The Jamuna-Brahmaputra River, Bangladesh   21

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21.1 BACKGROUND

21.1.1 The River

Bangladesh is dominated by three great rivers – the Jamuna-Brahmaputra, Ganga and Meghna – that combine to feed sediment into one of the World's largest deltas in the Bay of Bengal (Figure 21.1). Bangladesh has been shaped by, and is dependent upon, its rivers, which provide fertile soils and a diverse flora and aquaculture but also bring significant flood hazard and risk to infrastructure for a large and growing population. Current anthropogenic stresses, in terms of changing climate, water diversions, pollution and sediment extraction, are posing new pressures to the river and its inhabitants (Best, 2019). The people of Bangladesh have adapted their lifestyle for centuries to live with river flooding – frequently moving their temporary bankside homes, planting on newly emergent river bars, and sometimes raising their homesteads above water level in flood periods (Paul, 1997). However, a growing population, coupled with the expansion of infrastructure and economic development, has resulted in an increase in the intensity of flood damage (FPCO, 1995; Paul, 1997; CPD, 2004). The lives of many millions of Bangladeshi citizens are reliant on these rivers, with up to 2.3 million people living on the riverine islands alone (Schmuk-Widmann, 2001). Bangladesh's rural economy relies upon annual 'normal' floods to bring moisture and fresh sediments to the floodplain soils (Paul, 1997): for instance, two of the three seasonal rice varieties (*aus* and *aman*) cannot survive without floodwater and the fish caught both on the floodplain during flood season and from the many floodplain ponds (*'beels'*) provide the main source of protein for many rural populations (Chowdhury, 1994; Paul, 1997; de Graff, 2003; Shankar *et al.*, 2004). However, the effect of 'abnormal' floods can be devastating and result in appreciable damage to crops and houses, severe bank erosion with consequent loss of homesteads,

schools and land, and loss of human lives, livestock and fisheries (BDER, 2004; Shankar *et al.*, 2004). For example, in the 1998 flood, over 70 % of the land area of Bangladesh was inundated, affecting 31 million people and 1 million homesteads (Chowdhury, 2000). The 1998 flood, which had an unusually long duration from July to September, claimed 918 human lives and was responsible for damaging 16 000 and 6000 km of roads and embankments, respectively, and affecting 6000 km^2 of standing crops (Chowdhury, 2000). In the 2004 floods, over 25 % of the population of Bangladesh, or 36 million people, was affected by the floods; 800 lives were lost; 952 000 houses were destroyed and 1.4 million badly damaged; 24 000 educational institutions were affected, including the destruction of 1200 primary schools; 2 million government and private tubewells were affected, and over 3 million latrines were damaged or washed away, this increasing the risks of diarrhoea, cholera and other waterborne diseases. Also, 1.1 million ha of rice crop was submerged and lost before it could be harvested, with 7 % of the yearly *aus* (early season) rice crop lost; 270 000 ha of grazing land was affected, 5600 livestock perished together with 254 000 poultry and 63 Mt of lost fish production (BDER, 2004; CPD, 2004). In the districts that are dominated by the Brahmaputra-Jamuna River, the 2004 flood damage to infrastructure (homes, roads, culverts), tubewells and latrines, with ensuing unemployment of many of the population, were some of the areas of critical impact. The total cost of the damage caused by the 2004 flood is estimated at $7 billion (CPD, 2004).
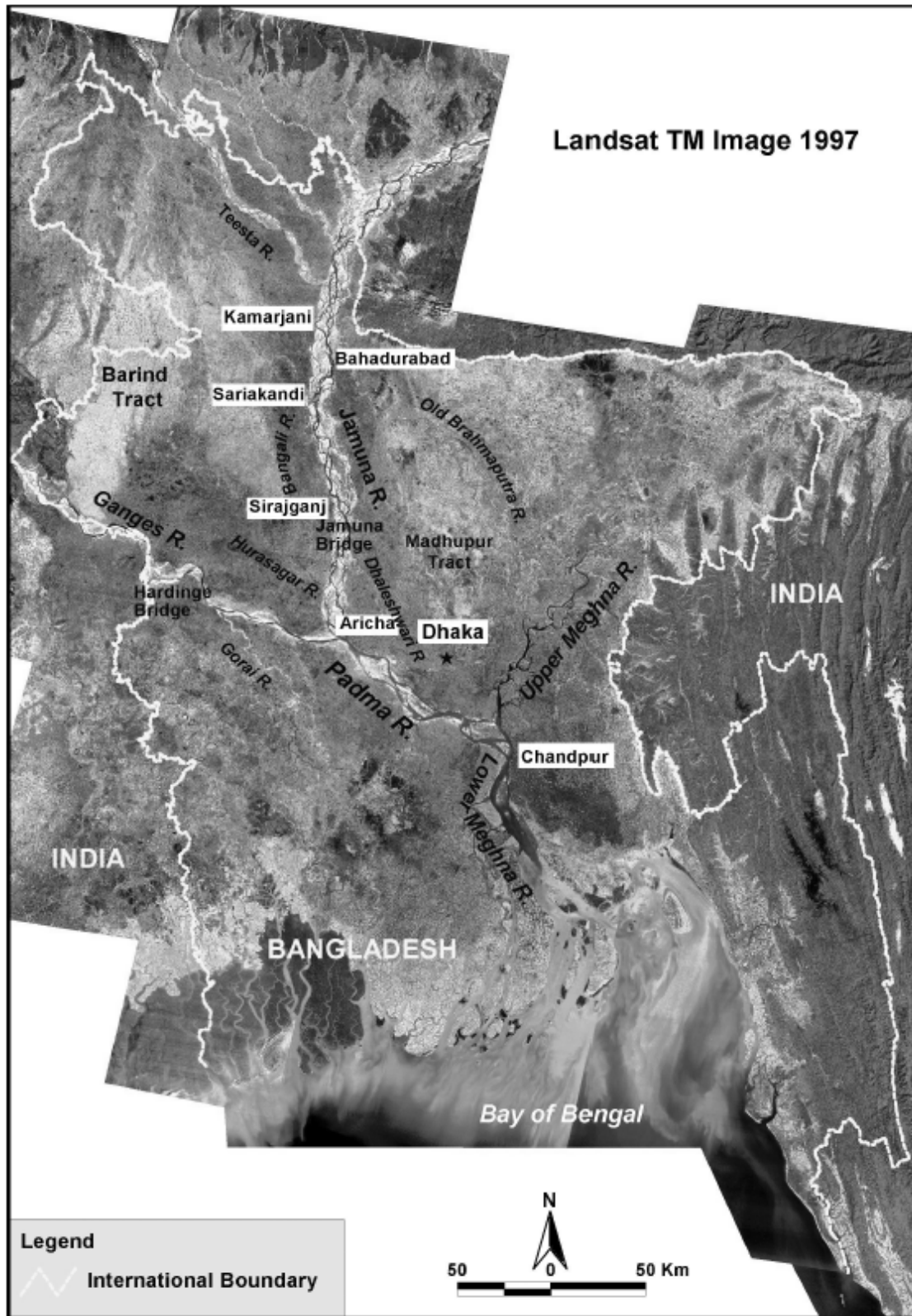
Figure 21.1 (See also colour plates.) Landsat image of Bangladesh, showing the Brahmaputra-Jamuna, Ganga (Ganges) and Meghna Rivers, together with the major features and towns referred to in this chapter

Hence, due to the nature of these devastating floods, and their recent occurrence in 1987, 1988, 1998, 2004 and 2007, the possible influences on catastrophic flooding, such as the role of Himalayan deforestation (Kattelman, 1990; Mirza *et al*., 2001), the type of intervention and infrastructural response to flooding [e.g. the Brahmaputra Right Embankment (BRE) from the Teesta to Hurasagar confluences; Figure 21.1] and the nature, scope and need for the Flood Action Plan (Haggart *et al*., 1994; Paul, 1997) have thus received much attention and debate over recent years (Boyce, 1990; Hossain, 1993, Haggart *et al*., 1994; Reavill and Rahman, 1995; Paul, 1997; Islam, 2001). Additionally, political debates concerning water usage and construction of dams have become a major issue for Bangladesh (Patel, 1996; Wood, 1999; Mirza, 2004), since over 90 % of the catchments of these three great rivers lies outside the boundaries of the country.

The Brahmaputra-Jamuna and Ganga Rivers combine to form the Padma, which carries the third greatest water discharge of all the World's rivers but is often ranked the highest in terms of sediment discharge (Schumm and Winkley, 1994), although a range of values exist for these estimates. The Jamuna is the local name given to the river for its entire length in Bangladesh to the Ganga junction (Figure 21.1; hereafter the river is referred to as the Jamuna). The Jamuna has one principal tributary input, the Teesta River in the north-west, and two major offtakes on the left bank that are the Old Brahmaputra (see below) and the Dhaleswari (Figure 21.1). The Jamuna River contributes ~51 % of the water discharge and 38 % of the sediment yield to the Padma according to Schumm and Winkley (1994), although FAP24 estimate these percentage contributions to the Padma at 66 and 65 % for water and sediment discharge, respectively (FAP24, 1996a), with the sediment yield being estimated at 590 Mt year^{-1} and the sand fraction contributing 34 % of this total (Sarker, 1996). The Jamuna can have a braidplain width up to 15 km in flood and scour depths of up to 40 m have been recorded (Klaassen and Vermeer, 1988). Thus, by any definition, the Jamuna is one of the World's truly great rivers (Best, 2019), and has a direct and daily influence on the prosperity of its population and the country's economic growth and political stability.

Since the seminal work of Coleman (1969), much research has been conducted on these rivers, especially in the 1990s as part of the Bangladesh Flood Action Plan (e.g. Haggart *et al*., 1994; Thorne and Thiagarajah, 1994; FAP24, 1996a–h; Paul, 1997), together with work from organizations such as the Center for Environmental and Geographic Information Services (EGIS) and Water Resources Planning Organization (WARPO) in Bangladesh, and this has allowed a dramatic increase in our knowledge of the behaviour of the Jamuna River. This work, aided by major advances in monitoring techniques, such as frequent, all-year satellite imagery and whole-flow depth monitoring within the main channels at even the highest discharges, has resulted in the river being characterized in more detail than ever before (Takagi *et al*., 2007). The recent book by Hofer and Messerli (2006) provides a detailed account on the history of flooding and hydrology of the Brahmaputra-Jamuna River, as well as highland–lowland linkages and case studies of various flood years. Recent attempts to predict morphological change have also met with some success (EGIS, 2002; CEGIS, 2003; Mosselman, 2006), and together with numerical modelling (Enggrob & Tjerry, 1999; Jagers, 2003) offer some hope to both understand and predict river channel movement, and establish management plans for such change. Additionally, development of large-scale infrastructure within Bangladesh, such as construction of the Bangabandhu Multipurpose Bridge across the Jamuna, and numerous bank-protection works

(Mosselman, 2006), has demanded an increased quantification of the alluvial channel processes and prediction of future channel change. This chapter seeks to provide a synthesis on aspects of the geomorphology and sedimentology of the Jamuna River within Bangladesh, between the northern Bangladesh border and its junction with the Ganga some 240 km to the south (Figure 21.1), and examines issues of applied geomorphology in response to the flooding and migration of this huge and largely untamed river. Details of the Brahmaputra River upstream of the Bangladesh border are given by Singh (see Chapter 18), and a recent synthesis on the water resources of the Brahmaputra Basin in India is provided by Singh *et al*. (2004), including a chapter on fluvial geomorphology by Bora (2004).

21.1.2 Basinal Setting and Controls on Sedimentation

The Jamuna River has developed in a region of significant tectonic activity associated with Himalayan uplift and development of the Bengal foredeep (Alam *et al*., 1990; Barua, 1994; Goodbred *et al*., 2003; Brammer, 2012), and the underlying structural control on the location of the major river systems of Bangladesh has been hypothesized by several researchers (Morgan and McIntire, 1959; Umitsu, 1993; Barua, 1994). Morgan and McIntire (1959) suggested there is a zone of 'structural weakness' along the present course of the Ganga–Jamuna–Padma Rivers due to either a subsiding trough or a fault at depth. However, much of the evidence on which this suggestion was based was indirect and awaits fuller seismic investigation to ascertain the exact subsurface controls on river channel migration and long-term evolution. The region is known to have suffered major seismic activity in the past 100 years (FAP24, 1996a), experiencing 20 earthquakes of Richter magnitude >7 in and around the Bengal Basin in the past 100 years, with the great 1950 Assam earthquake measuring Richter magnitude 8.6 and affecting up to 52 000 km^2 of territory in Assam (Sarker and Thorne, 2006; Sarker *et al.,* 2014). Seijmonsbergen (1999) reports on an analysis of Landsat MSS imagery and concludes that many structural lineaments, running broadly NW–SE and WSW–ENE, can be recognized from physical features on the floodplain, and concludes these are small faults that can influence local migration of the channels. Seijmonsbergen (1999) further contends that width changes in the Jamuna may respond to these faults and they may also cause increased sedimentation upstream of the fault. For example, Seijmonsbergen (1999; figures 4 and 7) presents images to argue that a fault downstream of the Bangabandhu Multipurpose Bridge has affected channel migration, although the channel behaviour does not to support this contention (see Section 21.7). The importance of local structural controls on channel sedimentation must await further coring of the sediments, coupled with ground examination of the purported lineaments, in order to ascertain if they are real and the effect that they may exert on river planform changes (Seijmonsbergen, 1999: p. 135).

Deepening of the Bengal Basin has also produced huge accumulations of sediment that have been fed from Himalayan erosion, with the thickness of sediment above the Precambrian basement increasing from a few hundred metres in the shelf region to over 18 km in the Bengal foredeep to the south (EGIS, 1997). Ongoing subsidence in the Bengal Basin, combined with high rates of Himalayan uplift, thus set the tectonic and climatic context for the large water and sediment discharges in the rivers of Bangladesh (Goodbred and Kuehl, 2000a,b). There is also evidence for a significant Late Quaternary climate signal

superimposed on the structural control on sediment supply and channel belt migration (Heroy *et al*., 2003).

