downstream accretion during 1989.

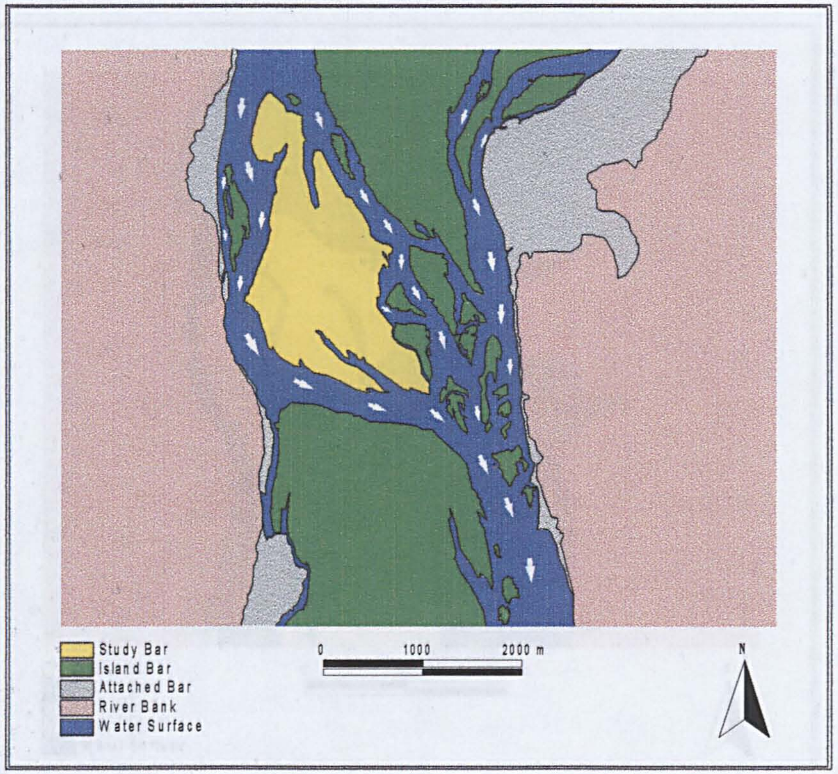


Figure 6.2c: Development of bar and channel widening during 1992.

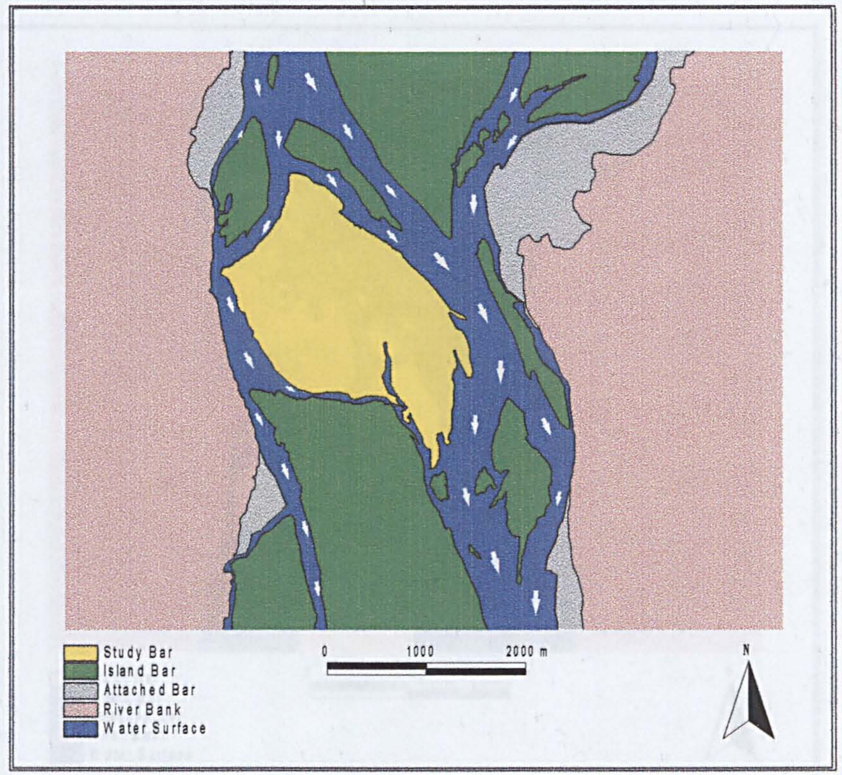


Figure 6.2d: Mega bar formation and flow divergence during 1994.

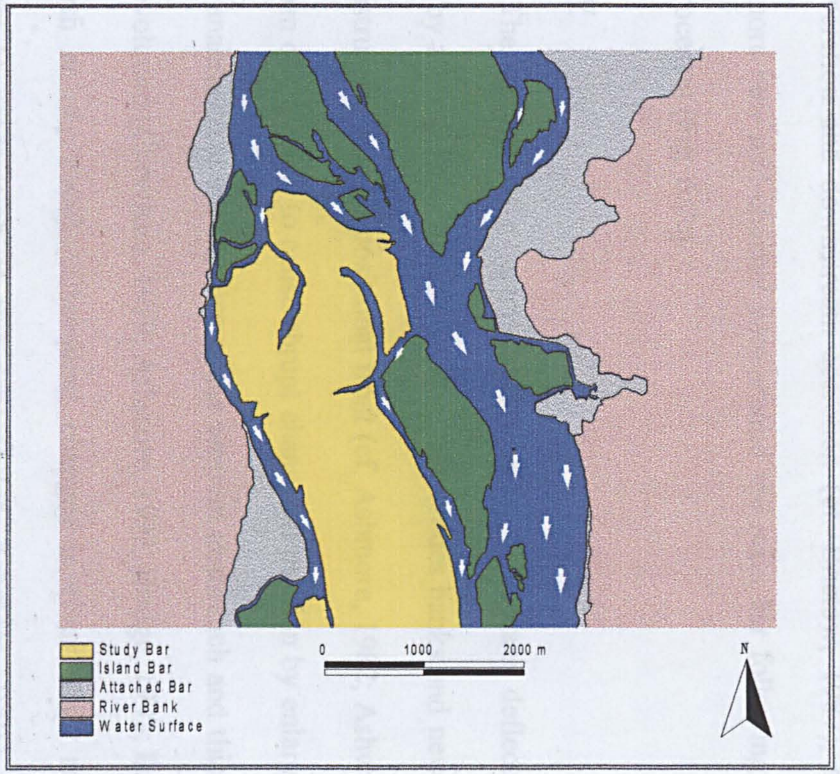


Figure 6.2e: Coalescence of mid-channel bars into a bar assemblage during 1996.

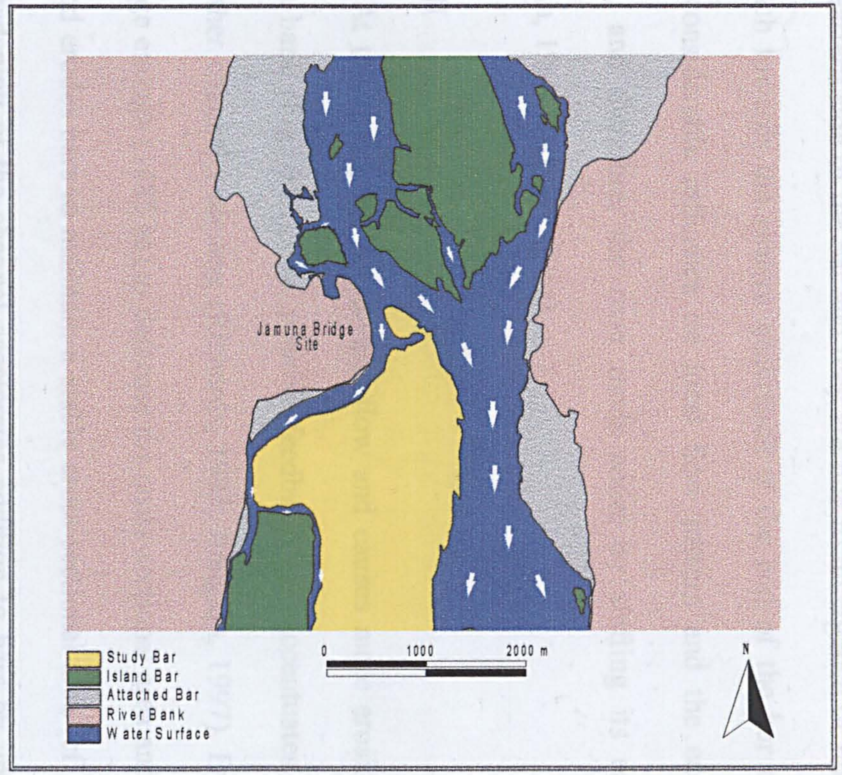


Figure 6.2f: Jamuna bridge project-induced changes of bars during 1997.

small unit bars (Bristow, 1987). The resulting accretionary features are most apparent on the eastern side of the bar and they are due to divergence of flow of the western anabranch towards the eastern anabranch at the end of the bar tail. This process exerts considerable influence on local flow pattern and the eastern bank faces erosion, and therefore, the river tends wider by shifting its east bankline (cf. Coleman, 1969; FAP24, 1996a).

Stage III

At this stage, the bar diverts flow and causes more erosion, mainly in the western bank (Fig. 6.2c), and positive feedback then accentuates bar development and further channel widening (Richards, 1985; Jiongxin, 1997). Eventually, the bar gets large enough (1485 ha) to decrease the cross-sectional area and the river cuts its bank and erodes bars to maintain a stable cross-sectional area (cf. Coleman, 1969). Local widening of the channel accelerates addition to bars by upstream accretion, flank accretion and downstream accretion (cf. Bristow, 1987), and ultimately to create more new mid-channel bars around the main bar following the repetition of these processes (Fig. 6.2c).

Stage IV

The bar gradually becomes enlarged by 472 ha and deflects flow across the bar tail by the eastern anabranch (Fig. 6.2d), erodes banks and newly deposited bars and constructs a broad depositional front (cf. Ashmore, 1982; Ashworth *et al.*, 2000). This form of bar tends to cause abrupt channel expansion by enlarging the dominant eastern anabranch at the expense of the western anabranch and this is an ideal mode of bar evolution (Cheetham, 1979; Ashmore, 1993; Bridge, 1993; Bridge *et al.*, 1998; Ashworth *et al.*, 2000). Subsequent changes in river stage are probably also important to progression of this process (cf. Ashmore, 1991). Eventually, with further flow divergence and channel widening, a mega mid-channel bar formed with scroll bars attached to one or both sides (cf. Bristow, 1987).

Stage V

At this final stage the mid-channel bar become coalesced with another downstream medial bar to form a bar assemblage (Fig. 6.2e) (analogous to the megaforms of Bristow, 1987). Complex bar megaforms are thought to be associated with channel multiplication (anastomosis) and are likely to be responsible for change of a nodal reach to an island reach, and the time span of these megaforms is approximately ten years, which corresponds to Bristow's (1987) study. However, the whole process could be reinstated, changed or interrupted if any major human induced modification take place (e.g. construction of bridge) or catastrophic flood events occurred (Fig. 6.2f).

The prototype formation and development of the mid-channel bar documented in the previous sections suggests that channel braiding may initiate with the formation of a mid-channel bar which is depositional in nature. The obvious appearance of a mid-channel bar, dividing a single channel into two or more anastomosing channels, acts to deflect the flow against the banks of the main channel causing bank erosion and channel widening, and ultimately growth of a bar complex. Although this prototype observation has been a somewhat simplified description of the braiding process, it attempts to outline the major features of bar development which correspond with some other studies.

6.3.3. Classification of Bars

Bars are important topographic features on all orders of river channels but their scalar variation is considerable and this introduces a problem of classification

(Williams & Rust, 1969). Moreover, bars occur in a bewildering variety of shapes, sizes and dimensions of alteration that challenge simple classification plans (Smith, 1974, 1978). In the past few years a large number of bar definitions has been introduced from both flume and field studies (e.g. Church & Jones, 1982; Ferguson & Werritty, 1983; Rundle, 1985b; Bristow, 1987; Ashmore, 1991), but there has been a lack of clarity and considerable overlapping embodied in much of the terminology that is difficult to apply to natural channels. Therefore, to overcome ambiguous classification bars should be classified either in terms of plan view or on the basis of morphological criteria whose existence depends more on the long-term position and shape of the channel (Smith, 1978). Accordingly, the braid bars of the Brahmaputra-Jamuna River are classified in these two ways as follows.

6.3.3.1. Planform Classification

The types of bars and their planform characteristics within the Brahmaputra-Jamuna River have been identified using Landsat images and field examinations. In plan view, the two-dimensional exposed bars are generally diamond-shaped or triangular (Coleman, 1969; Islam, 1990) having one apex in the upstream direction. Since most bars modify their shape, size and location from time to time because of rapid aggradation, frequent channel shifting, and change in local flow pattern they cannot easily be classified. However, frequently occurring quasi-stable bar forms were taken into consideration to classify planform pattern. These include longitudinal bars, lateral bars, diagonal bars and unit bars.

<u>Longitudinal Bars</u>

Longitudinal bars (cf. Smith, 1974; Church & Gilbert, 1975; Miall, 1977; Church & Jones, 1982; Ferguson & Werritty, 1983) are diamond shaped, formed in the centre of the channel at a relatively wide place (equivalent to 'medial bar' of Bluck, 1979; Bristow, 1987). They have a bigger and more elongated convex-upward surface, grow by upward accumulation and downstream accumulation (Church & Jones, 1982), and their length may reach tens of kilometres by forming bar complexes (Fig. 6.3a).

Lateral Bars

Lateral bars (cf. Miall, 1977; Ferguson & Werritty, 1983; Bristow, 1987) are elongated shaped, form either in gently curved channels, are separated from the bank by a smaller channel (Smith, 1974) or attached on one side to a floodplain by merging into it (Ferguson & Werritty, 1983) (Fig. 6.3b). Once developed, they undergo constant modification and occasionally emerge as a quasi-stable floodplain.

Diagonal Bars

Diagonal bars (Fig. 6.3c) are also elongated but are oblique across the channel and asymmetric to flow direction (cf. Smith, 1974; Church & Jones, 1982). They are usually triangular in shape with downstream margins consisting of avalanche faces (Smith, 1974).

Unit Bars

Unit bars (Fig. 6.3d) are detached forms which are deposited at flow divergence of second or third-order channels (the 'tributary bars' of Bristow, 1987). They occur in a wide variety of sizes and shapes (Smith, 1974), and are frequently destroyed by rapidly changing flow directions (Church & Jones, 1982). In general the progress of sediment accumulation is upward and downstream with lee slip faces (Ashmore, 1991).

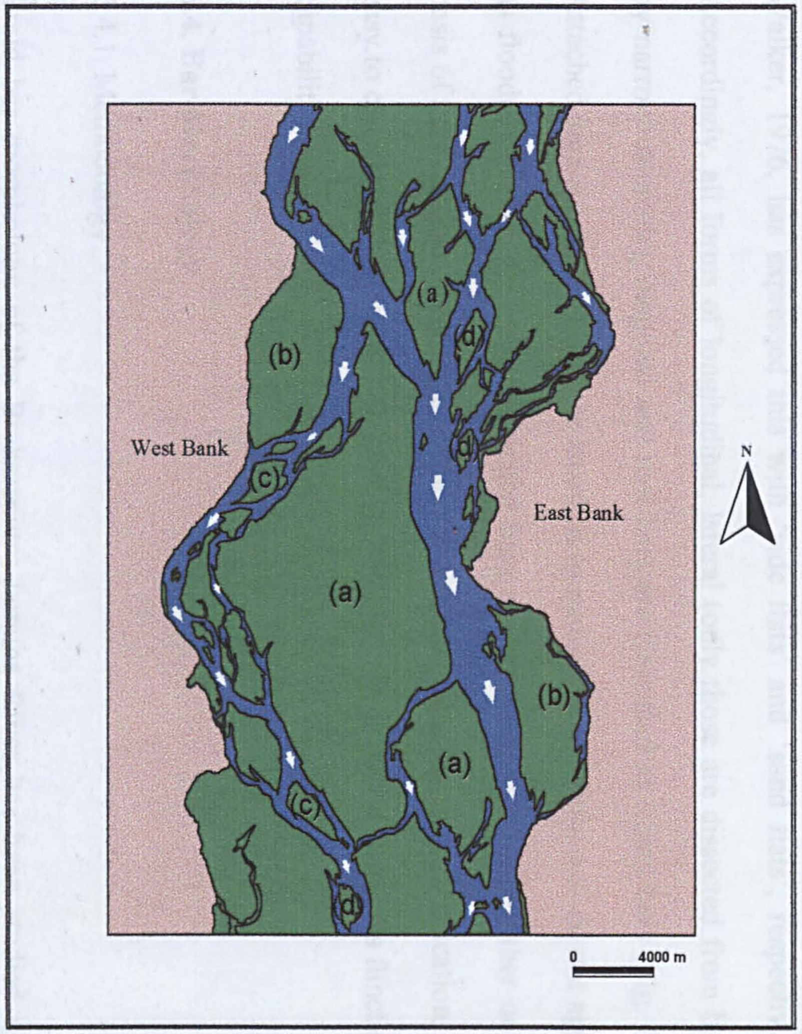


Figure 6.3: Aerial views of different bar types (a. longitudinal bar, b. lateral bar, c. diagonal bar and d. unit bar).

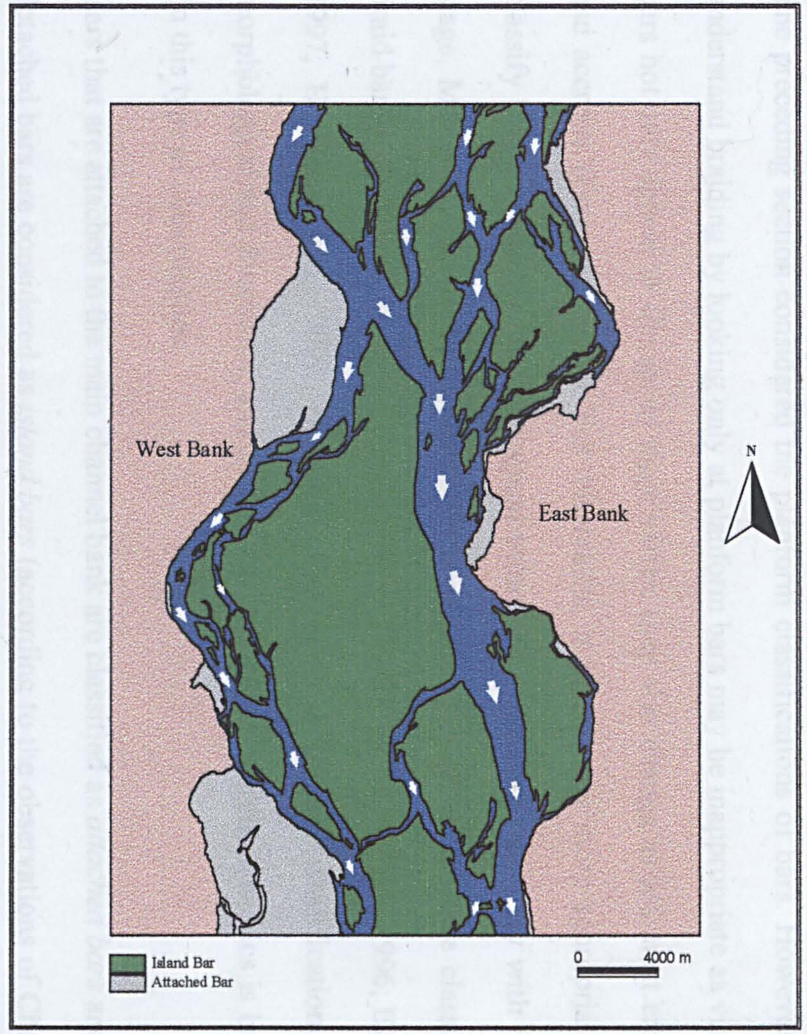


Figure 6.4: Morphological classification of bars.

6.3.3.2. Morphological Classification

The preceding section considered the planform classifications of bars. However, to understand braiding by looking only at planform bars may be inappropriate as visible bars not only appear to change as stage varies, they also change as sediment erodes and accretes (Ferguson, 1993). For this reason, it is probably more appropriate to classify bars according to morphological behaviour as this does not vary with river stage. Moreover, recent studies on the Brahmaputra-Jamuna River have classified braid bars according to morphological behaviour (FAP19, 1995; JMBA, 1996; EGIS, 1997; Hassan *et al.*, 1999). Therefore, the bases of present classification are morphological and functional, and further analysis of bar morphodynamics is based on this type of classification.

Bars that are attached to the main channel bank are classified as *attached bars* and all detached bars are considered as *island bars* (according to the observations of Church & Jones, 1982, which illustrate attached and detached bars; and Cant, 1978; also Walker, 1976, has expressed this with 'side flats' and 'sand flats', respectively). Accordingly, all forms of longitudinal, lateral (only those are dissected from banks by narrow channels), diagonal and unit bars are classified as island bars (Fig. 6.4). Attached bars are those which are attached to main channel banks and do not appear as floodplain. Floodplains and attached bars are separated from each other on the basis of their land cover and age of the land surface. By using this classification, it is easy to categorise both forms of bars from satellite images and it increases functional capability with less ambiguity compared to planform classification.

6.4. Bar Morphology

6.4.1. Methodology

Braid bar morphology of the Brahmaputra-Jamuna River has been studied using Landsat images and field data. The main data used in this analysis were digital images of braid bars. Classification of the land cover types was accomplished with a supervised maximum likelihood classification algorithm of the ERDAS Imagine program (version 8.3.1). The supervised classification method was chosen because it is recognised as the most accurate and robust classification method that can be verified with ground truth data (Dobson *et al.*, 1996; Ediriwickrema & Khorram, 1997; Brown *et al.*, 1998; Walsh *et al.*, 1998). This method was used to define spectral signatures from homogeneous areas corresponding to particular ground features, which allows iterative creating and editing of spectral signatures. Pixels were assigned to spectral feature classes on the basis of pixel signature similarity to input feature signatures derived from training. Reflectance at a pixel is likewise a composite of the reflectance of surface characteristics. The classified image data made mapping and quantification of within-channel change possible, and resulted in an improved understanding of channel bar morphology of the Brahmaputra-Jamuna river.

6.4.2. Number and Area of Bars

Total number of bars and bar area were measured on each year's classified images for the Bahadurabad Ghat and Jamuna Bridge reaches according to major bar types (i.e., attached bar and island bar) (Tables 6.3 and 6.4). Measurements were performed using ArcView theme attribute tables from classified images by the *identify tool* (ESRI, 1996).

Table 6.3: Year-wise measured bar area (in ha) and number of bars at Bahadurabad Ghat Reach.

Year	Attached Bar			Island Bar			Total Bar Area (ha)	Average Bar Area (ha)
	Number of Bars	Area of Bars (ha)	% of Total Bar Area	Number of Bars	Area of Bars (ha)	% of Total Bar Area		
1987	14	1534	7	48	19191	93	20725	334
1989	13	2373	12	76	17889	88	20262	228
1992	8	2612	12	48	19437	88	22049	394
1994	13	4311	19	42	18658	81	22969	418
1995	14	6701	27	33	18465	73	25166	535
1996	14	4540	19	38	19650	81	24190	465
1997	14	4446	19	42	19361	81	23807	425
Decadal Average	**13**	**3788**	**16**	**47**	**18950**	**84**	**22738**	**400**

Table 6.4: Year-wise measured bar area (in ha) and number of bars at Jamuna Bridge Reach.

Year	Attached Bar			Island Bar			Total Bar Area (ha)	Average Bar Area (ha)
	Number of Bars	Area of Bars (ha)	% of Total Bar Area	Number of Bars	Area of Bars (ha)	% of Total Bar Area		
1987	8	4860	26	24	13580	74	18440	576
1989	7	7802	40	35	11562	60	19364	461
1992	10	6105	28	37	15701	72	21806	464
1994	9	5492	25	30	16588	75	22080	566
1995	6	8311	35	25	15657	65	23968	773
1996	8	7390	32	29	15408	68	22798	616
1997	5	8103	38	29	13029	62	21132	622
Decadal Average	**8**	**6866**	**32**	**30**	**14504**	**68**	**21370**	**583**

Tables 6.3 and 6.4 reveal that the Bahadurabad Ghat Reach (widest reach) contains more bar areas compared to Jamuna Bridge Reach (narrowest reach), and the total area of bars increases over the time period of study at both reaches. Tables 6.3 and 6.4 also reveal that island bars are prominent features (approximately 84% at Bahadurabad Ghat Reach and 68% at Jamuna Bridge Reach) relative to attached bars (approximately 16% at Bahadurabad Ghat Reach and 32% at Jamuna Bridge Reach) at both reaches. The logical inference behind these findings is that both reaches may be expanding gradually due to bank erosion (decadal trends of bank retreating at Bahadurabad Ghat and Jamuna Bridge reaches are 448 ha yr^{-1} and 487 ha yr^{-1}, respectively), and there is no evidence in forming stable floodplains except temporary attachment of bars with the banks.

It is also evident from the tabulated results that Bahadurabad Ghat Reach contains more bars than the Jamuna Bridge Reach. The degree of braiding is higher at Bahadurabad Ghat Reach compared with the Jamuna Bridge Reach (see Tables 6.1 and 6.2). In contrast, the average bar areas at Bahadurabad Ghat Reach are smaller than the Jamuna Bridge Reach. This is probably because the wider reach experiences more internal bar reworking and channel switching within its braid belt at all level of stage variation than the narrowest reach (Bristow, 1987; Leys & Werritty, 1999). In addition to the contrasting relationship of average bar areas between the reaches, it is noticeable that there is no systematic increase or decrease of bar number in any of the reaches over the one or two-year period.

6.4.3. Land cover Classification

Identification and classification of land cover within the river banks is important as this could provide a basis for mapping geomorphological features and landuse patterns along with their spatial and temporal changes (EGIS, 1997). Thus, changes in the character of the two reaches of the Brahmaputra-Jamuna River occupied by the different land cover types may be used for mapping of geomorphological features, and for estimation of sediment balance by comparing erosional loss and depositional gain (see Chapter 8). Therefore, the main aim of this section is to map reach-scale patterns of land cover within the braid-belt and to identify any change over time using satellite images.

Satellite image classification is the process of sorting pixels into a finite number of individual classes based on their digital number (*dn*) values. If a pixel satisfies a certain set of criteria, the pixel is assigned to the class that corresponds to a particular homogeneous geomorphological features in the real world. The land cover classes that were used in this study were chosen to permit areas that had different characteristics to be differentiated in the land cover classification process and the same spectral signatures were used for the classification of each image. Land cover classification was accomplished with a supervised maximum likelihood algorithm using the ERDAS Imagine program.

The land cover classes applied in this study were selected after an intensive field examination of land covers in the selected river reaches (see Appendix 2). It was desirable to limit the number of land cover classes to be employed in an effort to simplify the classification and measurement process. The land cover classes selected to use in this study (that corresponds with some other studies, i.e. FAP19, 1996; EGIS, 1997; Hassan *et al.*, 1999), therefore, consisted of:

i) water,

ii) vegetated land (natural vegetation),

iii) crop land, and

iv) bare land.

The classified image data for the two reaches are listed in Tables 6.5 and 6.6. Classification results show that there are no indicative differences among the land cover classes between the reaches but they vary for a short period of time (one or two-year period) in a single reach. The land cover types are dominated by water and bare land surfaces. Crop land is also dominant compared to natural vegetal covers which are sparsely distributed (Figs. 6.5 and 6.6), however, it varies from time to time as bars modify their shape and size frequently by sediment accretion or erosion.

Table 6.5: Distribution of land cover types within the banklines at Bahadurabad Ghat Reach (in ha).

Year	Total Area	Water		Vegetated Land		Crop Land		Bare Land	
		Total	%	Total	%	Total	%	Total	%
1987	28629	7904	28	2487	9	7254	25	10984	38
1989	31011	10749	35	1013	3	5471	18	13778	44
1992	31621	9572	30	1544	5	7276	23	13229	42
1994	32010	9041	28	3216	10	8958	28	10795	34
1995	32157	6991	22	2768	9	9060	28	13338	41
1996	32675	8485	26	1935	6	10402	32	11853	36
1997	33105	9298	28	5475	17	5714	17	12618	38

Table 6.6: Distribution of land cover types within the banklines at Jamuna Bridge Reach (in ha).

Year	Total Area	Water		Vegetated Land		Crop Land		Bare Land	
		Total	%	Total	%	Total	%	Total	%
1987	25045	6604	26	2028	8	7008	28	9405	38
1989	27535	8170	30	387	1	4648	17	14330	52
1992	29376	7570	26	1963	7	7196	24	12647	43
1994	29516	7436	25	883	3	5962	20	15235	52
1995	30359	6391	21	3835	13	10786	35	9347	31
1996	30491	7694	25	1596	5	7751	26	13450	44
1997	29917	8786	29	4437	15	9932	33	6762	23

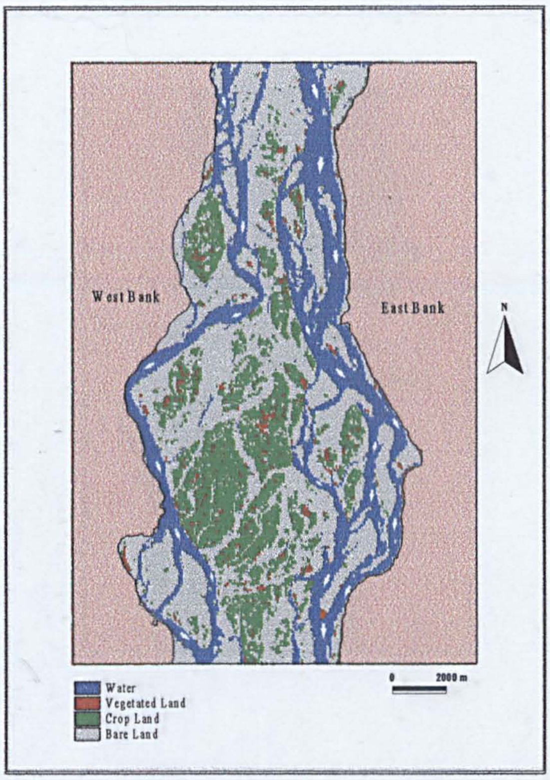


Figure 6.5a: Landcover types of the bars at Bahadurabad Ghat Reach during 1987.

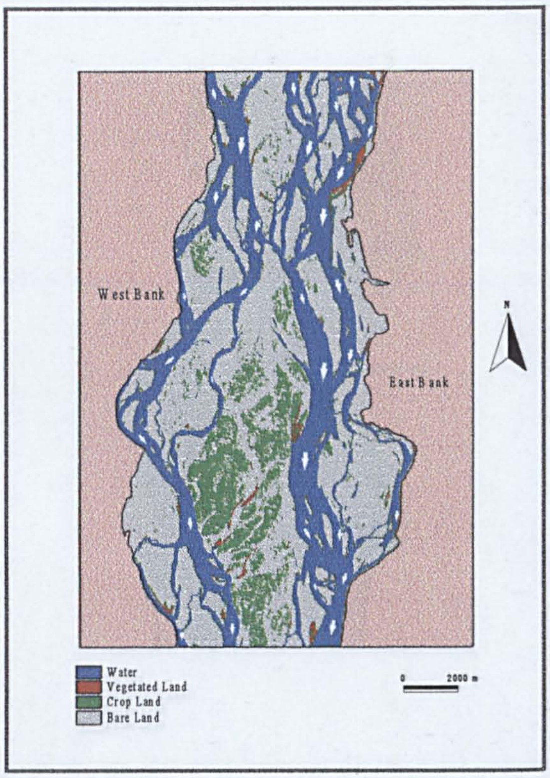


Figure 6.5b: Landcover types of the bars at Bahadurabad Ghat Reach during 1989.

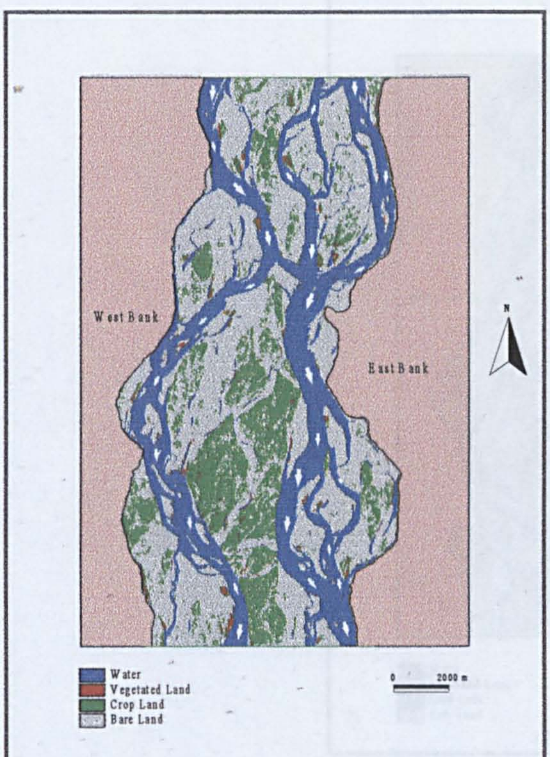


Figure 6.5c: Landcover types of the bars at Bahadurabad Ghat Reach during 1992.

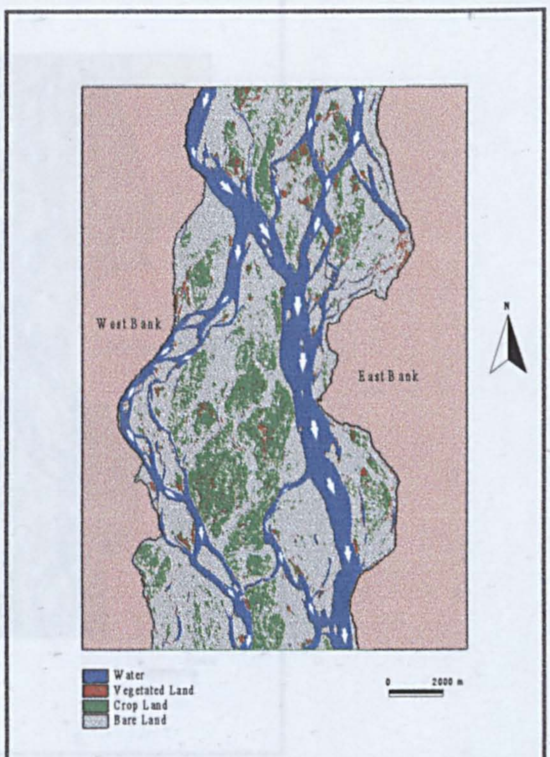


Figure 6.5d: Landcover types of the bars at Bahadurabad Ghat Reach during 1994.

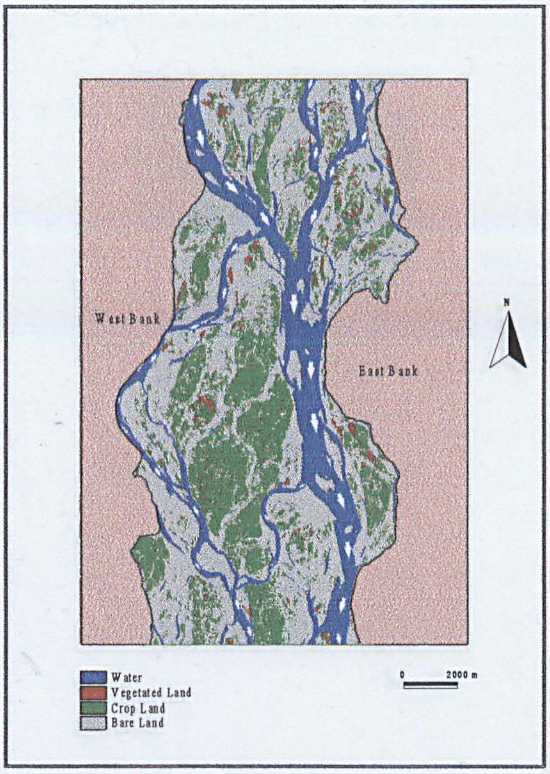


Figure 6.5e: Landcover types of the bars at Bahadurabad Ghat Reach during 1995.

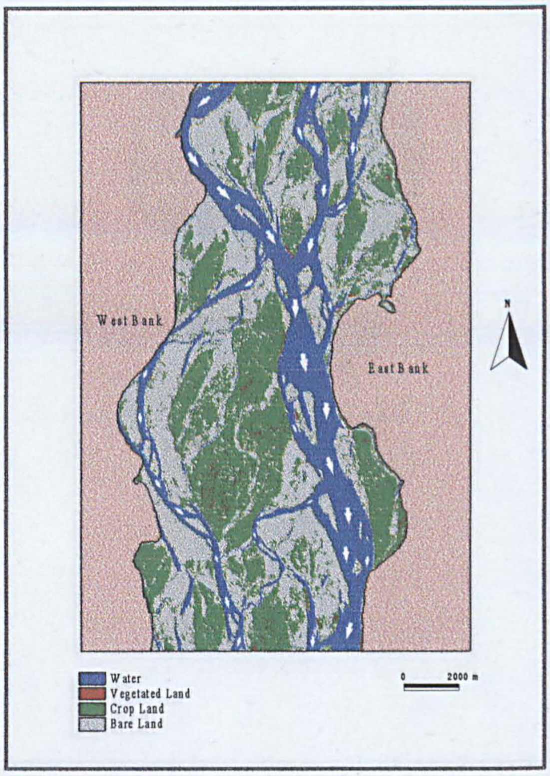


Figure 6.5f: Landcover types of the bars at Bahadurabad Ghat Reach during 1996.