The control of uplift and subsidence is, however, clear and Allison (1998), in a review of the geologic and environmental framework of the Ganga-Brahmaputra Delta, highlights the uplifted Pleistocene terraces of the Barind and Madhupur tracts (Figure 21.1) as being first-order controls on the courses of the Jamuna and Ganga Rivers. Barua (1994) also presents a synthesis of the major environmental controls on Bangladesh's river systems and, together with the major controlling factors of regional tectonics, geology, climate, sea-level rise and vegetation, highlights the controls by the 'fluvial loading' that is dictated by water and sediment discharge and sediment calibre. Recent research using strontium as a provenance indicator (Goodbred *et al.,* 2014; Sincavage *et al*., 2018) has revealed more details on the Holocene evolution of the rivers of Bangladesh, and their role is constructing the Ganges delta (Figure 21.2). These data show that the three great rivers of Bangladesh – the Ganges, Jamuna and Meghna – remained isolated from each other and constrained within their own valleys until around the mid-Holocene (*c.* 7 ka; Figure 21.2a). After this time, and as sea-level continued to rise, the rivers had essentially filled up their palaeovalleys and were then free to avulse and migrate over a wider area: this resulted in numerous channel reorganizations from the mid-Holocene to present (Goodbred *et al.,* 2014; Figure 21.2a). These provenance studies also suggest that the basin hydrology may have provided a first-order control upon sedimentation, strongly modifying the potential influence of tectonic subsidence. Evolution of the drainage pathways of these rivers over time has also led to changing patterns of deposition within the Ganges delta, and lithological and provenance studies have proposed various depocentres that have shifted in time as the rivers have changed course (Figure 21.2b). The nature of sea-level rise, together with anthropogenic effects on Bangladesh's rivers such as flood control, water usage, coastal saltwater intrusion and population growth, will clearly take on great importance in the next century (Begum and Fleming, 1997a,b; Choudhury *et al*., 1997; Mirza *et al.*, 2001; Mirza, 2002; Brammer, 2014).

21.1.3 Hydrology, Sediment Yield and Channel Size

The Ganga and Jamuna Rivers are sourced in the Himalayan range, whilst the Meghna rises in the Sylhet Trough. The Jamuna has a catchment area of ~560 000 km^2 that receives an average of 1.9 m rainfall year^{-1} (FAP24, 1996a; Sarker and Thorne, 2006), with approximately 8.1 % of the drainage basin area being within Bangladesh (Ojha and Singh, 2004). The rise in the hydrograph of the Jamuna begins due to Himalayan snowmelt in May, but the hydrograph is dominated by monsoon rainfall, and shows a broad peak between July and September (Figure 21.3). At Bahadurabad (Figure 21.1), the mean annual discharge is 20 200 m^3 s^{-1}, varying from a minimum dry season flow of ~2860 m^3 s^{-1} to ~100 000 m^3 s^{-1} in the disastrous 1988 flood (EGIS, 1997), and a record 102 500 m^3 s^{-1} in the 1998 flood (Chowdhury, 2000). Bankfull discharge is difficult to estimate because the channel bank edge and overbank level are ill-defined, but estimates range from 45 000 to 60 000 m^3 s^{-1} (FAP24, 1996e; Thorne *et al.*, 1993).The annual hydrograph shows a yearly change in water stage of ~6 m (FAP24, 1996a). The average water slope of the Jamuna is 0.000076 over the first 130 km and 0.000065 further downstream (FAP24, 1996b). Flow velocities within the main channels are of concern in design considerations and depth-averaged velocities may reach over 3.5 m s^{-1} (FAP24, 1996c).
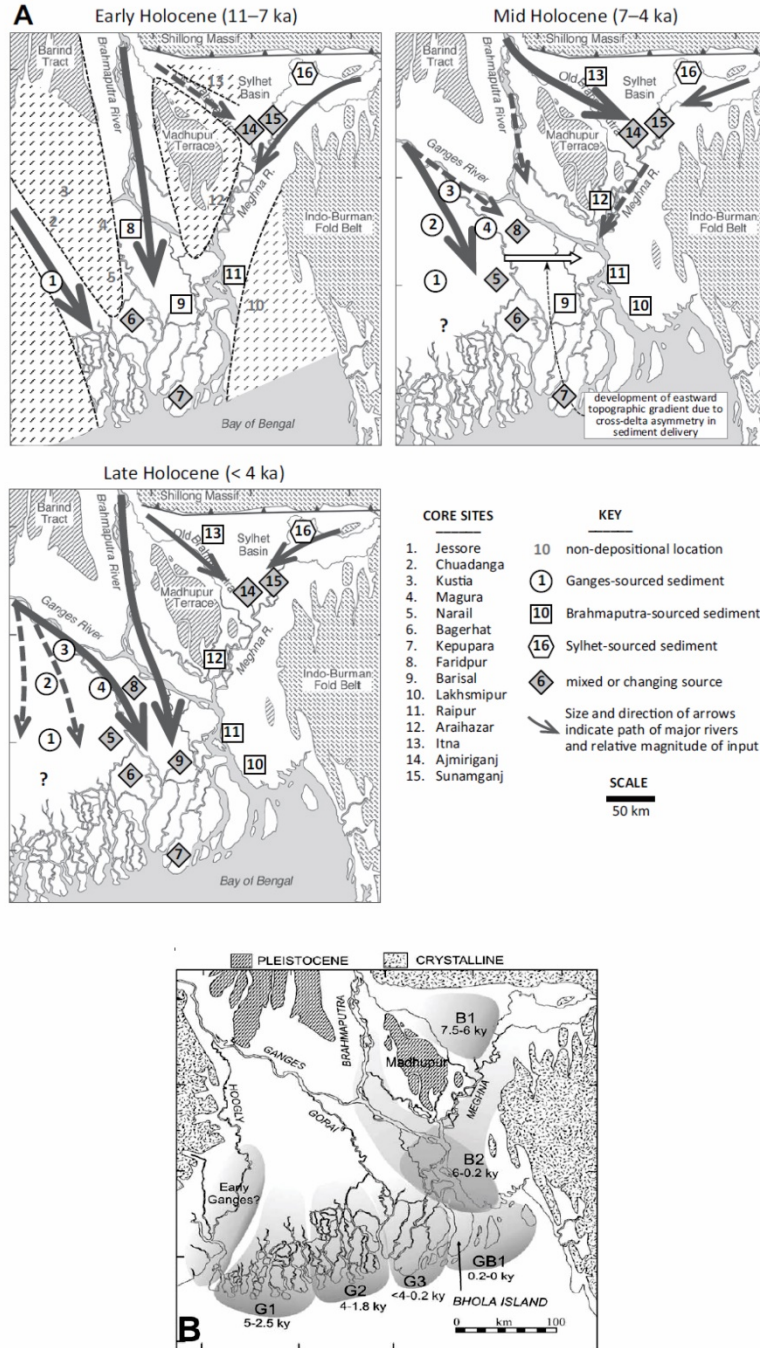
Figure 21.2 A. Schematic reconstruction of river pathways and general sediment distribution patterns associated with the Ganges, Brahmaputra (Jamuna), and Sylhet sources through the Holocene. Early Holocene: rivers are constrained within their lowstand valleys, with limited Brahmaputra influence in Sylhet basin. Mid-Holocene: Slowed sea-level rise allows rivers to infill their valleys and the rivers become more mobile across the delta. Late Holocene: the principal rivers interact on the central delta plain, shifting toward the modern confluence and shared river-mouth estuary. (From Goodbred et al., 2014); B. Pathways and the timing of phases of river channel shifting and formation of delta lobes (from Akter *et al.,* 2016).

The Jamuna is predominantly a braided river, with some anastomosed regions (cf. Sarker and Thorne, 2006, their figure 13) and possesses an average braidplain width of 11 km, flow depth of ~5 m and a Brice braiding index of 4–6 (FAP24, 1996a). Sarker and Thorne (2006) show that when slope is plotted against discharge on the classic channel pattern discrimination diagram proposed for smaller rivers by Leopold and Wolman (1957), the Jamuna, Padma and Meghna plot in the meandering field, highlighting the controls on channel planform are more complex than solely slope and discharge. The number of major channels in the braidbelt varies between three in the upper reaches and two in the lower reaches, with the planform being dominated by a range of vegetated and non-vegetated bars that divide the channel into a hierarchy of channel sizes (Bristow, 1987). Moreover, the river occupies a large width partly because it is anabranched, which is common for alluvial rivers with mean annual discharges greater than ~17,000 m^3s^{-1} (Latrubesse, 2008). The grain size of the Jamuna River shows a slight fining from north to south, with the median bed material grain size being 260 μm near the Indian border and 165 μm near Aricha (FAP24, 1996a), with an average of 220 μm (Barua, 1994; Sarker and Thorne, 2006). The majority of the sediment is fine sand and silt with less than 1 % clay (FAP24, 1996h). The fine and abundant sediment supply result in sediment transport occurring throughout the year and this, together with high water discharges, gives rise to the massive sediment yields from the Jamuna River, with estimates being of 590 Mt year^{-1} (FAP24, 1996a) to 792 Mt year^{-1} (Islam et $al.$, 1999) or 615 Mt year^{-1} (Rahman et $al.$, 2018). Various estimates of the percentage of the total load transported as bedload have been proposed, with values between 10 % (Islam et $al.$, 1999) and ~30 % of the total sediment load as bed material (Sarker et $al.$, 2003). Various estimates of the total suspended load have also been given, with a wide range of between 541 and 1147 Mt year^{-1} (Islam et $al.$, 1999). Recent work (Rahman et $al.$, 2018) has also suggested the total load of the Jamuna River may be decreasing by $c.$ 6 Mt year^{-1}, with the Ganges River decreasing by $c.$ 4 Mt year^{-1}. This represents a $c.$ 10 Mt year^{-1} reduction in sediment supply to the Bay of Bengal, which may have significant implications in future, although it is clear that higher fidelity data are required to test this contention.
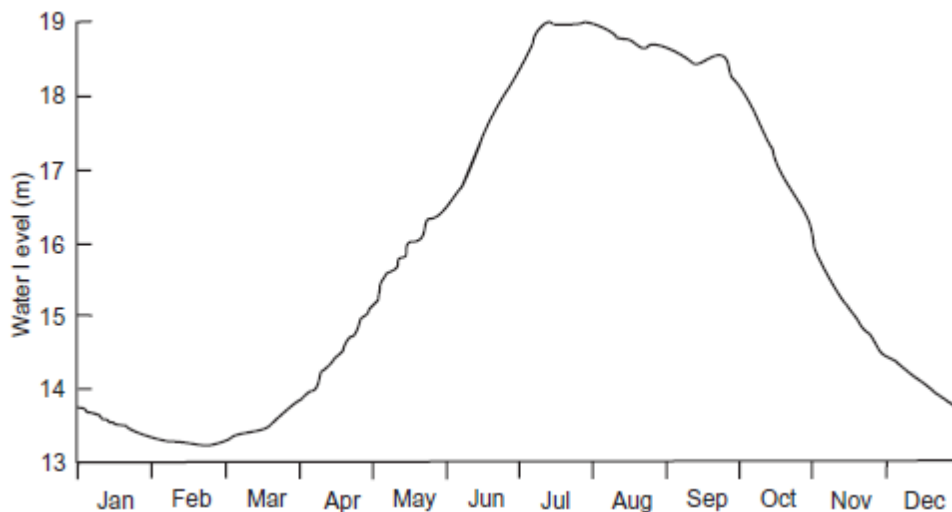
Figure 21.3 The stage-hydrograph of the Jamuna River at Bahadurabad (see Figure 21.1 for location), averaged over a 30-year period. Level is expressed relative to a standard low-water datum derived from long-term records. Reprinted from Braided Rivers: Process, Deposits, Ecology and Management, Eds Sambrook Smith *et al*., Special Pub. Int. Ass. Sedimentologists, Sarker, M.H. and Thorne, C.R., Morphological response of the Brahmaputra-Padma-Lower Meghna River system to the Assam earthquake of 1950, 2006, with permission of Blackwell Publishing

21.2 CHANNEL SCALE MORPHOLOGY AND RECENT HISTORICAL CHANGES IN THE COURSE OF THE BRAHMAPUTRA-JAMUNA RIVER

The course of the Brahmaputra-Jamuna River has changed dramatically over the past 250 years, with evidence of both large-scale avulsion in the period 1776–1850 and a more general westward migration of the Jamuna channel belt since this date (Figure 21.4). The avulsion of the Jamuna has been described by several authors, with Bristow (1999) presenting the most recent summary of theories for the trigger of the change in channel belt location. Prior to 1843, the Brahmaputra flowed within the channel now termed the 'old Brahmaputra' (Figures 21.1 and 21.4a), east of the Madhupur Tract, and joined the Meghna River. Sometime between 1830 and 1860, Bristow (1999) contends that avulsion of the river occurred, and caused a maximum of ~80 km of lateral shifting of the river course from the east to the west of the Madhupur Tract (Figures 21.4a and 21.5). Several studies have discussed the avulsion of the channel into its present course, and suggested a number of reasons including tectonic activity (Winkley *et al*., 1994), switches in the upstream course of the Teesta River (Morgan and McIntire, 1959), the influence of increased discharge (Coleman, 1969), catastrophic floods (La Touche, 1910) and river capture into an old river course (Bristow, 1999). From an analysis of maps between 1776 and 1843, Bristow (1999) concludes that the river avulsion was more likely gradual than catastrophic, and may have been generated by bank erosion, perhaps around a large mid-channel bar, causing diversion of the channel into an existing floodplain channel. The map of Rennell (1776) clearly shows a sequence of large bars near the offtake of what is now the Jamuna (Figure 21.5a,b, label x) suggesting local sediment overload and diversion of flow against the banks. Significant flow may have previously been diverted down the Jamuna offtake, since the right bank at this point shows two large embayments that would funnel water down the offtake (Figure 21.5b, label x).
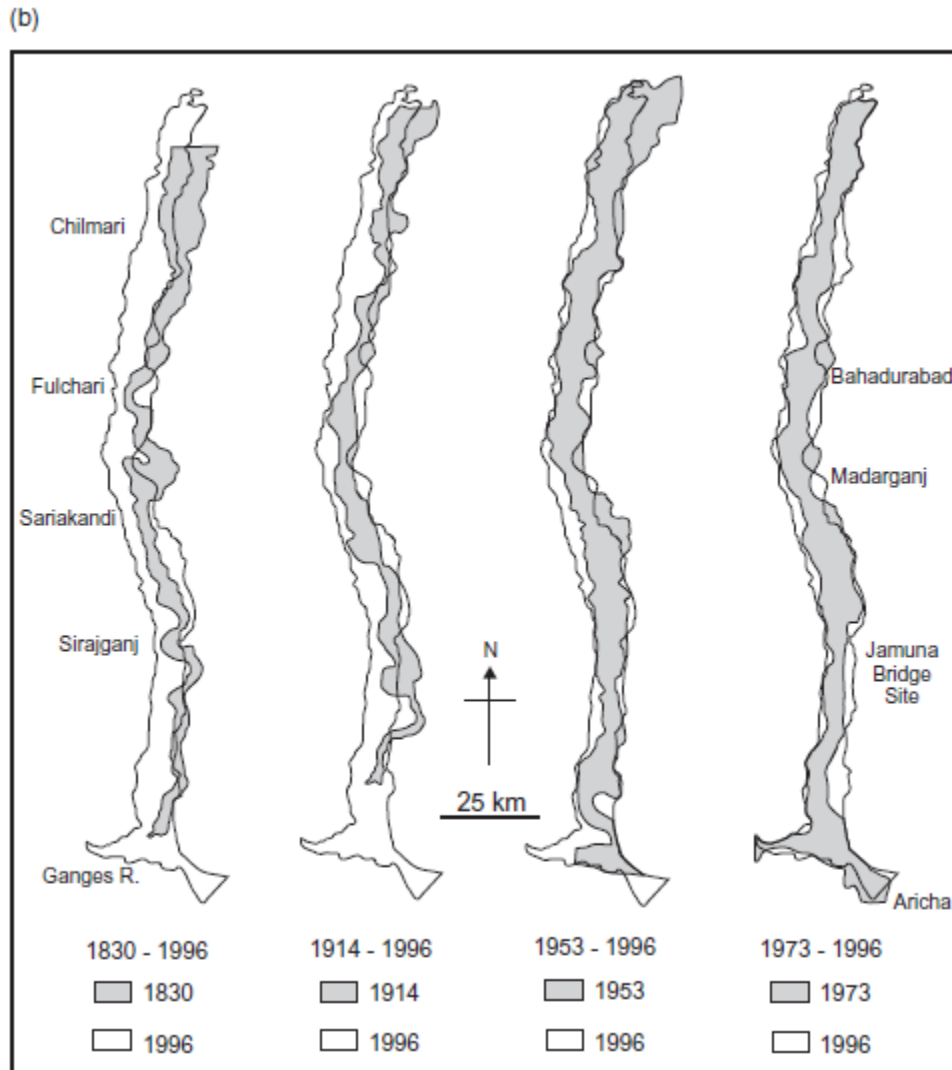
(a)