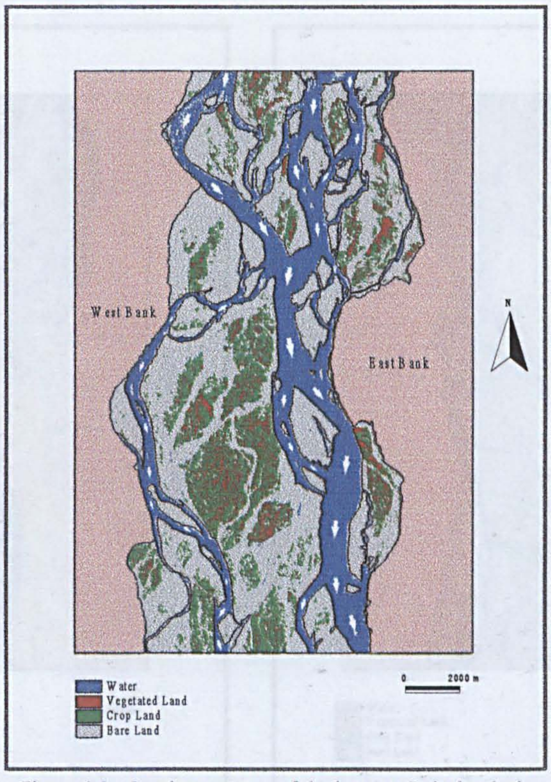


Figure 6.5g: Landcover types of the bars at Bahadurabad Ghat Reach during 1997.

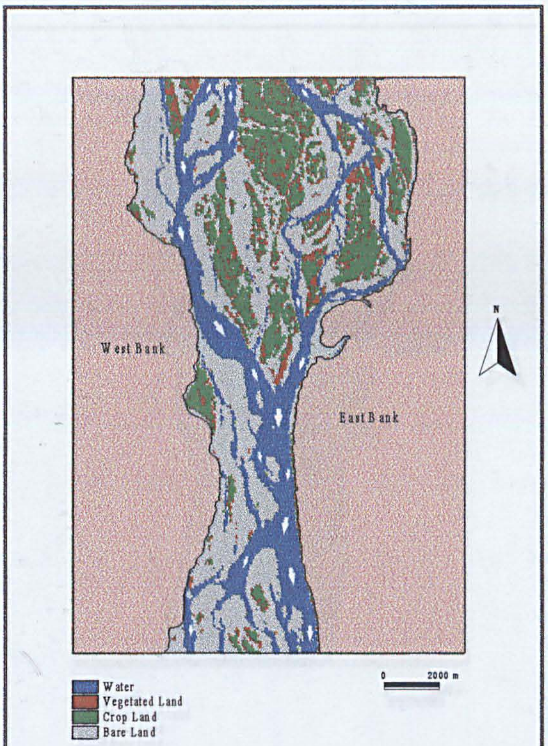


Figure 6.6a: Landcover types of the bars at Jamuna Bridge Reach during 1987.

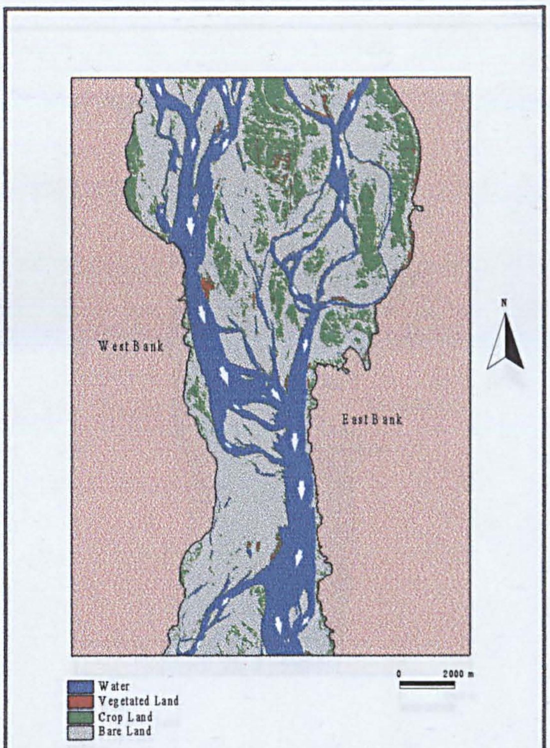


Figure 6.6b: Landcover types of the bars at Jamuna Bridge Reach during 1989.

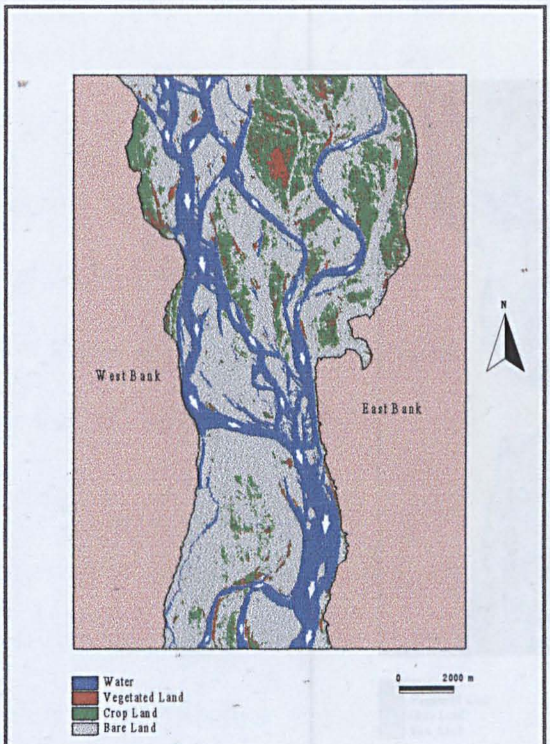


Figure 6.6c: Landcover types of the bars at Jamuna Bridge Reach during 1992.

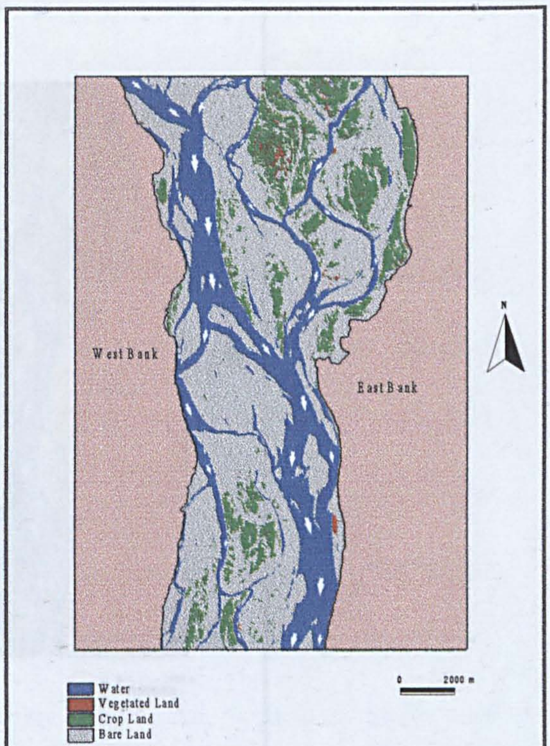


Figure 6.6d: Landcover types of the bars at Jamuna Bridge Reach during 1994.

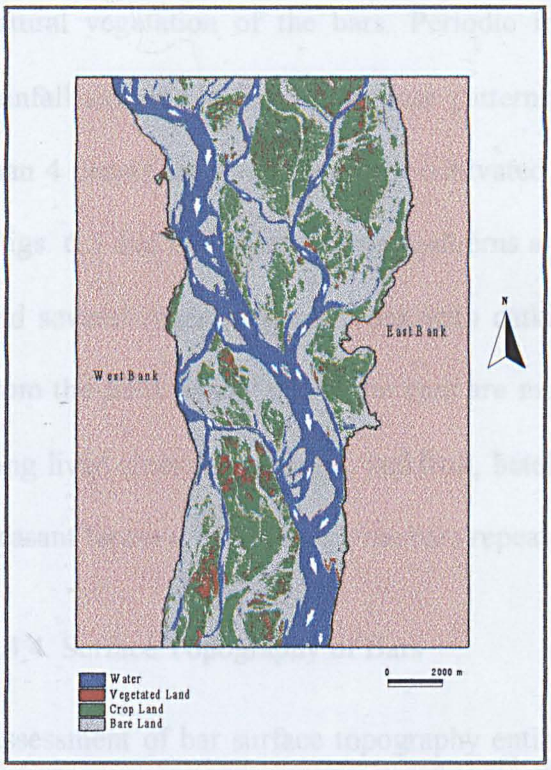


Figure 6.6e: Landcover types of the bars at Jamuna Bridge Reach during 1995.

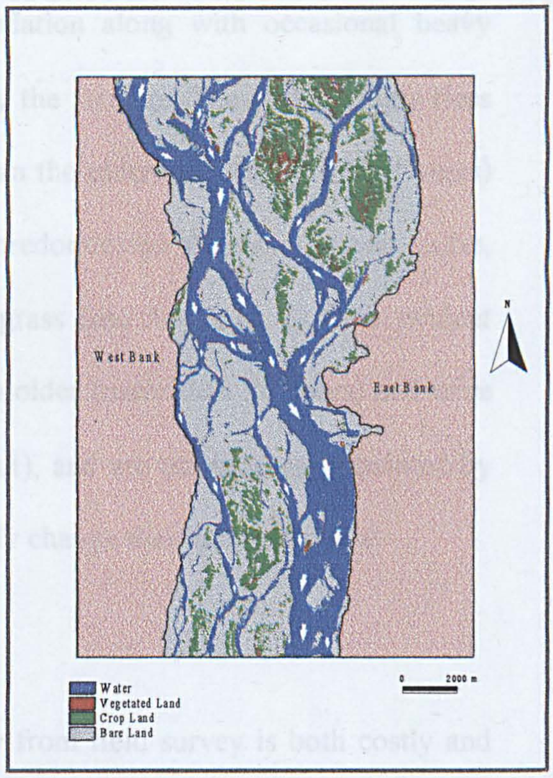


Figure 6.6f: Landcover types of the bars at Jamuna Bridge Reach during 1996.

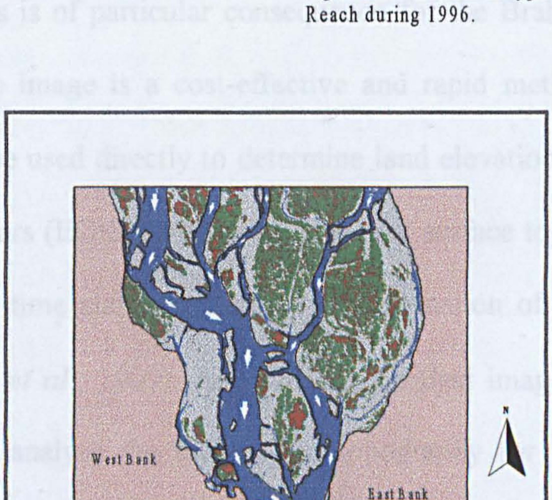


Figure 6.6g: Landcover types of the bars at Jamuna Bridge Reach during 1997.

The land cover types of the bars of the Brahmaputra-Jamuna River are controlled by the dynamism of the river, and the monsoon dominates the agronomic practices and natural vegetation of the bars. Periodic inundation along with occasional heavy rainfall allows a variety of landuse patterns by the farmers. The younger bars (less than 4 years) are less intensively cultivated than the older ones (more than 4 years) (Figs. 6.5 and 6.6). The cropping patterns are predominated by peanut, wheat, pulse, and several other seasonal crops with catkin grass (see Appendix 2). It is evident from the field survey that some bars are much older (more than 20 years) and have long lived trees (e.g. mango, jackfruit, betel nut), and are permanently inhabited by peasant farmers, even though the bars repeatedly change their shape and size.

6.4.4. Surface Topography of Bars

Assessment of bar surface topography entirely from field survey is both costly and time-consuming, and this is of particular consequence for the Brahmaputra-Jamuna River. Although satellite image is a cost-effective and rapid method of acquiring synoptic data, it cannot be used directly to determine land elevations in areas of low relief such as the braid bars (EGIS, 1997). However, bar surface topography may be assessed minimising the time and cost through a combination of field survey and satellite images (Hassan *et al.*, 1999). Accordingly, Landsat images and field data have been employed to analyse the bar surface topography for the two selected reaches of the Brahmaputra-Jamuna River. As the field bar survey was conducted during the 1997-1998 period, only the 1997 Landsat images for both reaches were considered for this analysis. Field observations of bar surface topography permitted the recognition of a multi-level topographic pattern for the bars of the Brahmaputra-Jamuna, and therefore, three main topographic levels were recognised in respect of elevation, denseness of vegetation, and the type and intensity of fluvial activity.

Level I

The first topographic level includes newly formed (more than 1 year) bars to 4-year old bars and it is considered the lowest and youngest part compared to the other levels. The topographic surface of this level is nearly homogeneous with sand dunes and ripples and almost free from vegetation cover (Fig. 6.7). Its relative height in respect to water level varies from 1.75 m to 4.50 m. This level is regarded to be the most active parts of the bars and changes its shape with any level of stage variation. Hence, morphologically this level is sometimes treated as bedform rather than bar as a result of its constantly shifting and reforming behaviour (Thorne *et al.*, 1993).

Level II

The second level is higher (4.50 m to 6.00 m) than level I and the age of this level ranges from 5 to 10 years. The top of this level is usually covered by current ripple lamination with loose sediment surface, probably deposited by waning flow as the water level fell (Bristow, 1993). This level is subject to reshaping at higher river stage during major floods, and changes in bar topography caused by smaller variations in discharge are less noticeable than on level one. A good vegetation cover is observed in this level but it is mainly confined to seasonal crops interspersed with natural shrubs and bushes (Fig. 6.8).

Level III

Level three is the highest (elevation range from 6.00 m to local floodplain level) and oldest (more than 10 years) part of the bars and in respect of both elevation and landuse it is very similar to local floodplain (Thorne *et al.*, 1993). It differs markedly from levels I and II in having a dense cover of perennial vegetation with better alluvial soil, dominated by intensive agricultural practices (Fig. 6.9a).

(a)

(b)

Figure 6.7: Surface appearance of (a) sand dunes and (b) colonisation of catkin grass.

(a)

(b)

Figure 6.8: Photographic representations of (a) peanut cultivation and (b) wild bushes.

(a)

(b)

Figure 6.9: Views of (a) intensive crop cultivation and (b) semi-permanent settlement patterns.

This level is the most stable part of the bars and some permanent scattered settlement patterns are observed in this area (Fig. 6.9b).

These three topographic levels were interpreted on satellite images for both reaches and compared with field observations (Figs. 6.10 and 6.11). The figures showed a good reflection of bar topography with relative appearance of different levels and provided a more comprehensive order of topographic expression that may be used to determine reach-scale sediment budgets (see Chapter 8). Moreover, these patterns are consistent with the description put forward by Thorne *et al.* (1993) which attributes the existence of a three level hierarchy of morphological features.

6.4.5. Planform Shape of Bars

It is observed from the previous sections that the Brahmaputra-Jamuna River contains different forms of bars with different topographies. It is also well documented that the bars of the Brahmaputra-Jamuna River are diamond or triangular in shape (Coleman, 1969; Islam, 1990). However, there are no quantitative investigations in relation to the different shapes of bars. Therefore, this section attempts to quantify and deduce a general shape model for the bars of the Brahmaputra-Jamuna River by measuring their lengths and widths. Measurements were performed on classified satellite images, and only island bars were considered because of their dominance and distinct planform features.

In order to identify the overall bar shape of the Brahmaputra-Jamuna River, 10 bars were randomly selected from each-year image and a total of 140 bars were measured on 7 image pairs at both reaches each sharing equal numbers. A bar *shape index* (SI) was employed for each sampled bar (as defined by Rachocki, 1981), such that

$$SI = B_l/B_W \qquad (6.2)$$

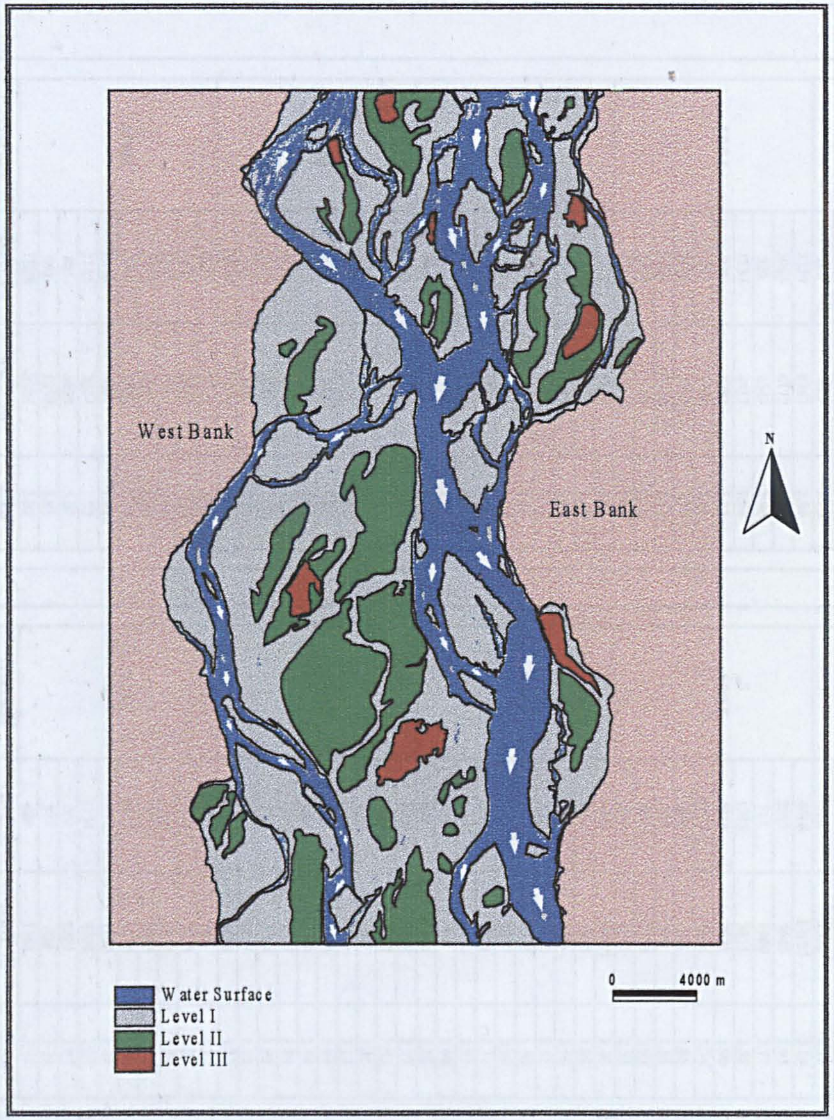


Figure 6.10: Areal distribution of different topographic levels at Bahadurabad Ghat Reach during 1997.

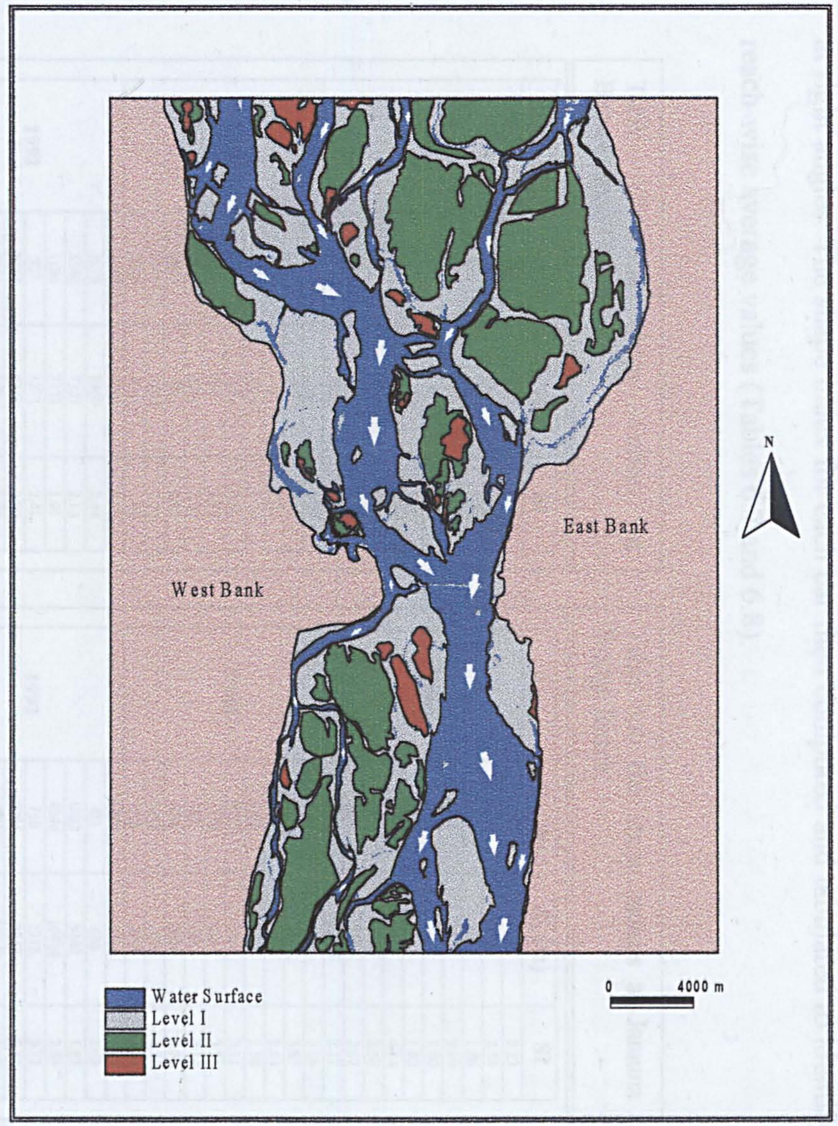


Figure 6.11: Areal distribution of different topographic levels at Jamuna Bridge Reach during 1997.

where, B_W is the width of bars, and B_L is the length of the bars intersecting bar width at right angles. The shape index for each bar then computed and tabulated to identify reach-wise average values (Tables 6.7 and 6.8).

Table 6.7: Bar shape indices at Bahadurabad Ghat Reach.

Year	B_W(m)	B_L(m)	SI
1987	619	1283	2.07
	778	2059	2.65
	803	2389	2.98
	433	708	1.63
	536	1565	2.92
	3831	7498	1.96
	1649	5674	3.44
	986	2155	2.19
	2735	6413	2.34
	2423	4842	2.00
1989	615	2456	3.99
	1227	3150	2.57
	598	1935	3.24
	3585	4809	1.34
	903	2263	2.51
	3067	8665	2.83
	603	1556	2.58
	2895	5517	1.91
	1104	2205	2.00
	2169	4045	1.86
1992	2097	3843	1.83
	3875	9469	2.44
	3340	7127	2.13
	1136	2171	1.91
	527	1271	2.41
	2935	8269	2.82
	2066	5336	2.58
	2430	4159	1.71
	466	1192	2.56
	220	815	3.70
1994	2339	6762	2.89
	3963	6172	1.56
	520	1549	2.98
	1234	2417	1.96
	996	1282	1.29
	1491	3739	2.51
	1676	3581	2.14
	3391	7280	2.15
	3354	7160	2.13
	9008	18219	2.02
1995	1571	4816	3.07
	5303	8734	1.65
	1190	3144	2.64
	417	795	1.91
	755	2196	2.91
	555	2721	4.90
	1515	5763	3.80
	429	1106	2.58
	1386	2771	2.00
	7964	17538	2.20
1996	2333	6422	2.75
	902	2974	3.30
	4863	6191	1.27
	810	1411	1.74
	216	828	3.83
	1053	3221	3.06
	3134	3595	1.15
	2768	6922	2.50
	528	884	1.67
	10168	15252	1.50
1997	3811	5220	1.37
	2479	5053	2.04
	3563	9412	2.64
	1558	2866	1.84
	1516	3048	2.01
	2346	4481	1.91
	1745	2674	1.53
	887	4498	5.07
	662	1857	2.81
	1183	2384	2.02
Average	2089.04	4453.96	2.13

Table 6.8: Bar shape indices at Jamuna Bridge Reach.

Year	B_W(m)	B_L(m)	SI
1987	1611	3571	2.22
	827	2136	2.58
	1534	3008	1.96
	834	2505	3.00
	2925	5858	2.00
	3934	7164	1.82
	1598	6608	4.14
	789	1879	2.38
	1292	3453	2.67
	8265	17918	2.17
1989	1618	5112	3.16
	732	2836	3.87
	334	883	2.64
	3363	8679	2.58
	2205	6864	3.11
	1158	2604	2.25
	304	651	2.14
	794	2006	2.53
	1478	3478	2.35
	655	1089	1.66
1992	1822	3616	1.98
	421	688	1.63
	1882	3440	1.83
	4246	10810	2.55
	710	2213	3.12
	3786	8048	2.13
	6170	11847	1.92
	204	516	2.53
	519	1052	2.03
	516	2528	4.90
1994	4418	14105	3.19
	2897	5645	1.95
	711	1969	2.77
	1313	3051	2.32
	4020	7632	1.90
	1697	4306	2.54
	394	728	1.85
	434	687	1.58
	893	3513	3.93
	444	1117	2.52
1995	4453	10685	2.40
	1024	1115	1.09
	293	673	2.30
	812	1872	2.31
	4865	7293	1.50
	842	3337	3.96
	1984	3391	1.71
	816	1850	2.27
	372	998	2.68
	636	1906	2.30
1996	2310	5158	2.23
	1045	3062	2.93
	232	304	1.31
	269	5.72	2.13
	3203	9583	2.99
	826	2099	2.54
	1559	4507	2.89
	900	1784	1.98
	1157	2237	1.93
	1802	5858	3.25
1997	576	875	1.52
	655	1253	1.91
	1303	3596	2.76
	1974	3275	1.66
	3030	6676	2.20
	997	1285	1.29
	1731	4768	2.75
	407	1201	2.95
	277	908	3.49
	808	2761	3.42
Average	1641.50	3867.93	2.36

The results show that shape indices at both reaches vary within the range 1.09 to 5.07, with average bar shape indices at Bahadurabad Ghat and Jamuna Bridge reaches are 2.13 and 2.36 respectively. The overall bar shape index for the combined data sets is 2.25 that can be compared with the observation of Rachocki (1981) who notes bar shape index as 2.35. The average figure demonstrates that the bar lengths are 2.25 times longer than the bar widths, and this quantification supports earlier observations that the bars of the Brahmaputra-Jamuna River are diamond or triangular shaped. The measured bar shape indices are also examined by scatter diagram with their widths and lengths, and show a very good relationships among them (Fig. 6.12). Hence, these observations of bar shape indices permit recognition of a prototype model for bar shape using a satellite image (Fig. 6.13) which provides a characteristic shape that is usually observed in the Brahmaputra-Jamuna River.

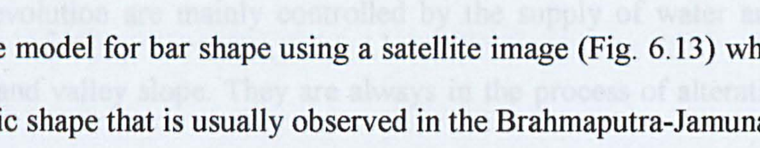


Figure 6.12: Scatter diagram showing the width-length relation of braid bars.

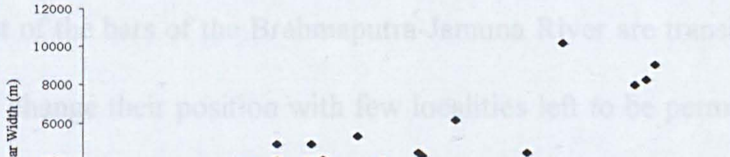


Figure 6.13: A prototype shape model of a braid bar.

6.5. Bar Dynamics

6.5.1. Methodology

The rate and movement of bars over a decadal period were monitored using the classified digital images of different types of land covers and their attributes along with field observations. The rates of bar accretion and erosion was calculated by comparing the results of two successive years images at both reaches.

6.5.2. Stability of Bars

It is evident that bars are essential features of braided rivers, and their initiation, growth and evolution are mainly controlled by the supply of water and sediment, flow pattern and valley slope. They are always in the process of alteration and their dynamic nature continues all the year round under competent flow patterns. Likewise, most of the bars of the Brahmaputra-Jamuna River are transient in nature, and constantly change their position with few localities left to be permanently stable (ISPAN, 1995b; JMBA, 1996). Thus bar movement and reworking occurs along the entire length of the river and their dynamic nature are thought to be related to three main processes which are closely linked to each other.

Firstly, most of the bars are submerged during summer high flow, and erosion tends to occur at the upstream end of bars and deposition on downstream sections (Coleman, 1969; Bristow, 1987; JMBA, 1996). In some cases bars are completely removed from their initial location and deposited in a new location (Coleman, 1969). Secondly, during falling stage upstream ends and lateral margins receive sediment deposits and the downstream zone suffers occasional erosion (Bridge, 1993; Ashworth *et al.*, 2000). Thirdly, chute cutting and abandonment of channels can occur at any flow stage, and this accelerates bar movement (Coleman, 1969; Bristow, 1987; Bridge, 1993). Note also that some of the processes may be reversed due to local hydraulic conditions, for example, upstream instead of downstream and accretion instead of erosion (Ashmore, 1993).

6.5.3. Bar Erosion and Deposition

Erosion and deposition of the attached and island bars between 1987 and 1997 have been calculated from the measurements of total bar area (see Tables 6.3 and 6.4). The total area of the two types of bars at both reaches between two successive years was compared and overall rates of erosion and deposition are given in Tables 6.9 and 6.10. The net decadal distribution of total bar erosion and deposition are mapped in Figures 6.14 and 6.15.

Table 6.9: Rates of bar erosion and deposition (in ha) at Bahadurabad Ghat Reach.

Year	Attached Bar	Island Bar	Total
1987-89	-839	+1302	+463
1989-92	-239	-1548	-1787
1992-94	-1699	+779	-920
1994-95	-2390	+193	-2197
1995-96	+2161	-1185	+976
1996-97	+94	+289	+383
1987-97	**-2912**	**-170**	**-3082**

Note: '+' sign indicates net erosion and '–' sign indicates net deposition.

Table 6.10: Rates of bar erosion and deposition (in ha) at Jamuna Bridge Reach.

Year	Attached Bar	Island Bar	Total
1987-89	-2942	+2018	-924
1989-92	+1697	-4139	-2442
1992-94	+613	-887	-274
1994-95	-2819	+931	-1888
1995-96	+921	+249	+1170
1996-97	-713	+2379	+1666
1987-97	**-3243**	**+551**	**-2692**

Note: '+' sign indicates net erosion and '–' sign indicates net deposition.

Table 6.9 shows that over the decadal period bar deposition (73%) was more intense compared to bar erosion (27%) at Bahadurabad Ghat Reach while bar erosion and accretion vary reasonably for the short period of times. The overall rate of bar deposition during 1994-1995 was the highest (2197 ha), which appears to be due primarily to the transfer of sediments from upstream as no significant bank erosion occurred in this period (see Table 5.2). Nevertheless, an interchangeable adjustment

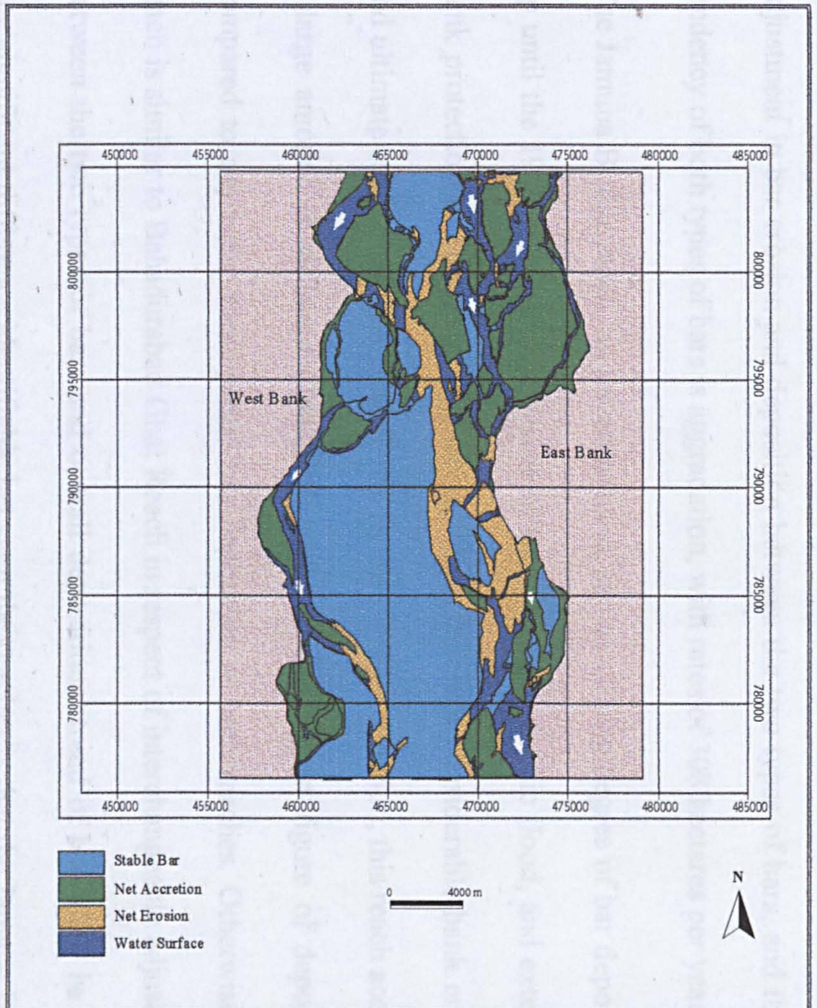


Figure 6.14: Bar accretion and erosion at Bahadurabad Ghat Reach during 1987-1997.

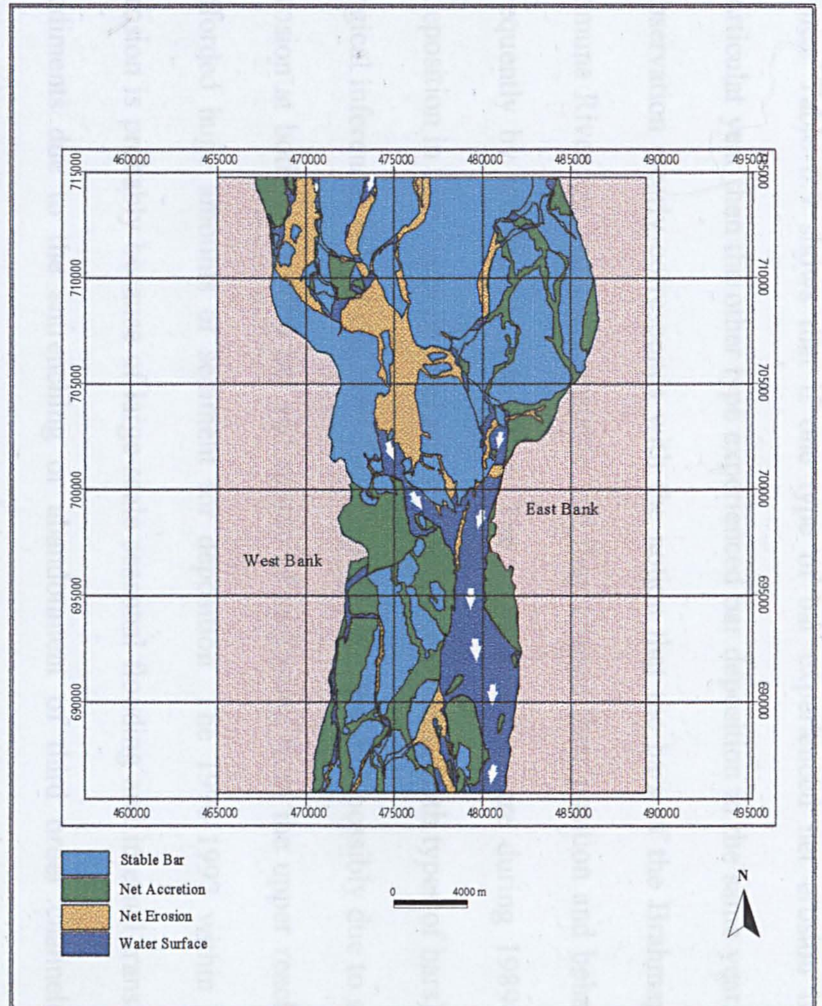


Figure 6.15: Bar accretion and erosion at Jamuna Bridge Reach during 1987-1997.

between the attached and island bars has been observed during the short period of times. Table 6.9 shows that if one type of bar experienced net erosion in any particular year then the other type experienced bar deposition in the same year. This observation clearly corresponds with the notion that the bars of the Brahmaputra-Jamuna River are extremely unstable and they change their position and behaviour frequently by erosion and deposition. The only exceptions are during 1989-1992 (deposition in both types of bars) and 1996-1997 (erosion in both types of bars). The logical inferences behind the 1989-1992 deposition is that it is possibly due to severe erosion at both banks (609 ha) and supply of sediments from the upper reach that afforded huge amounts of sediment for deposition. The 1996-1997 within reach erosion is probably because of large-scale seasonal flooding and internal transfer of sediments due to the entrenching or abandonment of third order channels (cf. Bristow, 1987). These observations demonstrate that there is a considerable mutual adjustment in bar erosion and deposition between the two types of bars, and the net tendency of both types of bars is aggradation, with rates of 308 hectares per year.

The Jamuna Bridge reach, on the other hand, shows varying degree of bar deposition up until the 1994-1995 period because of the 1988 catastrophic flood, and extensive bank protection and river training works which followed considerable bank erosion and ultimate bar deposition (Table 6.10). In the 1989-1992 period, this reach accreted a large amount of sediment (2442 ha), which is the highest figure of deposition compared to any other short period bar deposition at both reaches. Otherwise this reach is similar to Bahadurabad Ghat Reach in respect of interchangeable adjustment between the two types of bars and overall depositional trend of bars (269 ha yr^{-1}). The significant difference identifiable between the reaches is that the Jamuna Bridge Reach experienced a large amount of bar erosion (2836 ha in two years) during

1995-1996 and 1996-1997 periods, probably due to the inception of the Jamuna Bridge Project. This presumption corresponds with the observations of the Jamuna Multipurpose Bridge Authority (JMBA, 1996) where they found bar erosion around the construction zone.

The tables and figures indicate that over the decadal timescales both the study reaches were accreted by bar deposition, and that sediment generated by bank erosion at both reaches (see Chapter 5) represents a significant sediment source. Therefore, it is likely that there is a process-response linkage between bank erosion and bar deposition, and this linkage is not only accelerated or decelerated by severe flood peaks but also regulated by upstream erosion or accretion and constructional interruption.