A. Maj. J. Rennell, 1776

B. R. Wilcox, 1828

C. W. H. Allen, 1843

D. Landsat image, 1978

(b)
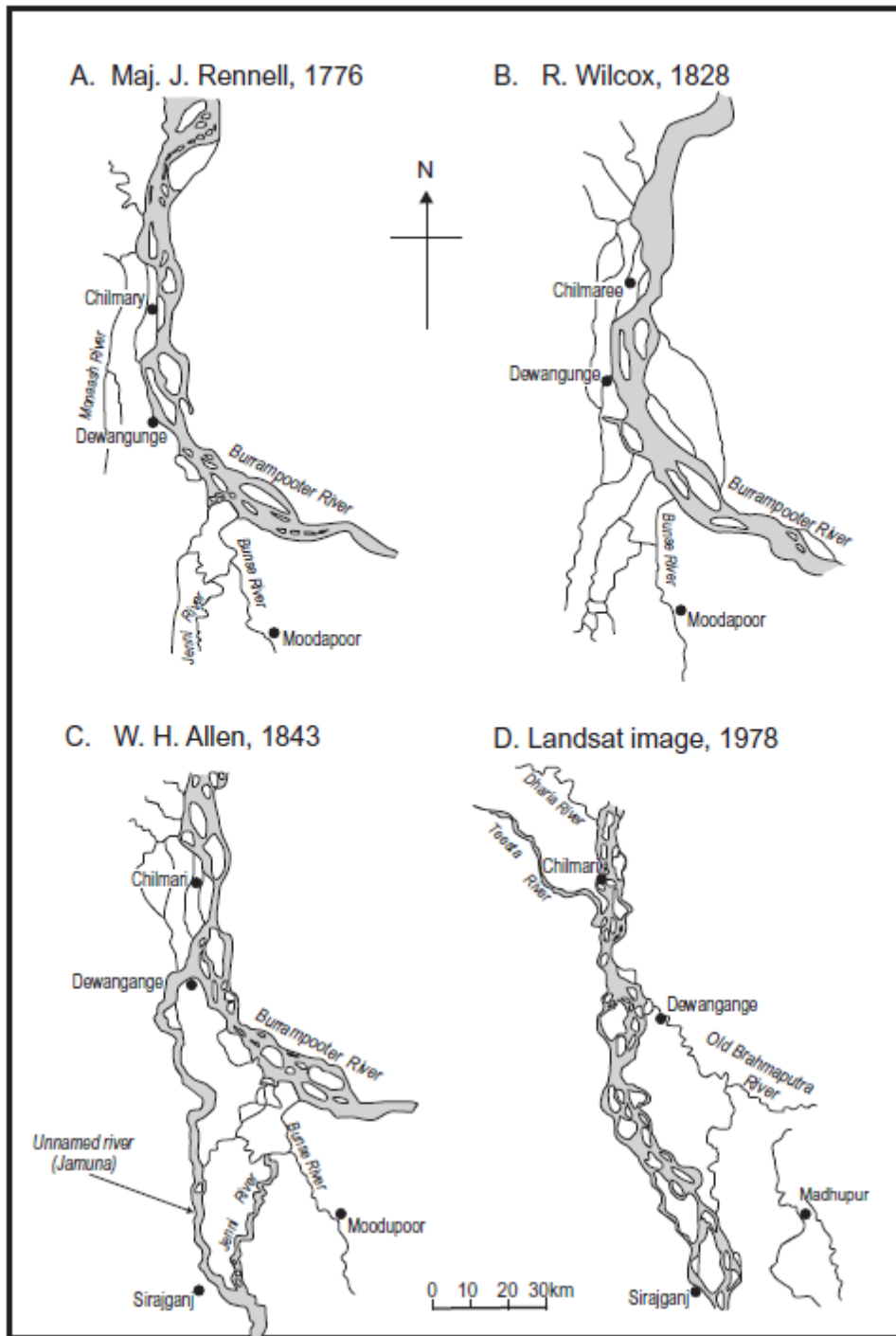
Figure 21.4 (a) Maps illustrating the position of the Jamuna River from 1776 to 1978: (A) 1776; (B) 1828; (C) 1843; (D) 1978. Reprinted from Fluvial Sedimentology 6, Eds Smith, N.D. and Rogers, J., Special Pub. Int. Ass. Sedimentologists, Bristow, C.S., Avulsion, river metamorphosis and reworking by underfit streams: a modern example from the Brahmaputra River in Bangladesh and a possible ancient example in the Spanish Pyrenees, 1999, with permission from Blackwell Publishing. (b) Historical changes in the position of the bankline of the Jamuna River. Reprinted from EGIS, Morphological dynamics of the Brahmaputra-Jamuna River, 1997, with permission from CEGIS

Several authors have also described the gradual westward migration of the Jamuna braidbelt (Coleman, 1969; Sarker, 1996; Khan and Islam, 2003) and noted that the braidbelt has widened since the early twentieth century (FAP24, 1996c; Sarker, 1996; EGIS, 1997, their figures 3 and 5). Even given the inherent uncertainties when using old maps to provide quantitative estimates of channel size, the trends in the mean braidplain width for the Jamuna (Figure 21.6) show a significant increase, although the rate of widening decreased from 152 m year^{-1} between 1973 and 1992, to 20 m year^{-1} between 1992 and 2010 (EGIS, 1997; Sarker and Thorne, 2006; Sarker *et al.,* 2014). The rate of widening averaged ~50 m year^{-1} over the period 1834–1992 (FAP24, 1996a), but with significant fluctuations in

average rate up to ~170 m year^{-1} (FAP24, 1996a; Khan and Islam, 2003), and with *local* erosion rates reaching up to 1 km year^{-1}. ISPAN (1993) estimated that the length-averaged width of the Jamuna River in 1914 was 5.5 km, which is close to that found in the 1830 map. Later, the width of the river in the 1940s (Coleman, 1969) was found to be much higher, with the length-averaged width being ~9 km in 1952 (ISPAN, 1993) and, except for the lower reach, braiding was the predominant planform along almost the entire Jamuna River. The development of a braided channel was especially rapid in the period between the maps of 1914 and 1953, with the period between 1830 and 1914 being marked by a reduction in meander amplitude but a westward migration of the river (FAP24, 1996c).

It is worthy of note that river erosion consumes *c.* 2 000 - 5000 ha of mainland floodplain annually, making many tens of thousands of people landless and/or homeless (Sarker *et al.,* 2014). Sarker *et al.* (2003) showed that in the period 1984-1992, the Jamuna River eroded 40,000 ha of floodplain but only accreted around 1400 ha. Schmuk-Widmann (2001) reports that some 2.3 million people live on the river islands, or 'chars', with Sarker *et al.* (2003) placing this number at 600,000, and whose income is reliant on agriculture supplemented by animal husbandry, small businesses and fishing (Schmuk-Widmann, 2001). However, the changing size of these chars due to erosion creates an internally displaced population over periods of years to decades, with estimates of annual population displacement in Bangladesh due to riverbank erosion being *c.* 200,000 people (Sarker *et al.,* 2019). This displaced population faces huge challenges in terms of economic welfare, security, access to food and health services, and issues of mental health, with older people, women and children being the most vulnerable (Islam and Rashid, 2011; Islam *et al.,* 2014; Sarker *et al.*, 2019).
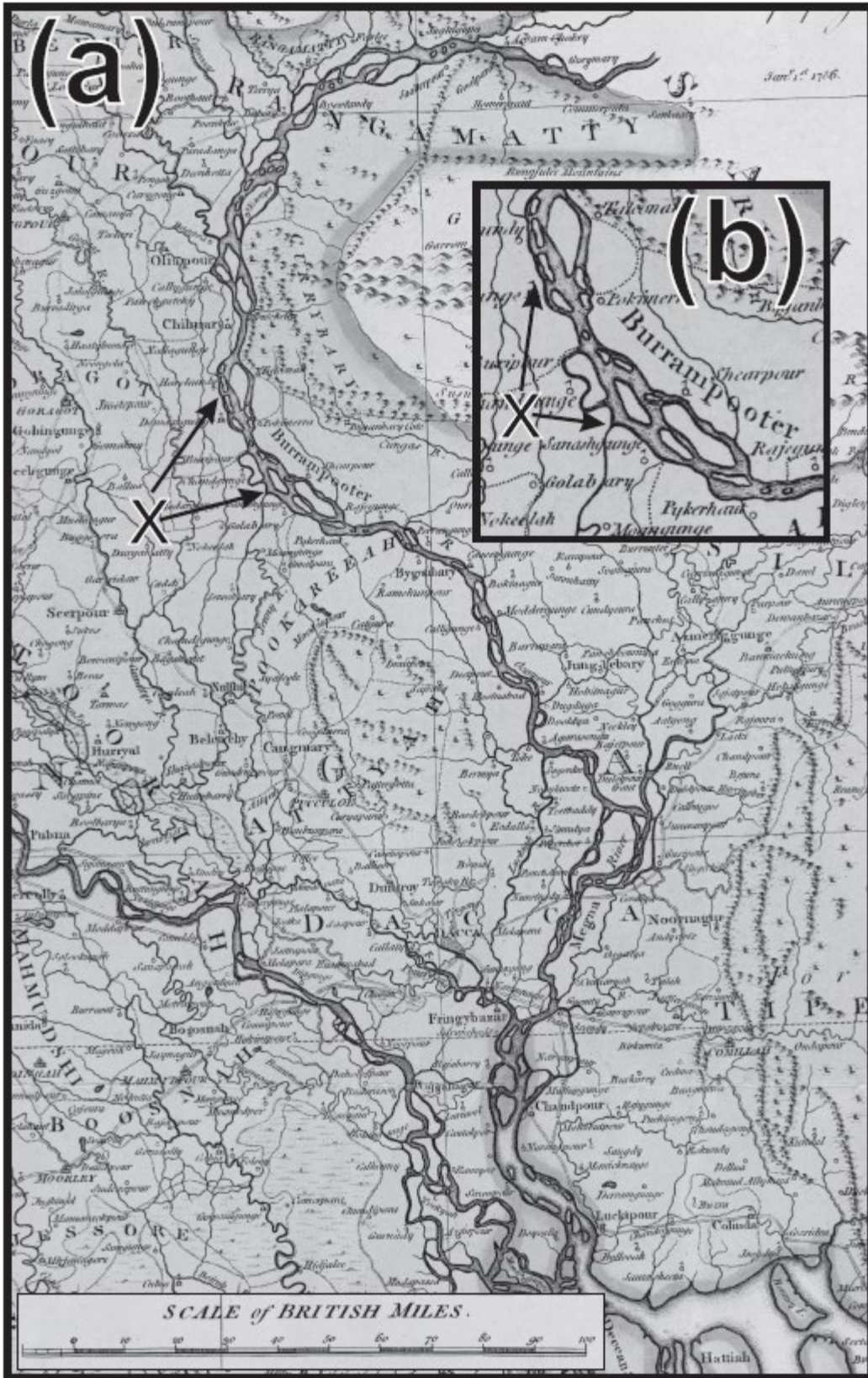
(a)

(b)

Jan.ˢᵗ 1786.

SCALE of BRITISH MILES.

Figure 21.5 (a) Reproduction of part of Rennell's 1776 map illustrating the course of the Old Brahmaputra (Burrampooter) and the course the Jamuna River was to adopt after its avulsion. Reprinted with permission from the David Rumsey Map Collection, www.davidrumsey.com. (b) Close up of the point of avulsion (labelled 'x' in a and b). Note the large bars formed at the avulsion point and the bank erosion that appears in this region. Also compare this map with the image shown in Figure 21.1, and how the course of the Ganges changed after avulsion of the Jamuna River. Today the Ganges/Jamuna combine to form the Padma, which then joins the Meghna to form one major channel exiting into the Ganges delta (Figure 21.1). In the map of Rennell (1776), the Ganges and Brahmaputra/Meghna Rivers form two separate channels flowing through the Ganges delta.
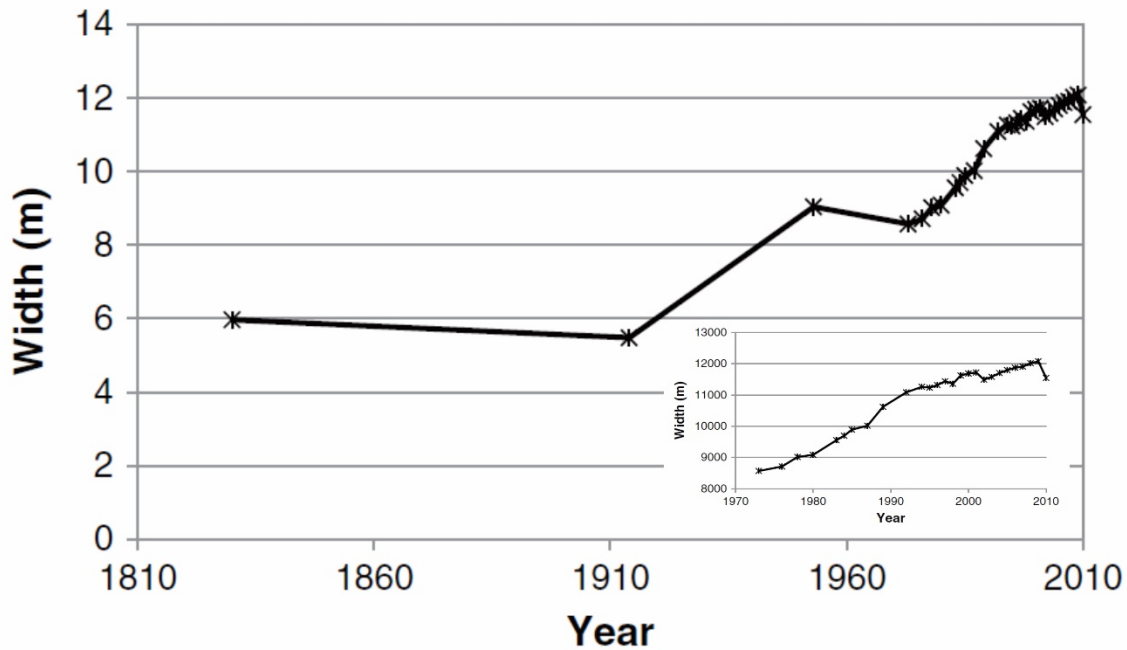

Figure 21.6 Trends in the mean width of the Jamuna River 1830–2010. Inset shows detail from 1970-2010. After Sarker *et al.*, 2014.