6.5.4. Bar Migration

It is evident that the bars are dynamic in nature and that their mobility varies spatially and temporally. Under different river stages sediment is mobilised, and accordingly shape and size are modified laterally and longitudinally. The rapidity of change is probably related to high channel slope (Rust, 1972), intensity and duration of floods (Rust, 1972; Smith, 1974) and extensive river management works (Erskine and Warner, 1999).

Such conditions exist in the Brahmaputra-Jamuna River, which is dominated by transient bars that commonly migrate laterally and longitudinally (Coleman, 1969). The intensity and duration of bar migration depends on the periodicity and duration of monsoonal floods (Coleman, 1969; Ashworth *et al.*, 2000). In rivers like the Brahmaputra-Jamuna, observation of bar migration is a difficult task as bars usually migrate nearly 500 m to 1500 m from one flood season to another flood season

(Coleman, 1969; Ashworth *et al.*, 2000) or in some cases bars are completely removed during a single flood (Coleman, 1969). Similar problems are encountered in decadal studies of bar migration for particular reaches because bar movement occasionally goes beyond the reach limit. However, notwithstanding these caveats, an attempt was made to interpret bar migration from satellite images and this is discussed in the following paragraphs.

6.5.4.1. Lateral Bar Migration

Lateral bar migration was monitored using 5 successive years Landsat images at Bahadurabad Ghat Reach beginning in 1992. The rationale behind these selections were twofold. First, the whole bar migration process appears to have been cyclic during the period of 1992-1997. Second, the sampled bars on selected images were the most distinct features that could be monitored with least ambiguity. Monitoring was commenced on an exposed lateral island bar (with an area of 121 ha) which was thought to have been formed during the period of the 1991 monsoon flood (Fig. 6.16a). The planform shape of the bar was triangular with two main bar tail limbs and located near the concave bend of the western bank in the middle stretch at Bahadurabad Ghat Reach. Such bar tail limbs are a common morphological feature of island bars of the Brahmaputra-Jamuna which are thought to be responsible for trapping huge amount of sediments for further growth and development (Ashworth *et al.*, 2000).

During the 1992-1994 period, the bar underwent considerable change by upstream, downstream and lateral accretion and migrated north-westward, having an elongated shape with almost 129 ha areal expansion (Fig. 6.16b). The north-westward lateral accretion and bar-head extension was accelerated by western anabranch incision and

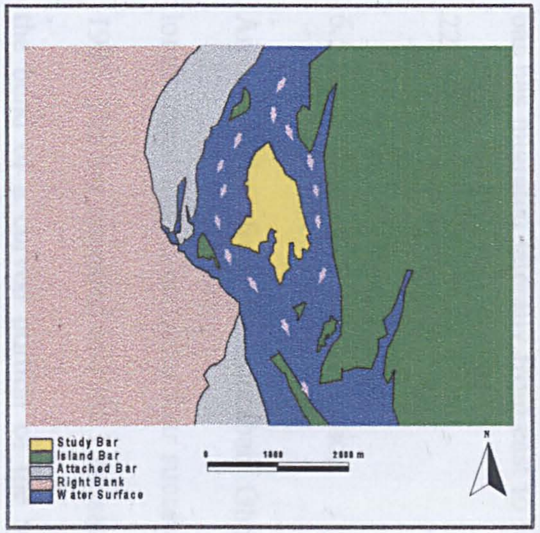


Figure 6.16a: Location of the study bar during 1992.

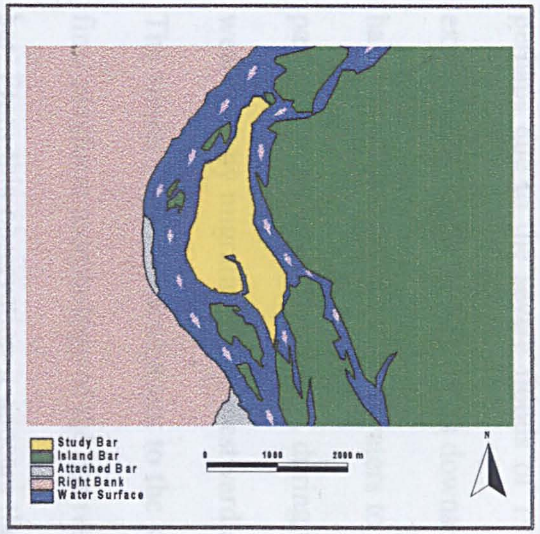


Figure 6.16b: Lateral bar migration during 1992-1994.

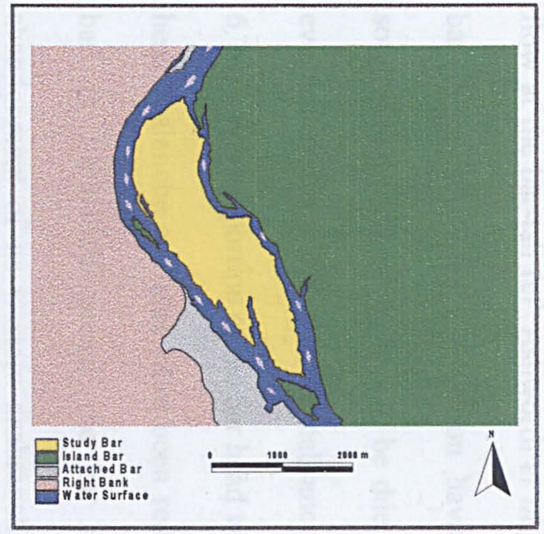


Figure 6.16c: Lateral bar migration during 1994-1995.

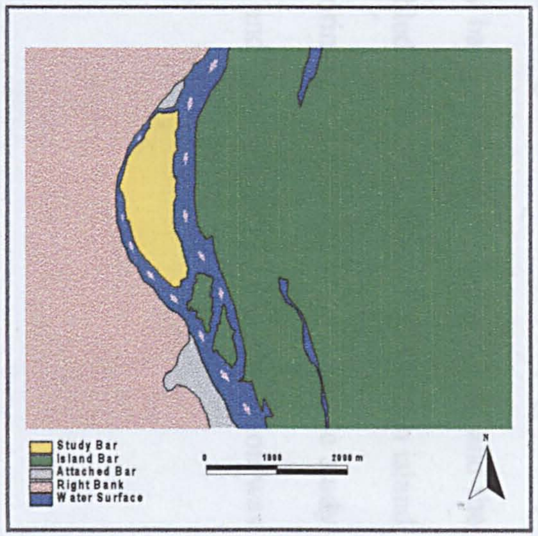


Figure 6.16d: Lateral bar migration during 1995-1996.

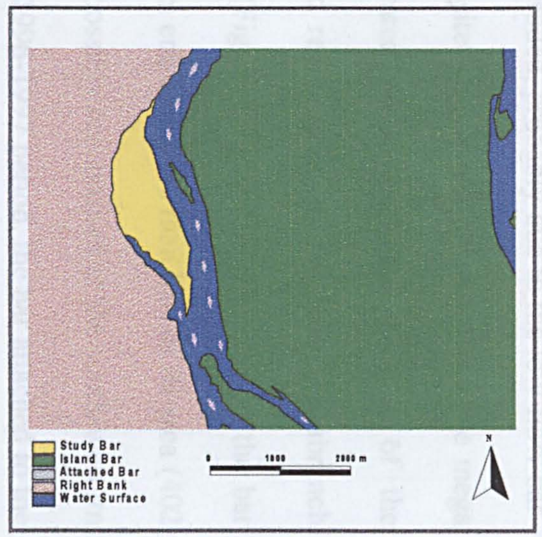


Figure 6.16e: Lateral bar migration during 1996-1997.

attached bar erosion due to flow divergence at the bar-head and inwardly moving flow at the bar-tail (cf. Ashworth *et al.*, 2000). In the next period (1994-1995), the bar experienced major alteration having a more elongated shape and migrated southward which is believed to be due to propagation of its nearest mega bar, and eventual constriction of both anabranches due to upstream flow deceleration (Fig. 6.16c). A good portion of the bar head was eroded, probably due to the low-flow bar-head avalanche and may have been redeposited at the nearest margin of the mega bar. In 1995-1996 period, the bar migrated westward again because of the abandonment of its western anabranch and rejuvenation of its eastern anabranch perhaps due to the severe floods of 1995 (Fig. 6.16d). During that period the bar experienced severe erosion of its downstream end and more than half of its area (402 ha) was washed away by floodwaters to be possibly redeposited at the south-western part of the mega bar. Eventually, during the 1996-1997 period, the bar attached to the west bank by migrating more westward and ceasing its island bar status (Fig. 6.16e). The western anabranch adjacent to the study bar was completely abandoned and the final planform morphology of the bar resembled an attached bar rather than an island bar. From this observation it appears that during the period of 1992-1997 the study bar has migrated laterally from east to west and the estimated rate of migration was 225 myr^{-1}.

6.5.4.2. Longitudinal Bar Migration

An island bar from Bahadurabad Ghat Reach was also selected to monitor its longitudinal migration using four successive satellite images for the period of 1989-1995. The bar appeared in 1989 Landsat image at approximately 3500 m away from the bend of a curved portion of the south-eastern reach near a large island bar, probably formed and emerged after the 1988 flood (Fig. 6.17a). The planform of the

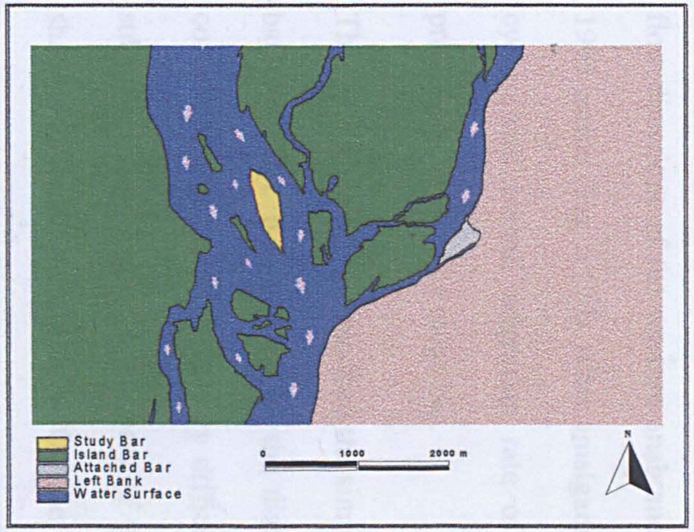


Figure 6.17a: Location of the study bar during 1989.

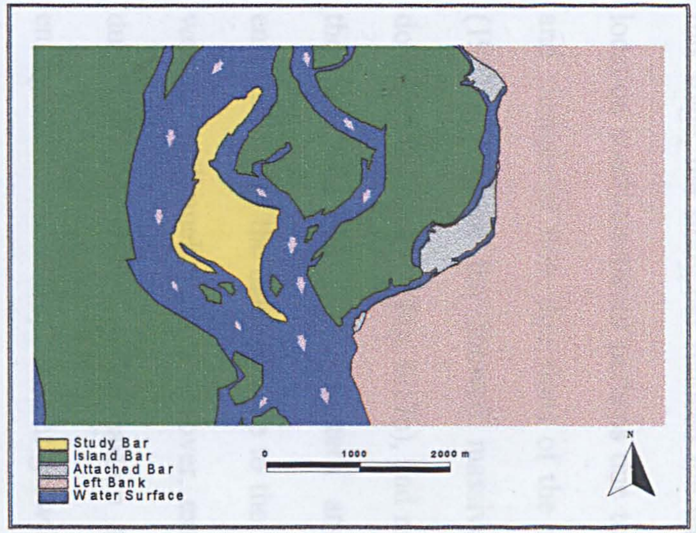


Figure 6.17b: Location of the study bar during 1989-1992.

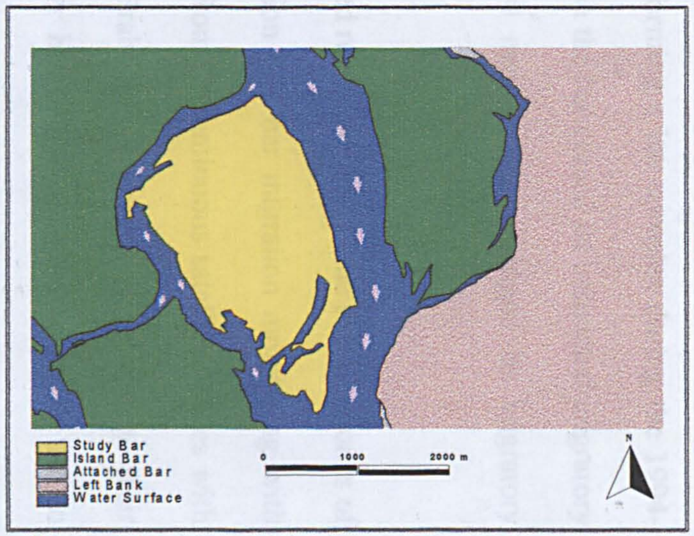


Figure 6.17c: Location of the study bar during 1992-1994.

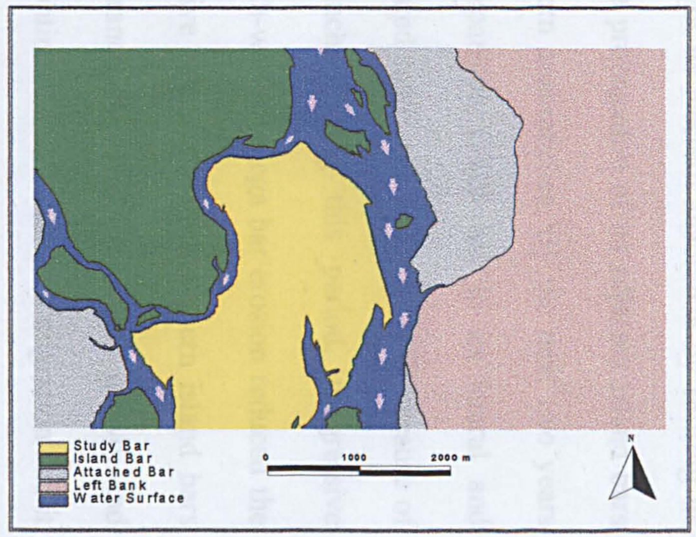


Figure 6.17d: Location of the study bar during 1994-1995.

bar at this time was almost oval shaped with an area of 52 hectares. During the 1989-1992 period, deposition of sediments around the study bar created a large diamond shaped bar (409 ha) with elongated bar-head and two bar-tail limbs (Fig. 6.17b). At this stage, the study bar reduced the width of its western anabranch by shifting its location south-westward perhaps due to the propagation of its adjacent island bars and changes of flow directions of the eastern anabranches. By the next two years (1992-1994), the bar showed massive expansion (1425 ha) to its lateral and downstream margins (Fig. 6.17c), and migrated south-westward probably because of the predominance of its eastern anabranch. During this period, progressive enlargement of the bar head due to the north-western mega bar erosion reduced the western anabranch flow. Moreover, extensive erosion of north-eastern island bars due to the expansion of the eastern anabranch also accelerated the growth and enlargement of the study bar. Bar growth continued with southward migration and it finally amalgamated with another island bar, probably because of the changes of flow directions of the western anabranch, forming a bar complex during the 1994-1995 period (Fig. 6.17d). After amalgamation the bar ceased its individual migratory cycle (with overall migration rate of 450 myr^{-1}) and prolonged its migratory propensity further as a mega bar.

The previous sections described the simplified representation of the two categories of bar migration. It is clear from the discussion that bar migration monitoring with considerable explanations is very difficult from discontinuous satellite images with substantial time gaps because bars of the Brahmaputra-Jamuna River change their shape and location repeatedly. On the other hand, it is almost impossible and to monitor on a day-to-day basis a single bar migration from a single reach and unreasonable to attempt this because bar characteristics vary from reach to reach with substantial feedback. Nevertheless, this simplistic description corresponds with the established notion that the bars of the Brahmaputra-Jamuna River are migratory in nature but they are nearly unpredictable at any level of observation because they change their location frequently and rapidly.

6.8. Conclusion

Observations of reach-scale braiding and bar morphodynamics have provided a description of characteristic bar morphology and variability monitored and found in the Brahmaputra-Jamuna River over a decadal timescale. From these diverse observations on the nature of the bars and their interrelations with the banks the following conclusions are drawn:

(1) The continuum of the Brahmaputra-Jamuna River braiding has been quantified by the braiding index, and it is observed that braiding varies considerably with time and space (5.16 to 8.35) and average braiding intensity is higher in the widest reach (6.90) than in the narrowest reach (5.45).

(2) Channel braiding initiates with the formation of a mid-channel bar which is depositional in nature and follows five key stage in its initiation, growth and development that corresponds with Leopold and Wolman's (1957) classical example of braiding. Four types of bars are present in the Brahmaputra-Jamuna River and they are, longitudinal, lateral, diagonal and unit bar; but, morphologically these four types are grouped into two major classes, namely, island and attached bar.

(3) Island bars are prominent features relative to attached bars and the decadal tendency of both types of bars is to increase in area on both reaches. There are four classes of land cover identified in the channel bars of the Brahmaputra-Jamuna River and they are, water, vegetated land, crop land and bare land. The

relative areas of the land cover classes are dominated by water surface and bare land compared to the others. Three main types of topographic levels are identified on both forms of bars in respect of elevation, denseness of vegetation, and the type and intensity of fluvial activity. The planform shape of the island bars is distinguished as diamond or triangular with average shape index 2.25.

(4) The bars of the Brahmaputra-Jamuna River are extremely unstable and they change their position and behaviour through localised erosion and deposition. There are considerable mutual adjustments in bar erosion and deposition between the two types of bars, and the bars appear to be in a state of aggradation. The bars commonly migrate laterally and longitudinally, and the intensity and prolongation of bar migration depends on the periodicity and duration of monsoonal floods and flow directions. However, processes of migration are nearly unpredictable at any levels of observation because the bars change their location frequently and rapidly.

CHAPTER VII: BAR SEDIMENTOLOGY

7.1. Introduction

Understanding of sedimentological characteristics is fundamental to the study of geomorphological processes along a fluvial system (Petts & Foster, 1985; McCave & Syvitski, 1991; Paola *et al.*, 1992; Guyot *et al.*, 1999). Moreover, sediment properties can provide valuable clues to the environment of deposition and sources of the detrital particles (Blatt, 1992; McEwen & Matthews, 1998). Under these circumstances a proper evaluation of sediment properties becomes crucial and this is equally true for the bar sediments of the Brahmaputra-Jamuna River. In this respect this section attempts to analyse reach-scale sediment size characteristics and sediment mineralogy in order to explain the environment of deposition and potential sources of sediments.

7.2. Sediment Size Characteristics

7.2.1. Methodology

In order to undertake comparative analysis of bar sediment size characteristics and their sources of origin at Bahadurabad Ghat and Jamuna Bridge reaches, a total of 88 samples were collected from 44 locations using stratified random sampling techniques (Figs. 7.1 and 7.2). Two samples were taken at each location from the surface and subsurface (at a depth of 3.0 m) levels (see Section 4.3). Out of 88 samples, 56 samples were taken from the bars and 32 samples were taken from the river banks (Tables 7.1 and 7.2). At each location samples were collected assuming these deposits represent the full range of grain size characteristics in that location (Church and Kellerhals, 1978; Dawson, 1988; Robinson & Slingerland, 1998). Thirty-four additional samples were also collected from the bars and banks at both reaches at locations between the two successive samples. These samples were not

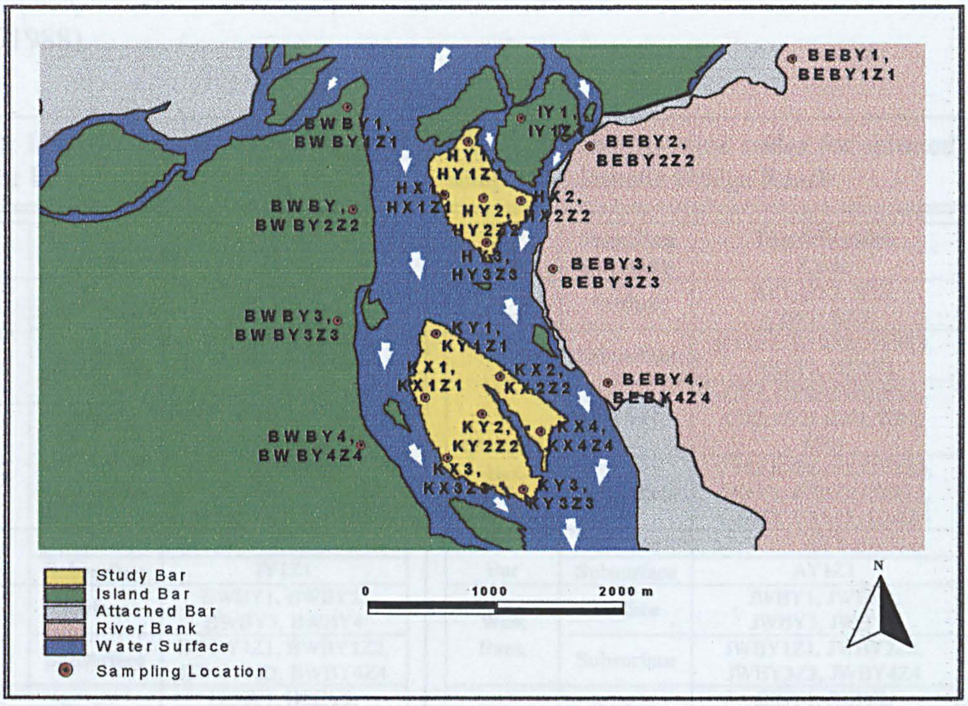


Figure 7.1: Sediment sampling locations at Bahadurabad Ghat Reach.

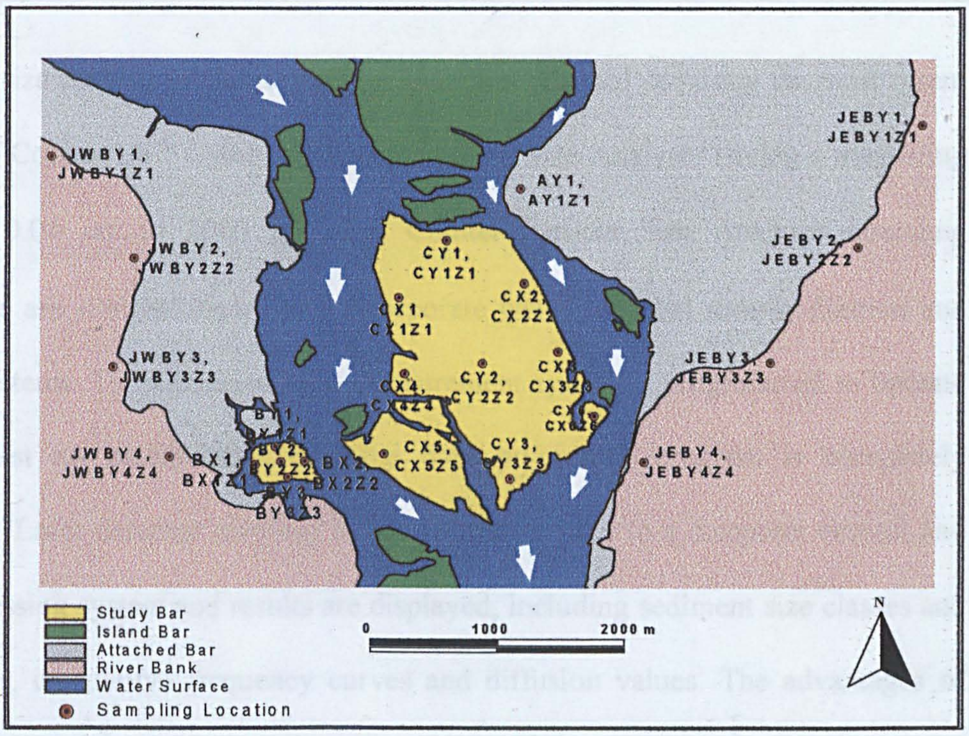


Figure 7.2: Sediment sampling locations at Jamuna Bridge Reach.

included in the laboratory analysis but retained as back-up if any distinct sedimentological variation was observed between two successive analysed samples (Dawson, 1988).

Table 7.1: Identification codes for selected samples at Bahadurabad Ghat Reach.

Bar/ Bank	Sampling Location	Identification Code
Harindhara Bar	Surface	HY1, HY2, HY3, HX1, HX2
	Subsurface	HY1Z1, HY2Z2, HY3Z3, HX1Y1, HX2Z2
Kulkandi Bar	Surface	KY1, KY2, KY3, KX1, KX2, KX3, KX4
	Subsurface	KY1Z1, KY2Z2, KY3Z3, KX1Y1, KX2Z2, KX3Z3, KX4Z4
Island Bar	Surface	IY1
	Subsurface	IY1Z1
West Bank	Surface	BWBY1, BWBY2, BWBY3, BWBY4
	Subsurface	BWBY1Z1, BWBY2Z2, BWBY3Z3, BWBY4Z4
East Bank	Surface	BEBY1, BEBY2, BEBY3, BEBY4
	Subsurface	BEBY1Z1, BEBY2Z2, BEBY3Z3, BEBY4Z4

Table 7.2: Identification codes for selected samples at Jamuna Bridge Reach.

Bar/ Bank	Sampling Location	Identification Code
Belutia Bar	Surface	BY1, BY2, BY3, BX1, BX2
	Subsurface	BY1Z1, BY2Z2, BY3Z3, BX1Y1, BX2Z2
Chatpier Bar	Surface	CY1, CY2, CY3, CX1, CX2, CX3, CX4, CX5, CX6
	Subsurface	CY1Z1, CY2Z2, CY3Z3, CX1Y1, CX2Z2,CX3Z3, CX4Z4, CX5Z5, CX6Z6
Attached Bar	Surface	AY1
	Subsurface	AY1Z1
West Bank	Surface	JWBY1, JWBY2, JWBY3, JWBY4
	Subsurface	JWBY1Z1, JWBY2Z2, JWBY3Z3, JWBY4Z4
East Bank	Surface	JEBY1, JEBY2, JEBY3, JEBY4
	Subsurface	JEBY1Z1, JEBY2Z2, JEBY3Z3, JEBY4Z4

Sediment size analysis of the selected samples were carried out using the most recent version of Coulter LS™ Laser Diffraction Particle Size Analyser having a measuring range of 0.04 μm to 2000 μm. The Coulter Particle Size Analyser operating procedures are straightforward and incorporate well-controlled sample dilution and mixing systems. The diffracted light measurement system is programmed to operate with almost no manipulation and the data processing program is completely automatic. Laser detector response is transmitted directly to a computer control and data processing system and results are displayed, including sediment size classes and parameters, cumulative frequency curves and diffusion values. The advantages of this system include capability for very small particle size characterisation, very small sample size requirements and reasonably rapid response (Agrawal *et al.*, 1991; Bott & Hart, 1996). All 88 samples were analysed using the Coulter Particle Size

Analyser with 3 runs per sample and 10% of samples reanalysed randomly to check the level of analytical consistency. To analyse statistical parameters and the sediment size trend, LS Control Program (version 2.11) was used.

7.7.2. Sediment Particle Size Characteristics

Changes in sediment particle size are among the most elementary and easily observed characteristics of sedimentary sequences. Particle size is the fundamental basis on which lithostratigraphic units are defined, and distribution of particle size has long been thought to contain important information about the process of sedimentation (Paola *et al.*, 1992; Livingstone *et al.*, 1999). The size distribution is also an essential property for assessing the dynamic conditions of transport and deposition (McCave & Syvitski, 1991; Church, 1999). Moreover, sediment particles possess many properties from which several characteristic linear dimensions may be obtained. The present section is designed to analyse and describe the particle size characteristics of the four selected bars at two reaches of the Brahmaputra-Jamuna River as well as to examine the mode of deposition of sediment following the laser diffraction methods and computer analysis.

7.2.2.1. Particle Size Distribution

52 sediment samples were analysed in total from four selected bars at both reaches (24 samples from Bahadurabad Ghat Reach and 28 samples from Jamuna Bridge Reach) of the Brahmaputra-Jamuna River (see Figs 7.1 and 7.2). The size of sediment particles in samples was ascertained and illustrated (Figs. 7.3 to 7.10) using the LS Control Program and the results were grouped into seven size classes by micrometer (μm) units (Tables 7.3 to 7.6). The size classes used in this study were based on the Udden-Wentworth particle size scale (Udden, 1914; Wentworth, 1922,

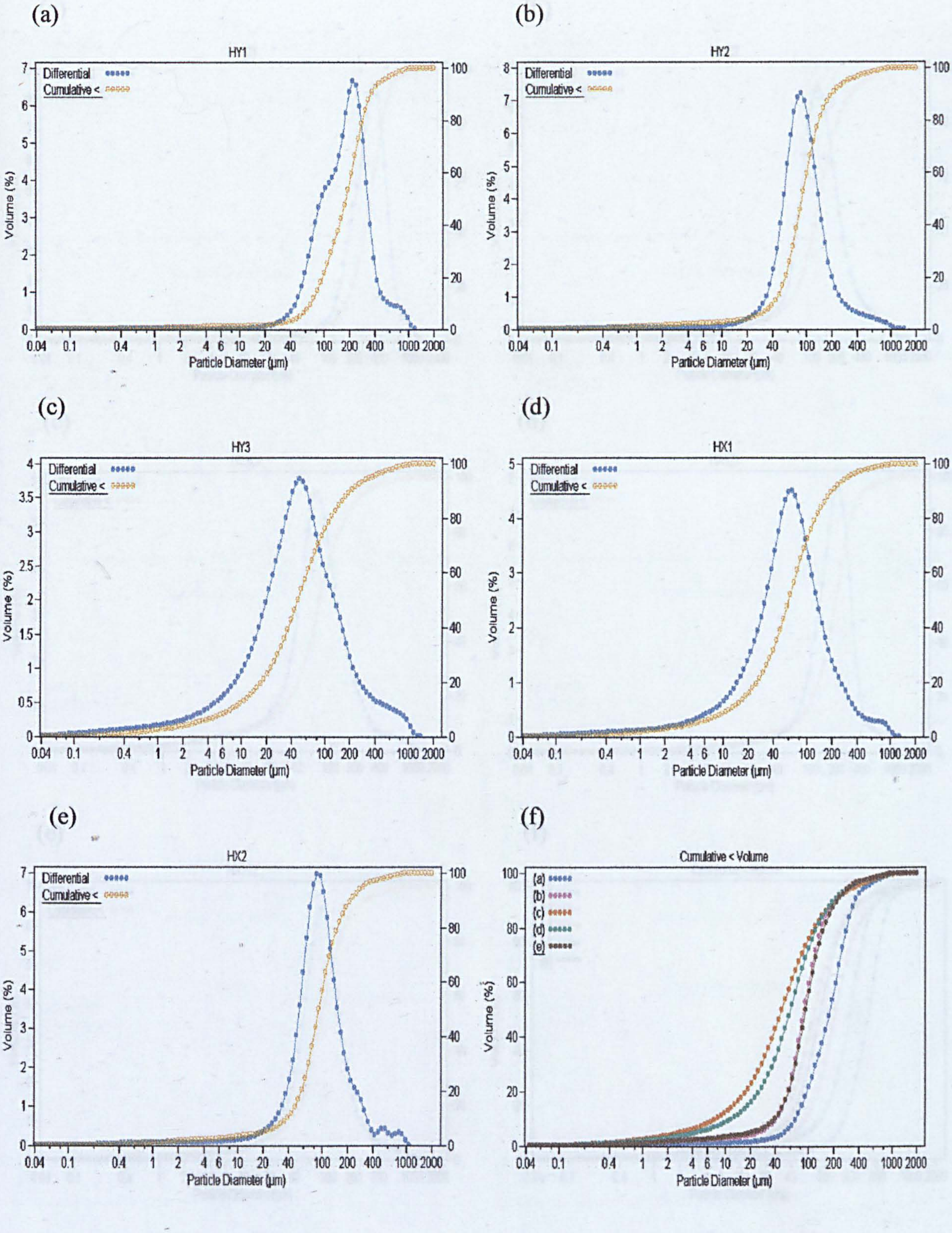


Figure 7.3: Particle size differential and cumulative [separately (a-e) and collectively (f)] distribution for surface samples along the Harindhara bar at Bahadurabad Ghat Reach.

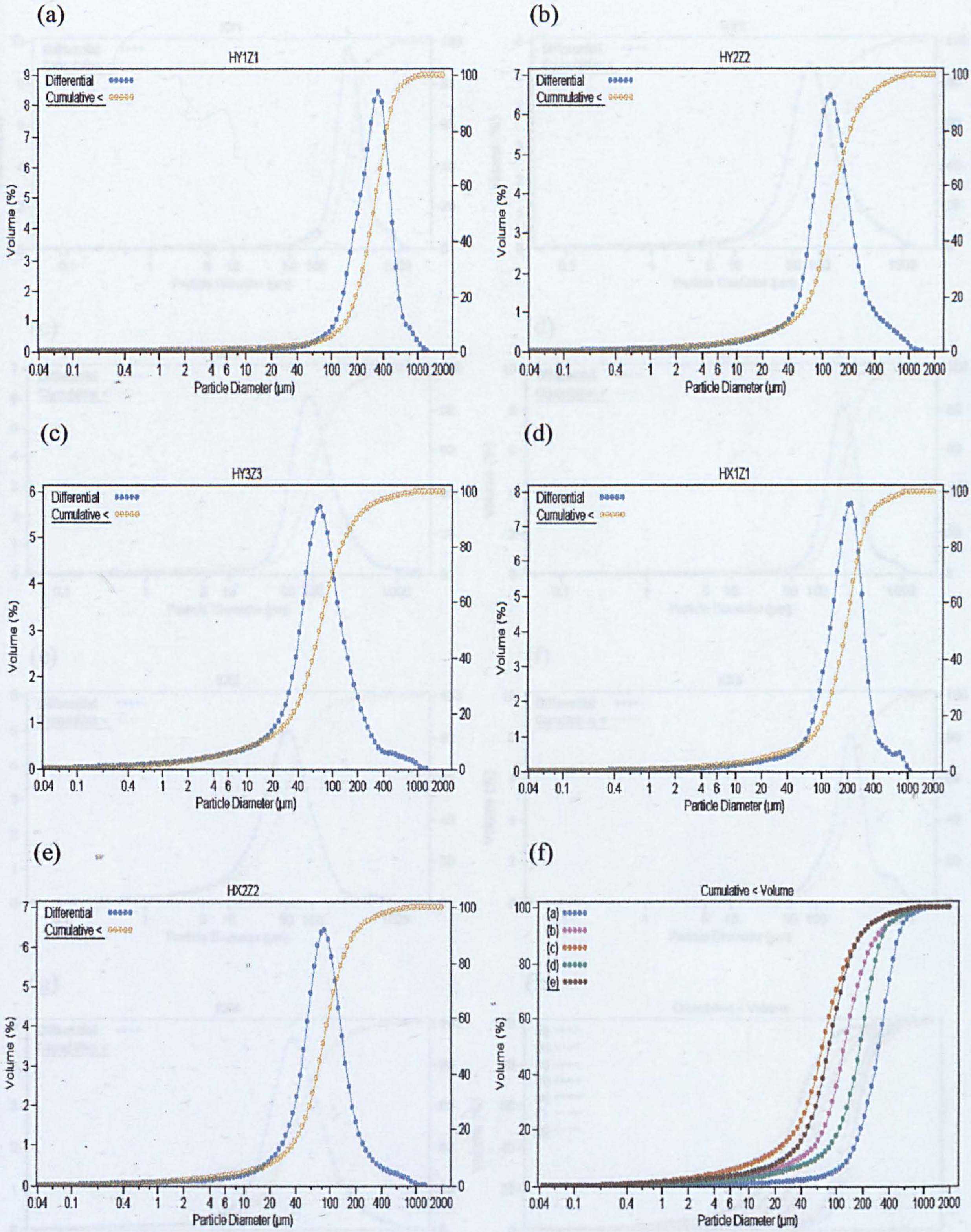


Figure 7.4: Particle size differential and cumulative [separately (a-e) and collectively (f)] distribution for subsurface samples along the Harindhara bar at Bahadurabad Ghat Reach.

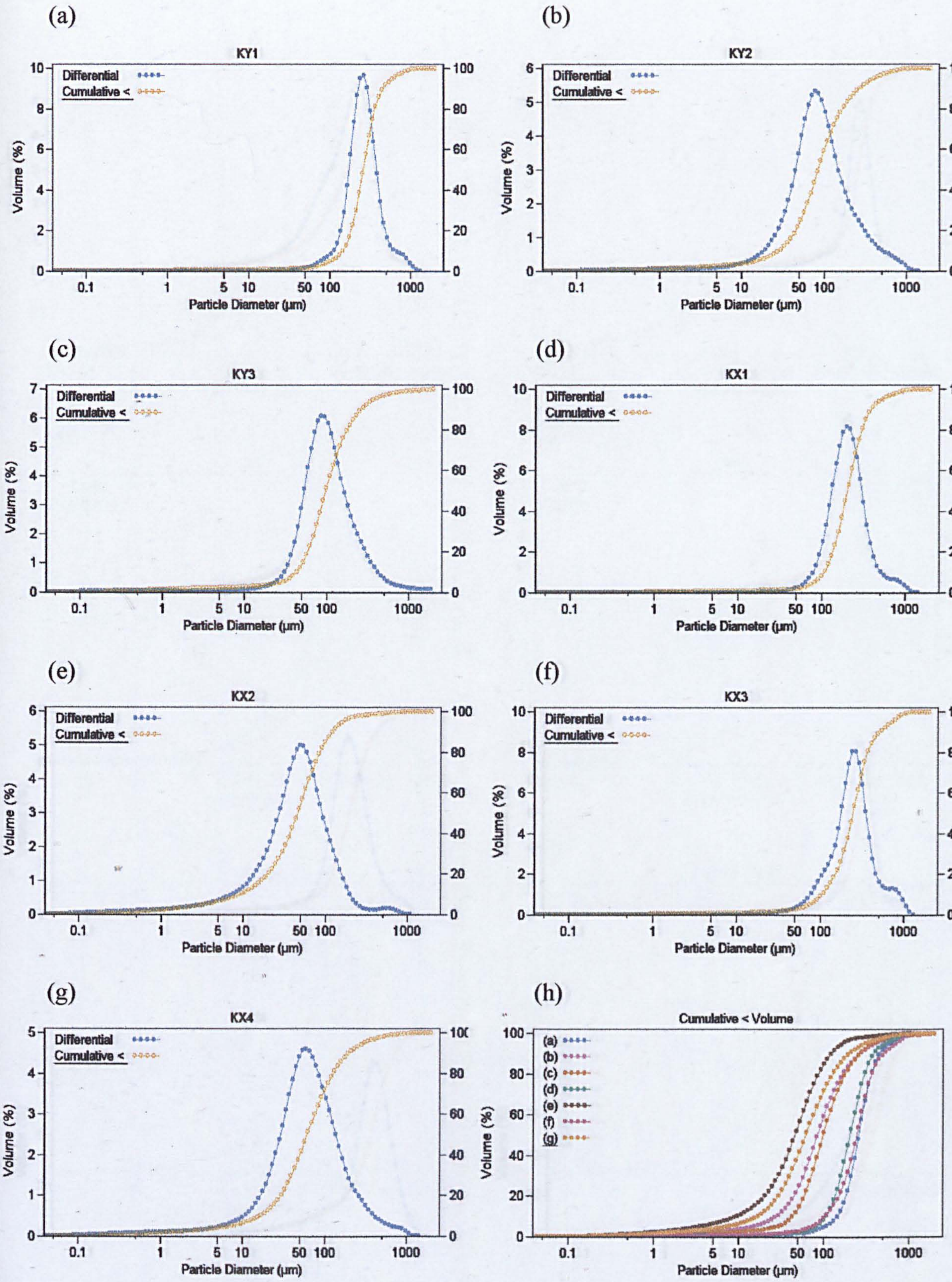


Figure 7.5: Particle size differential and cumulative [separately (a-g) and collectively (h)] distribution for surface samples along the Kulkandi bar at Bahadurabad Ghat Reach.

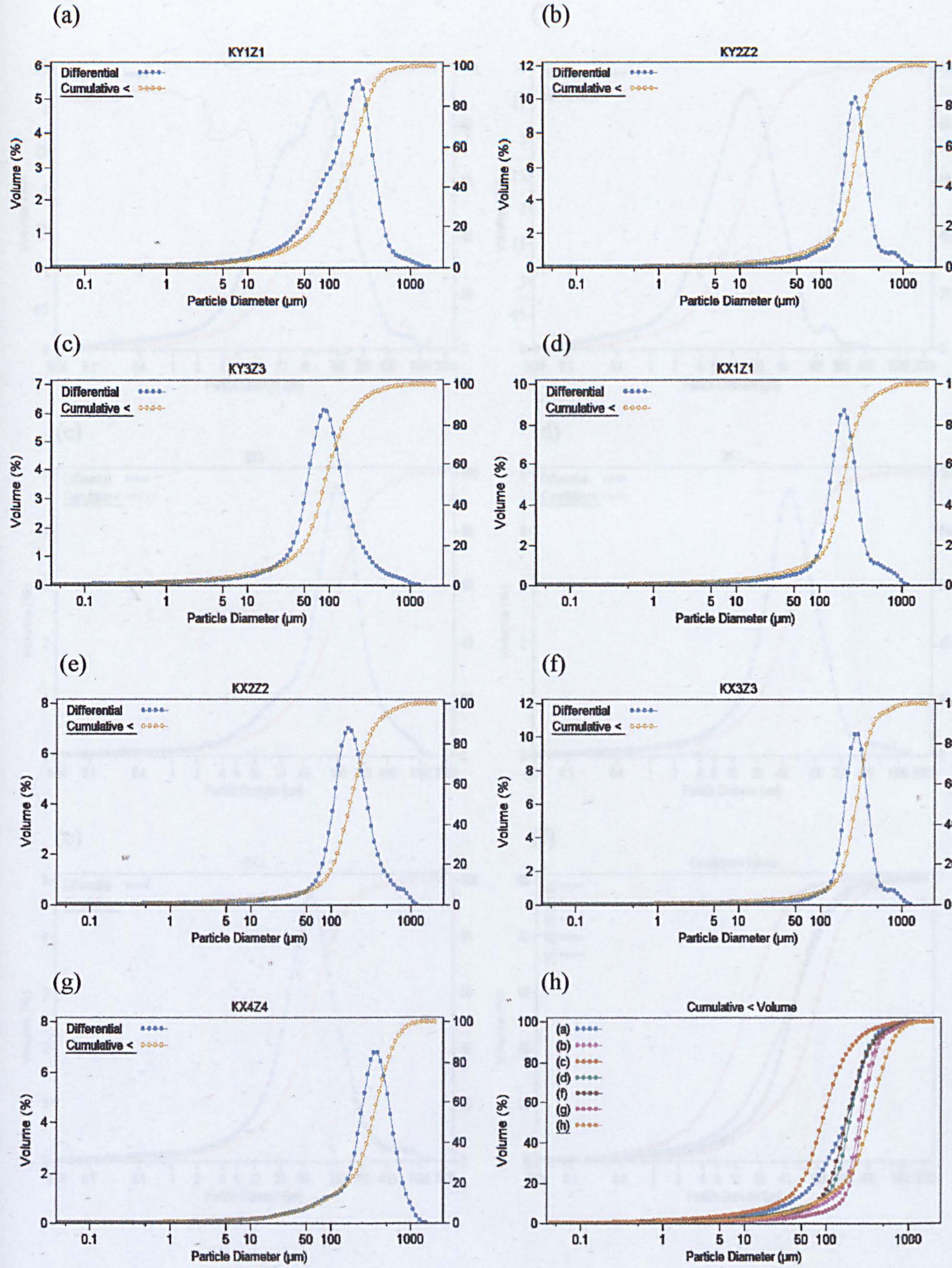


Figure 7.6: Particle size differential and cumulative [separately (a-g) and collectively (h)] distribution for subsurface samples along the Kulkandi bar at Bahadurabad Ghat Reach.

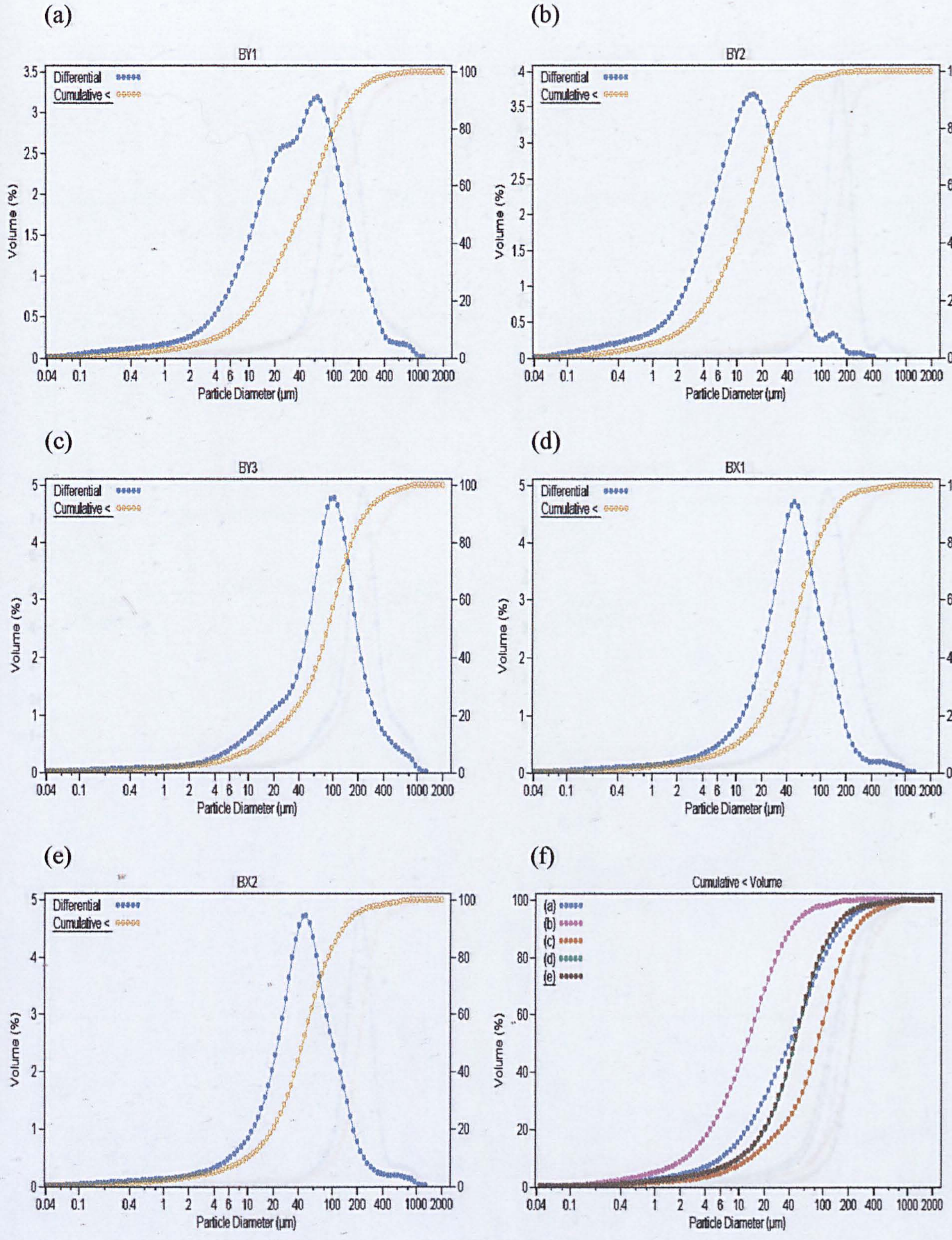


Figure 7.7: Particle size differential and cumulative [separately (a-e) and collectively (f)] distribution for surface samples along the Belutia bar at Jamuna Bridge Reach.

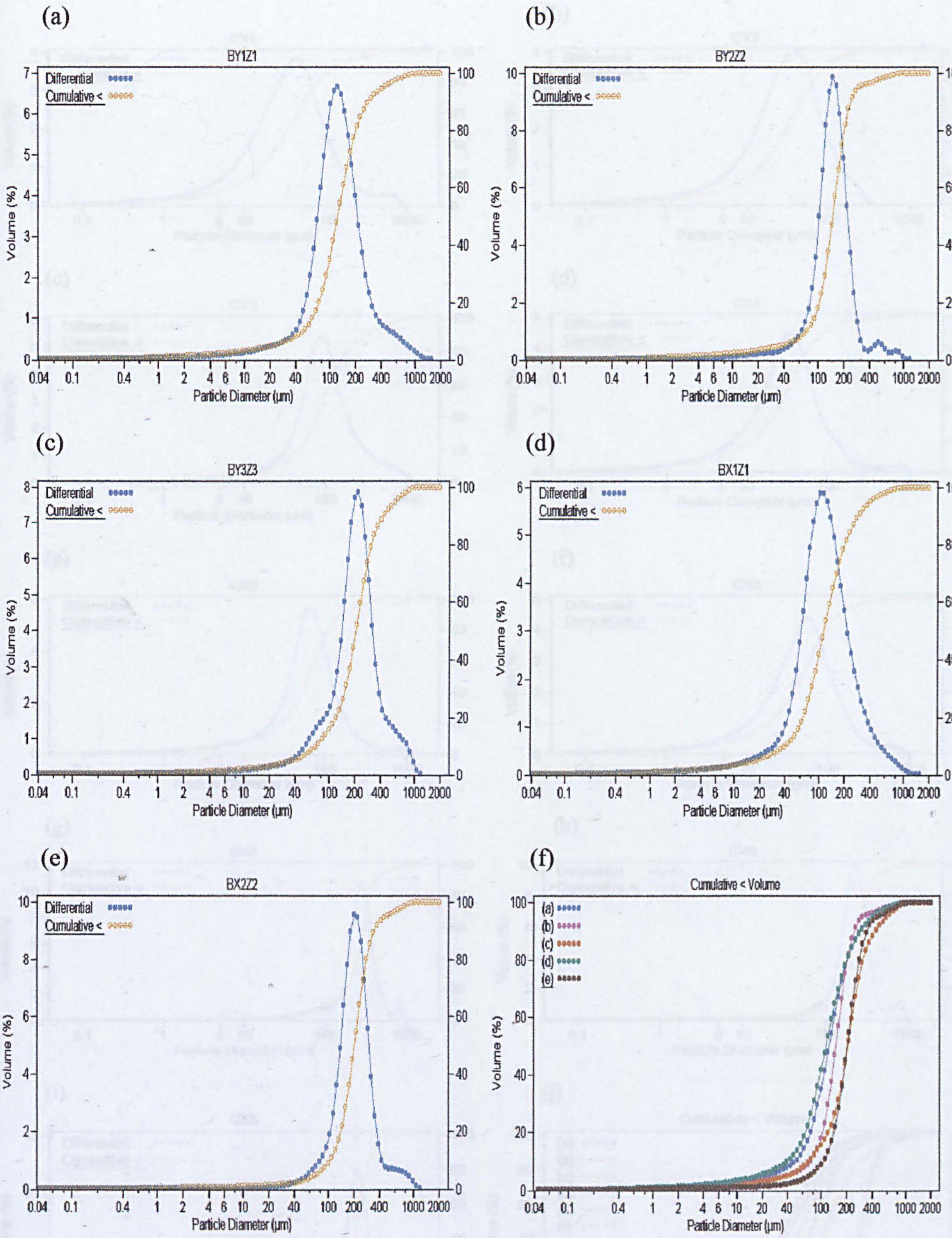


Figure 7.8: Particle size differential and cumulative [separately (a-e) and collectively (f)] distribution for subsurface samples along the Belutia bar at Jamuna Bridge Reach.

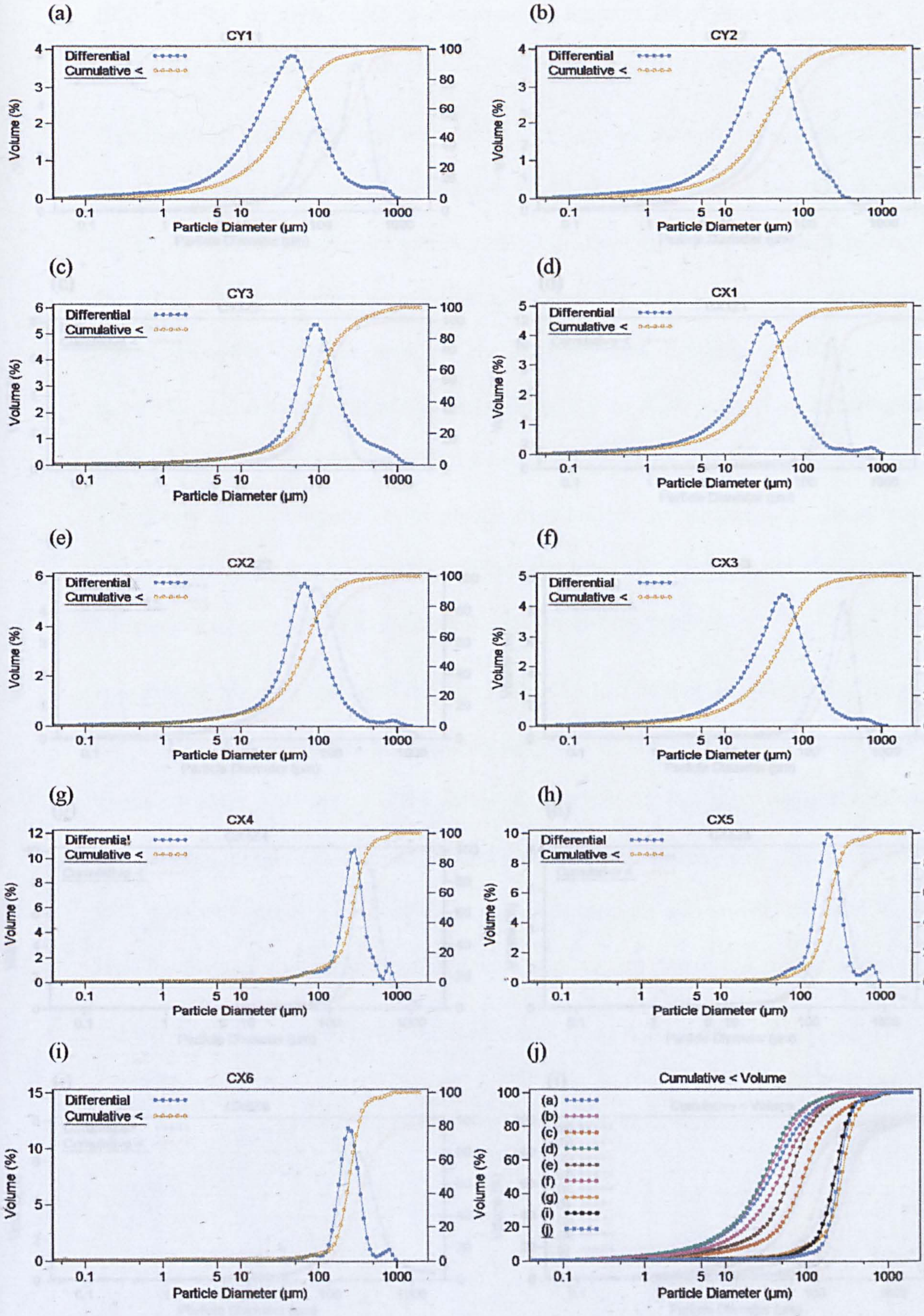


Figure 7.9: Particle size differential and cumulative [separately (a-i) and collectively (j)] distribution for surface samples along the Chatpier bar at Jamuna Bridge Reach.

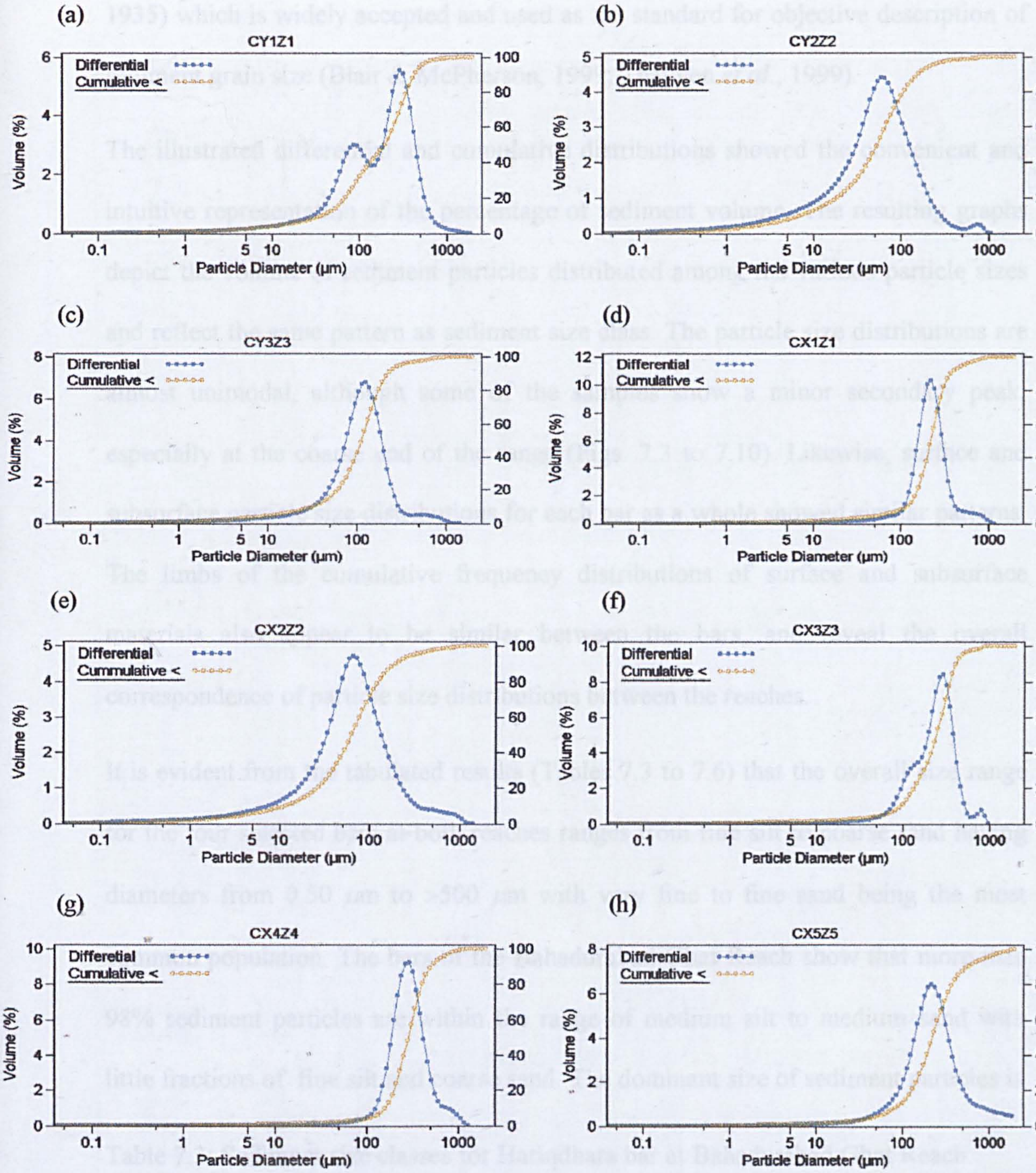


Figure 7.10: Particle size differential and cumulative [separately (a-i) and collectively (j)] distribution for subsurface samples along the Chatpier bar at Jamuna Bridge Reach.

1935) which is widely accepted and used as the standard for objective description of sediment grain size (Blair & McPherson, 1999; Thayyen *et al.*, 1999).

The illustrated differential and cumulative distributions showed the convenient and intuitive representation of the percentage of sediment volume. The resulting graphs depict the volume of sediment particles distributed among the various particle sizes and reflect the same pattern as sediment size class. The particle size distributions are almost unimodal, although some of the samples show a minor secondary peak, especially at the coarse end of the range (Figs. 7.3 to 7.10). Likewise, surface and subsurface particle size distributions for each bar as a whole showed similar patterns. The limbs of the cumulative frequency distributions of surface and subsurface materials also appear to be similar between the bars, and reveal the overall correspondence of particle size distributions between the reaches.

It is evident from the tabulated results (Tables 7.3 to 7.6) that the overall size range for the four selected bars at both reaches ranges from fine silt to coarse sand having diameters from 0.50 μm to >500 μm with very fine to fine sand being the most common population. The bars of the Bahadurabad Ghat Reach show that more than 98% sediment particles are within the range of medium silt to medium sand with little fractions of fine silt and coarse sand. The dominant size of sediment particles is

Table 7.3: Sediment size classes for Harindhara bar at Bahadurabad Ghat Reach.

Sampling Location	ID Code	Size Class (%)						
		Fine Silt (μm) (0.50-15.0)	Medium Silt (μm) (15.0-30.0)	Coarse Silt (μm) (30.0-60.0)	Very Fine Sand (μm) (60.0-125.0)	Fine Sand (μm) (125.0-250.0)	Medium Sand (μm) (250.0-500.0)	Coarse Sand (μm) (>500.0)
Surface	HY1				35	45	20	
Surface	HY2			15	65	20		
Surface	HY3	10	15	25	35	15		
Surface	HX1	5	10	25	40	20		
Surface	HX2		5	10	60	25		
Subsurface	HY1Z1				10	35	55	
Subsurface	HY2Z2			10	50	25	15	
Subsurface	HY3Z3	5	5	20	50	20		
Subsurface	HX1Z1		5	5	25	45	20	
Subsurface	HX2Z2		5	15	60	20		
Average		**2.00**	**4.50**	**12.50**	**43.00**	**27.00**	**11.00**	

Table 7.4: Sediment size classes for Kulkandi bar at Bahadurabad Ghat Reach.

Sampling Location	ID Code	Size Class (%)						
		Fine Silt (μm) (0.50-15.0)	Medium Silt (μm) (15.0-30.0)	Coarse Silt (μm) (30.0-60.0)	Very Fine Sand (μm) (60.0-125.0)	Fine Sand (μm) (125.0-250.0)	Medium Sand (μm) (250.0-500.0)	Coarse Sand (μm) (>500.0)
Surface	KY1				10	50	40	
Surface	KY2		5	15	55	25		
Surface	KY3			10	60	30		
Surface	KX1				25	50	25	
Surface	KX2	10	15	30	45			
Surface	KX3				20	45	35	
Surface	KX4	5	10	25	40	20		
Subsurface	KY1Z1		5	5	30	40	20	
Subsurface	KY2Z2			5	10	50	35	
Subsurface	KY3Z3		5	15	55	25		
Subsurface	KX1Z1			5	20	55	20	
Subsurface	KX2Z2			5	30	45	20	
Subsurface	KX3Z3				10	45	45	
Subsurface	KX4Z4			5	10	25	50	10
Average		**1.07**	**2.86**	**8.57**	**30.00**	**36.07**	**20.72**	**0.71**

Table 7.5: Sediment size classes for Belutia bar at Jamuna Bridge Reach.

Sampling Location	ID Code	Size Class (%)						
		Fine Silt (μm) (0.50-15.0)	Medium Silt (μm) (15.0-30.0)	Coarse Silt (μm) (30.0-60.0)	Very Fine Sand (μm) (60.0-125.0)	Fine Sand (μm) (125.0-250.0)	Medium Sand (μm) (250.0-500.0)	Coarse Sand (μm) (>500.0)
Surface	BY1	15	20	20	30	15		
Surface	BY2	40	35	15	10			
Surface	BY3	5	10	15	45	15	10	
Surface	BX1	10	15	30	35	10		
Surface	BX2	10	15	30	35	10		
Subsurface	BY1Z1		5	5	50	30	10	
Subsurface	BY2Z2			5	45	45	5	
Subsurface	BY3Z3			5	20	50	20	5
Subsurface	BX1Z1		5	5	55	25	10	
Subsurface	BX2Z2				25	55	20	
Average		**8.00**	**10.50**	**13.00**	**35.00**	**25.50**	**7.50**	**0.50**

Table 7.6: Sediment size classes for Chatpier bar at Jamuna Bridge Reach.

Sampling Location	ID Code	Size Class (%)						
		Fine Silt (μm) (0.50-15.0)	Medium Silt (μm) (15.0-30.0)	Coarse Silt (μm) (30.0-60.0)	Very Fine Sand (μm) (60.0-125.0)	Fine Sand (μm) (125.0-250.0)	Medium Sand (μm) (250.0-500.0)	Coarse Sand (μm) (>500.0)
Surface	CY1	15	20	25	30	10		
Surface	CY2	15	25	30	30			
Surface	CY3	5	5	10	50	20	10	
Surface	CX1	15	25	30	30			
Surface	CX2	5	10	20	50	15		
Surface	CX3	10	15	25	40	10		
Surface	CX4				15	45	40	
Surface	CX5				20	55	25	
Surface	CX6				5	65	30	
Subsurface	CY1Z1		5	5	30	30	30	
Subsurface	CY2Z2	10	15	20	45	10		
Subsurface	CY3Z3		5	10	55	25	5	
Subsurface	CX1Z1				20	60	20	
Subsurface	CX2Z2	5	10	25	45	10	5	
Subsurface	CX3Z3				25	40	35	
Subsurface	CX4Z4				5	50	35	10
Subsurface	CX5Z5				25	45	20	10
Subsurface	CX6Z6				20	40	25	15
Average		**4.45**	**7.50**	**11.11**	**30.00**	**29.44**	**15.56**	**1.94**

very fine sand and fine sand. While the bars of the Jamuna Bridge Reach show different figures and the sediment sizes ranging from fine silt to medium sand make up more than 98% out of total size classes. The dominant sizes are very fine to fine sand.

The preceding paragraphs describe the overall pictures of all the surveyed bars. But there is a considerable variation of sediment size classes observed between the samples and bars as well as between the reaches. The sediment size distribution of Harindhara bar (2 years old) at Bahadurabad Ghat Reach is dominated by very fine and fine sand with some coarse silt for both surface and subsurface samples (Table 7.3). Medium sand and medium silt are also present with a small fraction of fine silt but coarse sand is completely absent. The Kulkandi bar (4 years old) for the same reach is also dominated by very fine sand to fine sand with a good contribution from both coarse silt and medium sand (Table 7.4). Medium silt is present in this bar but as a comparatively small fraction, while fine silt and coarse sand are almost absent. There is no significant variation of size classes observed between the surface and subsurface samples. However, each bar comprises a coarse upstream portion and a comparatively fine downstream margin, and there is no major difference in particle size between the bars.

The bars of the Jamuna Bridge Reach are much older than the Bahadurabad Ghat Reach and their particle size distributions are relatively different, particularly in respect to longitudinal and vertical distribution. The Belutia bar (10 years old) at Jamuna Bridge Reach is dominated by very fine and fine sand particles with a contribution from medium and coarse silt (Table 7.5). Fine silt and medium sand are also present in this bar but they vary from surface to subsurface samples. All surface samples contain fine silt with almost no evidence of medium sand fraction. All subsurface samples contain medium sand with no presence of fine silt. The Chatpier bar, which is the largest and oldest (more than 25 years old) among the surveyed bars, is dominated by very fine and fine sand particles (Table 7.6) at both sampling locations. But the other particle size classes vary vertically as well as laterally and longitudinally. Fine, medium and coarse silt size classes are observed in the upper, middle and lower-central part of the bars while medium and coarse sand fractions are present in the lower western and eastern part of the bar. The variation is likely because the lower western and eastern part of the bar was overlain by the newly deposited sediments of the monsoon floods that buried the earlier sediments. On the other hand, the size range of surface sediments is smaller than the subsurface sediment in each sampling locations and this seems to indicate an upward fining depositional environment.

7.2.2.2. Particle Size Parameters and Sorting

The particle size parameters used in this study are mean, median, mode, and standard deviation with respective sediment sorting terms. The sediment size parameters were derived from computer analysis and sediment sorting was characterised by a sorting term using the literature of Passega (1977), Sly *et al.* (1983) and Thayyen *et al.* (1999). Tables 7.7 to 7.8 list the particle size parameters for the selected bars at both reaches.

The mean particle size for sediment samples of the Harindhara bar at Bahadurabad Ghat Reach shows longitudinal, lateral and vertical size variation. The mean grain size of surface and subsurface samples diminishes from bar head to bar tail (Table 7.7), and this diminution is probably because the coarse sediment load tends to be deposited on the bar head whereas finer sediment is deflected around the bar where it

Table 7.7: Sediment size parameters for Harindhara bar at Bahadurabad Ghat Reach.

Sampling Location	ID Code	Mean (μm)	Median (μm)	Mode (μm)	Standard Deviation (μm)	Sorting Terms
Surface	HY1	211.60	183.70	223.40	152.20	Well Sorted
Surface	HY2	117.80	88.76	87.90	117.60	Moderately Sorted
Surface	HY3	93.36	47.79	50.23	145.40	Well Sorted
Surface	HX1	95.66	60.71	66.44	124.80	Moderately Sorted
Surface	HX2	121.20	92.00	87.90	117.50	"
Subsurface	HY1Z1	327.00	310.60	356.10	166.60	Well Sorted
Subsurface	HY2Z2	160.10	124.90	127.60	142.50	"
Subsurface	HY3Z3	99.05	70.14	72.95	115.50	Moderately Sorted
Subsurface	HX1Z1	207.10	188.60	223.40	138.90	Well Sorted
Subsurface	HX2Z2	106.50	82.61	87.90	104.80	Moderately Sorted

Table 7.8: Sediment size parameters for Kulkandi bar at Bahadurabad Ghat Reach.

Sampling Location	ID Code	Mean (μm)	Median (μm)	Mode (μm)	Standard Deviation (μm)	Sorting Terms
Surface	KY1	291.60	261.40	269.20	157.20	Well Sorted
Surface	KY2	127.90	85.29	80.08	140.10	"
Surface	KY3	143.20	99.11	87.90	169.90	"
Surface	KX1	239.10	205.70	203.50	152.70	"
Surface	KX2	63.71	46.13	50.23	78.54	Moderately Sorted
Surface	KX3	285.90	246.40	269.20	188.70	Well Sorted
Surface	KX4	96.47	61.86	60.52	119.10	Moderately Sorted
Subsurface	KY1Z1	196.60	171.70	245.20	156.40	Well Sorted
Subsurface	KY2Z2	272.50	254.60	269.20	160.00	"
Subsurface	KY3Z3	118.40	89.43	87.90	116.60	Moderately Sorted
Subsurface	KX1Z1	219.60	194.40	203.50	148.00	Well Sorted
Subsurface	KX2Z2	210.40	174.80	168.80	152.40	"
Subsurface	KX3Z3	298.00	275.50	269.20	157.50	"
Subsurface	KX4Z4	118.40	89.43	87.90	116.60	Moderately Sorted

is deposited in the tail (Bluck, 1982; Ashworth *et al.*, 1992). The lateral distribution of mean grain size exhibits size diminution from the eastern to western margin and this is believed to be due to a secondary flow direction from the north-eastern to south- western direction (Ashmore, 1982; Ashworth *et al.*, 1992) (see Fig. 7.1). Similarly, surface and subsurface distribution of mean grain size clearly shows upward fining of sediments. The median and modal parameters also show the same patterns. The sediments of this bar are moderate to well sorted in each sampling location, and the frequency curves are nearly normal with some positive skewness and they are leptokurtic in character for all of the samples (Figs. 7.3 and 7.4). The mean grain size distribution of the Kulkandi bar for the same reach shows almost typical distribution of downstream fining with few exceptions. All of the sediment size parameters of surface and subsurface samples exhibit longitudinal (bar head to tail) and lateral (west margin to east margin) fining (Table 7.8). Although the trend of lateral fining at Kulkandi bar is reversed compared to Harindhara bar, this is also probably due to a secondary flow direction from the opposite side. On the other hand, the coarse upstream portion (head) and fine downstream portion (tail) show vertical differences of mean grain size distribution and both are characterised by upward coarsening. It is evident from the field work that the height of the upstream and downstream portions of the bar are comparatively lower than the middle part of the bar. The older sediments of these areas were buried by flood stage fluvial deposition, and the size variation of these portions appear to be due to that reason. However, the sediment of all locations is moderately to well sorted and their frequency distributions are less positively skewed with leptokurtic coefficients (Figs. 7.5 and 7.6). It is to be noted here that there is no indication of downstream fining of grain size along this reach, indeed the result exhibits opposite tendency showing downstream coarsening of sediment sizes. The possible causal factor is increased local sediment supply in the formation and growth of a bar.

The sediment size parameters of the Belutia bar at Jamuna Bridge Reach show a different pattern of sediment size distribution compared to Bahadurabad Ghat Reach (Table 7.9). The mean sediment size distribution of the Belutia bar exhibits downstream coarsening but upward fining longitudinally, and lateral fining from the west to east margin with an upward fining trend. The possible explanation behind this pattern is that the height of Belutia bar is near flood level and the bar head repeatedly suffered erosion by slab failure with no flood stage deposition for a long time while the lower bar tail accreted by seasonal floods with coarse grade fresh sediments.

Table 7.9: Sediment size parameters for Belutia bar at Jamuna Bridge Reach.

Sampling Location	ID Code	Mean (μm)	Median (μm)	Mode (μm)	Standard Deviation (μm)	Sorting Terms
Surface	BY1	71.88	40.93	66.44	98.72	Moderately Sorted
Surface	BY2	20.44	12.71	16.40	27.77	Very Poorly Sorted
Surface	BY3	120.50	87.60	105.90	131.70	Well Sorted
Surface	BX1	69.70	46.83	50.23	92.43	Moderately Sorted
Surface	BX2	69.44	45.46	50.23	95.58	"
Subsurface	BY1Z1	160.70	125.20	127.60	144.40	Well Sorted
Subsurface	BY2Z2	167.50	150.90	153.80	112.30	Moderately Sorted
Subsurface	BY3Z3	240.80	208.60	223.40	168.40	Well Sorted
Subsurface	BX1Z1	151.13	115.00	116.30	137.10	"
Subsurface	BX2Z2	227.50	203.80	203.50	137.40	"

Table 7.10: Sediment size parameters for Chatpier bar at Jamuna Bridge Reach.

Sampling Location	ID Code	Mean (μm)	Median (μm)	Mode (μm)	Standard Deviation (μm)	Sorting Terms
Surface	CY1	64.76	36.62	45.75	102.50	Moderately Sorted
Surface	CY2	45.28	31.93	41.67	46.31	Poorly Sorted
Surface	CY3	141.80	92.83	87.90	164.70	Well Sorted
Surface	CX1	49.14	29.95	34.58	86.14	Moderately Sorted
Surface	CX2	88.15	62.49	66.44	116.20	"
Surface	CX3	71.06	47.41	55.14	93.39	"
Surface	CX4	289.30	274.70	295.50	150.70	Well Sorted
Surface	CX5	245.90	222.90	223.40	140.60	"
Surface	CX6	271.20	251.40	245.20	128.20	"
Subsurface	CY1Z1	219.80	193.60	295.50	176.70	"
Subsurface	CY2Z2	76.97	53.26	60.52	99.08	Moderately Sorted
Subsurface	CY3Z3	134.00	112.20	127.60	121.40	"
Subsurface	CX1Z1	242.10	217.80	223.40	144.30	Well Sorted
Subsurface	CX2Z2	98.03	60.70	66.44	138.60	"
Subsurface	CX3Z3	255.10	245.50	295.50	144.10	"
Subsurface	CX4Z4	318.70	286.00	295.50	171.10	"
Subsurface	CX5Z5	301.70	222.10	223.40	294.00	Very Well Sorted
Subsurface	CX6Z6	285.90	221.30	223.40	260.50	"

The sediments of this bar fall into the categories of moderately to well sorted and exhibit positive skewness of size distribution with leptokurtic character (Figs. 7.7 and 7.8). The sediment size parameters of the largest Chatpier bar do not correspond with those of the other bars surveyed in the two reaches. The mean sediment size distribution shows neither downstream nor lateral fining while it exhibits diagonal sediment size coarsening from north-eastern side of bar head to south-western side of bar tail (Table 7.10). The logical inference behind this is that the north-eastern side of the bar is the highest part of the bar and suffered erosion by slab failure like the Belutia bar, and on the other hand, the south-western part of the bar is much lower than the north-east and was frequently inundated by flood water receiving coarser sediment particles. However, all of the sampling locations show upward fining and the sediment size arrangement is also similar to those of the other bars, with moderate to good sorting and a few very well sorted samples. The frequency curves are also positively skewed with leptokurtic distribution (Figs. 7.9 and 7.10). The only poorly sorted sediment size class is found at two surficial locations at both Belutia and Chatpier bars at Jamuna Bridge Reach and they are located in the higher middle part of the bars. These positions are also the older part of the bars and have been out of the flood level for a long time. The probable cause of such character is the admixture of finer fractions of silt derived from human activities (e.g. intensive farming) and organic decomposition.