Coleman (1969) related the westward channel migration to uplift of the Madhupur Tract Pleistocene sediment, an argument that has found support from ISPAN (1993) Thorne *et al.* (1993), and Sarker (1996), although Burger *et al.* (1988) have rejected this contention. The debate concerning the westward migration of the Jamuna River emerged from the outward movement of both banks of the Jamuna River since the 1970s. During 1973–1992, the rate of eastward migration of the left bank was 79 m year^{-1} whilst the westward migration of the right bank was 68 m year^{-1}. This persistent high outward migration rate of both banks caused the apparent eastward migration of the centreline during these two decades, and probably led to the debate concerning the westward migration of the river. However, since the beginning of the 1990s, the eastward migration of the left bank has been greatly reduced to 16 m year^{-1} and the westward migration of the right bank has been slightly reduced to 44 m year^{-1}, thus causing the centreline of the Jamuna River to migrate westward (EGIS, 1997). These observations indicate that apparently the 'nil or eastward' migration of the centreline of the Jamuna River during 1973–1992 was probably for a short period and related to the very high widening phase of the river. Such westerly migration may be a product of braidplain widening as the channel adapts to its new post-avulsion

course, and/or a response to underlying tectonic control (Morgan and McIntire, 1959). Thorne *et al*. (1993) also linked the location of erosion to the development of bankline curvature in the large-scale planform of the Jamuna and suggested this erosion on the outside of 'large scale meanders' in the braidplain may be used to predict future sites and rates of bank erosion.

The planform analysis of the Jamuna River performed by EGIS (1997, 2000), using time-series satellite images, shows the width (Figure 21.4b) and braiding intensity of the Jamuna River to be changing spatially and temporally, with Klaassen and Vermeer (1988) also documenting changes in the braiding intensity. Brammer (1995, 2012), Goodbred *et al*. (2003) and later Sarker (2009) and Sarker and Thorne (2006, 2014) have related these changes in morphological and planform parameters, including the braiding intensity in the Jamuna, Padma and Lower Meghna Rivers, to the propagation of a sediment wave or 'slug' generated from the August 15th, 1950 Assam earthquake that had a magnitude, M_w, of 8.6. Sarker and Thorne (2006) divided the Jamuna River into two halves and presented changes in width and braiding intensity for the upstream and downstream reaches (Sarker and Thorne, 2006, their figures 6 and 8a). Three points are worthy of note from these studies concerning the braiding intensity of the Jamuna River:

1. The braiding intensity is less in the downstream reaches of the Jamuna River than in the upstream reaches, possibly in response to a downstream decrease in slope (Klaassen and Vermeer, 1988).
2. The braiding intensity in the upstream reaches of the Jamuna River increased after 1973, but started to decrease from the early 1990s.
3. In the downstream reaches of the Jamuna River, the braiding intensity decreased in the 1970s, but then increased through the 1980s up to the first half of 1990s. The braiding intensity started to decrease in the downstream reaches of the Jamuna since the mid-1990s.

The rapid increases in channel width and floodplain erosion observed in the Jamuna River during the 1970's and 1980's were argued to have resulted from the arrival of the trailing edge of the sediment wave (Sarker *et al.,* 2014). The fine fraction of the sediment input from the Assam earthquake was argued to have passed through the fluvial system relatively quickly, but the coarser sand fraction was proposed to have taken approximately fifty years to reach the Bay of Bengal (Sarker, 2009; Sarker and Thorne, 2006; Sarker *et al.,* 2014). These contentions allowed Sarker *et al*. (2014) to propose a schematic representation of river response (Figure 21.7) to the forcing variables of avulsion, tectonics, earthquake-induced sediment supply and anthropogenic factors. Avulsion of the river into its new course from the Old Brahmaputra was a strong driver of channel change in the Jamuna River in the 19th and early 20th centuries but has now diminished, and recent work suggests that the influence of tectonics may be small compared to other driving factors such as hydrology (Goodbred *et al.,* 2014). Sarker *et al*. (2014) contend that the influence of the sediment wave generated by the 1950 Assam earthquake had its maximum influence on river morphology in the 1980's, and overwhelmed the westward migration of the braidplain that had prevailed for the previous 150 years. Sarker *et al*. (2011) and Akter *et al*. (2015) also suggest that the sediment yielded by the 1950 Assam earthquake subsequently led to a period of high net accretion in parts of the Meghna Estuary. Sarker *et al*. (2011) contend there were two phases of accretion linked to the sediment wave: the first characterized by rapid accretion due to the accumulation of fine silts and clays immediately after the

earthquake and that lasted until the early 1970's, and a second phase in the mid-1980's to mid-1990's due to the arrival of the coarser sediment wave. Lastly, Sarker *et al.* (2014) indicate that human interventions, such as engineered embankments, hard points, bridges and guide bunds, will likely have an increasing future effect on morphological change.
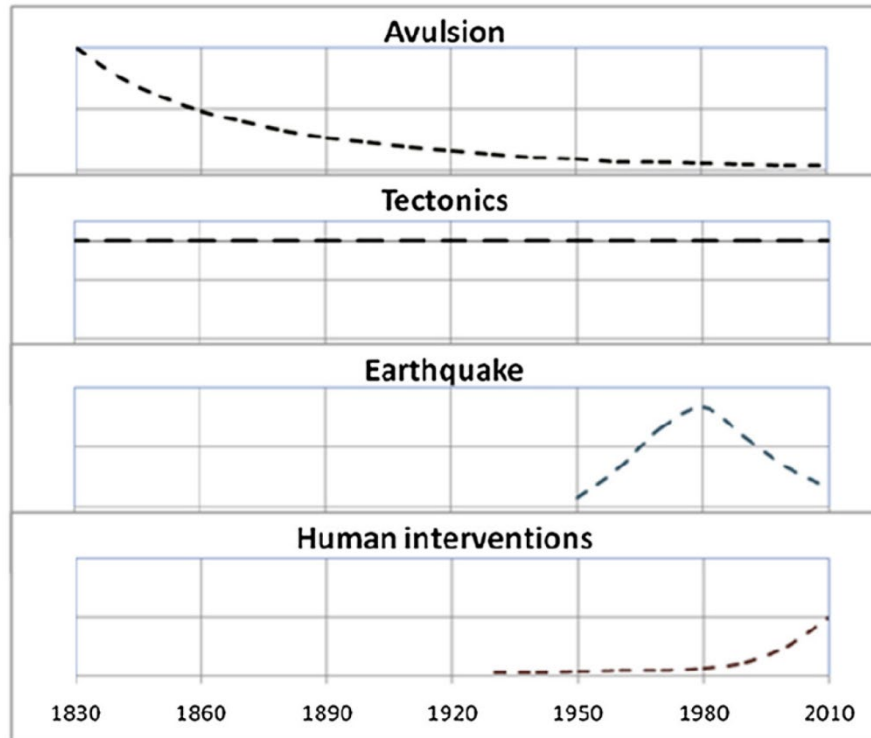

Figure 21.7. Schematic representation the influence of different drivers of morphological change in the Jamuna River. Avulsion was a strong driver during the 19th and early 20th Centuries, but has now diminished as the main channel has adjusted to the avulsion and very little flow still spills to the Old Brahmaputra. Tectonics continues to influence channel behavior, but may be a second order driver on decadal-century scale river channel change. The 1950 Assam Earthquake was an important driver during the second half of the 20th Century, but its influence has now diminished as the sand wave it generated has reached the Bay of Bengal. Human interventions had little impact on the Jamuna River prior to the 1980s, but their influence is growing from the local to the reach scale. (After Sarker *et al.,* 2014).

However, whilst accepting as indisputable that the sediment wave generated by the 1950 Assam earthquake had significant morphological consequences, RBIP (2015) contend other mechanisms can also explain the available data. In addition to the adjustments in width of the Jamuna River linked to its continuing adjustment to its avulsion from the Old Brahmaputra, and the influence of bank protection works, as both highlighted by Sarker *et al.,* (2014), RBIP (2015) argue that hydrologic variability was likely key in generating river widening. Although recognizing that the annual peak flow has not increased significantly through time, RBIP (2015) argue that the actual peak flows have oscillated in time, with particularly large flood peaks in 1974, 1988 and 1998. Data show that the period between the 1970's and late 1990's (and especially the mid-1980's to late 1990's) had higher peak flows than the periods on either side of this time. RBIP (2015) contend that the period of most rapid morphological change, and critically widening that influenced the entire length

of the Jamuna River and the upstream Brahmaputra River in Assam between 1972 and 1989, corresponded with a period of very high flow, and that the beginning of satellite coverage and measurements began in the relatively dry period (1970's) before this period of higher peak flows.

Using satellite images from 1967–2002, Takagi *et al*. (2007) showed that the temporal change in river activity and dynamics may fall into four distinct phases associated with alternating periods of quasi-dynamic equilibrium and more complex conditions. The transition between phases, such as the widening of the channel during the mid-1980's to early 1990's, may have been triggered by significant and frequent flooding events, such as the huge 1987 and 1988 floods. This contention also supports the significance of hydrological variability suggested by RBIP (2015).

Sarker (1996) and Bristow (1999) noted that the initial planform of the Jamuna after the 1770–1830 avulsion was meandering with a dominantly braided planform in its upstream reaches, and that a fully braided planform has only developed since then. Coleman (1969) surmised that, with the increase in discharge generated by the joining of the Teesta River, the Jamuna started to braid. The date at which, and if, the Teesta River joined the Jamuna is unclear, with Morgan and McIntire (1959) stating this was contemporary with the avulsion of the Brahmaputra River. However, the absence of the Teesta River in the 1828 map of Wilcox makes this uncertain (Figure 21.3a), and only in the map of 1860 is the Teesta River found as a tributary of the Jamuna River. However, maps of 1860 and 1914 show that the planform of the Jamuna River was predominantly meandering, with the presence of a braided planform in some upstream reaches. Coleman (1969) recognized three nodal points along the banks of the Jamuna River, one downstream of Bahadurabad, another near Sirajganj, and the third upstream of Aricha (Figure 21.1). In these areas, which have remained fixed for long periods of time, the river is relatively narrow and deep, and it has been proposed that cohesive clays, together with the slightly more resistant natural levee, do not allow the river to migrate freely here as in other areas (Coleman, 1969). Klaassen and Masselink (1992), however, rejected the existence of such nodal points. Thorne *et al*. (1993) also considered the composition of the bank materials along the Jamuna River to be uniform and that the banks are formed in weakly cohesive silty-sand, which is highly susceptible to erosion. However, they also state that clay deposits exist along the right bank at Sariakandi, 40 km upstream of Sirajganj (Figure 21.1), and in the left bank at Bhuapur opposite Sirajganj, although these locations are not the same as mentioned by Coleman (1969). An analysis of the banklines derived from satellite images over the past three decades does suggest the existence of non-erodible bank materials in the left bank around Aricha, which corresponds with the location of the most downstream nodal point identified by Coleman (1969). Except for this location, the characteristics of the bank materials along the Jamuna River appear largely invariant.

A slight deviation from this homogeneity in bank erodibility was noticed by EGIS (2002), who report that the erosion rate was higher along bends on the left bank than along right bank bends with similar geometrical characteristics. This feature was attributed to the westward migration of the Jamuna River, which leaves relatively unconsolidated bank materials along its left bank. Analysis of high-resolution satellite images and aerial photographs shows the scars of recent channels on the eastern bank of the Jamuna River, the size of which is comparable with the active channels along this bank. However, such scars are not visible along the western right bank, thus supporting the contention that the

river has migrated westwards. At present, the floodplains being eroded by the Jamuna River along its left (eastern) bank are newly formed, unconsolidated sediments, whilst those being eroded along its western, right bank comprise relatively old and consolidated floodplains. These consolidated floodplains are more resistant to erosion, and are also more fertile and productive than the unconsolidated and newly accreted floodplains along the left bank.

Recent studies have also illustrated the great potential of using remote sensing to examine large-scale bankline change within the Jamuna River. Baki and Gan (2012) used Landsat imagery between 1973 and 2003 and showed that the right bank underwent more erosion than the left bank, with the average erosion rate for short and long term analysis of the river being 207 and 83 m year^{-1} respectively. They also found that smaller river chars (< 50 ha) tended to be very unstable whereas islands larger than *c.* 150 ha tended to be more stable. Bhuiyan *et al.* (2015) examined images of the lower Jamuna River from 1973 - 2011 and found two main periods of bankline adjustment: one from 1972-1992, where channel planform changes were irregular, and a second phase between 1992 and 2011 where the channel change was unidirectional and to the east. The second phase was characterized by an average migration rate of 225 m year^{-1} that was three times the rate of the first phase. Bhuiyan *et al.* (2015) also suggest the influence of river training works on the channel, in that downstream of the Bangabandhu Bridge (see Chapter 21.7) the river was widening and shifting eastwards, whereas upstream of the bridge a westward migration was occurring.

21.3 BEDFORM TYPES AND DYNAMICS

Sediment within the Jamuna River is carried as bed, suspended and wash load, with the majority of the sediment being carried within the water column (Klaassen *et al.*, 1988). However, the bed load, although only ~10 % of the total sediment load, is critical in generating a wide array of bedforms of different scale that drive channel change and migration. Bedload transport occurs at all flow stages in the Jamuna and the role of high-stage flood flow and subsequent reworking, or modification, of the high-stage deposits becomes significant on the falling limb of the flood hydrograph. The synthesis presented herein splits bedforms into two scales: (1) smaller-scale bedforms that are a small fraction of the flow depth (ripples, upper-stage plane beds) or generally scale with flow depth [dunes, this also including the 'megaripples' of Coleman (1969)] and (2) bedforms that scale with the channel width and are usually a significant fraction of the flow depth (various types of bars). Figure 21.8 shows some examples of these bedforms and their sedimentary structures.