The surface and subsurface sediment grain size parameters for the two reaches as a whole and for individual bars show different patterns of local sorting, and, there is no trend of downstream diminution of sediment sizes along either study reach, 70 km apart, other than sediment size coarsening in some cases. Therefore, it seems likely that downstream fining of sediment sizes, while associated with decreases in grain size in the gravel-bed braided rivers, is not applicable for the Brahmaputra-Jamuna River. Although the reach-scale grain size parameters do not conform to the notion of downstream diminution of sediment sizes, however, the bar-scale sediment size distributions confirm the established fact that the bars of the braided rivers are characterised by upward fining.

7.2.3. Sources of Bar Sediments

Sediment characteristics of channel bedforms are associated with different sources that cannot be so easily distinguished (McEwen & Matthews, 1998), and there is no satisfactory basis for ascertaining either from where or when the sediment load has been derived (Campbell, 1992; Loughran & Campbell, 1995). Although there are many types of sources of sediments that are input into the river from its origin to its confluence, bank materials represent the main source for bed and bar forms (Tharp, 1984; Clark, 1995). Moreover, from different forms of quantitative analysis in different river environments, it appears that a considerable amount of river sediments are derived from bank erosion (Pickup, 1984; Ashbridge, 1995; Clark, 1995).

The banks of the Brahmaputra-Jamuna River are formed in readily removable sediments and it is believed that the formation and growth of bars is largely dependent on the addition of sand to the channel through intensive bank erosion (Thorne *et al.*, 1993). It is also evident from the literature that average bank erosion rates are much greater adjacent to island reaches than the nodal reaches (Coleman, 1969; JMBA, 1986;Thorne *et al.*, 1993; EGIS, 1997). Although most of the sediment load for the formation of bars come from the river banks, extensive reworking of bar sediment deposits appear to add and accelerate downstream growth of bars (Church & Jones, 1982; Jiongxin, 1997), and sediment is continuously circulated and redistributed within the bars. Keeping these views in consideration, the present section attempts to assess whether bank erosion is closely related to the growth and development of a braid bar in the Brahmaputra-Jamuna system and if it is the main source of bar sediment. Sediment sources were characterised in terms of average sediment particle size data for both bars and banks as sediment sizes often reflect the pattern of sediment sources (Ashbridge, 1995; McEwen & Matthews, 1998).

River banks and upstream bar sediment samples for Bahadurabad Ghat and Jamuna Bridge reaches were used to determine sediment sources for the four study bars (see Figures 7.1 and 7.2). A total 36 samples (18 samples from each reach) was taken into consideration, and size indices computed from sediment samples are summarised in tables (Tables 7.11 and 7.12). As the sediment particle size range varies from bar to bar and bank to bank, it is difficult to infer conclusions about their origin from individual particle size range. Therefore, average particle size ranges for both banks and bars were used to determine sediment sources of bars on the grounds that overall size range may be more consistent determinants than the individual sample sizes.

Table 7.11: Sediment size classes of the west and east bank and upstream island bar at Bahadurabad Ghat Reach.

Bar/ Bank	Sampling Location	ID Code	Size Class (%)						
			Fine Silt (μm) (0.50-15.0)	Medium Silt (μm) (15.0-30.0)	Coarse Silt (μm) (30.0-60.0)	Very Fine Sand (μm) (60.0-125.0)	Fine Sand (μm) (125.0-250.0)	Medium Sand (μm) (250.0-500.0)	Coarse Sand (μm) (>500.0)
Island Bar	Surface	IY1		10	20	45	20	5	
	Subsurface	IY1Z1				5	25	60	10
West Bank	Surface	BWBY1					50	45	5
	Surface	BWBY2	5	10	20	40	15	10	
	Surface	BWBY3	15	15	25	25	15	5	
	Surface	BWBY4				5	45	45	5
	Subsurface	BWBY1Z1		5	15	35	25	20	
	Subsurface	BWBY2Z2		5	5	10	45	25	10
	Subsurface	BWBY3Z3				20	60	20	
	Subsurface	BWBY4Z4					35	55	10
East Bank	Surface	BEBY1	5	10	25	40	15	5	
	Surface	BEBY2	15	20	30	25	10		
	Surface	BEBY3	20	20	15	15	20	10	
	Surface	BEBY4	20	25	25	15	10	5	
	Subsurface	BEBY1Z1	20	15	15	15	20	15	
	Subsurface	BEBY2Z2		5	5	10	50	30	
	Subsurface	BEBY3Z3	20	15	25	25	15		
	Subsurface	BEBY4Z4					30	60	10
Average			**6.67**	**8.61**	**12.50**	**18.33**	**28.05**	**23.06**	**2.78**

Table 7.12: Sediment size classes of the west and east bank and upstream attached bar at Jamuna Bridge Reach.

Bar/ Bank	Sampling Location	ID Code	Size Class (%)						
			Fine Silt (μm) (0.50-15.0)	Medium Silt (μm) (15.0-30.0)	Coarse Silt (μm) (30.0-60.0)	Very Fine Sand (μm) (60.0-125.0)	Fine Sand (μm) (125.0-250.0)	Medium Sand (μm) (250.0-500.0)	Coarse Sand (μm) (>500.0)
Attached Bar	Surface	AY1			10	30	45	15	
	Subsurface	AY1Z1		5	5	10	35	30	15
West Bank	Surface	JWBY1	20	25	25	20	10		
	Surface	JWBY2	15	15	20	20	15	15	
	Surface	JWBY3	25	25	30	20			
	Surface	JWBY4	20	20	30	20	10		
	Subsurface	JWBY1Z1	20	25	25	20	10		
	Subsurface	JWBY2Z2				15	55	30	
	Subsurface	JWBY3Z3	25	30	30	15			
	Subsurface	JWBY4Z4	20	15	20	25	20		
East Bank	Surface	JEBY1		5	15	40	25	10	5
	Surface	JEBY2	25	20	25	20	10		
	Surface	JEBY3			5	50	35	10	
	Surface	JEBY4		5	10	25	25	30	5
	Subsurface	JEBY1Z1	20	15	30	25	10		
	Subsurface	JEBY2Z2		5	10	40	30	15	
	Subsurface	JEBY3Z3				20	45	30	5
	Subsurface	JEBY4Z4	5	5	25	40	20	5	
Average			**10.83**	**11.94**	**17.50**	**25.28**	**22.22**	**10.56**	**1.67**

It is observed from the analysed sediment samples that the average particle size classes of Harindhara and Kulkandi bars at Bahadurabad Ghat Reach (see Tables 7.3 and 7.4) are almost similar to the average size classes of both banks and upstream island (Table 7.11). The overall sediment size classes of the banks are dominated by sand size (72%) that correspond with the dominant sand size fractions of Harindhara bar (81%). The sediment size distribution of Kulkandi bar for the same reach showed almost similar pattern while it constituted 86% of sand particles among the total sediment size classes. The overall silt size fractions of the banks (28%) also correspond with the study bars (19% and 13% for Harindhara and Kulkandi bars, respectively) as it exhibited less dominance than the sand size classes.

The average particle size classes of the banks and attached bar at Jamuna Bridge Reach (Table 7.12) showed a very good relationship with the average particle sizes of both Belutia and Chatpier bars (see Tables 7.5 and 7.6). The dominant size of banks is the sand fraction (60%) which is also the dominant size of the study bars (69% and 77% for Belutia and Chatpier bars, respectively). Likewise the less dominant silt size class of source sediments (40%) corresponds to the study bars (32% and 23% for Belutia and Chatpier bars, respectively). Although the dominant and less dominant sediment size fractions of the study bars correspond to source sediments it is evident from the average individual size classes that their percentiles vary from supposed sources to destinations. Nonetheless, the variation is likely because of either eroded source sediments may have been disintegrated rapidly by corrosion and abrasion during transportation (Thorne *et al.*, 1993; Ashbridge, 1995) or sediments may be transferred from immediate upper reach with different size fractions depending on flow competence (Jiongxin, 1997).

Thus, the average sediment particle size data display a comprehensive similarity between banks and bars, and the distribution of particle size of banks reflects their potential source role for the bar sediments. In addition, particle size fractions of sediment samples at both reaches are graphed on a CM diagram (C is D_{99}, the coarsest fraction and M is D_{50}, the median grain size) to assess the relationship between bank and bar sediment deposits (cf. Passega, 1957, 1964; Passega & Byramjee, 1969; Brown, 1985; Passmore *et al.*, 1992; Bravard & Peiry, 1999). The CM diagram (Fig. 7.11) shows that the D_{99} and D_{50} of both banks and bars are well clustered and the pattern it determines is believed to suggest a close link between bank erosion and bar growth. Although there may be other sources of bar sediments, and their formation may depend on different factors, however it is likely that the growth and development of bars of the Brahmaputra-Jamuna River are largely depended on the eroded bank materials. Also it appears that a significant relationship exists between bank erosion and bar formation despite the variable sediment size characteristics.

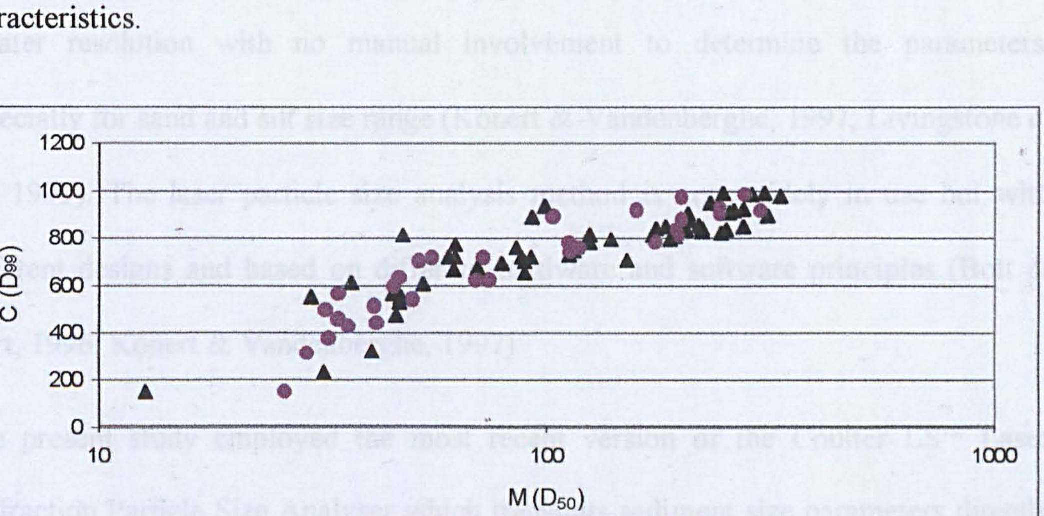


Figure 7.11: A CM diagram of bar and bank sediments.

7.2.4. Precision Assessment

Sediment size measurement precision is the standard of how closely the sediment sample results reproduce the population particle size distribution (Petrie & Diplas, 2000). It is very difficult to specify the precision of measurement of sediment size distribution when the particles are of variable size and shape, and several methods are in use (McCave & Syvitski, 1991). However, to a great extent measurement precision is dependent upon the performance of the method in determination of the size of a standard (McCave & Syvitski, 1991; Lieberman, 1996). Many earlier studies have used different methods, specially sieving and pipette to ascertain particle size distribution and plotting of their values of parameters, and in many cases, it was not possible to ascertain results from these measurements more precisely (Livingstone *et al.*, 1999).

Several hi-tech methods are available for detecting particles, and characterising particle size and size distribution with more precision (Lieberman, 1996). From the point of view of laboratory efficiency and measurement accuracy, the laser particle sizing techniques are far superior and producing particle size distribution of much greater resolution with no manual involvement to determine the parameters, especially for sand and silt size range (Konert & Vandenberghe, 1997; Livingstone *et al.*, 1999). The laser particle size analysis method is now widely in use but with different designs and based on different hardware and software principles (Bott & Hart, 1996; Konert & Vandenberghe, 1997).

The present study employed the most recent version of the Coulter LS™ Laser Diffraction Particle Size Analyser which transmits sediment size parameters directly to a computer control and results are displayed automatically. This method depends on analysing the diffraction patterns produced when particles of different sizes are exposed to a collimated beam of light. As the patterns are characteristic of the particle size, statistical analysis can produce more accurate, reproducible picture of the size distribution (Bott & Hart, 1996). Nevertheless, to check the level of analytical precision, 10% sediment samples (9 out of 88 samples) were reanalysed randomly. Different parameters of sediment particles of reanalysed samples then compared with the results of primary samples and their percentage of difference were calculated and tabulated (Table 7.13). The comparison between primary and reanalysed sediment parameters gives information about the precision of the primary results in relation to reanalysed results. The results demonstrate a very good analytical precision of sediment size analysis which varies from 86.68% to 100%. Therefore, it is believed that this method measured sediment particle sizes precisely and that the statistical inferences which were made from sediment sample data, are significant.

Table 7.13: Comparative assessment of different sediment size parameters.

Sample ID	Sample Status	Sediment Parameters (μm)								
		Mean	Median	Mode	S.D.	D_{10}	D_{25}	D_{50}	D_{75}	D_{90}
BX1	Primary Sample	69.70	46.83	50.23	92.43	10.26	25.26	46.83	80.89	138.00
	Reanalysed Sample	66.26	44.81	50.23	89.05	9.66	24.10	44.81	76.42	130.60
	Difference (%)	4.94	4.31	0	3.66	5.85	4.59	4.31	5.53	5.36
JWBY4 Z4	Primary Sample	77.55	45.60	116.30	103.10	5.51	16.28	45.60	106.60	169.00
	Reanalysed Sample	75.51	43.24	116.30	103.40	5.22	15.46	43.24	103.90	165.90
	Difference (%)	2.63	5.18	0	0.29	5.26	5.04	5.18	2.53	1.83
BY2Z2	Primary Sample	167.50	150.90	153.80	112.30	75.26	114.20	150.90	193.80	248.50
	Reanalysed Sample	167.70	151.00	153.80	112.20	74.99	114.30	151.00	194.00	248.90
	Difference (%)	0.20	0.07	0	0.09	0.36	0.09	0.07	0.10	0.16
CX2	Primary Sample	88.15	62.49	66.44	116.20	13.89	37.01	62.49	98.19	160.60
	Reanalysed Sample	81.93	60.04	66.44	110.70	12.04	35.15	60.04	92.10	143.20
	Difference (%)	7.06	3.92	0	4.73	13.32	5.03	3.92	6.20	10.83
CY2Z2	Primary Sample	76.97	53.26	60.52	99.08	7.00	24.24	53.26	92.98	156.40
	Reanalysed Sample	74.60	51.15	60.52	101.70	6.41	22.76	51.15	89.29	149.20
	Difference (%)	3.08	3.96	0	2.64	8.43	6.11	3.96	3.97	4.60
AY1Z1	Primary Sample	278.70	230.80	245.20	212.70	60.58	136.80	230.80	364.50	547.40
	Reanalysed Sample	278.50	231.40	269.20	212.60	58.87	136.90	231.40	364.30	544.30
	Difference (%)	0.07	0.26	9.79	0.05	2.82	0.07	0.26	0.05	0.57
HY2	Primary Sample	117.80	88.76	87.90	117.60	41.31	62.24	88.76	128.50	201.60
	Reanalysed Sample	117.50	88.63	87.90	116.60	41.14	62.13	88.63	128.30	202.10
	Difference (%)	0.25	0.15	0	0.85	0.41	0.18	0.15	0.16	0.25
KX4	Primary Sample	96.47	61.86	60.52	119.10	16.80	35.04	61.86	109.80	200.10
	Reanalysed Sample	91.00	62.27	60.52	106.30	17.37	35.66	62.27	106.60	179.50
	Difference (%)	5.67	0.66	0	10.75	3.39	1.77	0.66	2.91	10.29
BEBY1	Primary Sample	95.10	69.80	72.95	105.90	20.50	43.08	69.80	109.70	174.80
	Reanalysed Sample	90.22	67.30	72.95	100.10	17.98	40.77	67.30	105.40	165.20
	Difference (%)	5.13	3.58	0	5.48	12.29	5.36	3.58	3.92	5.49

7.3. Sediment Mineralogy

7.3.1. Methodology

River sediments comprise fragments of different kinds of rocks and crystals of a wide variety of minerals (Bogardi, 1974). Information on the mineralogical composition is a valuable contribution to the characteristics of sediment material and can be useful in interpreting the environments of deposition (Bogardi, 1974; Merefield, 1995; Le Pera & Sorriso-Valvo, 2000). Moreover, mineralogical information derived from an analysis of fluvially deposited sediments may reveal the sources from which the sediments were yielded (Kennedy, 1965; Bogardi, 1974; Petts & Foster, 1985; Merefield, 1995). This section, therefore, considers the mineralogical composition of bar sediments and their potential sources at Bahadurabad Ghat and Jamuna Bridge reaches in the Brahmaputra-Jamuna River. 22 sediment samples were taken into consideration for mineralogical analysis from the banks and selected bars at both reaches (Figs. 7.12 and 7.13). Sediment samples were chosen using stratified sampling techniques from the 88 samples, which were subjected to particle size analyses (see Section 7.2.1).

In order to prepare the thin sections of sediment samples for mineralogical analysis the loose fractions were indurated using araldite resin, whereafter $3.5 \times 2.5 \times 1.0$ cm^3 blocks were prepared and left 72 hours for complete consolidation. The consolidated blocks were then mounted on glass slides, and ground and polished until the appropriate analytical thickness (0.03mm) was achieved. Examining the birefringence of dominant quartz content the accurate thickness of the glass slides was adjudged. The mineralogical composition of the sediment sample prepared in this way was determined under a polarising petrographic microscope by counting 300 particles on each thin section (Dryden, 1931; Twenhofel & Tyler, 1941; Ingersoll *et al.*, 1984; Bridgland, 1986; Edgington & Harbury, 1993).

7.3.2. Mineralogical Composition of Sediments

Analytical results obtained by particle counting from thin section petrographic study of the braid bar and river bank sediment samples taken from the two selected reaches of the Brahmaputra-Jamuna River have been compiled in Tables 7.14 and 7.15.

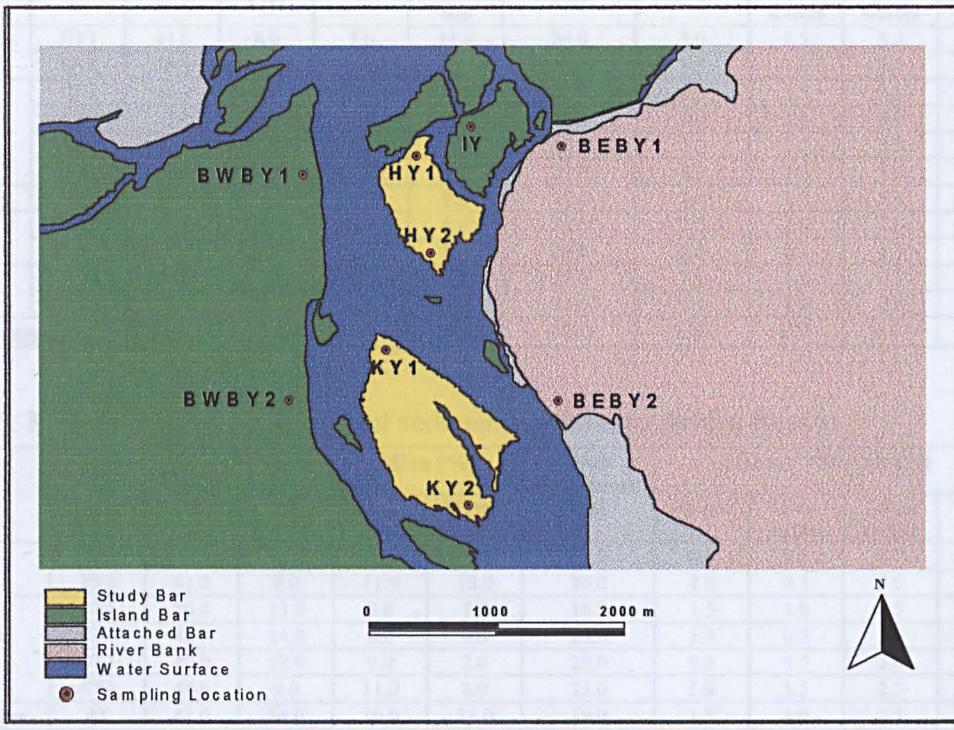


Figure 7.12: Sediment sampling locations at Bahadurabad Ghat Reach.

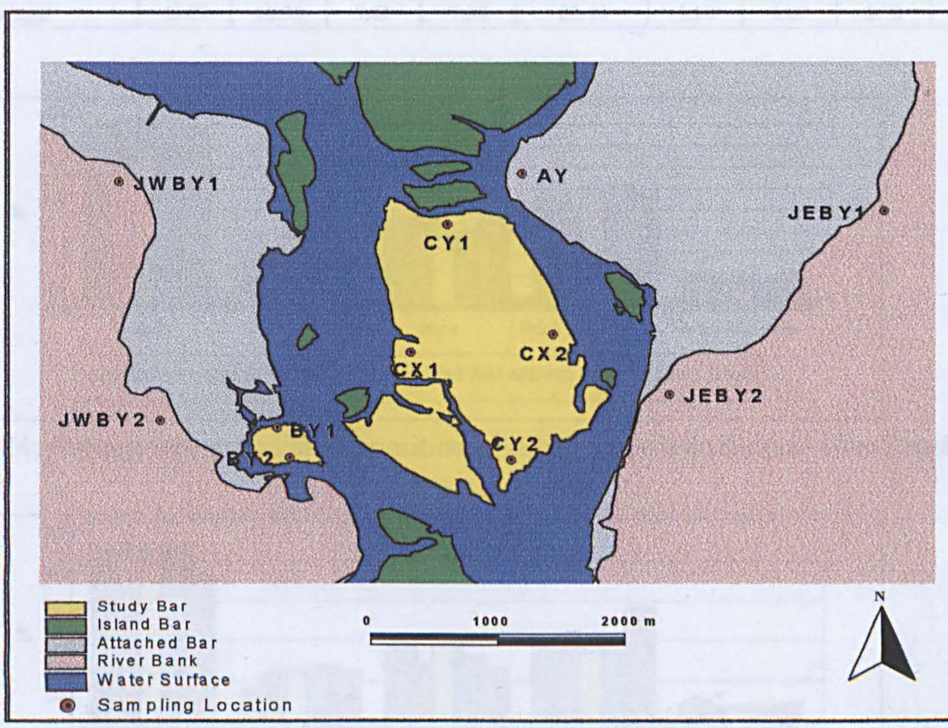


Figure 7.13: Sediment sampling locations at Jamuna Bridge Reach.

Table 7.14: Mineralogical composition of sediments at Bahadurabad Ghat Reach.

Bar/ Bank	ID Code	Quartz (%)	Felds-par (%)	Mica (%)		Rock Fragments (%)	Heavy Minerals (%)			
				Biotite	Musco-vite		Opaque	Ultra-stables	Meta-stables	Total
Harindhara Bar	HY1	42.0	8.0	7.0	11.0	24.0	3.0	1.5	3.5	8.0
	HY2	39.0	10.0	12.0	9.0	25.0	1.5	1.0	2.5	5.0
Kulkandi Bar	KX1	46.0	9.0	8.0	10.0	22.0	1.5	1.5	2.0	5.0
	KX2	43.0	8.0	8.0	13.0	21.0	2.0	2.0	3.0	7.0
	KY1	43.0	9.0	10.0	8.0	23.0	2.0	1.5	3.5	7.0
	KY2	36.0	18.0	7.0	12.0	21.0	1.5	1.5	3.0	6.0
Island Bar	IY	37.0	16.0	6.0	9.0	27.0	2.0	1.0	2.0	5.0
East Bank	BEBY1	45.0	10.0	8.0	6.0	25.0	2.5	1.0	2.5	6.0
	BEBY2	39.0	9.0	10.0	8.0	29.0	2.0	0.5	2.5	5.0
West Bank	BWBY1	38.0	15.0	9.0	5.0	27.0	2.0	1.5	2.5	6.0
	BWBY2	43.0	13.0	8.0	6.0	23.0	2.5	1.0	3.5	7.0
Average		**41.00**	**11.36**	**8.46**	**8.82**	**24.27**	**2.05**	**1.27**	**2.77**	**6.09**

Table 7.15: Mineralogical composition of sediments at Jamuna Bridge Reach.

Bar/ Bank	ID Code	Quartz (%)	Felds-par (%)	Mica (%)		Rock Fragments (%)	Heavy Minerals (%)			
				Biotite	Musco-vite		Opaque	Ultra-stables	Meta-stables	Total
Belutia Bar	BY1	46.0	11.0	8.0	9.0	21.0	0.5	2.5	2.0	5.0
	BY2	41.0	8.0	11.0	12.0	20.0	2.5	0.5	5.0	8.0
Chatpier Bar	CX1	50.0	13.0	9.0	7.0	16.0	1.5	1.0	2.5	5.0
	CX2	45.0	14.0	8.0	6.0	23.0	1.0	0.5	2.5	4.0
	CY1	40.0	17.0	9.0	2.0	29.0	0.5	0.5	2.0	3.0
	CY2	44.0	9.0	11.0	8.0	23.0	1.0	1.5	2.5	5.0
Attached Bar	AY	41.0	14.0	10.0	11.0	19.0	1.5	1.0	2.5	5.0
East Bank	JEBY1	40.0	20.0	10.0	7.0	19.0	1.0	1.0	2.0	4.0
	JEBY2	51.0	9.0	8.0	9.0	18.0	1.0	1.0	3.0	5.0
West Bank	JWBY1	39.0	11.0	9.0	7.0	28.0	1.5	1.5	3.0	6.0
	JWBY2	36.0	16.0	7.0	5.0	31.0	1.0	1.0	3.0	5.0
Average		**43.00**	**12.91**	**9.09**	**7.54**	**22.46**	**1.18**	**1.09**	**2.73**	**5.00**

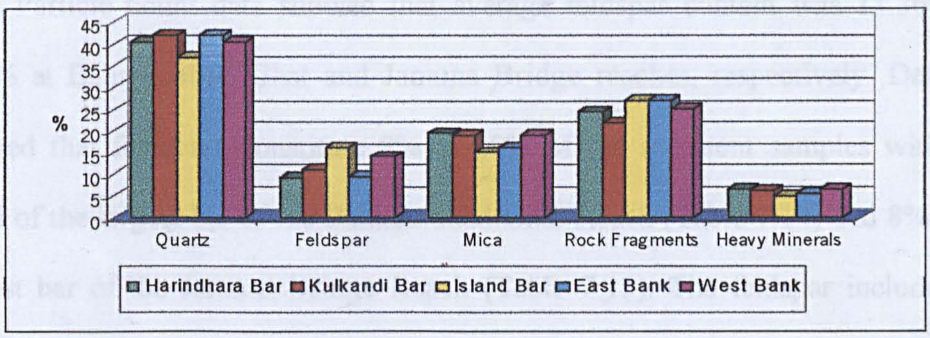


Figure 7.14: Average mineralogical composition of sediments at Bahadurabad Ghat Reach.

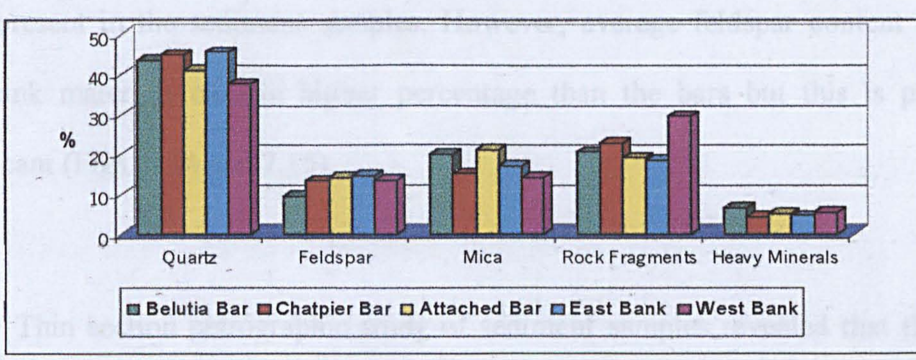


Figure 7.15: Average mineralogical composition of sediments at Jamuna Bridge Reach.

Average compositions of mineral contents are presented in Figures 7.14 and 7.15 and thus can be used to unravel information on the spatial distribution of mineral concentrations. The following paragraphs describe the amount of individual minerals in samples with comparative representations.

Quartz

The most abundant mineral content present in sediment samples was quartz which predominantly occurred as monocrystalline either strained or unstrained grains and polycrystalline grains. Average figures indicated that quartz constitutes 41% of each sample at Bahadurabad Ghat Reach and 43% at Jamuna Bridge Reach (Tables 7.14 and 7.15). The lowest figure of quartz was found in west bank (36%) while the highest percentage was found in east bank (51%) at Jamuna Bridge Reach. However, there were no significant variations observed in quartz contents between the bank and bar sediment samples (Figs. 7.14 and 7.15).

Feldspars

Particle count data showed that average feldspar content was 11.36% and 12.91% at Bahadurabad Ghat and Jamuna Bridge reaches, respectively. Data also indicated that feldspars constitute 8% to 18% of the sediment samples with 18% typical of the largest bar of the Bahadurabad Ghat Reach (Table 7.14) and 8% of the smallest bar of the Jamuna Bridge Reach (Table 7.15). The feldspar includes two common types of potassium and plagioclase feldspars, and both groups of feldspars were present in the sediment samples. However, average feldspar content showed that bank materials contain higher percentage than the bars but this is probably significant (Figs. 7.14 and 7.15).

Mica

Thin section petrographic study of sediment samples revealed that the most predominant types of mica were biotite and muscovite. Average figures showed that

Bahadurabad Ghat Reach contained 8.46% and 8.82% while Jamuna Bridge Reach comprised 9.09% and 7.54% of biotite and muscovite, respectively. However, mica minerals were present in slightly higher proportions in the study bars than the banks at both reaches (Figs. 7.14 and 7.15).

Rock Fragments

In addition to the lightweight minerals, the sediment samples contain considerable amounts of rock fragments, between 16% to 31%. Among the two reaches, rock fragments were slightly more predominant at Bahadurabad Ghat Reach (24.27%) than Jamuna Bridge Reach (22.46%), but there were no identifiable differences observed between the bars and banks (Figs. 7.14 and 7.15). The most common rock fragments found were chert, schist and argillaceous varieties.

Heavy Minerals

The heavy mineral contents vary from 3% to 8% of the total minerals and average concentrations of heavy minerals were slightly higher at Bahadurabad Ghat Reach (6.09%) than Jamuna Bridge Reach (5%) (Tables 7.14 and 7.15). Several types of heavy minerals were found in the sediment samples as minor detrital grains (Tables 7.16 and 7.17) and they have been categorised into three main groups (Krumbein and Pettijohn, 1938):

i) Opaque,
ii) Ultrastable, and
iii) Metastable.

Among the heavy mineral groups, metastable minerals (2% to 5%) were predominant in the sediment samples that contains amphiboles and pyroxenes mainly. Ultrastable (0.5% to 2.5%) and opaque (0.5% to 3%) minerals were less dominant compared to metastables while opaque minerals were mainly composed of magnetite.

Table 7.16: Relative abundance of heavy minerals (particle/slide) at Bahadurabad Ghat Reach.

Bar/ Bank	ID Code	Opaque				Ultrastables			Metastables				
		Mag-netite	Ilme-nite	Pyrite	Hema-tite	Zircon	Tour-maline	Rutile	Oli-vine	Apa-tite	Amph-ibole	Pyro-xene	Kya-nite
Harindhara Bar	HY1	3	1	2	Trace	Trace	2	1	-	1	4	2	1
	HY2	2	-	1	-	Trace	1	Trace	-	1	2	1	1
Kulkandi Bar	KX1	2	-	1	-	-	2	1	-	1	3	1	Trace
	KX2	3	-	1	-	Trace	3	1	-	1	3	1	1
	KY1	2	Trace	1	-	-	2	1	Trace	2	3	1	Trace
	KY2	2	-	Trace	-	-	2	Trace	-	1	3	1	Trace
Island Bar	IY	3	-	1	Trace	-	1	1	-	Trace	2	1	Trace
East Bank	BEBY1	3	-	1	1	-	2	Trace	-	1	2	1	1
	BEBY2	3	-	1	-	-	Trace	-	Trace	Trace	2	2	Trace
West Bank	BWBY1	3	-	1	-	Trace	1	1	-	1	2	2	Trace
	BWBY2	3	-	1	Trace	-	1	1	Trace	Trace	3	2	1

Table 7.17: Relative abundance of heavy minerals (particle/slide) at Jamuna Bridge Reach.

Bar/ Bank	ID Code	Opaque				Ultrastables			Metastables				
		Mag-netite	Ilme-nite	Pyrite	Hema-tite	Zircon	Tour-maline	Rutile	Oli-vine	Apa-tite	Amph-ibole	Pyro-xene	Kya-nite
Belutia Bar	BY1	1	-	-	-	-	4	2	-	-	4	1	-
	BY2	3	1	Trace	1	-	1	-	-	1	4	2	2
Chatpier Bar	CX1	2	-	1	-	-	1	1	-	1	2	1	1
	CX2	1	-	1	-	-	1	-	-	1	2	1	1
	CY1	1	Trace	-	-	-	-	1	-	Trace	2	1	1
	CY2	1	Trace	1	-	-	2	1	-	1	2	2	1
Attached Bar	AY	2	-	1	Trace	Trace	1	1	-	1	2	2	1
East Bank	JEBY1	2	-	1	-	Trace	1	1	-	1	2	2	Trace
	JEBY2	2	-	Trace	-	-	2	1	-	1	3	2	1
West Bank	JWBY1	2	-	1	Trace	Trace	2	1	-	1	3	1	1
	JWBY2	1	-	Trace	-	-	1	1	Trace	Trace	3	1	1

7.3.3. Sources of Minerals and Depositional Environment

Mineralogical compositions of sedimentary deposits generally reflect the lithology over which a water course flows, however, the origin of sediment is difficult to trace, since large areas and many fluvial aspects are involved in depositional processes (Bogardi, 1974). Moreover, mineralogical compositions contain fragments and crystals of a very large number of rocks and minerals, and are subject to mechanical and chemical weathering with substantial modification (Bogardi, 1974; Le Pera & Sorriso-Valvo, 2000). Hence, it should be obvious that the rational determination of the ultimate place of origin is almost impossible without extensive and lengthy explorations. However, careful examination of mineralogical composition of sediments can thus be used to establish relationships with their localised sources to gain better understanding of lithological evolution (Le Pera & Sorriso-Valvo, 2000).

The analysis of mineralogical composition of surface sediments at both banks and bars of the Brahmaputra-Jamuna River show admixture of several kinds of minerals. From the results of the analysed sediment samples, it is also evident that there is no significant variation of mineral compositions between the widest upper reach and narrowest lower reach, and between the banks and bars within a single reach. It is very difficult to make any conclusions from this result about the bar mineral sources whether they are products of banks or transported from upper catchments because the sediments become progressively less representative of the source rock mineralogy, and shifted towards quartzose composition (Le Pera & Sorriso-Valvo, 2000). The lack of significant variations of mineral composition between banks and bars may be taken to infer that eroded bank materials may be the source sediments that are responsible for localised bar formation (as discussed in section 7.2.3). Moreover, from different previous mineralogical studies, it is affirmed that the mineralogical characteristics of bars have a similarity with the mineralogical compositions of adjacent bank materials from which they were formed (Choudhury, 1989; ISPAN, 1995a; FAP24, 1996b). Bank erosion has had an impact on bar formation, but the possibility of influence of upper catchment sediments should not be rejected. Unless the sediment mineralogy is examined during the monsoon and the dry season for the whole course of the river, the present consideration may be useful to gain better understanding about the sources of sediment minerals.

7.3.4. Precision Assessment

A particle counting technique was employed to quantify the mineralogical contents from the thin sections of sediment samples. A total of 300 particles was counted from each glass slide and the percentage of every identified particle was tabulated and was thought to be representative of the total countable particles. For counts intended to determine the composition of minerals 300 particles were chosen as this is a widely used optimum number and recommended for standard results (Dryden, 1931; Twenhofel & Tyler, 1941; Ingersoll *et al.*, 1984; Bridgland, 1986; Edgington & Harbury, 1993; Le Pera & Sorriso-Valvo, 2000). The likely precision of results has been estimated calculating the *standard error* at a 95% confidence level. The calculation employed the following equation [after Bridgland (1986) and Edgington & Harbury (1993)]:

$$\text{Standard Error (95\% confidence level)} = 2\sqrt{(pq/n)} \qquad (7.1)$$

where,

p = observed frequency (%)

$q = 100 - p$

n = number counted.

It is observed from the calculated results (see Appendix 3) that probable error is less than 6% for all mineral contents against count total. Therefore it is likely to be presumed that the clast counting technique yielded acceptable results of mineralogical compositions of sampled sediments.

7.4. Conclusion

This chapter discusses the sedimentological properties of bar and bank sediments of the two selected reaches in the Brahmaputra-Jamuna River. It also demonstrates the relationships between bank erosion and bar sedimentation processes. The main observations of this chapter are as follows:

(1) The sediments vary from fine silt to coarse sand with diameters from 0.50 μm to >500 μm, with very fine sand to fine sand being the most common population. The particle size distribution is predominantly unimodal, and surface and

subsurface samples of each bar as a whole show similar patterns. Nevertheless the bars at Jamuna Bridge Reach are much older than the Bahadurabad Ghat Reach and their particle size distributions are comparatively different, particularly in respect of longitudinal and vertical arrangements. Sediment sorting is mainly moderate to well-sorted in all the bars at both reaches, and the differential curves are nearly normal with some positive skewness and they are leptokurtic in nature. There is no evidence for channel-scale downstream fining of sediment grain size while the reach-scale results exhibit a somewhat opposite trend revealing downstream coarsening. Bar-scale sediment size distributions mostly fine upwards with a downstream size decreasing tendency. The average particle size range suggests that bank erosion is linked to the growth and development of braid bars and may be the potential source of bar sediments.

(2) The mineralogical composition of surface sediments at both banks and bars of the Brahmaputra-Jamuna River shows admixtures of several kinds of minerals. The most abundant mineral content present in sediment samples is quartz and it constitutes more than 40% of the total minerals, while feldspar and mica are less dominant and rock fragments contribute a good percentage. There is no significant variation of mineral composition between the widest upper reach and narrowest lower reach, and neither between the banks and bars within a single reach. The banks appear to be the possible source of the parent materials of bars.

CHAPTER VIII: SEDIMENT YIELD AND BALANCE

8.1. Introduction

The fluvial system is characterised as a process-response system which relates to the interaction of erosional and depositional processes (Petts & Foster, 1985; Rhoads, 1988; Martin & Church, 1995). Indeed, these processes vary from river to river, and even from reach to reach. In braided channels the processes of erosion and deposition are less predictable than in single-thread rivers (Ferguson & Ashworth, 1992), and they are characterised by complex and transient morphologies and associated spatial and temporal fluctuations in sediment transportation rate (Goff & Ashmore, 1994). However, recent studies have demonstrated that information about the different forms of sediment exchange can be inferred from a morphological approach (by assessment of erosion and deposition) to sediment yield analysis (e.g. Martin & Church, 1995). Sediment yield is the total outflow from a catchment or a drainage basin or within spatially contiguous reaches of river over a specified period (Petts & Foster, 1985; Einsele, 1992; Owens & Slaymaker, 1993; Trimble, 1995; Milne & Sear, 1997), and the amount of sediment load is a function of different fluvial processes (Petts & Foster, 1985).

The amount of sediment yield and storage or removal is commonly estimated using sediment budget or sediment balance analysis while the actual patterns of sediment storage or removal are usually much more complicated and the most poorly understood components of a fluvial system (Swanson *et al.*, 1982; Goff & Ashmore, 1994). Nevertheless, the simple construction of a sediment budget involves the quantification of sediment inputs, outputs and storage changes in a particular reach (Clark, 1995; Martin & Church, 1995; Trimble, 1995). The total inflow of sediment load into any reach represents the sum of the inflow at the upstream end of the reach and the inflow from all tributaries entering the reach (Bordas & Walling, 1988). By comparing the total inflow with the outflow of sediments at the downstream end of the reach, an estimate of storage or removal of sediments within the reach is obtained. The objective of this chapter is, to estimate reach-scale storage and removal of sediments using areal and volumetric measurement approaches, and to evaluate these approaches by field observations in the Brahmaputra-Jamuna River.

8.2. Methodology

Different morphological and sedimentary evidences cited in the previous chapters (Chapters 5, 6 and 7) imply that the braiding of the Brahmaputra-Jamuna River is largely dependent on the addition of sediments to the channel through bank erosion, and consequently, bars are responsible for further bank erosion. Moreover, it is believed that storage or removal of sediments is closely related to the yielding of sediments by bank erosion. As the changes in storage or removal of sediments reflect the sediment budgets, quantification of the latter would have important implications for the explanation of the process-form linkage between bank erosion and braid bar deposition (Thorne *et al.*, 1993). Two methods are commonly used to estimate sediment budgets for a channel or contiguous reach, one based on a sediment continuity approach (Goff & Ashmore, 1994; Martin & Church, 1995), the other on measured cross-sections (Goswami, 1985; Milne & Sear, 1997). The sediment continuity approach was not considered for this study as it investigates only two discrete reaches which are 70 kilometres apart from each other, while the measured cross-section approach could not be solely used because of the unavailability of 1987-1992 period's cross-sections at Bangladesh Water Development Board (BWDB). Therefore, the present study made an attempt to introduce a new method to estimate a temporal sediment budget (more specifically sediment balance) for the two selected reaches. This method estimated areal erosional loss or depositional gain from satellite images for the decadal timescale (1987-1997); and volumetric sediment balance using cross-section elevations from morphological survey data with the combination of satellite images for the 1992-1997 period. It also assessed the comparative accuracy of the estimated sediment balances using bar-scale and reach-scale field observations. Although this study considers temporal estimation of sediment budgets this approach can be extended upstream or downstream for spatial representations to make an assessment of sediment continuity.

8.3. Estimation of Sediment Balance by Area

Major land cover distributions between 1987 and 1997 at Bahadurabad Ghat and Jamuna Bridge reaches of the Brahmaputra-Jamuna River have been estimated from classified land cover images and this was accomplished by a supervised maximum likelihood classification algorithm (see Section 6.4 and Figures 6.5 and 6.6). As the total area of each year's image frame is exactly similar to each other for a particular reach (total area of each year's image frame for the Bahadurabad Ghat and Jamuna Bridge reaches are 582.07 million square metre (Mm^2) and 592.92 Mm^2, respectively), so two-dimensional assessment of storage or removal of sediments from the area of land cover distributions may contribute to an overall assessment of the decadal sediment balance of the Brahmaputra-Jamuna River. Year-wise measured land cover distributions are presented in Tables 8.1 and 8.2 which have been used to estimate reach-scale sediment balance (Tables 8.3 and 8.4).

Table 8.1: Major land cover distributions at Bahadurabad Ghat Reach.

Year	Channel Bank (Mm^2)			Channel Bar (Mm^2)	Water Surface (Mm^2)
	West Bank	East Bank	Total		
1987	136.04	159.73	295.77	207.25	79.05
1989	123.84	148.10	271.94	202.63	107.50
1992	118.78	147.08	265.86	220.49	95.72
1994	119.52	142.45	261.97	229.69	90.41
1995	118.21	142.28	260.49	251.66	69.92
1996	118.35	136.95	255.30	241.90	84.87
1997	114.96	136.06	251.02	238.07	92.98

Table 8.2: Major land cover distributions at Jamuna Bridge Reach.

Year	Channel Bank (Mm^2)			Channel Bar (Mm^2)	Water Surface (Mm^2)
	West Bank	East Bank	Total		
1987	159.86	182.62	342.48	184.41	66.03
1989	152.37	165.21	317.58	193.65	81.69
1992	143.17	155.99	299.16	218.06	75.70
1994	142.87	154.89	297.76	220.80	74.36
1995	142.69	146.63	289.32	239.68	63.92
1996	139.77	148.24	288.01	227.97	76.94
1997	146.35	147.40	293.75	211.31	87.86

8.3.1. Sediment Balance at Bahadurabad Ghat Reach

Areal erosional loss and depositional gain of sediments at both banks and bars between 1987 and 1997 have been calculated from major land cover distributions (Table 8.1). Total area of sediment at both banks and bars between two successive years has been compared and net erosion and deposition with reach-scale sediment storage or removal tabulated (Table 8.3).

Table 8.3: Sediment balance (Mm^2) at Bahadurabad Ghat Reach during 1987-1997.

Period	Bank Erosion/Deposition			Bar Erosion/ Deposition	**Net Storage/ Removal**
	West Bank	East Bank	Total		
1987-1989	+12.20	+11.63	+23.83	+4.62	**+28.45**
1989-1992	+5.06	+1.02	+6.08	-17.86	**-11.78**
1992-1994	-0.74	+4.63	+3.89	-9.20	**-5.31**
1994-1995	+1.31	+0.17	+1.48	-21.97	**-20.49**
1995-1996	-0.14	+5.33	+5.19	+9.76	**+14.95**
1996-1997	+3.39	+0.89	+4.28	+3.83	**+8.11**
1987-1997	**+21.08**	**+23.67**	**+44.75**	**-30.82**	**+13.93**

Note: '+' sign indicates net erosion (removal) and '–' sign indicates net deposition (storage).

The result of the computations show that over the decadal period total bank erosion (44.75 Mm^2) was more than bar accretion (30.82 Mm^2). These figures show that during the 1987-1997 period the Bahadurabad Ghat Reach lost more sediments than the total gain and it removed 13.93 Mm^2 sediments to its downstream reach. However, the short period reach-scale sediment storage or removal data reveal a different picture. In the 1987-1989 period, both banks and bars suffered severe erosion, most probably due to the 1988 catastrophic flood and they together removed 28.45 Mm^2 sediments to the downstream. From 1989 through 1992, a different pattern prevailed and it is revealed from the calculations that both banks eroded only

6.08 Mm^2 sediments while the bars accreted 17.86 Mm^2 sediment and the reach gained 11.78 Mm^2 sediment from upstream. This trend continued up to the next two periods and Bahadurabad Ghat Reach gained 5.31 Mm^2 and 20.49 Mm^2 from upstream for the 1992-1994 and 1994-1995 periods, respectively. The most likely cause behind this is that during the 1989-1995 period major monsoonal floods have not affected the Brahmaputra-Jamuna River and there was massive upstream bar reworking that accelerated sediment removal to the downstream reach. In the following periods (1995-1996 and 1996-1997) both banks and bars lost sediments, releasing 14.95 Mm^2 and 8.11 Mm^2 sediment, respectively. During these periods Bahadurabad Ghat Reach removed a good amount of sediment to its downstream, and this is probably because of major flooding and internal transfer of sediments (cf. Bristow, 1987).

8.3.2. Sediment Balance at Jamuna Bridge Reach

Sediment balance measurement for Jamuna Bridge Reach was also performed from estimated landcover distributions (Table 8.2). During the decade, both banks of this reach suffered erosion (48.73 Mm^2) while net bar accretion was observed 26.90 Mm^2, and total sediment removal to its downstream was 21.83 Mm^2 (Table 8.4). This reach exhibited the same pattern of storage or removal of sediments for two to three years time period as Bahadurabad Ghat Reach except the variation of total amount. In 1987-1989 period, this reach lost 15.66 Mm^2 while in the next successive three periods it gained sediments from upstream (5.99 Mm^2, 1.34 Mm^2 and 10.44 Mm^2, respectively), and during the 1995-1996 and 1996-1997 period it again removed sediments to its downstream reach (13.02 Mm^2 and 10.92 Mm^2, respectively). The possible causes for such variations are thought to be due to the variability of flood discharge and river training works.

Table 8.4: Sediment balance (Mm^2) at Jamuna Bridge Reach during 1987-1997.

Period	Bank Erosion/Deposition			Bar Erosion/ Deposition	**Net Storage/ Removal**
	West Bank	East Bank	Total		
1987-1989	+7.49	+17.41	+24.90	-9.24	**+15.66**
1989-1992	+9.20	+9.22	+18.42	-24.41	**-5.99**
1992-1994	+0.30	+1.10	+1.40	-2.74	**-1.34**
1994-1995	+0.18	+8.26	+8.44	-18.88	**-10.44**
1995-1996	+2.92	-1.61	+1.31	+11.71	**+13.02**
1996-1997	-6.58	+0.84	-5.74	+16.66	**+10.92**
1987-1997	**+13.51**	**+35.22**	**+48.73**	**-26.90**	**+21.83**

Note: '+' sign indicates net erosion (removal) and '–' sign indicates net deposition (storage).

8.4. Estimation of Sediment Balance by Volume

Sediment balance by volume at the two selected reaches of the Brahmaputra-Jamuna River was estimated using the classified land cover database and average year-wise cross-section elevation data (each reach incorporates information from a single cross-section). Major land cover distributions between 1992 and 1997 have been estimated from classified land cover images, and average reach-scale cross-section elevation data have been compiled from morphological survey information of monumented cross-sections of Bangladesh Water Development Board (BWDB) (see Appendix 4). Year-wise measured land cover distributions and average cross-section elevation data are presented in Tables 8.5 and 8.6 that have been used to estimate reach-scale volume of sediments multiplying total bank or bar area by average cross-section elevations (Tables 8.7 and 8.8).

Table 8.5: Major land cover distributions and average cross-section elevation data at Bahadurabad Ghat Reach.

Year	Channel Bank (Mm^2)			Channel Bar (Mm^2)	Water Surface (Mm^2)	Average Cross-section Elevation (m)
	West Bank	East Bank	Total			
1992	118.78	147.08	265.86	220.49	95.72	16.77
1994	119.52	142.45	261.97	229.69	90.41	16.48
1995	118.21	142.28	260.49	251.66	69.92	16.52
1996	118.35	136.95	255.30	241.90	84.87	16.94
1997	114.96	136.06	251.02	238.07	92.98	16.68

Table 8.6: Major land cover distributions and average cross-section elevation data at Jamuna Bridge Reach.

Year	Channel Bank (Mm^2)			Channel Bar (Mm^2)	Water Surface (Mm^2)	Average Cross-section Elevation (m)
	West Bank	East Bank	Total			
1992	143.17	155.99	299.16	218.06	75.70	8.58
1994	142.87	154.89	297.76	220.80	74.36	8.79
1995	142.69	146.63	289.32	239.68	63.92	9.85
1996	139.77	148.24	288.01	227.97	76.94	9.69
1997	146.35	147.40	293.75	211.31	87.86	9.23

Table 8.7: Estimated sediment volume (Mm^3) at Bahadurabad Ghat Reach.

Year	Channel Bank			Channel Bar
	West Bank	East Bank	Total	
1992	1991.94	2466.53	4458.47	3697.62
1994	1969.69	2347.58	4317.27	3785.29
1995	1952.83	2350.47	4303.30	4157.42
1996	2004.85	2319.93	4324.78	4097.79
1997	1917.53	2269.48	4187.01	3971.01

Table 8.8: Estimated sediment volume (Mm^3) at Jamuna Bridge Reach.

Year	Channel Bank			Channel Bar
	West Bank	East Bank	Total	
1992	1228.40	1338.39	2566.79	1870.95
1994	1255.83	1361.48	2617.31	1940.83
1995	1405.50	1444.31	2849.81	2360.85
1996	1354.37	1436.45	2790.82	2209.03
1997	1350.81	1360.50	2711.31	1950.39

8.4.1. Sediment Balance at Bahadurabad Ghat Reach

Volumetric erosion and deposition of sediments at both banks and bars from 1992 to 1997 have been calculated using Table 8.7. Total sediment volumes at both banks and bars between two successive years were compared and net erosional loss and depositional gain with reach-scale sediment storage or removal are tabulated (Table 8.9).

Table 8.9: Sediment balances (Mm^3) at Bahadurabad Ghat Reach during 1992-1997.

Period	Bank Erosion/Deposition			Bar Erosion/ Deposition	**Net Storage/ Removal**
	West Bank	East Bank	Total		
1992-1994	+22.25	+118.95	+141.20	-87.67	**+53.53**
1994-1995	+16.86	-2.89	+13.97	-372.13	**-358.16**
1995-1996	-52.02	+30.54	-21.48	+59.63	**+38.15**
1996-1997	+87.32	+50.45	+137.77	+126.78	**+264.55**
1992-1997	**+74.41**	**+197.05**	**+271.46**	**-273.39**	**-1.93**

Note: '+' sign indicates net erosion (removal) and '–' sign indicates net deposition (storage).

The tabulated results show that during the 1992-1997 period total bank erosion (271.46 Mm^3) was similar to bar accretion (273.39 Mm^3). These figures indicate that during 1992-1997 Bahadurabad Ghat Reach was almost in balance between its total volume of erosion and accretion, with only a minimal volume of sediment storage (1.93 Mm^3). However, the short period reach-scale sediment gain or losses show different patterns. In 1992-1994 period, both east and west banks suffered severe erosion (141.20 Mm^3) while the bars accreted 87.67 Mm^3 eroded sediments and the rest of the sediments (53.53 Mm^3) were removed to the downstream reach. This tendency continued in the next period but at that time the banks experienced some degradation (13.97 Mm^3) while the bars underwent considerable aggradation (372.13 Mm^3). These figures reflect the fact that during the 1994-1995 period Bahadurabad Ghat Reach stored 358.16 Mm^3 sediments that it gained from upstream. Since flood flow for 1994-1995 was not excessive, accumulation of a large amount of sediment appears to have resulted from transfer of materials from upstream at a rate which was considerably higher than during 1992-1994. During the 1995-1996 period, this reach showed a different pattern by eroding its bars (59.63 Mm^3) and accreting banks (21.48 Mm^3), and removing 38.15 Mm^3 sediments downstream due to the severe floods of 1995. Furthermore, in the following period (1996-1997) both banks and bars lost sediment (264.55 Mm^3) to downstream. Although during the 1996-1997 period Brahmaputra-Jamuna River was not affected by catastrophic flooding other than a major monsoon flood, a large amount of sediment was transferred downstream. This is most probably because of the long-sustained flood flows and internal reworking between the bars.

8.4.2. Sediment Balance at Jamuna Bridge Reach

The volumetric pattern of sediment balance at Jamuna Bridge Reach was also performed, using computed quantities of sediment (Table 8.8) and net erosion and deposition with reach-scale sediment storage or removal tabulated (Table 8.10). This reach exhibited a different pattern of storage or removal of sediments compared to the Bahadurabad Ghat Reach. Taken as a whole, both banks and bars at Jamuna Bridge Reach registered a net gain from upstream (144.52 Mm^3 and 79.44 Mm^3, respectively) in 1992-1997 period, and total sediment storage was 223.96 Mm^3 (Table 8.10). However, data exhibited considerable aggradation (120.40 Mm^3) at both banks and bars during 1992-1994, followed by enormous amount of sedimentation (652.52 Mm^3) during 1994-1995 which stored more than five fold of the volume of sediments deposited during 1992-1994. These patterns of sedimentation are most likely related to building of embankments for bridge construction where there has been significant middle-reach channel narrowing observed without bank erosion. In the next two periods (1995-1996 and 1996-1997) both banks and bars experienced severe erosion and a significant amount of sediments (210.81 Mm^3 and 338.15 Mm^3, respectively) were removed downstream. This large amount of sediment loss is probably a consequence of major flood and bridge construction activity, which impeded the natural flow pattern and ultimately both banks and bars suffered from huge erosion in both upstream and downstream of bridge site. This loss is only comparable with the 1988 catastrophic flood event that eroded enormous amount of bank and bar sediments.

Table 8.10: Sediment balances (Mm^3) at Jamuna Bridge Reach during 1992-1997.

Period	Bank Erosion/Deposition			Bar Erosion/ Deposition	**Net Storage/ Removal**
	West Bank	East Bank	Total		
1992-1994	-27.43	-23.09	-50.52	-69.88	**-120.40**
1994-1995	-149.67	-82.83	-232.50	-420.02	**-652.52**
1995-1996	+51.13	+7.86	+58.99	+151.82	**+210.81**
1996-1997	+3.56	+75.95	+79.51	+258.64	**+338.15**
1992-1997	**-122.41**	**-22.11**	**-144.52**	**-79.44**	**-223.96**

Note: '+' sign indicates net erosion (removal) and '–' sign indicates net deposition (storage).

8.5. Comparative Assessment of Estimated Sediment Balance

There is a considerable variation in the magnitude of sediment balance between the areal and volumetric methods (Tables 8.3, 8.4, 8.9 and 8.10). During the 1992-1997 period Bahadurabad Ghat Reach stored 15.59% more sediments (calculation based on Table 8.3) than it had eroded from its banks while it showed only 0.71% sediment storage by volumetric measurement for the same period (calculation based on Table 8.9). On the other hand, Jamuna Bridge Reach exhibits the opposite trend, losing 12.16 Mm^2 area between 1992 and 1997 while it showed 223.96 Mm^3 sediment deposition by volumetric measurement. The short period sediment balance estimates also showed discrepant figures between areal and volumetric estimations. Reasonably, there is one serious drawback in using areal differencing to estimate sediment balance as areal measurement illustrates two-dimensional status of sediment erosion or deposition, and accordingly, it cannot be directly compared to volumetric sediment balance. Therefore, volumetric estimation of reach-scale sediment balance could be more appropriate to assess overall pattern of sediment balance of the Brahmaputra-Jamuna River. In order to assess the reliability of the volumetric estimates, the section below provides a comparison with field data.

To test the validity of using average cross-section elevation data in estimating sediment volumes from satellite images, bar-scale and reach-scale field information were used. An island bar has been selected from Jamuna Bridge Reach for the computations of bar-scale sediment volume which was subsequently surveyed and bar elevations were measured using echo-sounding in 1995 and 1996 by Surface Water Modelling Centre (SWMC) of Bangladesh (Figs. 8.1 and 8.2). Total bar-scale sediment volume has been computed using average bar elevation data and then compared with estimated results for the same bar (Table 8.11). It is evident from the table that volumetric computation of sediments from secondary cross-section elevation data underestimates the total volume of sediments compared with the field observations and the imputed error ranges from 24.81% to 26.51%.

Table 8.11: Comparative assessment of bar-scale sediment volume at Jamuna Bridge Reach.

Year	**Study Bar Area (Mm^2)**	**Estimation Using Field Data**		**Estimation Using Secondary Data**		**Difference (%)**
		Bar Elevation (m)	Sediment Volume (Mm^3)	Bar Elevation (m)	Sediment Volume (Mm^3)	
1995	25.61	13.10	335.49	9.85	252.26	24.81
1996	20.15	13.12	264.37	9.69	195.25	26.15

The results of reach-scale error analysis for estimated sediment balance are presented in Table 8.12. The average elevation of surface topography (see Section 6.4.4 and

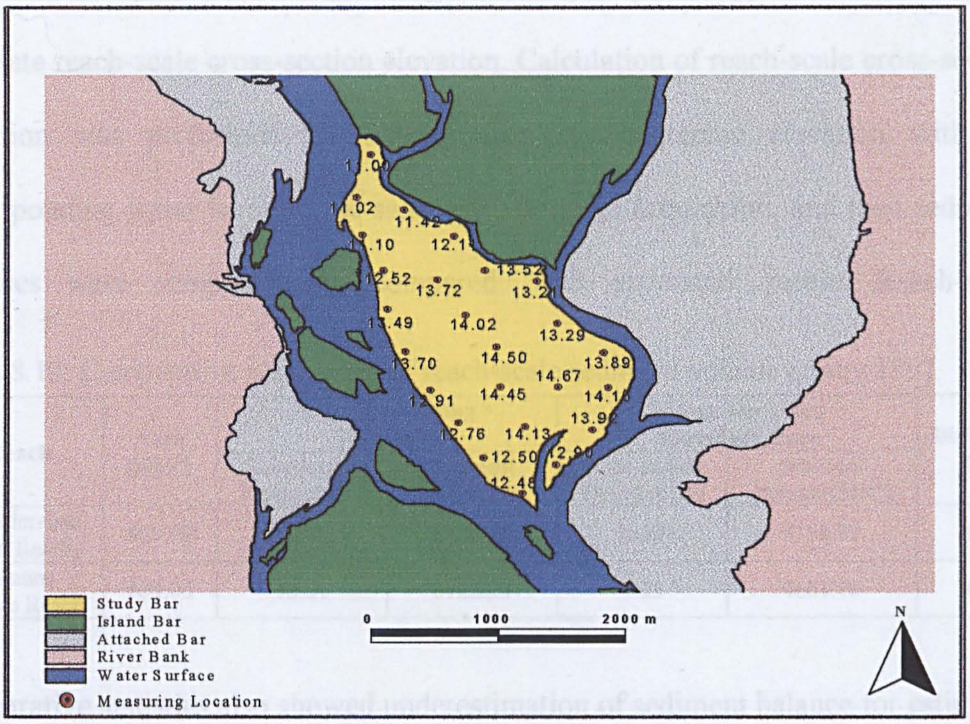


Figure 8.1: Measured elevations on the study bar at Jamuna Bridge Reach during 1995.

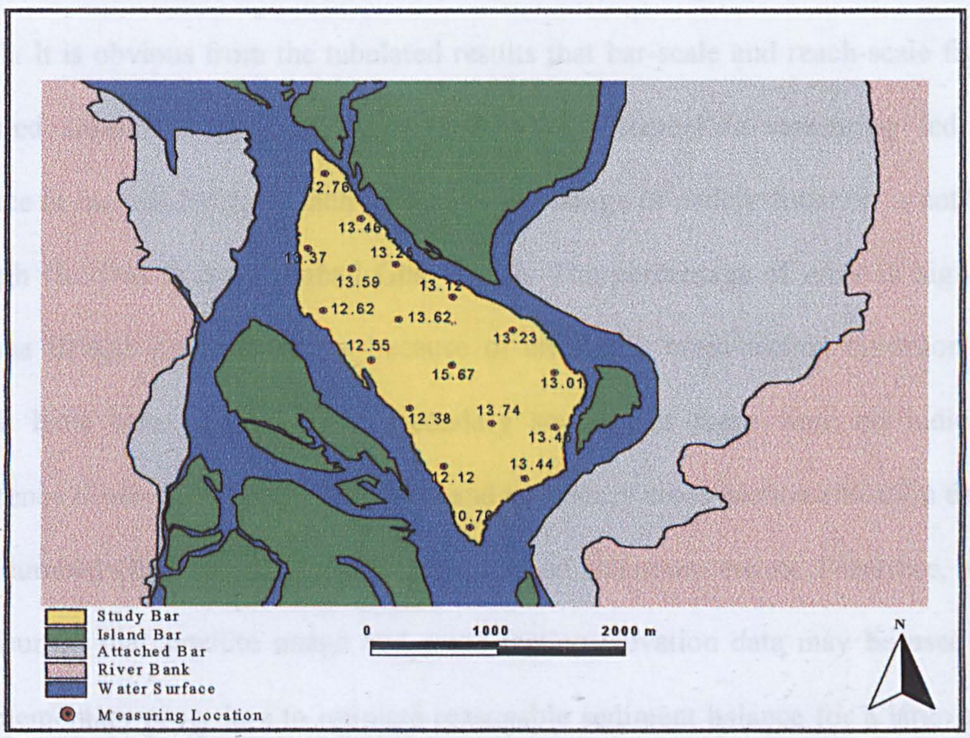


Figure 8.2: Measured elevations on the study bar at Jamuna Bridge Reach during 1996.

Figures 6.10 and 6.11) and corresponding water level reading (14.63m and 7.51m for Bahadurabad Ghat and Jamuna Bridge reaches, respectively) have been used to calculate reach-scale cross-section elevation. Calculation of reach-scale cross-section elevation was performed by adding average topographic elevation with the corresponding water level on the same day of image acquisition, and then sediment volumes were computed and compared with estimated results. Reach-scale

Table 8.12: Comparative assessment of reach-scale sediment volume during 1997.

Reach	Area (Mm^2)	Estimation Using Field Data		Estimation Using Secondary Data		Difference (%)
		Cross-section Elevation (m)	Sediment Volume (Mm^3)	Cross-section Elevation (m)	Sediment Volume (Mm^3)	
Bahadurabad Ghat Reach	489.09	18.26	8930.78	16.68	8158.02	8.65
Jamuna Bridge Reach	505.06	13.31	6722.35	9.23	4661.70	30.65

comparative statistics also showed underestimation of sediment balance for estimated results over field observations, and the computed error due to cross-section elevation variability are 8.65% for Bahadurabad Ghat Reach and 30.65% for Jamuna Bridge Reach. It is obvious from the tabulated results that bar-scale and reach-scale figures revealed almost similar percentage of error involvement in measuring sediment balance at Jamuna Bridge Reach while the percentage of underestimation is not large enough (8.65%) at Bahadurabad Ghat Reach. The percentage of error is higher at Jamuna Bridge Reach probably because of erroneous cross-section elevation data which have been derived from secondary source but there were no indicative difference observed between field level and secondary cross-section elevation data at Bahadurabad Ghat Reach as they likely incurred minimum errors. Therefore, it can be assumed that satellite image and cross-section elevation data may be used as a complementary procedure to estimate reasonable sediment balance for a large sand-bed braided river that suffers from lack of reliable data sources and drastic changes of channel from one time period to another. However, for a complete estimation of sediment budget, the volumes of erosion and sedimentation outside the study reaches must be assessed and included in the balance. Moreover, caution must be stressed over the reliability of cross-sectional elevation data because single cross-section involves uncertainty arising from the fact that storage or removal at a cross-section may not be representative of conditions in a long reach.

8.6. Conclusion

The construction of a sediment budget requires measurements of sediment inputs, outputs and storage change in a defined reach (Martin & Church, 1995). However, problems remain in determining a reliable volume of erosion, transportation and deposition of sediments (Lane *et al.*, 1994; Milne & Sear, 1997). Measurement of morphological changes by repeated survey of cross-sections provides a basis for evaluating of aggradation or degradation in a particular reach or a river (Martin & Church, 1995). However, this method could not be considered for the Brahmaputra-Jamuna River for practical problems. Therefore, an alternative method of evaluating sediment balance based on satellite image and cross-section value was used for the two reaches of the Brahmaputra-Jamuna River. Using this method areal and volumetric estimation of sediment balance was performed and evaluated. In comparison, areal estimation was ascertained to be inconsistent over the volumetric measurement of sediment balance. The estimated volumetric results showed that over the 1992-1997 period the Bahadurabad Ghat Reach was almost in balance between the total volume of erosion and accumulation. This was probably due to its high braiding intensity, and internal exchange of sediments between the bars and the banks (cf. Goswami, 1985). The Jamuna Bridge Reach exhibited a different pattern with net storage of large amounts of sediment gained from upstream. This was presumably because of the building of bank protection embankments and construction of a large bridge. Although the method employed underestimates sediment balance from 8.65% to 30.65% compared to field assessments, satellite image and cross-section data may be used as a complementary procedure to estimate reasonable sediment balance for a large-scale river that suffers from lack of reliable data sources.

CHAPTER IX: DISCUSSION

9.1. Introduction

A knowledge of braiding and changes in channel position through time is critical to many geomorphological and river management problems. Many advances have been made in the study of braided rivers in recent decades, although sand-bed braided rivers have received much less attention than gravel-bed ones. Recent literature has shown considerable progress in specific areas of research in both types of rivers, although several important areas remain relatively unstudied. This study tries to investigate some of the unresolved issues in the previous chapters, these are: quantitative analysis of braiding processes in relation to bank erosion, bankline shifting and channel width change; spatial variability of sedimentary properties in connection to flow patterns; and changes in channel morphology and sediment balance. This chapter therefore provides insight into the interrelationships identified amongst the results presented in previous chapters, and investigates the effects of flooding on channel migration and bar permanency, human settlements and vegetation patterns.

9.2. Bank Erosion and Channel Braiding

The Brahmaputra-Jamuna River is well known for its rapid bank retreat with large quantities of in-channel sedimentation and its braiding index which is well above the critical value of 1.5, varying between 5.16 to 8.35. Channel bank morphology appears to be a critical factor in braiding in the Brahmaputra-Jamuna River due to the abundance of non-cohesive silty-sand in both banks. Analysis of braiding intensity (see Chapter 6) indicates that island reaches (sedimentation zones) are wider than the nodal reaches (transportation zones), and the spatial distribution of island and nodal reaches are likely to be controlled by bank erodibility. Flow velocities below a nodal reach usually decelerate due to channel expansion, causing the transported sediment to be deposited and form braid bars, and further channel widening may occur due to the consequent enlargement of bars. This is a generalised model of braiding and channel expansion which is thought to operate in the Brahmaputra-Jamuna River (e.g. Coleman, 1969; Thorne *et al.*, 1993), but the detailed understanding of the actual process of braiding is poor.

The satellite image interpretation and field observation undertaken in this thesis indicate that floods determine the initial location and formation of braid bars. It is practically difficult to predict the initiation of a braid bar at a particular location at the time of high flood flows due to the rapidity of flow velocities and bank erosion. However, it is observed that braiding begins with the formation of a mid-channel bar in an undivided first-order channel at the time of the flood season. The area of deposition in the central part of the channel immediately downstream of the node of a flow convergence (cf. Ashmore, 1993; Bristow *et al.*, 1993; Ashworth *et al.*, 2000) is likely to be caused by flow expansion and deceleration (cf. Leopold & Wolman, 1957; Bristow & Best, 1993), and local sediment transport incompetence (cf. Ferguson, 1993; Hooke, 1997). During floods river banks of upstream island reaches face severe erosion and the sediment is transported to downstream nodal reaches (cf. Jiongxin, 1997). The coarser fraction of it is probably laid down in the mid-channel areas, which causes the river bed to aggrade sufficiently to form a bar nucleus (cf. Leopold & Wolman, 1957). Once the bar nucleus forms, it possibly acts as a template, which traps sediment of similar calibre (cf. Bluck, 1982) to form a shoal. When the flood water subsides, further flow deceleration and decreasing channel depth accelerate shoal aggradation and expansion and, ultimately, a braid bar is exposed (cf. Carson, 1984).

Widening in meandering rivers may occur due to point bar growth in the inner bank and toe scouring and retreat in the outer bank (Nanson & Hickin, 1983; Pizzuto, 1994), while in braided rivers, bank erosion by flows deflected around growing braid bars is often put forward as a primary cause of widening (Leopold & Wolman, 1957; Best & Bristow, 1993; Jiongxin, 1997; ASCE, 1998a; Goswami *et al.*, 1999). Likewise, the growing bars locally decrease the cross-sectional area and increase the degree of obstruction to the flow, which is then diverted sideways leading to an increase in bank erosion, resulting in channel widening and further braiding (cf. Coleman, 1969). Subsequently, the bar enlarges vertically and laterally which further widens the river channel. Thus, feedbacks operate to maintain and enhance braiding once it is initiated. During the period of flood recession, bars aggrade vertically probably due to decline of sediment transport competence (cf. Ferguson, 1987; Fujita, 1989) and rapid changes of river stage. Lateral accretion of the mid-channel bar is presumably related to flow divergence at the bar head and flow convergence at the bar tail (cf. McLelland *et al.*, 1999; Ashworth *et al.*, 2000), and successive merging of small unit bars (cf. Bristow, 1987; Thorne *et al.*, 1993) during low flow stages. Occasionally, the mid-channel bar coalesces with another medial bar through lateral accretion to form a mega-bar (cf. Bristow, 1987) at the time of major floods. Complex mega-bars are thought to be associated with channel multiplication and are probably responsible for the change of an unbraided reach to a braided reach. These inferences anticipate that the alteration of nodal reach (unbraided reach) to an island reach (braided reach) is likely to be controlled by bank erodibility. This is consistent with the observations of Leopold and Wolman (1957), Coleman (1969) and Thorne *et al.* (1993) who attribute bank erosion to the growth and multiplication of mid-channel bars that accelerate further bank erosion and channel widening.

Estimated results of areal erosional loss and depositional gain of sediments (see Chapters 5 and 6) also indicate that both the study reaches of the Brahmaputra-Jamuna River lost sediments due to severe bank erosion and gained sediments by bar deposition during the 1987-1997 period. Bank erosion and sedimentation rates are highly variable depending on the magnitude and duration of floods and presence or absence of river training works. The results suggest that about 69% and 55% (Bahadurabad Ghat and Jamuna Bridge reaches, respectively) of total eroded bank materials are stored in the study reaches, with the remainder transferred downstream. Moreover, it is evident from the measurements that both reaches were wider in 1997 (Bahadurabad Ghat and Jamuna Bridge reaches are widened 52% and 49%, respectively) than they were in 1987. This widening is most likely to have resulted when flow acceleration due to a decreasing cross-sectional area, coupled with current deflection around growing bars, generates bank erosion. This demonstrates the close relationship between bank erosion and channel sedimentation, and the difficulty of disentangling causal relationships. References to different studies carried out on river bank erosion and channel sedimentation in sand-bed braided systems (e.g. Jiongxin, 1997; Goswami *et al.*, 1999) suggest the same notion that low-resistant banks supply large quantities of sediments to the channel, leading to the formation of bars and inducing further channel expansion. Flume and field results also support this view. Ashmore (1991), in his flume experiments of central bar initiation, observes that some bank erosion is due to flow deflection around the bar margins. The flume results of Ashworth (1996) reinforce Ashmore's observation and suggest that aggradation of the mid-channel bar certainly contributes to the divergence of flow and acceleration of bank erosion. A relationship between mid-channel bar growth and bank erosion has also been documented by Ferguson and Werritty (1983), Ashworth and Ferguson (1986) and Goff and Ashmore (1994). Therefore, there is strong evidence of a process-form linkage between bank erosion and bar deposition, and this linkage is accelerated or decelerated by channel bank materials and flow patterns.

However, this apparent relationship is extremely complex with numerous and poorly understood feedbacks operating between morphology, flow and sediment transport. The exact nature of this relationship in sand-bed braided systems is not certain as there is much greater potential for sediment entrainment and transport during different flows compared to gravel-bed braided rivers (Bridge & Gabel, 1992; Bridge, 1993). It may be that processes and relationships observed during low-moderate flows are different from those occurring during high magnitude and long duration flows during the main flood season. For instance, at lower stages channel location and flow direction is strongly controlled by bed and bar morphology. Under these conditions it may be that sediment is redistributed locally over short distances, with material transferred from eroding bank to nearby bar. At higher flows, water surface slope and maximum velocity flow lines may be very different and bear little relationship to lower flow patterns. With a huge downstream momentum, and high sediment transport capacity, it is likely that any sediment eroded from banks and bars at this time is transferred rapidly downstream. In these conditions it is possible to envisage sediment being deposited under a number of different scenarios: i) selectively, with coarser material first, on flow recession; ii) grain-by-grain at points of local reductions of flow competence. Thus, low flow conditions may relate to the growth and maintenance of bars while bar initiation may occur under high flows, with different sediment sources and flow-form interactions under each. This is analogous in some ways to the discussions about formation and maintenance of riffle-pool sequences in gravel-bed rivers (Church & Jones, 1982; Bridge, 1985, 1993; Ferguson, 1993).

Therefore, an alternative explanation of the spatial relationship between bank erosion and mid-channel bar formation might argue not that erosion causes bars, but the opposite. Thus, the processes of braiding and channel expansion are likely to be interdependent which highlights the 'chicken and egg' relationships between them. Once a bar is initiated it will influence local flow conditions and may lead to deflection of flow towards the bank, leading to erosion. Bank erodibility is also important and may ultimately control the location of braided reaches, with channel width being an important factor. It is therefore reasonable to conclude that bank erosion has an impact on braid bar location, although the link is not direct and involves many feedbacks.

9.3. Flow Patterns and Sediment Size Distribution

Channel bars represent the major storage places for the sediment load of a braided river, and their formation and evolution is conditioned by the rate of sediment supply, in terms of both volume and calibre, and the flow hydraulics of the river, which determine the amounts and sizes of material that can be transported (Knighton, 1998). The sedimentary characteristics of channel bars are more a reflection of sediment supply conditions and channel processes, and they can play an important role in determining the morphology of braided channels and their associations with flow patterns (Church & Jones, 1982). Under these circumstances, a comparative analysis of bar and bank sediment characteristics of the two study reaches of the Brahmaputra-Jamuna River was evaluated and interpreted. The sediment size analysis shows that the overall sediment particle size characteristics at both reaches vary from fine silt to coarse sand with very fine sand to fine sand being the most common population. The particle size distributions are mainly unimodal and sediment sorting is generally moderate to well-sorted.