21.3.1 Small-Scale Bedforms (ripples, dunes and upper-stage plane beds)

Recent work has shown that sand dunes are the predominant smaller-scale bedform within the Jamuna at all flow stages and in all parts of the channel (FAP24, 1996g; Roden, 1998): they thus form the nucleus of many larger scale bars (see below) and are a key component of the sedimentary facies (Best *et al.*, 2003). Surveys over a 2-year period at Bahadurabad and Sirajganj (Figure 21.9) show that over 40 % of the bed is occupied by dunes at any flow stage, and this figure may rise to nearly 100 % (Roden, 1998). Ripples and smaller dunes are commonly superimposed on larger dunes, but upper-stage plane beds are rare

and largely restricted to fast, shallow flows on bar-tops. Dune height and wavelength, plotted from a database of 1400 measurements at three sites (Figure 21.8a,b), range from 0.10 to 6 m (Figure 21.8a,b,c) and 2 to 331 m respectively. Both distributions are log-normal and the form index of the dunes (height/wavelength) ranges from 0.0005 to 0.27 (Figure 21.10c). The leeside slope angle of these dunes (Figure 21.10d) shows a wide spread from 1 to 58° (steeper than the angle-of-repose probably due to intense eddying in the leeside), with a mean of 8.4°. This demonstrates that many dunes do not possess an angle-of-repose leeside and may be of a form that does not generate permanent flow separation in the leeside, as has been demonstrated in other large rivers (Smith and McLean, 1977; Kostaschuk and Villard, 1996; ten Brinke *et al*., 1999; Best *et al*., 2001; Best and Kostaschuk, 2002). This finding is of considerable importance in considerations of dune form factor and estimates of flow resistance in alluvial channels, since previous work (Ogink, 1988) has demonstrated that a considerable reduction in roughness height is present for low-angle dunes due to the lesser effects, or even absence, of permanent flow separation in the dune leeside (Best and Kostaschuk, 2002). Plots of the form index of dunes (Figure 21.11) as a function of leeside slope shows the form index is lower at lower leeside slopes: for the average slope of 8.4°, the contribution to the form roughness would decrease to ~45 % of the value for an angle-of-repose dune, whereas for a leeside slope of 4.5° this decrease would be to ~10 % (see figure 4.1 in FAP24, 1996c). These figures thus demonstrate that the contribution of dune-related roughness to total roughness may be much smaller than considerations based solely on dune height (FAP24, 1996c; Cisneros *et al*., 2020), a conclusion also reached by Klaassen *et al*. (1988). Additionally, these data suggest that the shape of the dune must be quantified accurately if bedform tracking is to be used as a method for estimating bedload transport (FAP24, 1996g). Ideally this should include quantification of both the dune profile and three-dimensional planform morphology, as available from side-scan sonar (Figure 21.12) or developments in multibeam echo sounding (Parsons *et al*., 2005; Cisneros *et al*., 2020).

Plots of dune height and wavelength against flow depth (Figure 21.13) show a wide scatter but illustrate that maximum dune height approximates 0.25–0.33 of the flow depth, and that dune wavelength is generally less than seven times the flow depth (Julien and Klaassen, 1995). The scaling of maximum dune height with flow depth fits well with past work (Jackson, 1976; Best, 1996), with the smaller dunes either being present under non-equilibrium conditions or growing in response to the boundary layer thickness developed by larger dunes or bars. The planform of the dunes is often both two- and three-dimensional (Figure 21.12). Dune superimposition is ubiquitous, with the height of the secondary dunes generally becoming larger with the size of the primary dune (Figure 21.14) and showing superimposition on the stoss side, shoulder and leeside of the primary dunes, again confirming the absence of permanent large-scale flow separation in some leesides. This also highlights the likelihood of downstream dipping accretion surfaces, with superimposed smaller cross-stratification, being preserved in the depositional record. Analysis of dune dimensions through the flood hydrograph (Figure 21.15) shows that generally both dune height and wavelength increase with flow velocity, although both positive and negative hysteresis loops are present. However, the form factor of the dunes shows little change and there is little tendency for dunes to flatten as velocity rises: this again demonstrates that the majority of flows within the Jamuna River generates bedforms within the dune stability field and not in the transitional regime to upper-stage plane beds,

except in shallow flows on bar-tops (Bristow, 1993a; Julien and Klaassen, 1995; FAP24, 1996a,g; Figure 21.8e). Dune migration rates range from 1.1 to 16.8 m h^{-1} for dunes that range in height from 1 to 6 m (FAP24, 1996c), although from this limited database there is no indication of any strong link between dune height and migration rate.

Figure 21.8 Examples of different bedforms and sedimentary structures found within the Jamuna River. (a) Small-scale (up to 0.3 m high) three-dimensional dunes; (b) large-scale (up to 3 m high) dunes; (c) dune cross-stratification in a 4 m high cutbank; (d) climbing ripples; (e) topset, bottomset and foresets preserved in a sand dune in the transitional regime to upper-stage plane beds; the topsets consist of upper stage plane-beds, whilst the toesets contain counter-current ripples, with current ripples below overlying upper-stage plane bed laminae. Reprinted from Braided Rivers, Eds Best, J.L. and Bristow, C.S., Bristow, C.S.; Sedimentary structures in bar tops in the Brahmaputra River, Bangladesh, pp. 277–289, 1993, with permission from the Geological Society of London.
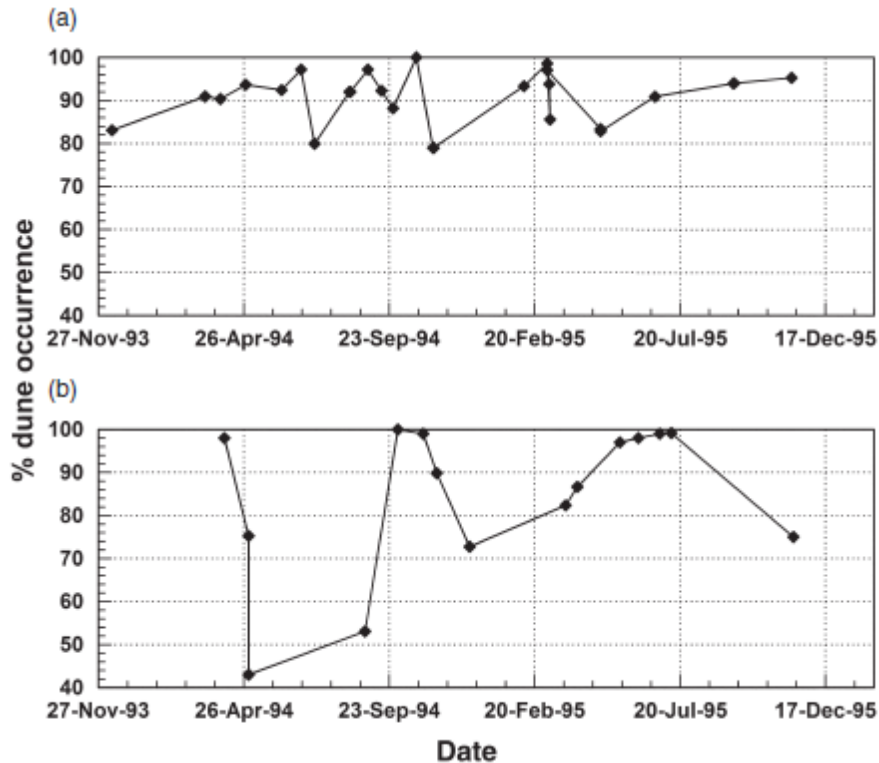
Figure 21.9 Percentage occurrence of dunes in the main channels of the Jamuna River at (a) Bahadurabad and (b) Siraganj, November 1993–December 1995 (from FAP24, 1996g).

The large dunes present in the Jamuna have also been described in relation to their mean flow field (FAP24, 1996g; Roden, 1998) and macroturbulence, the latter often seen as eruptions or 'boils' on the water surface (Figure 21.16; Coleman, 1969; Roden, 1998; Best, 2005). Such large-scale turbulence is related to upwellings of fluid over the dune troughs (Figure 21.8b) and has been linked to (1) eddy shedding of Kelvin–Helmholtz instabilities generated along the separation zone shear layer of steep leeside angle dunes, and (2) temporary shear layer development, and possible temporary flow separation (Best and Kostaschuk, 2002) in the lee of low-angle dunes, or in response to temporary dune oversteepening, possibly as a result of the migration and amalgamation of superimposed dunes (FAP24, 1996g).

Besides dunes, two other small-scale bedforms are present in the Jamuna: ripples (Figure 21.8d) and upper-stage plane beds (Figure 21.8e). Ripples are also ubiquitous and found both superimposed on dunes and also commonly on the bar-tops. The ripples on bar-tops may often be preserved as climbing ripples (Figure 21.8d) with high angles-of-climb, demonstrating the occurrence of high sedimentation rates (Bristow, 1993a). Aeolian erosion and sand transport, as ripples and small barchanoid dunes, may rework the top 0.1–0.5 m of bar surfaces during periods of exposure.

21.3.2 Large-Scale Bedforms (bars and bar complexes)

The Jamuna River contains two different scales of larger bedforms that may be termed 'bars' and 'islands' (Thorne *et al.*, 1993). Bars have lengths of the same order or greater than the channel width and heights that are comparable with the mean depth of the

generating flow (ASCE, 1966). Islands are vegetated, relatively stable, large bar complexes (known locally as 'chars'), up to 15 km in length and with heights up to the adjacent floodplain level. Bars are frequently found attached to these islands but more commonly within the anabranches that bifurcate around the node–island–node configuration that appears to dominate the downstream configuration of the active Jamuna channel belt (Figure 21.1). The Jamuna contains all sizes of sand bars ranging from tens of metres to several kilometres in length. Recent work has suggested the surface geometry of bars in the Jamuna (expressed as the ratio of long-to-intermediate bar axis) and some aspects of the subsurface facies associated with these bars may be scale independent and share many of the morphological and sedimentological characteristics of other sandy braided rivers (Best *et al.*, 2003; Sambrook Smith *et al.*, 2005).
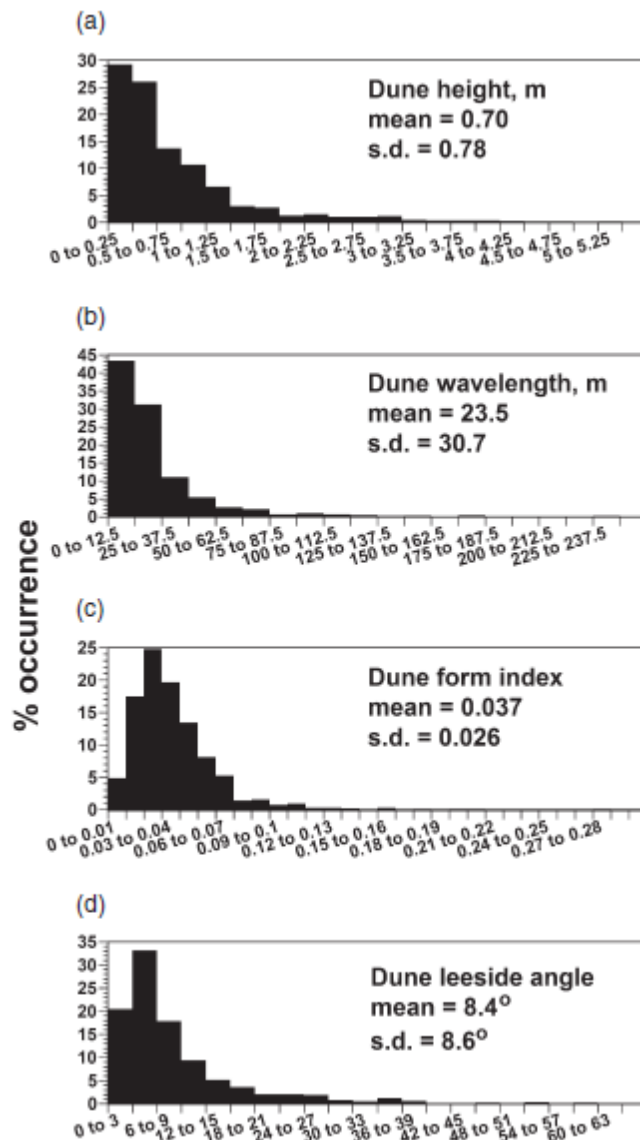
Figure 21.10 Histograms of (a) dune height, (b) dune wavelength, (c) dune form index (height/wavelength) and (d) dune leeside angle, from three study sites in the Jamuna River (from FAP24, 1996g and Roden, 1998). Sample size = 1400 dunes
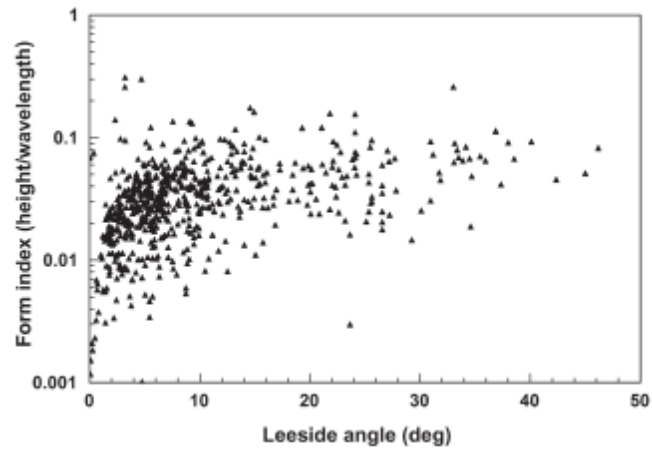
Figure 21.11 Form index of dunes in the Jamuna River as a function of leeside angle (from Roden, 1998)
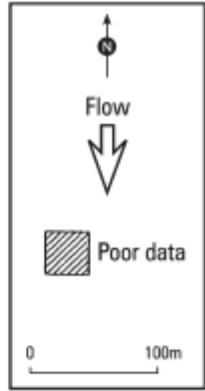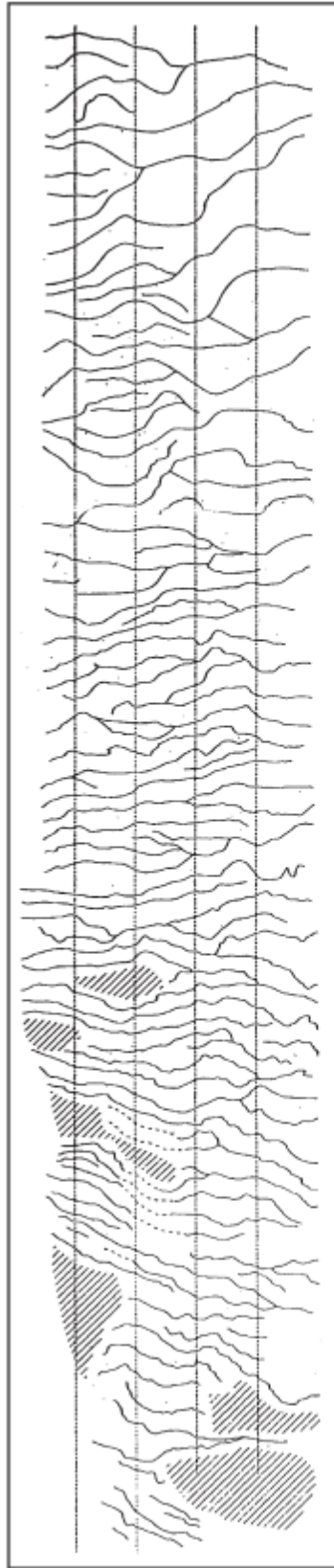
Flow

Poor data

0   100m

Figure 21.12 Composite tracing of dune crestline planform morphology as derived from sidescan sonar data collected in March 1995 near Bahadurabad (from FAP24, 1996g and Roden, 1998).
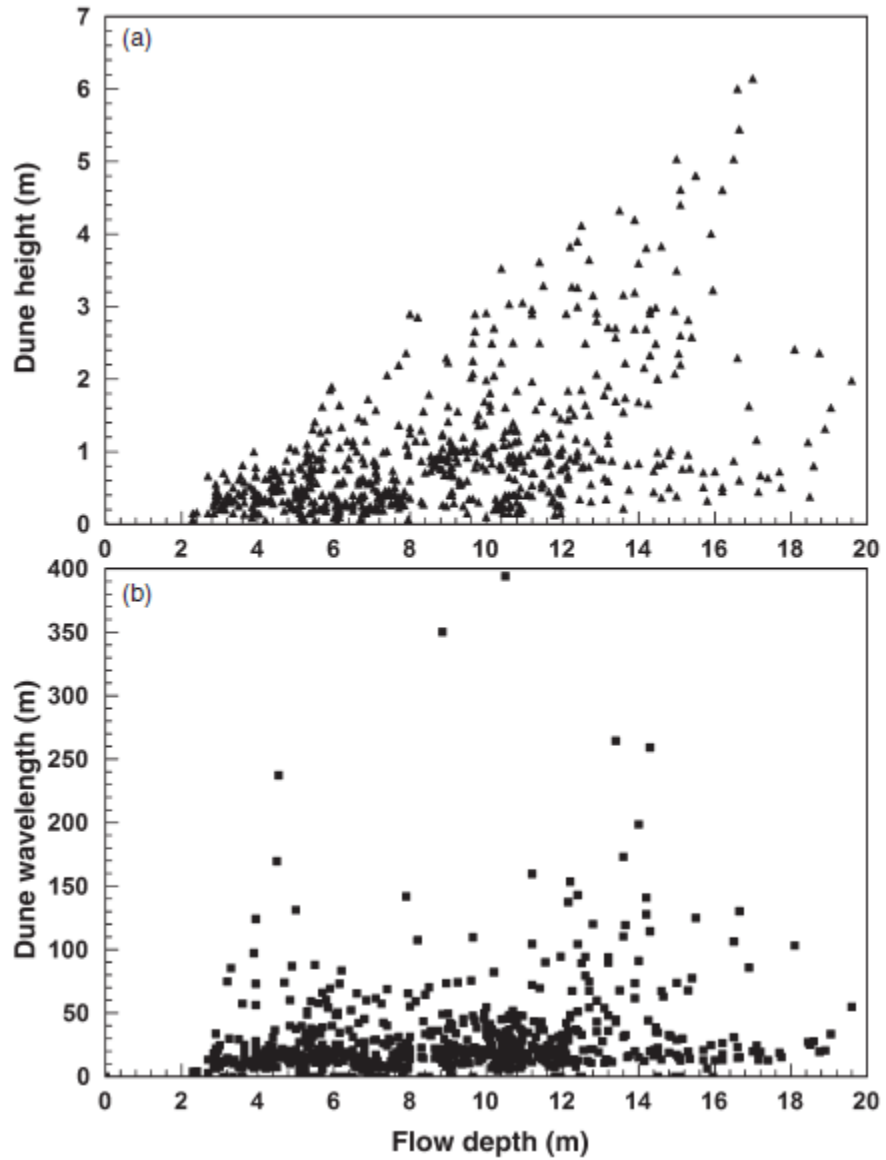

Figure 21.13 Plots of (a) dune height and (b) dune wavelength as a function of flow depth (from FAP24, 1996g).
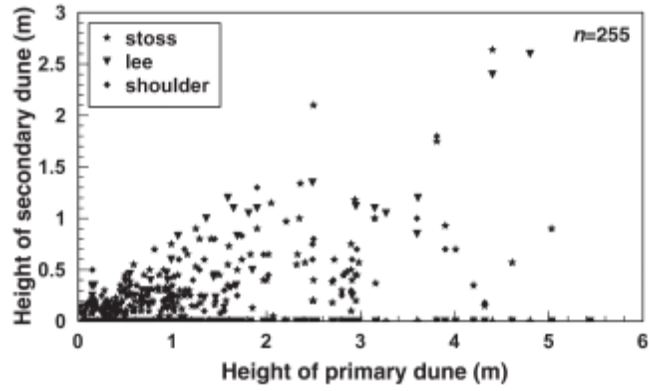
Figure 21.14 Plot of primary dune height against height of secondary dunes that are superimposed on the primary dune. The symbols denote the position on the primary dune where the secondary dunes are superimposed (stoss side, leeside and on crestal shoulder; from FAP24, 1996g).
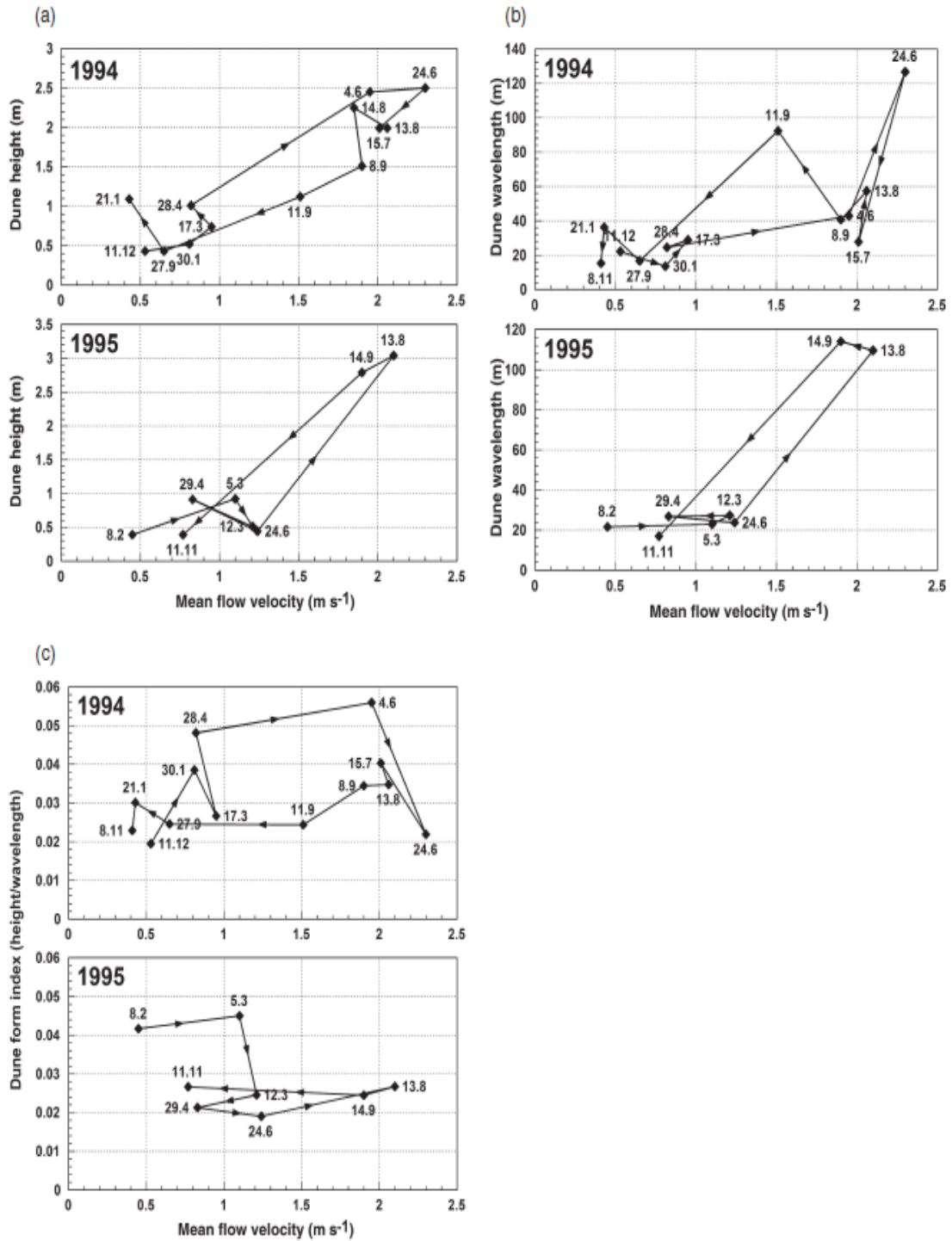
Figure 21.15 Hysteresis plots for 1994 and 1995 hydrographs at Bahadurabad (see Figure 21.1 for location) for (a) dune height, (b) dune wavelength and (c) dune form index as a function of mean flow velocity (as derived from acoustic Doppler current profiling records). Numbers on graphs refer to day and month of each data point (from FAP24, 1996g).

The most common bar types are the scroll (or point) bar and mid-channel (compound braid) bar (Bristow, 1987; Ashworth *et al*., 2000). Bridge and Lunt (2006) suggest that

mid-channel bars in the Jamuna River develop from double-row alternate bars (Fujita, 1989; Yalin, 1992) which create a 'unit bar' (Bridge, 1993, Figure 1), although no data are presented to substantiate this hypothesis. Ashworth *et al.* (2000) tracked the development of a 1.5 km long, 0.5 km wide, 12 m high, symmetrical mid-channel bar over a 28-month period in a major anabranch of the Jamuna near Bahadurabad (Figures 21.1 and 21.17) and noted that the bar was probably initiated by the stalling and amalgamation of dunes in the main channel thalweg. Supporting evidence for this mode of bar initiation was displayed in Best *et al.* (2003) using Ground Penetrating Radar (GPR) that imaged the subsurface of the same bar down to 12 m and revealed stacked two- and three-dimensional dunes at the base of the bar. Many mid-channel bars in the Jamuna enlarge (both up-, down- and across-stream) by the addition of smaller unit bars. Bristow (1987) calculated that up to 57 % of the total area of bar deposition in the Jamuna may be through lateral accretion by the successive addition of individual unit or scroll bars to the bar nucleus. Unit bars are dominated by dunes whose crestlines are often oblique to the local anabranch direction (Bridge, 1993). Mid-channel bars in the Jamuna often develop downstream extensions to the bartails that have been termed 'horns' (Cant and Walker, 1978), 'limbs' (Ashworth, 1996) or 'wings' (EGIS, 2002) that may extend for up to 50 % of the bar length.

Figure 21.16 Macroturbulence erupting on the water surface of the Jamuna River near Bahadurabad: this locality was above a field of 3–4 m high dunes at the time of survey (Best, 2005). Flow left to right, and flow depth ~15 m.

Surprisingly, the Jamuna River does not display many examples of the 'cross-channel bar' that features strongly in the 'classic' sand braid bar depositional model of Cant and Walker (1978). Many of the kilometre-wide anabranches are devoid of near-emergent lobate unit bars (Figure 21.16a–c) which is very different from observations of many other sand-bed braided rivers (e.g. Platte, South Saskatchewan; cf. Sambrook Smith *et al.*, 2006). Width-depth ratios of the main anabranch channels are predominantly over 100 (up to 700, cf. Thorne *et al.*, 1993) and can result in a simple flow convergence and divergence around and over bartops, rather than the development of single- and double-cell secondary flow circulation in the anabranches around bars (cf. Richardson and Thorne, 1998; McLelland *et al.*, 1999; see Section 21.4).

Figure 21.17 shows a model for sand braid-bar growth in the Jamuna from Ashworth *et al.* (2000) based on 12 ship and land surveys, taken in the period 1993–1996, in a 9 × 2.5 km area immediately north of Bahadurabad (location in Figure 21.1). The model shows the

creation of a central, symmetrical mid-channel bar from dune stacking in the channel thalweg (stages 2–3, Figure 21.17), followed by the enhanced development of one anabranch around the bar (stages 4–5, Figure 21.17), which then creates a lobate depositional front (stage 6, Figure 21.17) and an overall planform that resembles an alternate bar rather than a central unit braid bar. The availability of annual low-flow Landsat imagery since 1996 (represented by stage 6 in Figure 21.17) has allowed us to evaluate the longer-term stability and development of this particular kilometre-scale bar.