Although the overall pictures show similarity, there is a considerable variation of sediment size classes observed between the banks and bars as well as between the reaches due to the local variations of flow patterns and sources of sediments. The mean particle size for sediment samples of the Harindhara bar (2-year old) at Bahadurabad Ghat Reach shows longitudinal, lateral and vertical size variation. The mean grain size of surface and subsurface samples diminishes from bar head to bar tail, and this diminution is probably because the coarse sediment load tends to be deposited on the bar head whereas finer sediment is deflected around the bar where it is deposited in the tail. Ashworth *et al.* (1992) observed similar evidence on bedload transport and sorting in a flume experiment, and Bluck (1987) also suggests that coarser material is usually trapped during bar head aggradation, while finer material is more readily transported downstream. Under these circumstances the configuration and extent of sediment size distribution of the Harindhara bar seems to be influenced by the selective sorting and oriented to the flow direction (Fig. 9.1). Although coarse size fractions of the bar head have sometimes been attributed to intensity of flow turbulence which effects a more thorough removal of fine material towards downstream (e.g. Bluck, 1982), there is no strong evidence of near-bed or near-surface turbulent flow at any level of river stage at Bahadurabad Ghat Reach. The flow structure is dominated by a simple divergence of flow over the bar head and flow convergence at the bar tail (McLelland *et al.*, 1999). The lateral distribution of surface sediment size exhibits size diminution from the eastern to the western margin and the size distribution of the north-eastern part of the bar is very similar to that of upstream bars and the eastern bank. This similarity suggests that anabranch flow direction is responsible for lateral sediment size distributions of the Harindhara bar. This form of anabranch flow patterns and suspended sediment concentration on to the bar is also observed by McLelland *et al.* (1999) in their study in the

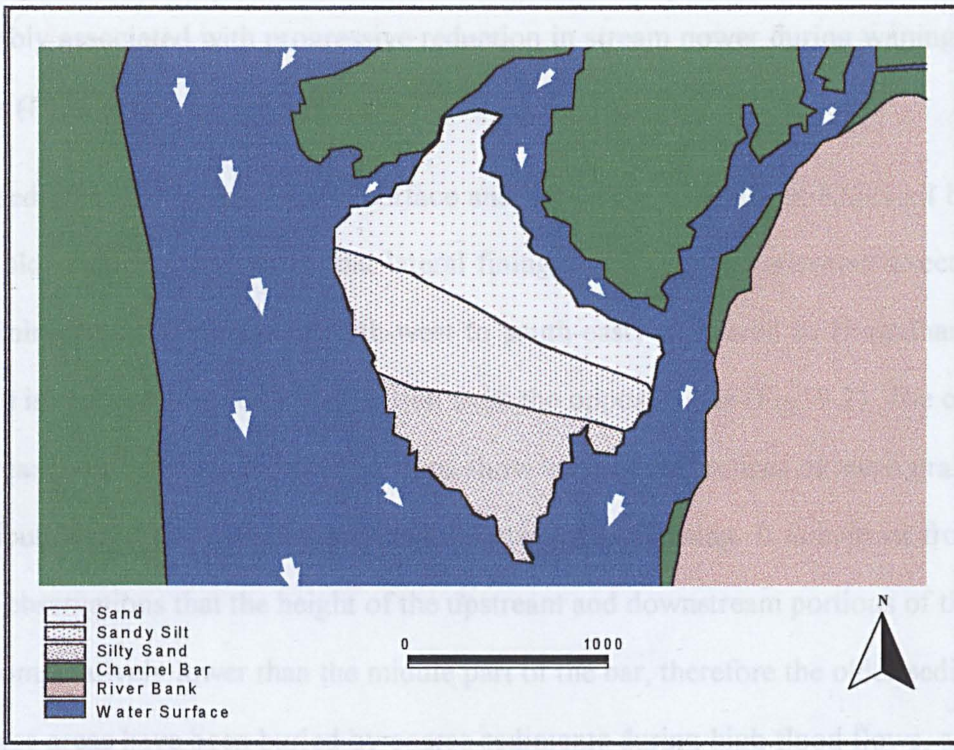


Figure 9.1: Surface sediment size distribution of Harindhara bar.

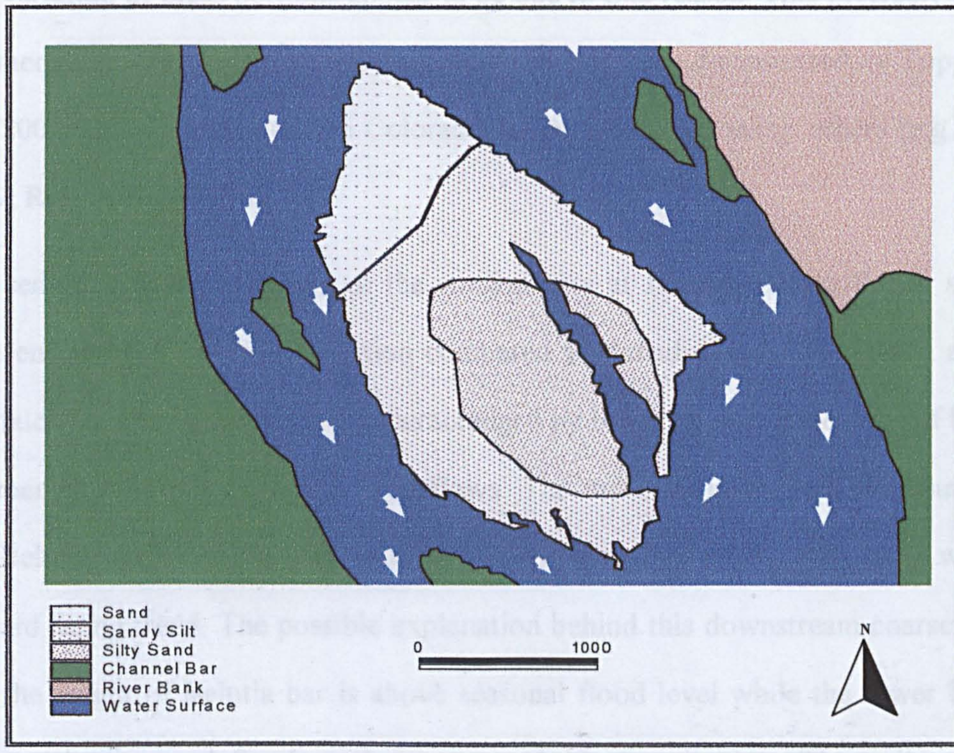


Figure 9.2: Surface sediment size distribution of Kulkandi bar.

Brahmaputra-Jamuna River. Investigation of the vertical variation of mean grain size indicates a general trend toward upward fining. These fining upward sequences are probably associated with progressive reduction in stream power during waning flood flows (Petts & Foster, 1985; Bristow, 1993).

The sediment size parameters of surface and subsurface samples at Kulkandi bar (4-year old) exhibit longitudinal and lateral fining, although the transverse direction of the fining trend is reversed (north-west to south-east) compared to Harindhara bar, which is probably due to flow direction from the opposite side (Fig. 9.2). The coarser upstream and finer downstream portions show vertical differences of mean grain size distribution and both are characterised by upward coarsening. It is evident from the field observations that the height of the upstream and downstream portions of this bar are comparatively lower than the middle part of the bar, therefore the older sediments of these areas have been buried by coarse sediments during high flood flows, and the size variation of these portions appear to be due to that reason. This inversely graded sediment size distribution during peak flow has also been documented by Topping *et al.* (2000) in their study on the Colorado River, USA, and many others (e.g. Iseya, 1989; Rubin *et al.*, 1998).

The sediment size parameters of the studied bars at Jamuna Bridge Reach show a different pattern of size distribution compared to Bahadurabad Ghat Reach as they are much elevated and tend to be characterised by lower or negligible rates of bar top sedimentation during seasonal flood flows. The mean sediment size distribution of the Belutia bar (10-year old) exhibits downstream coarsening (Fig. 9.3) with an upward fining trend. The possible explanation behind this downstream coarsening is that the height of Belutia bar is above seasonal flood level while the lower bar tail accreted by seasonal floods with coarse grade fresh sediments. The sediment size parameters of the largest Chatpier bar (>25-year old) of the Jamuna Bridge Reach do not correspond with the other surveyed bars of the two reaches. The mean sediment

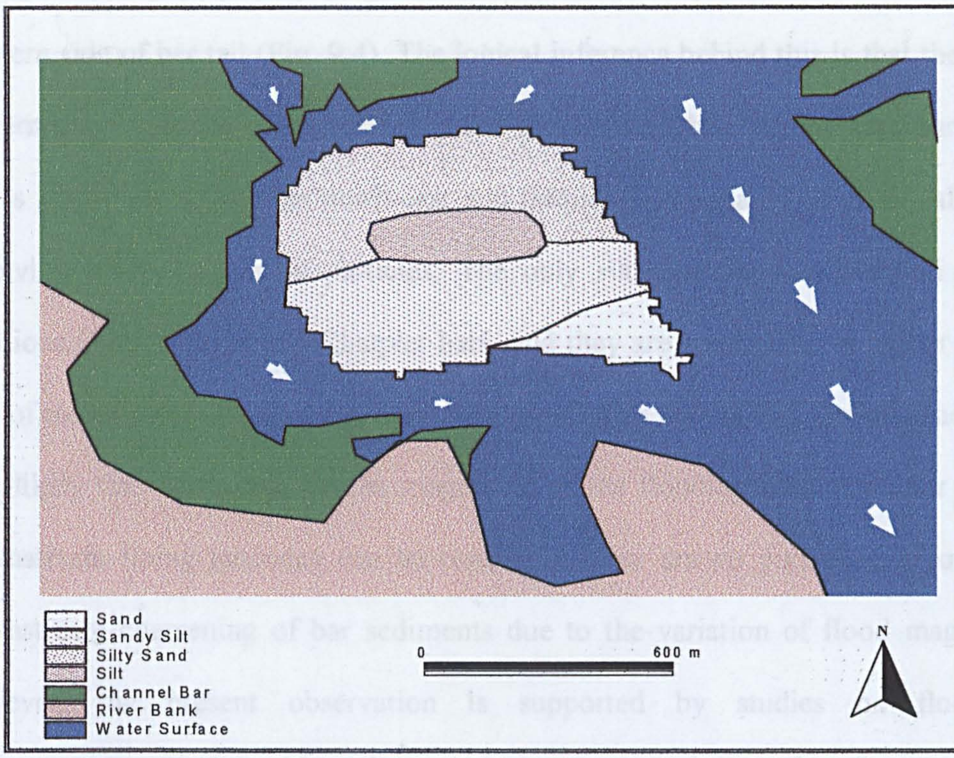


Figure 9.3: Surface sediment size distributions of Belutia bar.

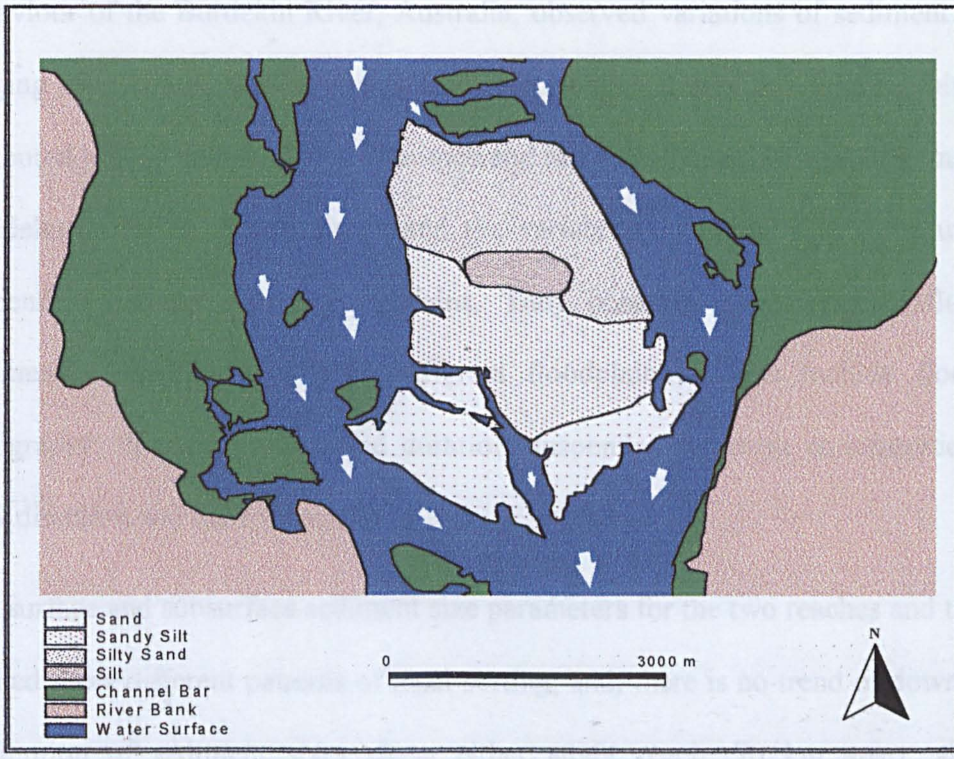


Figure 9.4: Surface sediment size distributions of Chatpier bar.

size distribution shows neither downstream nor lateral fining while it exhibits diagonal sediment size coarsening from the north-eastern side of bar head to south-western side of bar tail (Fig. 9.4). The logical inference behind this is that the north-eastern side of the bar is the highest part of the bar, and the south-western part of the bar is much lower than the north-east and frequently inundated by seasonal floods receiving coarser sediment particles. The only silt size fraction is found at two locations in the Belutia and Chatpier bars, and they are located in the higher middle part of the bars and remain unaffected by major floods for a longer period. Therefore, it is likely that depending on the magnitude of the flooding relative to bar height, downstream fining tendency can be reversed. There are no published accounts of downstream coarsening of bar sediments due to the variation of flood magnitude, however, the present observation is supported by studies on floodplain sedimentation. For example, Alexander *et al.* (1999) in their study on the flood behaviour of the Burdekin River, Australia, observed variations of sediment calibre ranging from coarse sand to gravel along floodplains and point bar tops which they attributed to the variable flood magnitude and rapid discharge change. Asselman and Middelkoop (1995, 1998) also noted the variability of grain size distribution of suspended sediment along floodplains. They observed that factors influencing sediment deposition within the different floodplain sections include floodplain topography, flood magnitude and duration, suspended sediment concentration, and flow direction and flow velocity.

The surface and subsurface sediment size parameters for the two reaches and the bars studied show different patterns of local sorting, and, there is no trend of downstream diminution of sediment sizes along either study reach, 70 km apart, although sediment size coarsening occurs in some cases (see Chapter 7). This difference in size distributions with distance downstream is likely to be related to bar elevation and flow direction, and may be produced as a consequence of local sediment supply from bank erosion as there is no evidence of tributary inputs of sediment with different calibre. Identifying which of many factors have a persistent downstream influence on sediment size distribution is not straightforward. However, some authors maintain that the effect of local sediment supply and tributary inputs is important in the variation of downstream fining. Along the Brahmaputra River, Assam, India, Goswami (1985) found no progressive downstream decrease in grain size due to the presence of large number of tributaries which contribute sediment of varying quantity and calibre. Rice and Church (1998) noted a high degree of variability and general downstream coarsening by lateral non-alluvial sediment inputs along two gravel-bed rivers in Canada. The effect of local sediment input is also supported by the observations of Knighton (1980) and Dawson (1988). Petts and Foster (1985) express the similar opinion that inputs of relatively coarse sediment from tributaries and bank erosion can superimpose local variations on the size changes caused by progressive sorting. Therefore, it seems likely that downstream fining of sediment sizes due to abrasion and selective sorting, although associated mainly with the gravel-bed braided rivers (e.g. Smith, 1974; Hein & Walker, 1977; Bluck, 1982; Ashworth *et al.*, 1992; Paola *et al.*, 1992; Hoey & Bluck, 1999), is not important in the Brahmaputra-Jamuna River.

9.4. Bar Elevation and Inundation Frequency

The channel planform of the Brahmaputra-Jamuna undergoes large changes with flood stages. During the low flow season the river flows in a highly braided channel characterised by the presence of all forms of bars (e.g. lower sand bars, attached bars, island bars). As the flow begins to rise at the time of the monsoon season, most of the lower sand bars are submerged and the river then exhibits less braiding. This observation implies that there is a relationship between planform patterns and river stage, hence, relationships will exist between bar elevation and river stage. Similar observations have also been reported by many authors who note that most of the bars of braided rivers may disappear at high flow stages and reform as discharge falls (e.g. Smith, 1974; Cant & Walker, 1978; Bluck, 1979; Church & Jones, 1982; Carson, 1984; Bridge *et al.*, 1986). Therefore, examination of bar elevation and flow stage trends may provide a basis for estimating the likely extent of channel bar inundation under different flood magnitudes.

Landsat images, hydraulic records and field data have been combined to monitor channel bar inundation frequency of the study reaches of the Brahmaputra-Jamuna River. Using all this information, three categories of bar height are recognised in respect of different magnitudes of flood discharge (Table 9.1). Bar areas with 1.75 m

Table 9.1: Relation between bar elevation and inundation frequency.

Flood Types	Discharge Range (m^3s^{-1})	Bar Elevation (m)	Inundation Frequency
Annual flood	60,000 – 65,000	1.75 – 4.50	Every year
Major flood	65,000 – 75,000	4.50 – 6.00	5 – 8 years
Catastrophic flood	>75,000	>6.00	>20 years

to 4.50 m elevation are considered as the lowest level compared to the other levels (cf. Thorne *et al.*, 1993; EGIS, 1997) (Figs. 9.5 and 9.6). These are young features (2 to 4 years old) that are usually inundated at the time of the annual floods (annual flood discharge is defined by the Bangladesh Water Development Board within the range of 60,000 m^3s^{-1} to 65,000 m^3s^{-1}). This level comprises the most active parts of the bar and changes in topography occur by vertical aggradation at stages associated with the annual flood (cf. Ashworth *et al.*, 2000). The second level varies in height from 4.50 m to 6.00 m (Figs. 9.7 and 9.8), and is usually inundated by the floods with 5 to 8-year return period, corresponding to major floods with discharges

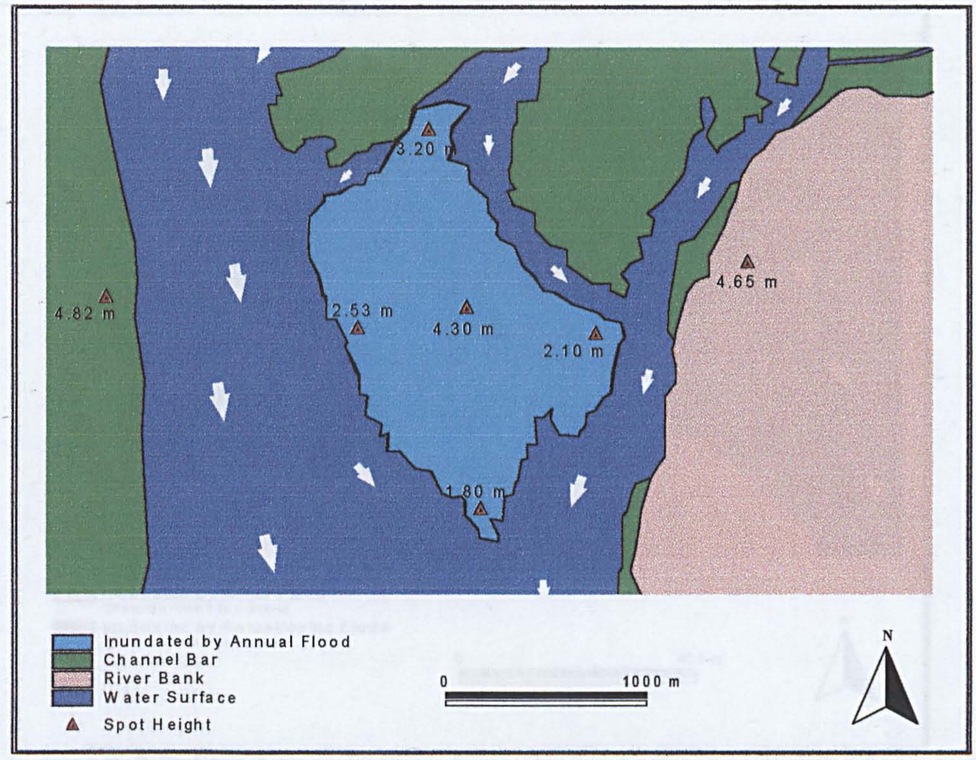


Figure 9.5: Flood frequency and inundation patterns in Harindhara bar.

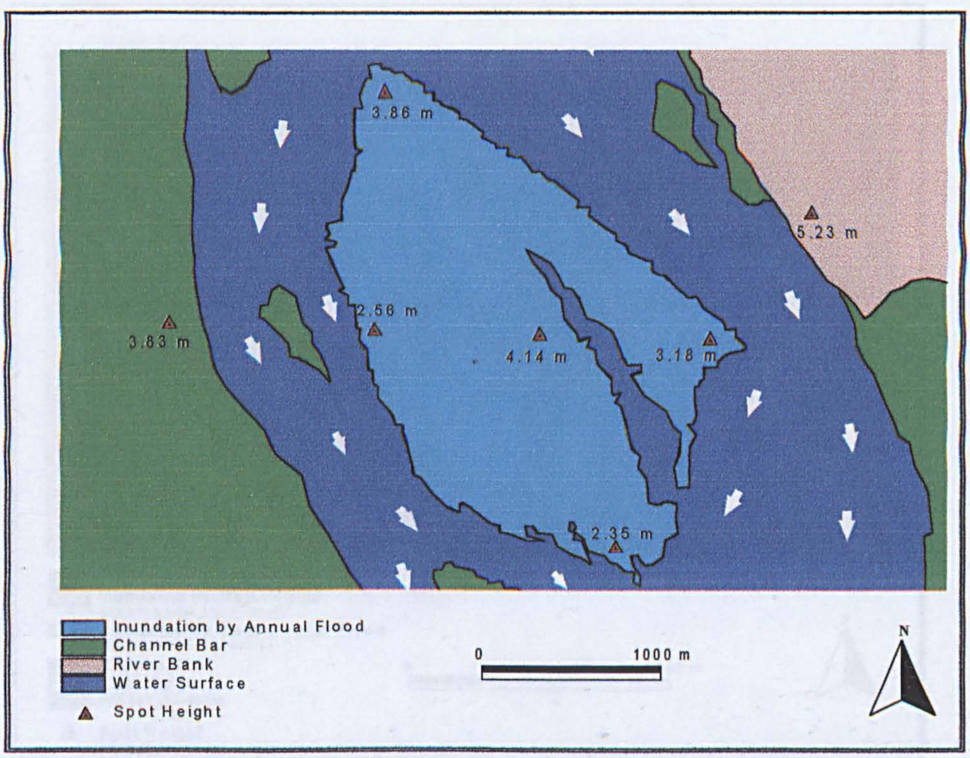


Figure 9.6: Flood frequency and inundation patterns in Kulkandi bar.

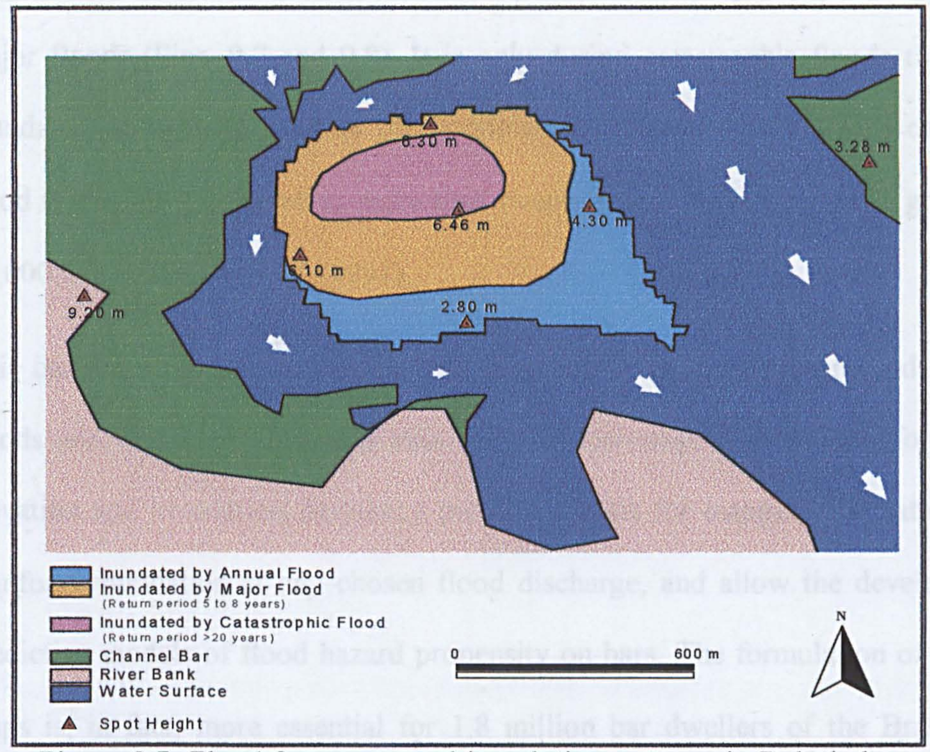


Figure 9.7: Flood frequency and inundation patterns in Belutia bar.

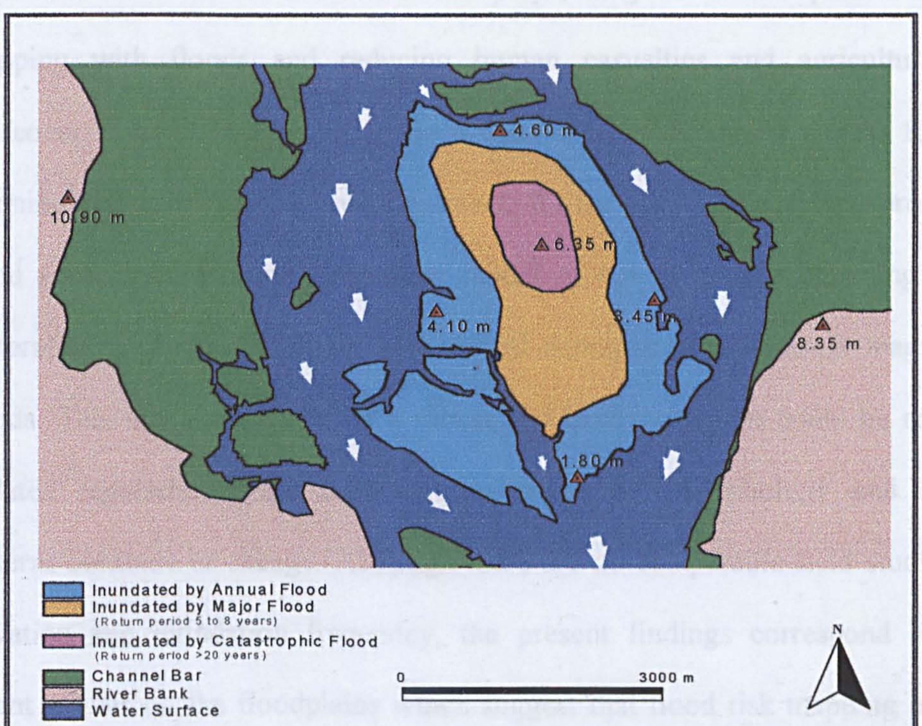


Figure 9.8: Flood frequency and inudation patterns in Chatpier bar.

between 65,000 m^3s^{-1} to 75,000 m^3s^{-1} (Bhuiya *et al.*, 1991). Level three is the highest part of the bars (more than 6.00 m) and normally remains unaffected during major floods (Figs. 9.7 and 9.8). It is only during catastrophic floods this level is inundated, along with most of the floodplains. The return period of a catastrophic flood is usually considered as more than twenty years and flood flow is greater than 75,000 m^3s^{-1} (Bhuiya *et al.*, 1991).

This bar elevation profile reveals that lower bars are usually inundated by annual floods and higher bars are less vulnerable to low-stage floods. Therefore, the bar elevation and inundation frequency provide a basis for mapping the pattern of bar planform inundation at any chosen flood discharge, and allow the development of predictive models of flood hazard propensity on bars. The formulation of flood risk maps is, in fact, more essential for 1.8 million bar dwellers of the Brahmaputra-Jamuna River as the use of flood risk maps probably the most important measure in cropping with floods and reducing human casualties and agricultural losses. Moreover, a flood risk map may be a basic tool in flood-prone areas for landuse planning and priority setting of investments for the establishment or improvement of flood security. Therefore the present model of bar inundation mapping can be a preferable method in reducing the potential damages from different magnitudes of floods. This model also may be a robust and handy tool that could be refined and updated regularly as the Brahmaputra-Jamuna bar morphology and settlement patterns continue to change. Although there are no comparable field studies on bar elevation and inundation frequency, the present findings correspond with some recent studies on the floodplains which suggest that flood risk mapping is essential for floodplain management to reduce the potential for future damages, and socio-economic benefits from use of floodplains (e.g. Consuegra *et al*, 1995; Toth, 1995; Yevjevich, 1995; Philippi, 1996; Riebau, 1999).

9.5. Bar Permanency, Vegetation Pattern and Human Settlement

Most of the bars of the Brahmaputra-Jamuna River are transient in nature, and constantly change their size, shape and position during summer high flows (Coleman, 1969; Bristow, 1987 ISPAN, 1995b; JMBA, 1996). It is common for bars to migrate 500 m to 1500 m from one flood season to another flood season (Coleman, 1969; Ashworth *et al.*, 2000), or for them to be completely removed during a large flood (Coleman, 1969). As outlined above, older bars are higher than the younger ones, and they are also more permanent (FAP 19, 1995; EGIS, 1997; Hassan *et al.*, 1999), leading to greater vegetation cover and higher population density (FAP 19, 1995).

It is observed from field survey that newly formed bars are covered with sand dunes and catkin grass, and due to immature soils and frequent flood propensity they are less cultivated (Figs. 9.9 and 9.10). Peanuts appear to be the most important crop in low lying sand bars. Human settlements are very temporary in these locations (daily or weekly dwelling) and people usually live in the nearest mainland. A more extensive vegetation cover is observed in much older bars (5 to 10-year old), with different types of seasonal crops (e.g. wheat, pea-legume, pulse) and semi-permanent settlement patterns (Fig. 9.11). People generally migrate from the nearest mainland to these bars and stay for the whole dry period. At the time of the flood season they move back to their permanent residence. The highest and most permanent bars (more than 10 years old) have vegetation covers and population characteristics very similar to the nearest floodplains. These bars having a dense cover of perennial vegetation with better alluvial soils, dominated by intensive agricultural practices (e.g. paddy, oil seed, coriander) (Fig. 9.12). The settlement pattern of these bars is almost permanent and they are located mainly in the central higher part of the bars.

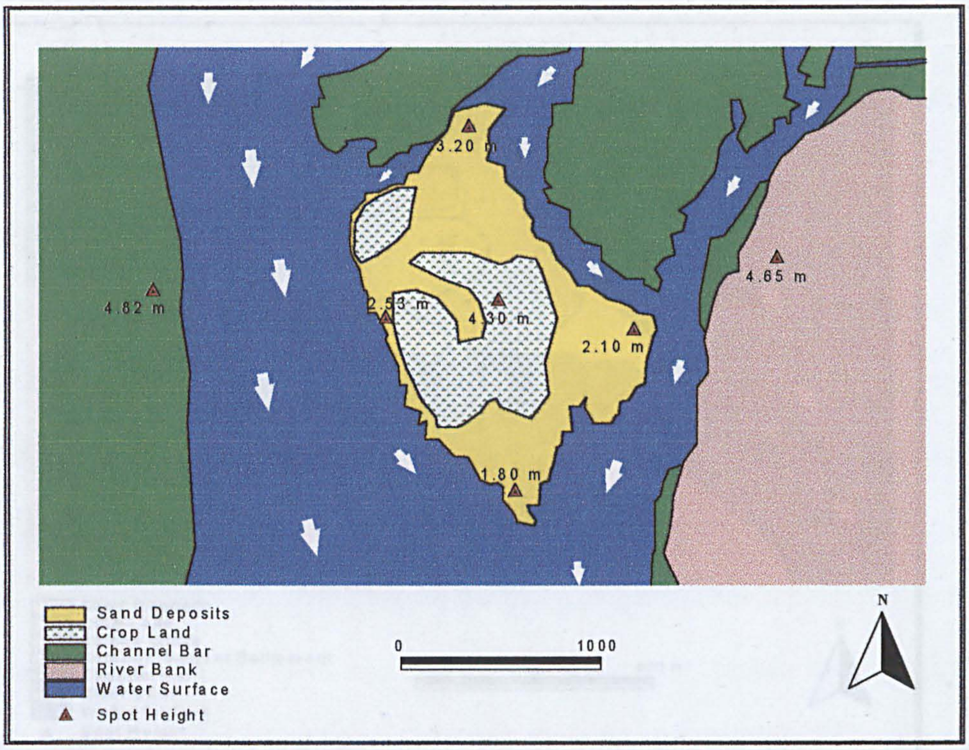


Figure 9.9: Bar elevation and landuse patterns in Harindhara bar.

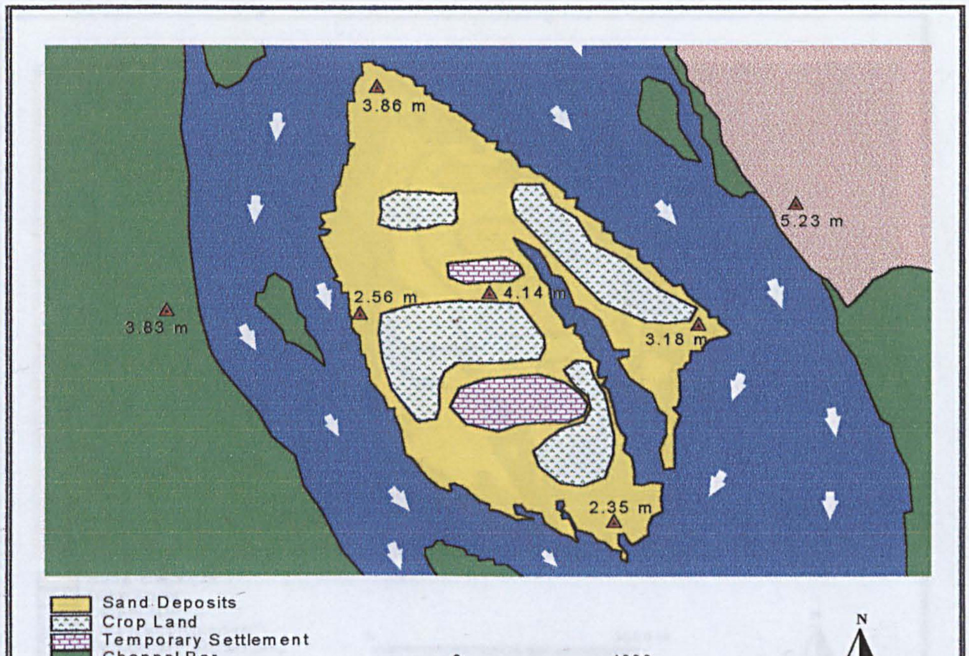


Figure 9.10: Bar elevation and landuse patterns in Kulkandi bar.

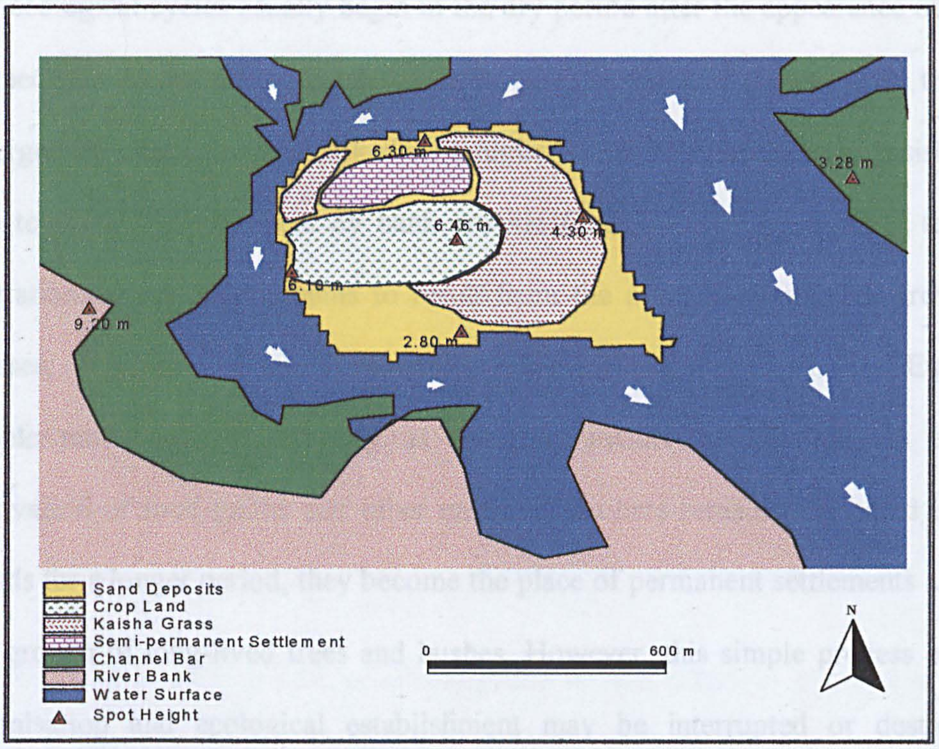


Figure 9.11: Bar elevation and landuse patterns in Belutia bar.

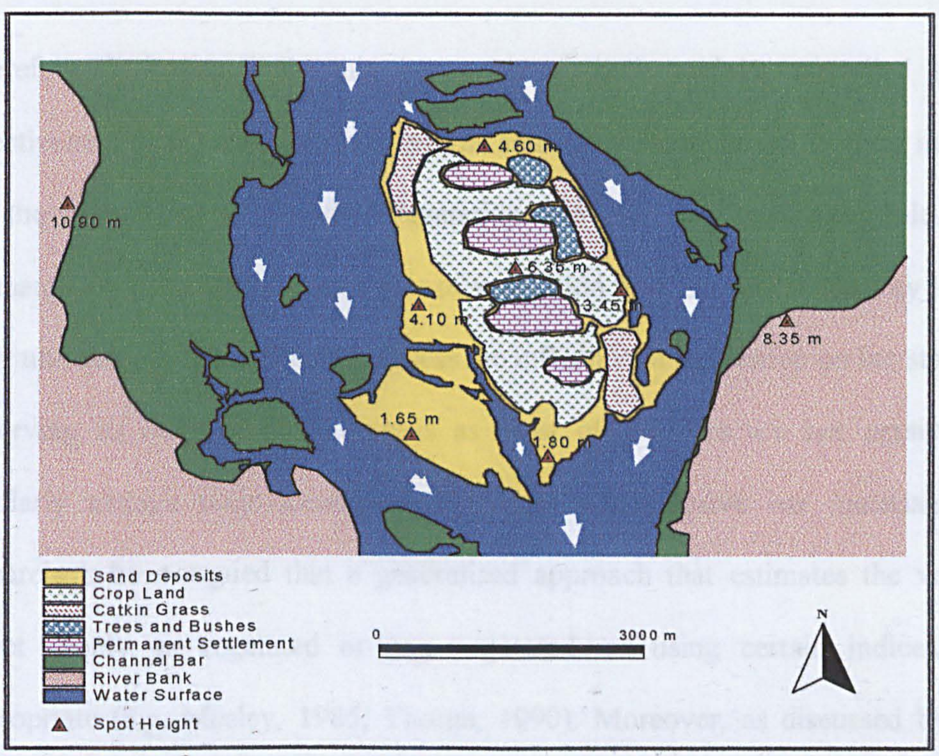


Figure 9.12: Bar elevation and landuse patterns in Chatpier bar.

Hence, it is evident that the bars are important in various ways especially as substrate for agricultural production and surface for construction of homesteads. The social and ecological cycles usually begin in the dry period after the appearance of a newly formed bar or reappearance of the older bars. Population migration in the newly emerged bars appears to be linked with higher floodplain population densities, often due to forced displacement by bank erosion (FAP 19, 1995). Initially, temporary migration occurs and it seems to result from the availability of sand-grow catkin grasses, which are an important resource for cattle grazing and fuel. Eventually, people move semi-permanently as the bars mature and favour the extensive cultivation of food-grains and other crops. If the bars remain unaffected by major floods for a longer period, they become the place of permanent settlements and allow the growth of long-lived trees and bushes. However, this simple process of human colonisation and ecological establishment may be interrupted or destroyed by catastrophic floods.

Therefore, it seems likely that bar permanency is mainly controlled by flood effectiveness, and bar vegetation patterns and human settlements are also influenced by the magnitude of floods. Vegetation can play an important role on bar permanency, although the actual role of vegetation in affecting bar stability is not yet fully understood. It is difficult to assess the influence of vegetation on bar stability by observing its denseness or thinness as most of the bars are not persistent and regularly change their location due to the non-cohesive bar materials. Some researchers have argued that a generalised approach that estimates the vegetation effect simply as vegetated or non vegetated, or using certain indices, is not appropriate (e.g. Mosley, 1985; Thorne, 1990). Moreover, as discussed by Hickin (1984), conventional bar morphology studies generally focus on flow patterns and sedimentation process and do not include vegetation as an important geomorphic factor. Hence, the role and importance of vegetation on bar stability remains under studied. Several researchers have suggested that vegetation generally reduces bank sediment erodibility (e.g. Smith, 1976; Hickin, 1984; Gregory & Gurnell, 1988; Thorne, 1990; Friedman *et al.*, 1996; Huang & Nanson, 1997) and increases mass stability (e.g. Gray & Leiser, 1982), however, the actual role of vegetation in bank erosion processes remains to be fully explored (Abernethy & Rutherfurd, 1998). Recently several authors have emphasised that a great deal of further research is necessary before vegetation effects can be properly understood and incorporated into the description of bank material characteristics under conditions representative of the range of environments encountered along natural streams (e.g. Darby & Thorne, 1996; Thorne *et al.*, 1997).

Despite this distinctive lack of observations on the effect of vegetation on bank erosion and limited bar vegetation study, several recent studies suggest that vegetation on in-channel ridges and gravel bars reduces flow velocities, and accelerates deposition and vertical accretion which leads to reduced flooding of the ridges and bars and enhanced vegetation growth (e.g. McKenney *et al.*, 1995; Wende & Nanson, 1998). However, the transferability of these studies to the Brahmaputra-Jamuna system is not clear because the in-channel vegetation involved is predominately savanna woodland, willow and tall trees which are likely to have different effects on flow patterns, channel sedimentation and ridge and bar stabilisation, in contrast to the primary vegetation cover of the bars of the Brahmaputra-Jamuna River which are seasonal crops with short-lived bushes. Indeed, in the Brahmaputra-Jamuna system, annual flood-prone areas usually remain out of cultivation at the time of the monsoon season, and major flood-prone areas are cultivated by small perennial vegetation, and this may have little impact on the obstructions of flood flows. During the catastrophic floods most of the floodplains are submerged by flood water, with high rates of erosion and accretion so that even the most long-lived of the riparian vegetation may be uprooted and damaged. Moreover, growth of different tree species within floodplains or on bars requires exposed mineral soils, viable seeds, and a long period without flooding when the trees can become established (Sigafoos, 1964, 1976); most of these criteria for vegetation colonisation do not prevail on many of the bars of the Brahmaputra-Jamuna River. Therefore, while different studies demonstrating links between erosion processes and vegetation at channel banks, there is no conclusive evidence that vegetation has an important influence on erosion resistance and bar permanency in the Brahmaputra-Jamuna River.

9.6. Morphological Changes and Sediment Balance

Estimation of sediment balance in river systems and interaction between sediment transport and river morphology has been the topic of much recent research (e.g. Ferguson & Ashworth, 1992, Goff & Ashmore, 1994; Martin & Church, 1995; Milne & Sear, 1997). The amount of sediment yield and storage or removal is commonly estimated using sediment budget or sediment balance analysis (Swanson *et al.*, 1982; Goff & Ashmore, 1994), but there is a problem in reliably determining volumes of erosion and deposition (Milne & Sear, 1997). Very recently, GPS technology has been used for rapid appraisal of morphological changes and it has been shown to be a robust and convenient method of data acquisition which enables the rapid production of digital elevation models (DEMs) (e.g. Higgitt & Warburton, 1999; Brasington *et al.*, 2000; Smith *et al.*, 2000). Nevertheless, the major problem with this approach is that it is time consuming and DEM construction requires high resolution topographic data. These approaches are restricted therefore to small-scale studies and may not be feasible for large rivers. In this context, an alternative approach has been developed and applied in this thesis to evaluate morphological change and sediment balance at both study reaches of the Brahmaputra-Jamuna River, based on satellite image and cross-section survey data.

The estimated volumetric results show that during the 1992-1997 period, the Bahadurabad Ghat Reach exhibited equilibrium between the total volume of erosion and accumulation while, the Jamuna Bridge Reach showed a different pattern with net storage of large amounts of sediment. However, both reaches show a considerable variation in sediment balance over the short term in response to the magnitude and duration of floods. The estimated short-term sediment balance at both study reaches is presented in Figure 9.13 in comparison with peak flood flows. Overall, the data show that storage of sediment in a reach decreases with increasing flood discharges. This trend is probably due to the higher stream power and transport rate at higher river discharge (cf. Goff & Ashmore, 1994) which enables erosion of substantial amounts of sediment from both banks and bars. This general correlation between morphological change and flood discharge is also observed in some gravel-bed braided systems. Goff and Ashmore (1994) note that rapid morphological change and high sediment transport rates coincide with periods of high discharge in their study on the Sunwapta River, Canada, with complete destruction and reconstruction

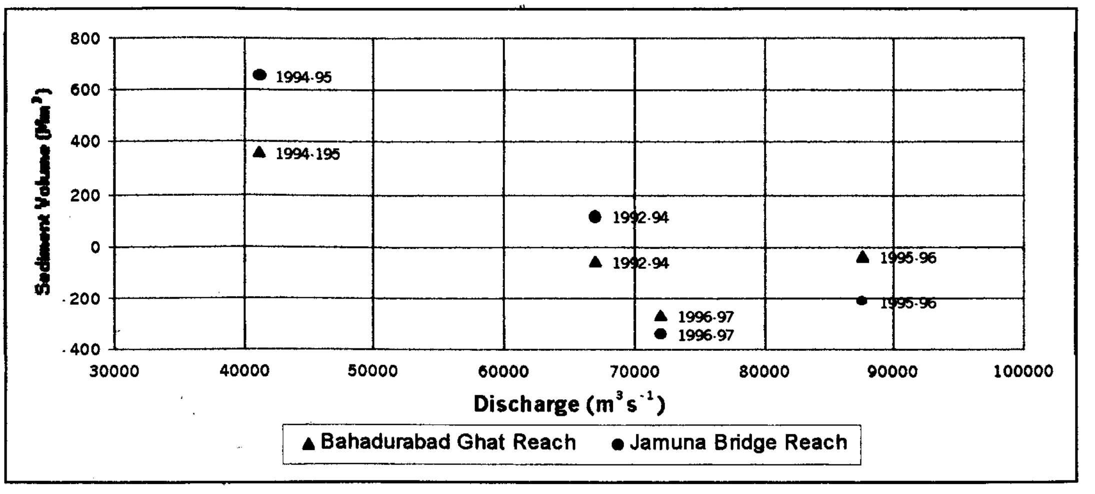


Figure 9.13: Sediment balance in relation to peak flood discharge at both study reaches.

of bars at peak discharge. Martin and Church (1995) make similar inferences by assessment of erosion and deposition in the Vedder River, Canada. They observed that moderate and long-sustained floods transport proportionately more sediment than do high magnitude, but short-lived floods.

However, there remain some notable differences between the two study reaches regarding rates of storage or removal of sediment at the same flood flows (Fig. 9.13). These differences are probably due to difference in braiding intensity and location of major river training works. At Bahadurabad Ghat Reach, the average braiding intensity is higher (6.90) than the Jamuna Bridge Reach (5.45) and there are no major river training works. The higher braiding intensity is associated with large-scale reworking of bars and banks and high rates of third-order channel switching, to produce enormous internal erosion (cf. Bristow, 1987). In contrast, the Jamuna Bridge Reach has been subject to massive river training works to maintain a stable width for the construction of one of the largest bridges in the world. Therefore, the large amount of sediment loss is probably a consequence of bridge construction activity, which impeded the natural flow pattern and ultimately both banks and bars suffered from huge erosion except at the bridge site.

The main exception to the pattern of decreasing storage with increasing discharge, is observed during the 1995-1996 period at both reaches. During this period the Brahmaputra-Jamuna River experienced the most severe floods since 1988, with discharge approaching 90,000 m^3s^{-1} at both reaches. In this period both reaches transferred less quantities of sediment than would be expected. The possible explanation for this is that the duration of this flood was very short, and thus less sediment was transported than on the moderate but more prolonged floods. This finding is also supported by Martin and Church (1995) who observed that large floods of short duration transport smaller volume of sediment than long-sustained flood flows. Therefore, it seems likely that morphological changes by sediment storage or removal in the study reaches of the Brahmaputra-Jamuna River are mainly related to magnitude and duration of floods while, local sediment balance may be influenced by the degree of braiding or river training works.

Apart from this study, the only other major study of sediment balance at different reaches of the Brahmaputra River was undertaken in Assam, India, by Goswami (1985). He compared two independent methods, one based on the sediment continuity approach and the other on measured cross-sections and he found more than 50% estimation difference between the two methods. He also notes that estimation of sediment balance from a sediment continuity approach, or by widely spaced cross-sections and little reliable channel width data involves uncertainty and estimation error is very high in a river like the Brahmaputra-Jamuna. Therefore, the combination of cross-sections and satellite images as used in this study provides information of quality comparable to that of measured cross-sections or the sediment continuity approach. As such, this is recommended as the preferred method for sediment balance estimation for a large-scale river that suffers from lack of reliable data sources.

9.7. Concluding Discussion

The Brahmaputra-Jamuna is one of the most heavily sediment-laden braided rivers in the world and has profound effects on the land, people and resources along its course. A quantitative analysis of bar morphology in relation to channel dynamics requires an understanding of the interaction between bankline shifting and channel width change, bar formation and dynamics, spatial and temporal variation of bar sediment properties, amount of sediment movements, bar vegetation and human settlements. This study tried to investigate most of these issues and their process-form relationships.

The present study shows that there is a relationship between bar formation, flow patterns and morphological change. However, this relationship is extremely complex with numerous feedbacks operating between morphology, flow patterns and sediment transport. The exact nature of this relationship in the Brahmaputra-Jamuna River is not certain because there is much greater variability of sediment yield and transport during different flows compared with gravel-bed braided systems. However, a number of common themes are apparent which are scale invariant. First, local sediment transport incompetence and flow deceleration will develop a bar nucleus in the central part of the channel downstream node of a flow convergence. Second, the growing bars locally decrease the channel cross-sectional area and this may lead to deflection of flow towards the bank, leading to erosion, channel widening and further braiding.

Nevertheless, the change in channel morphology as a mid-channel bar grows is highly variable in the Brahmaputra-Jamuna River. Bank erosion, sediment transportation and deposition and morphological changes during low-moderate flows are different from those occurring during high magnitude and low duration floods. Also, major river training works are responsible for bank erosion and channel migration. Therefore, while the process-form linkages between bank erosion, bar formation and channel change are scale invariant, the magnitude and frequency of floods and river training works appear to be the main controls of braiding and channel dynamics in the Brahmaputra-Jamuna River, and they are likely to be scale dependent due to their spatial and temporal variability.

The results of this study address the dynamic nature of the bars and channels over the decadal period, including bank erosion, channel shifting and widening and different patterns of submergence, erosion and accretion of braid bars. Morphological and sedimentary evidence reveals that bars are dynamic places wherein physical, social and ecological processes combine over a range of temporal and spatial scales. The configuration and extent of sediment size distribution of bars are related to flow patterns, flood magnitudes and relative elevations. Morphological changes by sediment storage or removal are also related to magnitude and duration of floods and degree of braiding and river training works. Older bars appear to be more permanent than the younger ones, and they are also the place of greater vegetation cover and higher population density, which resemble the local floodplains. Vegetation can exert a significant influence on channel morphology through altering channel flow resistance and bank strength, however its influence on bar morphology in the Brahmaputra-Jamuna River is not clear. Moreover, the interaction between channel morphology and vegetation varies as a function of changing channel scale (Abernethy & Rutherfurd, 1998). Therefore, the role of vegetation in influencing channel morphology seems to be scale dependent.

In summary, this study concludes that digital satellite image and field observation provided a potential means of quantitative analysis of the different morphological aspects of the Brahmaputra-Jamuna River. It has also emphasised that a combination of both methods and relevant computer analysis is useful as a means of mapping and quantifying spatial and temporal change of channel morphology over spatial scales from the reach to the basin, and over temporal scales from days to decades.

CHAPTER X: CONCLUSIONS

10.1. Conclusion

This study presents a detailed investigation of braiding and channel morphodynamics in the Brahmaputra-Jamuna River. The large scale of the system, multiplicity of channels and insufficient database provided great logistical difficulties for this study; and entailed development and application of methodologies using digital satellite images and repeated field survey data. The study has revealed a number of key findings on the process-form linkages of braiding and channel dynamics, and the principal conclusions drawn from this study are outlined below.

In Bangladesh the Brahmaputra-Jamuna flows in a highly braided channel characterised by the presence of numerous islands as well as attached bars. The persistent channel bank erosion appears to be a critical factor in braiding in the river. An increased amount of sediment load in excess of competency and flow deceleration downstream of a convergence zone is believed to initiate the process of development of new mid-channel bars. Eventually the accumulated sediment creates a degree of obstruction to the flow which is then diverted sideways leading to an increase in bank erosion and this results in channel widening. The speed of bank erosion, however, is evidently related to the high shear stress exerted on non-cohesive bank materials during severe floods.

Over a decadal timescale both the Bahadurabad Ghat and Jamuna Bridge reaches were more severely affected by bank erosion (15% and 14%, respectively) than bank accretion and bank erosion supplies large quantities of sediment to the channel. Very high rates of erosion occurred over periods of one or a few years due to unusual floods, but they were not sustained for many years at the same location and they did not occur at both reaches simultaneously. Both banks are retreating each year (448 ha yr^{-1} at Bahadurabad Ghat Reach and 487 ha yr^{-1} at Jamuna Bridge Reach) but retreat rates are not uniform between the reaches because the channel geometry, flow structure and bank material characteristics vary both in time and space. Occasional channel accretion was observed due to abandonement of secondary-channels caused by merging attached bars.

A uniformity of bankline shifting has been observed between the west and east bank of the two reaches. The west bankline of the Bahadurabad Ghat and Jamuna Bridge reaches shows westward movement at rates of 109 myr^{-1} and 90 myr^{-1}, respectively, while the east bankline of both reaches exhibits eastward movement (114 myr^{-1} at Bahadurabad Ghat Reach and 96 myr^{-1} at Jamuna Bridge Reach). However, short-term unsettled bankline shifting trends in both reaches are thought to be triggered either by catastrophic flood events or by major river training works. As a consequence of bankline shifting, average channel width at both reaches has increased significantly during the 1987-1997 period. The annual rate of channel widening is 223 myr^{-1} at Bahadurabad Ghat Reach and 186 myr^{-1} at Jamuna Bridge Reach.

The braiding intensity of the Brahmaputra-Jamuna River varies considerably with time and space (5.16 to 8.35) and average braiding intensity is higher in the widest reach (6.90 at Bahadurabad Ghat Reach) than the narrowest reach (5.45 at Jamuna Bridge Reach). Bars of the Brahmaputra-Jamuna River are transient in nature, most are submerged during high flows, and change their geometry and location frequently. Satellite image interpretation and field observation suggest that floods determine the initial location and formation of braid bars. Braiding appears to be initiated by the formation of a mid-channel bar in an undivided channel immediately downstream of a flow convergence. The actual hydraulic conditions that cause mid-channel bar formation are not well known, however, the area of deposition in the central part of the channel is thought to be caused by deceleration of flow and local reduction in competence.

The bars of the Brahmaputra-Jamuna River are usually diamond or triangular-shaped in plan view (average shape index of 2.25) and their long axes are oriented parallel to the channel. Most bars modify their shape, size and location from time to time due to aggradation, frequent channel shifting, and change in local flow pattern. However, frequently occurring quasi-stable bar forms were used as a basis for planform classification and these include longitudinal, lateral, diagonal and unit bars. According to their morphological behaviour, these four types of bars are categorised into two groups, attached and island bars. Bars that are attached to the main channel bank are classified as attached bars and all detached bars are considered as island bars. Island bars are prominent features (84% at Bahadurabad Ghat Reach and 68% at Jamuna Bridge Reach) compared to attached bars (16% at Bahadurabad Ghat Reach and 32% at Jamuna Bridge Reach) and the decadal tendency of total bar areas is increasing at both reaches.

Three main topographic levels were recognised on bars in respect of elevation, denseness of vegetation, and the type and intensity of fluvial activity. The first topographic level includes newly formed (more than 1 year) bars to 4-year old bars and this is the lowest and youngest part compared to the other levels. The topographic surface of this level is nearly homogeneous with sand dunes and ripples and almost free from vegetation cover and its relative height in respect to water level varies from 1.75 m to 4.50 m. The second level is higher (4.50 m to 6.00 m), ranges in age from 5 to 10 years, is usually covered by current ripple lamination with loose sediment surface, probably deposited by waning flow as the water level fell. This level is subject to reshaping during higher river stage in major floods, and changes in bar topography caused by variation in discharge are less noticeable than on level one. A good vegetation cover is observed in this level but this is mainly confined to seasonal crops and some colonisation with natural shrubs and bushes. Level three is the highest (elevation range from 6.00 m to local floodplain level) and oldest (more than 10 years) part of the bars and in respect of both elevation and landuse it is very similar to the local floodplain. This level is the most stable part of the bars and is subject to some permanent scattered settlements.

Most of the bars of the Brahmaputra-Jamuna River are submerged during summer high flow, and erosion tends to occur on the upstream end of bars and deposition on downstream sections. In some cases bars are completely removed from their initial location and deposited in a new location. During falling stage patterns of erosion and deposition are reversed, with upstream end and lateral margin deposition and downstream erosion. Chute cutting and abandoning of channels can happen at any flow stage and this tends to accelerate bar movement. Considerable mutual adjustments are observed in bar erosion and deposition between the two forms of island and attached bars. Over the decadal timescale both the study reaches were subject to net bar deposition (4903 ha at Bahadurabad Ghat Reach and 5527 ha at Jamuna Bridge Reach), and the Brahmaputra-Jamuna River is in a condition of active aggradation. The aggradation process is not only accelerated or decelerated by major flood peaks but is also regulated by the upstream erosion or accretion and massive river training works. Island bars commonly migrate laterally and longitudinally, and the intensity and prolongation of bar migration depends on the periodicity and duration of monsoonal floods.

Sediment particle size characteristics at both reaches vary from fine silt to coarse sand with diameters from 0.50 μm to >500 μm, and very fine sand to fine sand is the most common range. Particle size distributions are mainly unimodal, and surface and subsurface samples of each bar and both banks as a whole show similar patterns. Sediment sorting is mainly moderate to well sorted and there is no significant variation between the bars and banks at both reaches. The differential curves are nearly normal with some positive skewness and they are leptokurtic in nature. Insignificant variation of sediment size characteristics between the bars and banks indicates the process-form linkage between bank erosion and bar formation. There is no evidence for channel-scale downstream fining of sediment grain size while the reach-scale results exhibit a somewhat opposite trend revealing downstream coarsening. Bar-scale sediment size distributions mostly fine upwards with slight downstream size decreasing tendency.

Mineralogical composition of surface sediments at both banks and bars of the Brahmaputra-Jamuna River shows admixtures of several kinds of minerals. The most abundant mineral content present in sediment samples is quartz and it constitutes more than 40% of the total minerals, while feldspar and mica are less dominant (17% and 8% biotite and muscovite, respectively) and rock fragments contribute a good percentage (23%). There is no significant variation of mineral composition between the widest upper reach and narrowest lower reach, and neither between the banks and bars within a single reach. The similarity of sedimentary characteristics of both bars and banks indicated channel bank materials as the potential source of bar sediments.

In order to evaluate sediment aggradation and degradation rates at both reaches, a method was developed and applied for determining sediment balance based on satellite image and cross-section values. Areal and volumetric estimation of sediment balance was performed and evaluated using this method, and there were found to be inconsistencies between areal and volumetric measurements of sediment balance, with the latter regarded as more accurate and reliable. The estimated volumetric results showed that over the 1992-1997 period Bahadurabad Ghat Reach was almost balanced between its total volume of erosion (271 Mm^3) and accumulation (273 Mm^3). Jamuna Bridge Reach, however, exhibited a different pattern with the net storage of a large amount of sediments (224 Mm^3), which is thought to be most likely linked with the building of bank protection embankments and construction of a large bridge. The method employed is shown to underestimate sediment balance from 8.65% to 30.65% compared to field assessments. However, it is concluded that satellite image and cross-section data may be used as a complementary procedure to estimate reasonable sediment balance for a large-scale river that does not have reliable data or systematic flow and sediment measurements.

10.2. Recommendations

Developments in geographical information system and remote sensing technology have enabled progress in geomorphological study and in spatial database management, and the combination of these two parallel developments have allowed study of spatial patterns of processes in braided rivers. However, observation and quantification of the process-form systems in the Brahmaputra-Jamuna River reveal an extremely complex set of phenomena which are not easy to describe, analyse and interpret. The detailed investigation of decadal, reach-scale braiding and channel morphodynamics of the Brahmaputra-Jamuna River presented in this thesis highlights several areas that need to be pursued and where more quantitative and collective works are required. Moreover, some approaches adopted in this study require further testing and refinement. Therefore, the following propositions are recommended for future studies:

(1) Channel morphology, water flow and sediment transport in the Brahmaputra-Jamuna River interact and vary spatially and temporally, ultimately resulting in erosion and deposition, formation and migration of bars and retreat of channel banks. An understanding of this interaction is important in geomorphological and engineering problems such as bank erosion and flood risk, sedimentation in navigated channels, construction of bridges, and protection of riverside infrastructures and agricultural lands. Although this study undertook reach-scale investigation concerning these diverse applications, a comprehensive study of flow patterns, sediment transport and morphology of such a dynamic and enormous system is far beyond the capabilities of individual studies. Such an undertaking would require a substantial database and a wide range of expertise with sophisticated analytical techniques. It is therefore recommended that a methodology is developed, which will enable bar-forming processes and morphological dynamics of the Brahmaputra-Jamuna River to be studied at different flow stages over a long period through an integrated and multidisciplinary collaboration. In particular, some approaches could be used as baseline for the development of predictive models of flood propensity in reducing the potential damages from different magnitude of floods.

(2) Results from the reach-scale sediment size distribution work exhibited inconsistency concerning downstream fining patterns and there was confusion over the downstream fining of braided rivers. It appears that sediment size distribution patterns depend on local sediment supply from bank erosion and vary with different flow stages and bar elevations. This reach-scale study showing differences in sediment size distribution with local sediment sources depends on assumptions and is uncertain because at different places along the river, sediment

of a given size may move in different modes and have different consequences for river morphology. Therefore, future work will need to extend to channel-scale grain-size distribution analysis to confirm or refute the results of the present study.

(3) This study investigated the possibility and consistency of estimation of reach-scale volumetric sediment balance using satellite image and cross-section information. Estimated results represent information of quality compared to measured cross-sections or the sediment continuity approach. When applied over a longer time period, the method can offer advantages in estimation of sediment balances that may not be assessed employing direct field measurements. However, further research effort is needed before making it the preferred method for long-term sediment budget estimation along the contiguous reaches of the Brahmaputra-Jamuna River. Moreover, a better understanding must be developed of how different flood flows determine sediment movement rates because it is evident that patterns of sediment storage and removal vary with magnitude and duration of floods.

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APPENDICES

APPENDIX I: ARCVIEW LINE THEME AND BANKLINE DELIMITATION PROCEDURES

The georeferenced digital satellite images were used to delimit the banklines of the two study reaches of the Brahmaputra-Jamuna River. The bankline that separates the floodplain from the active braid belt was used to delimit the margins of the primary channel to assess bankline movement between images and to define the width of the river.

To delimit the banklines on digital satellite image using ArcView GIS (version 3.1) line theme algorithm, the following steps were considered:

1. First a project window of a classified image (i.e. bank, attached bar, island bar, water) was activated and visually interpreted by different colour combinations.
2. To delimit banklines, ArcView *line tool* was then selected from *drawing tool palette*.
3. Using ArcView line tool banklines were delimited clicking each vertex along the channel banks.
4. Provisional banklines were then interpreted, examined and modified as appropriate with the known GPS values and field experience.
5. Finally, these iterative processes yielded the most consistent banklines and these procedures were applied to the entire image series.

APPENDIX II: MORPHOLOGICAL SURVEY DATA

A2.1. BRAID BAR: HARINDHARA

Reach: Bahadurabad Ghat

Facts & Findings

1. Shape of the Bar : Diamond
2. Relative elevations of the Bar :

North: 3.20 m	South: 1.80 m
East: 2.10 m	West: 2.53 m
Centre: 4.30 m	

3. Age of the Bar : 2 years
4. Landforms :
   a. Homogeneous with gentle slopes from north-west to south-west
   b. Fluvial sand deposits covered almost all area of the bar
5. Erosion : Little erosion in the eastern part
6. Deposition : Western part
7. Wet sand : North and north-eastern part
8. Dry sand : Southern part
9. Bare sand deposits : Almost all of the bar covered by uncultivable sand deposits
10. Crop types with canopy :

Crop types	Canopy(%)
a. Peanuts	70
b. Pea-legume	65
c. Pulse	55

APPENDIX II (cont…)

11. Vegetation types with canopy :

Vegetation types	Canopy(%)
a. Catkin grass	50

12. Relative elevations of the left and right Banks :

Left Bank (East): 4.65 m

Right Bank (West): 4.82 m

13. Nearest gauging station reading : 14.63 m

APPENDIX II (cont…)

A2.2. BRAID BAR: KULKANDI

Reach: Bahadurabad Ghat

Facts & Findings

1. Shape of the Bar : Diamond
2. Relative elevations of the Bar :

North: 3.86 m	South: 2.35 m
East: 3.18 m	West: 2.56 m
Centre: 4.14 m	

3. Age of the Bar : 4 years
4. Landforms :
   a. Gently undulating middle part
   b. Fluvial deposits covered the whole bar except south-central part
5. Erosion : North and north-western part
6. Deposition : South and south-western part
7. Wet sand : South and south-western part
8. Dry sand : Northern part
9. Bare sand deposits : North, west and southern part
10. Crop types with canopy :

Crop types	Canopy(%)
a. Peanuts	70
b. *Kaon* (Oil seed)	65
c. Pulse	55

APPENDIX II (cont…)

11. Vegetation types with canopy :

Vegetation types	Canopy(%)
a. Catkin grass	50

12. Relative elevations of the left and right Banks :

Left Bank (East): 5.23 m

Right Bank (West): 3.83 m

13. Nearest gauging station reading : 14.63 m

APPENDIX II (cont…)

A2.3. BRAID BAR: BELUTIA

Reach: Jamuna Bridge

Facts & Findings

1. Shape of the Bar : Square

2. Relative elevations of the Bar :

North: 6.30 m	South: 2.80 m
East: 4.30 m	West: 6.10 m
Centre: 6.46 m	

3. Age of the Bar : 10 years

4. Landforms :

   a. Gently undulating surface with low-lying south-central part

5. Erosion : North and north-eastern part

6. Deposition : Little deposition in the south-western part

7. Wet sand : Central and south-western part

8. Dry sand : North-eastern part

9. Bare sand deposits : South-eastern part

10. Crop types with canopy :

Crop types	Canopy(%)
a. *Kaon* (Oil seed)	65
b. Wheat	50
c. Pea-legume	80

APPENDIX II (cont…)

A2.4. BRAID BAR: CHATPIER

Reach: Jamuna Bridge

Facts & Findings

1. Shape of the Bar : Oval

2. Relative elevations of the Bar :

North: 4.60 m	South: 1.80 m
East: 3.45 m	West: 4.10 m
Centre: 6.35 m	

3. Age of the Bar : 25 – 30 years

4. Landforms :

   a. Homogeneous with gentle slopes from north to south

   b. Aeolian deposition in the south-eastern part

   c. Fluvial deposition in the north, north-west, and east-central part

5. Erosion : North-western part

6. Deposition : South-eastern part

7. Wet sand : South and central part

8. Dry sand : North and south-eastern part

9. Bare sand deposits : South-east and south-central part

10. Crop types with canopy :

Crop types	Canopy(%)
a. Peanuts	70
b. Wheat	50

APPENDIX II (cont…)

c. Sesame	60
d. Coriander	75
e. *Kaon (Oil seed)*	65
f. Paddy	40

11. Vegetation types with canopy :

Vegetation types	Canopy(%)
a. *Kaisha* grass	85
b. Catkin	50
c. Trees and bushes	35

12. Relative elevations of the left and right Banks :

Left Bank (East): 8.35 m

Right Bank (West): 10.90 m

13. Nearest gauging station reading : 7.51 m

APPENDIX III: PRECISION ASSESSMENT OF MINERALOGICAL COMPOSITIONS

Table A3.1: Precision assessment of mineralogical compositions at Bahadurabad Ghat Reach.

Bar/ Bank	ID Code	Quartz (%)	S.E. (%)	Feldspar (%)	S.E. (%)	Mica (%)	S.E. (%)	Rock Fragments (%)	S.E. (%)	Heavy Minerals (%)	S.E. (%)
Harin-dhara Bar	HY1	42.0	5.70	8.0	3.13	18	4.44	24.0	4.93	8.0	3.13
	HY2	39.0	5.63	10.0	3.46	21	4.70	25.0	5.00	5.0	2.52
Kulkandi Bar	KX1	46.0	5.75	9.0	3.30	18	4.44	22.0	4.78	5.0	2.52
	KX2	43.0	5.72	8.0	3.13	21	4.70	21.0	4.70	7.0	2.95
	KY1	43.0	5.72	9.0	3.30	18	4.44	23.0	4.86	7.0	2.95
	KY2	36.0	5.54	18.0	4.44	19	4.53	21.0	4.70	6.0	2.74
Island Bar	IY	37.0	5.57	16.0	4.23	15	4.12	27.0	5.13	5.0	2.52
East Bank	BEBY1	45.0	5.74	10.0	3.46	14	4.01	25.0	5.00	6.0	2.74
	BEBY2	39.0	5.63	9.0	3.30	18	4.44	29.0	5.24	5.0	2.52
West Bank	BWBY1	38.0	5.60	15.0	4.12	14	4.01	27.0	5.13	6.0	2.74
	BWBY2	43.0	5.72	13.0	3.88	14	4.01	23.0	4.86	7.0	2.95

Table A3.2: Precision assessment of mineralogical compositions at Jamuna Bridge Reach.

Bar/ Bank	ID Code	Quartz (%)	S.E. (%)	Feldspar (%)	S.E. (%)	Mica (%)	S.E. (%)	Rock Fragments (%)	S.E. (%)	Heavy Minerals (%)	S.E. (%)
Belutia Bar	BY1	46.0	5.75	11.0	3.61	17	4.34	21.0	4.70	5.0	2.52
	BY2	41.0	5.68	8.0	3.13	23	4.86	20.0	4.62	8.0	3.13
Chatpier Bar	CX1	50.0	5.77	13.0	3.88	16	4.23	16.0	4.23	5.0	2.52
	CX2	45.0	5.74	14.0	4.01	14	4.01	23.0	4.86	4.0	2.26
	CY1	40.0	5.66	17.0	4.34	11	3.61	29.0	5.24	3.0	1.97
	CY2	44.0	5.73	9.0	3.30	19	4.53	23.0	4.86	5.0	2.52
Attached Bar	AY	41.0	5.68	14.0	4.01	21	4.70	19.0	4.53	5.0	2.52
East Bank	JEBY1	40.0	5.66	20.0	4.62	17	4.34	19.0	4.53	4.0	2.26
	JEBY2	51.0	5.77	9.0	3.30	17	4.34	18.0	4.44	5.0	2.52
West Bank	JWBY1	39.0	5.63	11.0	3.61	16	4.23	28.0	5.18	6.0	2.74
	JWBY2	36.0	5.54	16.0	4.23	12	3.75	31.0	5.34	5.0	2.52

APPENDIX IV: CROSS-SECTION ELEVATION DATA

Table A4.1: Year-wise cross-section data at Bahadurabad Ghat Reach.

Cross-section Location	Cross-section Elevation (m) from PWD*				
	1992	1994	1995	1996	1997
1	19.12	19.12	19.30	19.30	19.21
2	10.19	8.50	19.21	18.89	14.20
3	12.63	9.51	18.69	19.14	14.99
4	9.33	16.62	18.34	19.46	15.94
5	13.18	13.50	17.79	14.62	14.77
6	15.61	13.50	16.93	17.33	15.84
7	17.57	19.22	17.08	17.57	17.86
8	18.36	18.18	16.13	16.43	17.28
9	18.36	19.09	18.62	15.48	17.89
10	19.08	18.63	18.09	17.76	18.39
11	20.62	19.18	18.38	18.19	19.09
12	18.79	8.68	18.52	18.51	16.13
13	9.97	11.18	14.46	14.06	12.42
14	16.90	12.34	13.40	9.67	13.08
15	18.98	18.71	17.06	16.30	17.76
16	18.94	19.55	17.75	18.32	18.64
17	17.96	18.76	19.02	18.08	18.46
18	20.37	19.03	18.62	18.02	19.01
19	18.07	14.97	15.16	17.68	16.47
20	17.14	15.79	17.93	18.72	17.40
21	16.33	17.36	13.53	13.63	15.21
22	18.17	18.98	14.38	14.49	16.51
23	18.02	18.06	14.72	17.37	17.04
24	18.73	18.96	13.19	15.98	16.72
25	13.18	18.78	9.99	15.02	14.24
26	17.95	19.33	11.49	18.83	16.90
27	19.30	19.30	18.39	18.48	18.87
Average	**16.77**	**16.48**	**16.52**	**16.94**	**16.68**

*A horizontal datum applied by Public Works Department (PWD), Bangladesh.

Table A4.2: Year-wise cross-section data at Jamuna Bridge Reach.

Cross-section Location	Cross-section Elevation (m) from PWD*				
	1992	1994	1995	1996	1997
1	12.26	12.12	12.18	12.26	12.21
2	12.39	12.55	12.36	5.19	10.62
3	3.42	2.52	8.32	9.47	5.93
4	4.42	11.14	10.69	12.18	9.61
5	6.42	9.38	10.77	6.77	8.34
6	11.08	9.36	10.45	11.53	10.61
7	6.43	6.61	10.30	12.07	8.85
8	4.68	10.06	10.99	12.21	9.49
9	11.99	12.26	10.07	10.69	11.25
10	5.17	7.47	10.35	1.52	6.13
11	11.22	8.15	9.14	8.24	9.19
12	5.64	7.21	11.06	11.96	8.97
13	3.64	7.05	10.44	10.01	7.79
14	3.89	1.09	2.23	3.53	2.69
15	4.39	4.04	1.48	5.52	3.86
16	2.39	6.79	4.48	3.29	4.24
17	8.14	4.78	6.98	9.20	7.28
18	12.35	10.77	11.30	12.32	11.69
19	12.63	10.11	11.84	13.00	11.90
20	12.24	10.09	11.15	11.45	11.23
21	12.73	12.32	12.36	12.39	12.45
22	11.48	9.82	12.86	12.95	11.78
23	13.14	12.36	11.73	11.98	12.30
24	13.73	12.92	12.77	12.91	13.08
Average	**8.58**	**8.79**	**9.85**	**9.69**	**9.23**

*A horizontal datum applied by Public Works Department (PWD), Bangladesh.