Figure 21.18a shows the morphology for the study reach at the end of the monitoring period described in Ashworth *et al*. (2000, their figure 5f: p. 540). The emergent mid-channel bar (labelled 1) had a 1 km long bartail and a discontinuous lobate bar front (labelled 2), but there was also deposition of a 3 km long mid-channel bar 2.5 km upstream (labelled 3) and side bars (labelled 4). Figure 21.18b shows that at low flow in 1997 the mid-channel bar under surveillance (labelled 1) appears to have migrated downstream by 3 km but maintained the same overall size and morphology. The lobate bar front (labelled 2) remained in place and became emergent, showing it was not an integral part of the mid-channel bar morphology as suggested in Ashworth *et al*. (2000). The study reach experienced downstream and lateral accretion of both bars 3 and 4. By 1998 (Figure 21.18c), the mid-channel bar had either been completely reworked or migrated downstream to accrete onto a bar complex (labelled 5). Bars 3 and 4 continued to grow but the 2 km wide main anabranch was essentially devoid of any partially emergent or newly developing mid-channel bars. Together with the survey data presented in Ashworth *et al*. (2000), this example of channel evolution near Bahadurabad illustrates that kilometre-scale bars may have a life-cycle of about 5 years (i.e. more than one flood season but then of limited duration). Mid-channel bars may maintain their basic morphological shape during development even when they migrate kilometres downstream. The annual record of bar evolution shown in Figure 21.18a–c illustrates that in a river the size of the Jamuna, even kilometre-scale bars are extremely mobile and may be transient features in the braidplain depositional record.
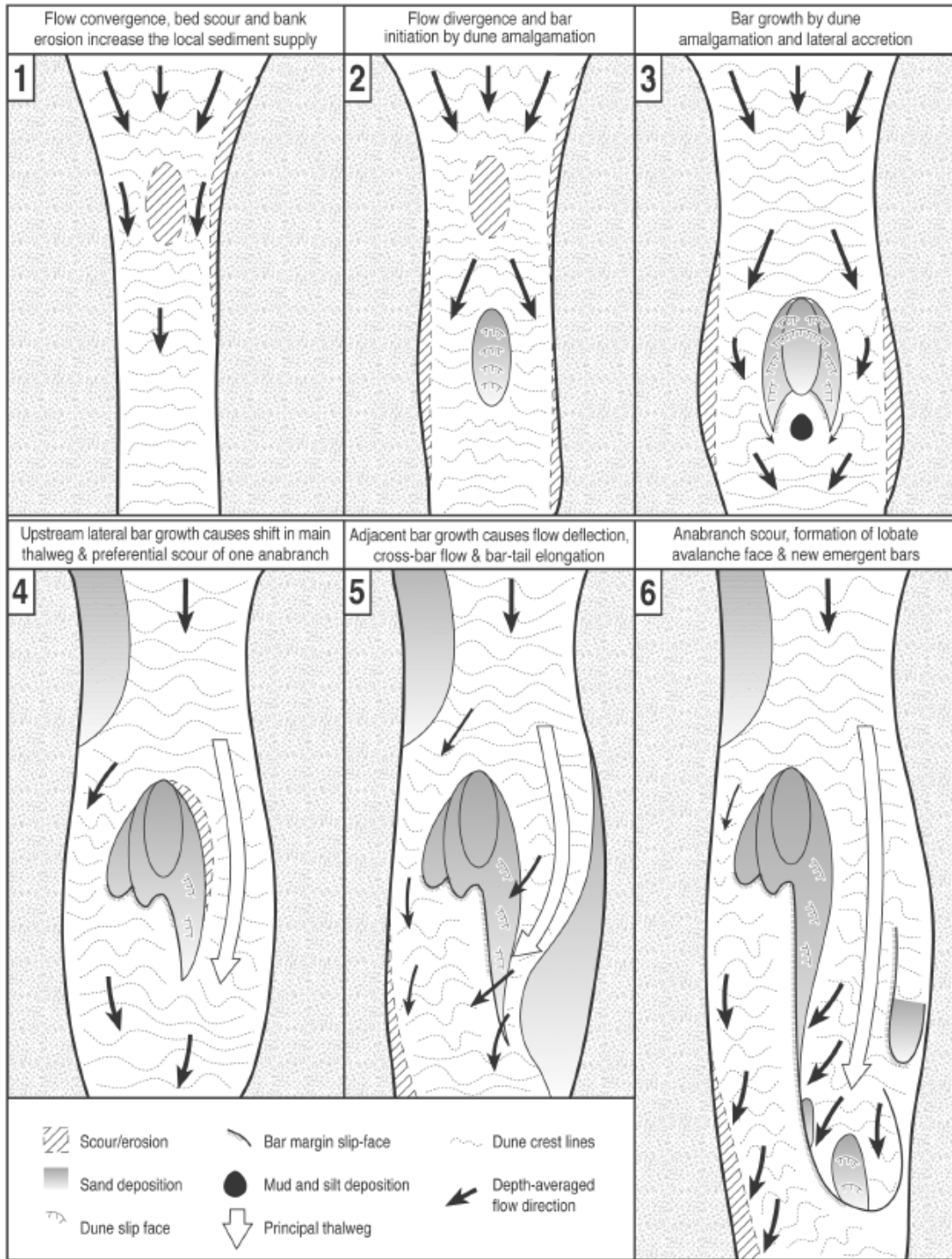
Figure 21.17 Summary model of the key stages in the evolution of a kilometre-scale mid-channel sand bar. Dune orientations and flow directions at the bed are inferred from the data presented in Roden (1998) and McLelland *et al.* (1999). Reprinted from Sedimentology, Vol. 47, Ashworth *et al.* Morphological evolution and dynamics of a large sand braid-bar, Jamuna River, Bangladesh, pp. 533–555, 2000, with permission from Blackwell Publishing
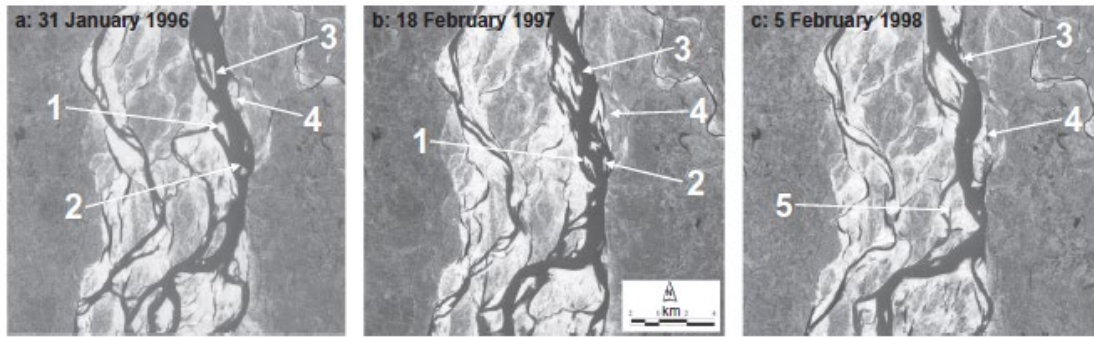
Figure 21.18 (See also colour plates.) Morphological evolution of the reach studied by Ashworth *et al.* (2000) at Bahadurabad: (a) January 1996 (which represents stage 6 in Figure 21.15); (b) February 1997; (c) February 1998.

21.4 BIFURCATIONS, OFFTAKES AND CONFLUENCES

Within the Jamuna River, the ubiquitous occurrence of bifurcations and confluences is a key aspect of the river channel pattern and dynamics, and these features form important nodes in the braidbelt. The braided nature of the river means that these nodes are present at a range of scales and orders of channel, and are central in dictating local and channel-wide erosion, deposition and morphological change.

Bifurcations occur as flow divides around the numerous braid bars and there has been much debate concerning the nature of flow within the distributaries, with Richardson *et al.* (1996) and Richardson and Thorne (2001) favouring a model that considers the flow similar to two back-to-back meander bends with helical flow developing at the bar-head. However, McLelland *et al.* (1999) argue that the main features of flow at the barhead bifurcation are convective acceleration as the flow shallows and modification of the primary flow caused by bedforms; they reason that these features, together with the high width : depth ratio of the channels and high relative roughness of dunes, cause a simpler flow pattern to that proposed by Richardson and Thorne (1998, 2001), with simple flow divergence around the barhead bifurcation.

EGIS (2002) report that of the 121 bifurcations considered in their study, 49 % were symmetrical in planform whilst 51 % were asymmetrical, and that the magnitude and direction of bifurcation migration were independent of angle asymmetry. EGIS (2002) further detail that 17 % of the bifurcations migrated upstream whilst 83 % either remained static in position or migrated downstream. The rate of migration of bifurcations in the Jamuna ranges from -2200 to 3000 m year^{-1} (EGIS, 2002), whilst the length of the bifurcation, defined as the distance from bifurcation to confluence, varies between 2 and 40 km (EGIS, 2002). An important consideration in the evolution of bifurcations is the probability of channel abandonment of one of the distributaries, a process that is common in development of asymmetrical braid bars (Ashworth *et al.*, 2000). Klaassen *et al.* (1993) and Mosselman *et al.* (1995) found that higher angle bifurcations are associated with higher rates of channel abandonment (Figure 21.19), with bifurcation angles <20° being very stable. Shampa and Ali (2019) also illustrate the influence of bifurcation angle of flow division at these nodes, with higher angle bifurcations (>30°) sharing a smaller fraction of the total flow being routed into one of branches, thus favouring abandonment.
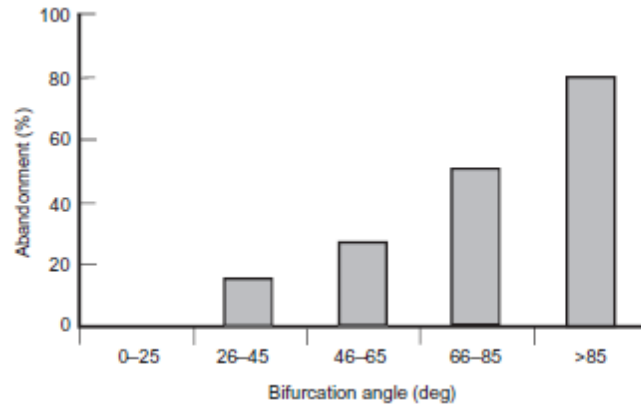
Figure 21.19 Distribution of channel abandonment as a function of bifurcation angle for bifurcations without appreciable barforms. Reprinted from EGIS, Developing and updating the empirical methods for predicting the morphological changes in the Jamuna River, 2002, with permission from CEGIS (original references for data: Klaassen *et al.* (1993) and Mosselman *et al.* (1995)).

Besides bifurcations around braid bars, channel offtakes, which are more permanent divisions of flow, are key elements of the river morphology in Bangladesh. The dynamics of such offtakes have undoubtedly been of great significance during channel avulsions, such as: (1) the occupation of the current Jamuna channel and abandonment of the Old Brahmaputra (Figures 21.4 and 21.5), (2) the division of flow from the Jamuna into the Dhaleswari, and (3) the current concern regarding the flow reduction and infilling of the Gorai channel which is an offtake from the Ganga just upstream of the Jamuna-Ganga confluence (Figure 21.1). The reduction in flow discharge down the Gorai River over the past decades has meant that during low flow the south-western region of Bangladesh receives much less fresh water, and therefore there is greater intrusion of the saline wedge from the Bay of Bengal into the distributary channels – a factor that has changed the livelihood of largely rural subsistence farmers (Alam, 1984). Study of the Gorai offtake (FAP24, 1996f) using historical data, satellite images and two-dimensional morphological modelling, highlights the influence of curvature in the upstream Ganga channel in affecting flow at the offtake and also the significant influence of flow stage in determining the division of flow. Rising flow stages appear to favour shallowing and widening of the channel at the offtake and during falling stage the channel becomes narrower and deeper. However, the influence of large, severe floods is significant and sediment accumulation in a bar at the mouth of the offtake generated during a very high flow can remain during subsequent years of normal floods (FAP24, 1996f).

Channel confluences are also key sites within the Jamuna, and have been documented as important sites of bed scour (Klaassen and Vermeer, 1988; FAP24, 1996a; Best and Ashworth, 1997; EGIS, 2002; Dixon *et al.,* 2018; Sambrook Smith *et al.,* 2019). The depth of the central confluence scour shows some dependence on the junction angle (Figure 21.20), with higher confluence angles possessing scour depths up to six times that of the confluent channels. Local factors, such as hydrograph shape, upstream channel curvature and low-stage modification may make this junction angle–scour depth relationship more complex, but the predictive equation of Klaassen and Vermeer (1988) is a reasonable estimate of scour depth (Sarker, 1996), and is given by:

$$h_{cs}/h = 1.292 + 0.037\theta$$

where h_{cs} is the confluence scour depth, h is the mean flow depth of the upstream channels and θ is the junction angle in degrees. Additionally, recent work comparing Jamuna scour data with other rivers in the World (Sambrook Smith *et al.*, 2005) has suggested that scour depth relative to mean channel depth may be scale invariant over a threefold order of channel depths. Detailed bathymetric maps of the Jamuna-Ganga junction have shown the scale and rapidity of bed morphological change (Best and Ashworth, 1997), with the 30 m deep confluence scour migrating 2 km in two flood seasons (Figure 21.21). Dixon *et al.* (2018) analyzed satellite images from 1973-2014 and found that the junction between the Jamuna and Ganges rivers responded to changes in the north-south migration of the Ganges River at the junction, as well as periodic changes to the orientation and position of the dominant thalwegs in the Jamuna River. Consequently, over this 40-year time period, the confluence encompassed a region 14 km long and 4.2 km wide.

21.5 FLOODPLAIN SEDIMENTATION

ISPAN (1995) provide a summary of sedimentation on the Jamuna floodplain, where most land is seasonally flooded, and which is characterized by an irregular relief. The nature of floodplain sedimentation and inundation is vital in planning annual crop growth and may adopt great significance in the ongoing debate on the sources, causes and accumulation of arsenic in the groundwaters of Bangladesh [see Ahmed *et al.* (2004) for a review]. ISPAN (1995) define several principal types of relief within the Jamuna floodplain (Figure 21.22):

1. Bars, scroll bars and sand dunes: generated by flood waters at the edge of the floodplain, often on the margins of the main or cross-floodplain channels. The difference in elevation between the top and bottom of this channel topography is rarely more than 1–2 m.
2. River levees: found along the edges of the active channels and formed by deposition from overbank flow, with grain size and deposition rate decreasing exponentially with distance from the channel. The height difference between the levee top and surrounding floodplain can be ~1 m over a distance of 100 m along small channels, but 2–3 m over 500 m or more alongside the major channels.
3. Crevasse splays: initiated due to a breach in the levee that forms a lobe of sediment which progrades onto the adjacent floodplain. The grain size of this crevasse splay decreases with distance from the initial breach.
4. Flood basin: nearly enclosed depressions between the levees of adjacent rivers that usually drain out through small channels on their downstream side. Subsidiary levees can form along these smaller channels and the flood basins may contain silts and clays that settle out in quiet water, whilst more permanently flooded areas in older floodbasins contain peat accumulations.

The older parts of the floodplain thus become more complex in topography (ISPAN, 1995), with the initial topography being smoothed out but with clay deposits up to 1 m thick. Elevation differences are generally 2–3 m over a lateral distance of 0.5–1 km. Soils within the Jamuna floodplain change from east to west, from stratified alluvium on the active Jamuna floodplain to soils with well-developed profiles on the older floodplain and Old Brahmaputra. The main changes in soil-forming processes across this transect from east to west (Figure 21.23) involve increasing acidification, destruction of clays and

accumulation of organic matter, with the soils increasingly displaying greater biotic mixing, mottling, coatings around peds and developing soil structure.
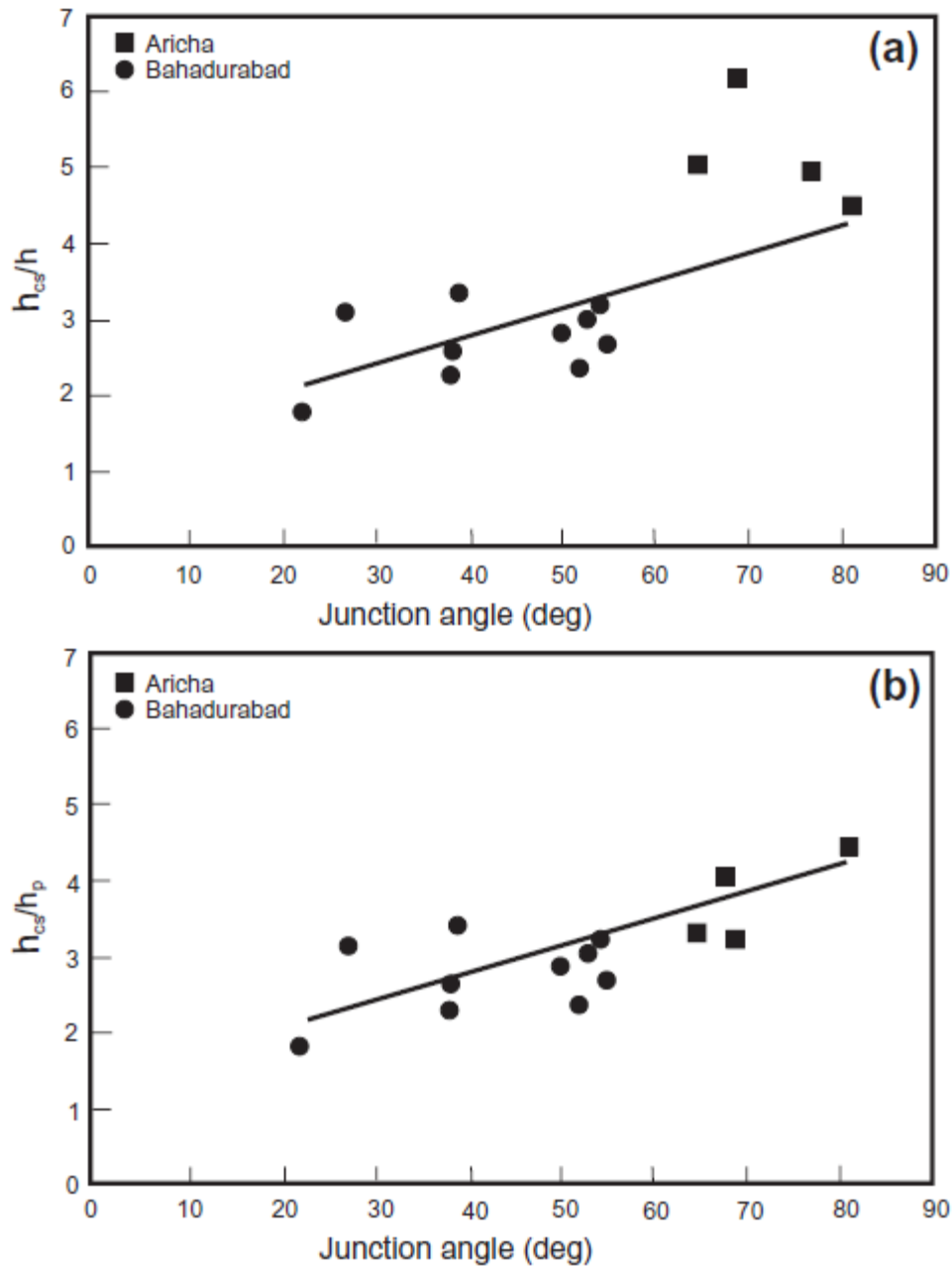

Figure 21.20 Confluence scour depth as a function of junction angle for data collected on the Jamuna river at Bahadurabad and Aricha: (a) with scour depth, h_{cs}, expressed in relation to flow depth at the time of measurement, h; (b) with scour depth, h_{cs}, expressed in relation to average flow depth in the upstream channels during the flood season, h_p. (b) shows a better relationship between junction angle and flow depth (from FAP, 1996d)

The depth of floodplain inundation is critical to farmers as this determines the annual cropping pattern and which type of rice will be grown. A classification of inundation on

the floodplain (Table 21.1) shows the normal water depths in various categories of floodplain, although the effects of local ground subsidence (for instance earth-quakes) and flood protection schemes, such as localized embankments that may increase flood inundation levels outside the embankments, may change the local floodplain water depths. ISPAN (1995) report average annual sedimentation rates of 7.6 mm year^{-1} obtained from a GIS study, with a range from 0 to 76 mm year^{-1}. Allison *et al*. (1998) also report accumulation rates of ~40 mm year^{-1} on the levees to <10 mm year^{-1} within a few tens of kilometres into the floodplain flood basin. Allison *et al*. (1998) state that the important controls on local sedimentation rate are proximity to distributary channels, local topography and interannual variability of the flood pulse. Model results suggest that between 31 and 71 % of the total alluvial sediment budget may be trapped landward of the Ganga-Brahmaputra mouth, and highlight the key role of floodplain storage in controlling the sediment yield to the oceans (Allison *et al*., 1998). Islam *et al*. (1999) estimate that ~49 % of the total load is deposited before the coastal region, with 28 % being deposited on the floodplain and 21 % within the active channels. Islam *et al*. (1999*)* contend this deposition thus leads to significant aggradation within the channels as well as on the floodplain.
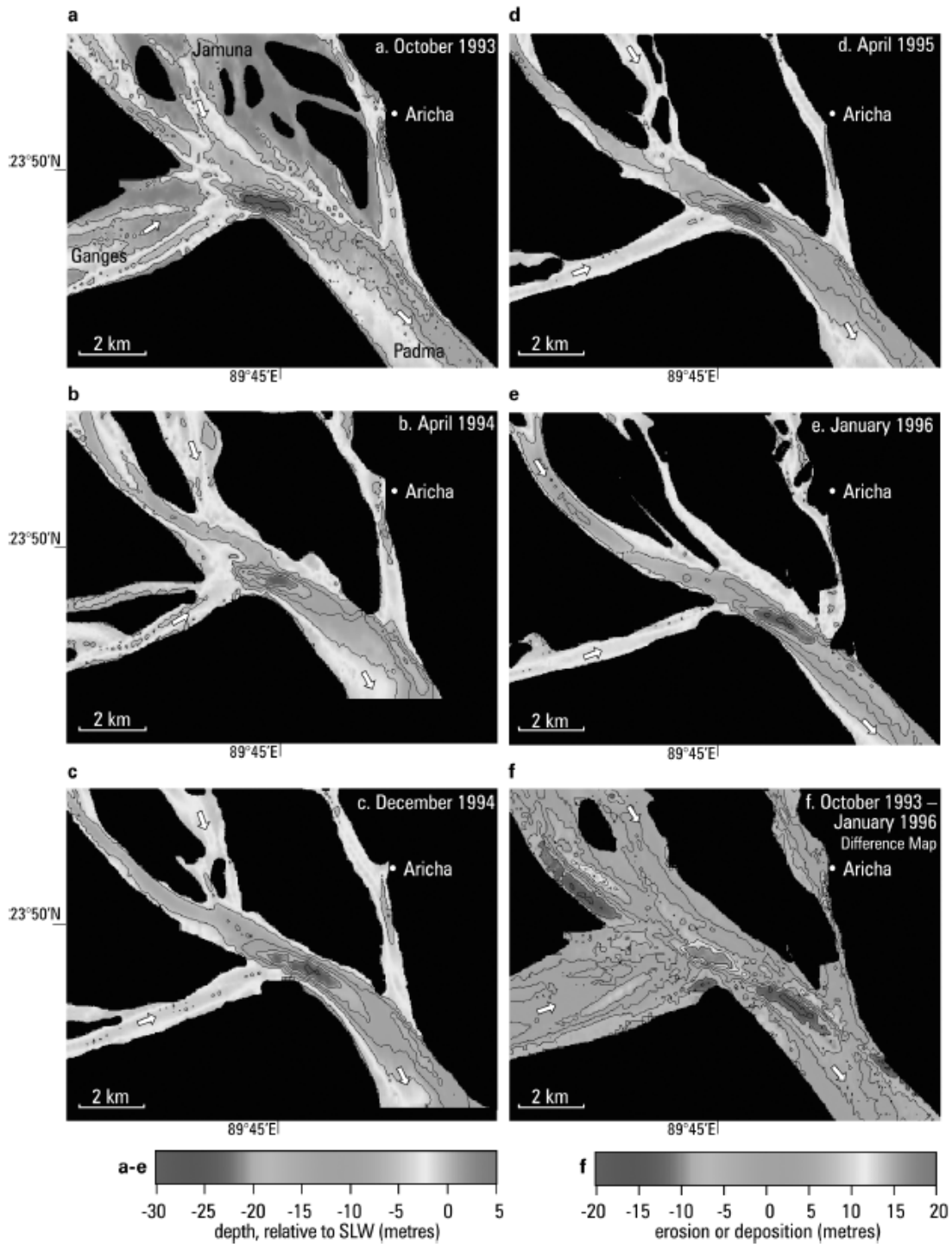
Figure 21.21 (See also colour plates.) Plots of bed morphology and channel change at the junction of the Jamuna and Ganga Rivers. SLW refers to Standard Low Water level. Reprinted by permission from Macmillian Publishers Ltd: Nature, Vol. 387, Best, J.L. and Ashworth, P.J., Scour in large braided rivers and the recognition of sequence stratigraphic boundaries, pp. 275–277, 1997.
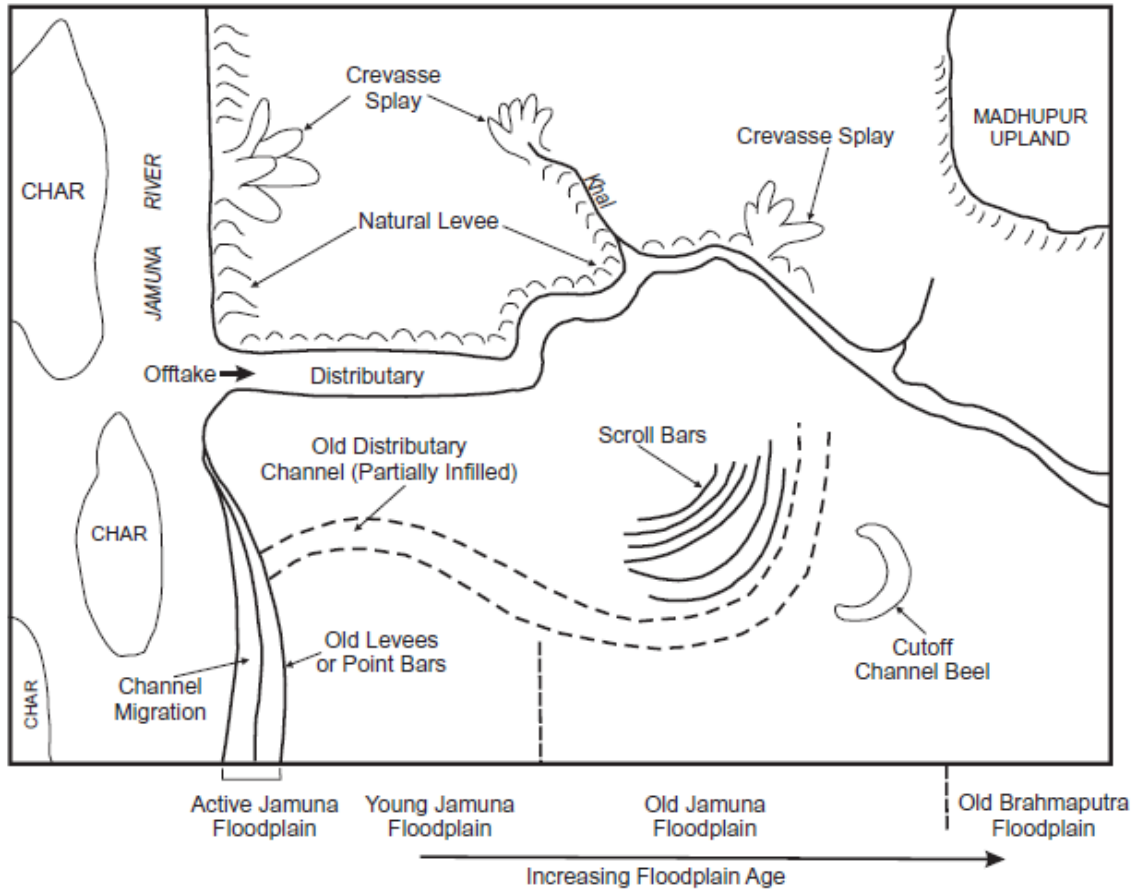
Figure 21.22 Representative landforms of the Jamuna floodplain. Reprinted from ISPAN, A study of sedimentation in the Brahmaputra-Jamuna floodplain, 1995, with permission from CEGIS.
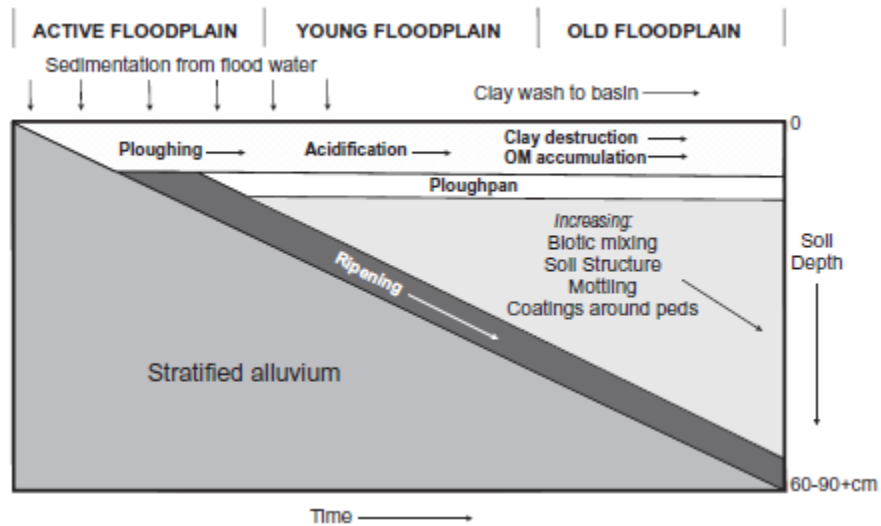

Figure 21.23 Stages of floodplain soil development in Bangladesh (after ISPAN, 1995). See text for discussion of lateral changes in soil characteristics. Reprinted from ISPAN, A study of sedimentation in the Brahmaputra-Jamuna floodplain, 1995, with permission from CEGIS.

Table 21.1 Classification of floodplain water depths (after ISPAN, 1995).

Agro-ecological zone	Normal maximum water depth during flood (cm)
Highland	0
Medium highland-1	0–30
Medium highland-2	30–90
Medium lowland	90–180
Lowland	180–300
Very low lowland	>300
Bottomland	Mainly >300, but includes perennial wetland in other depth classes

The nature of the annual flood hydrograph exerts a strong control on the grain size of floodplain sedimentation, and hence the contribution to soil fertility and subsequent crop success. For example, the large floods of 1998 and 2004 were very different, with overbank flows experienced for 65 and 45 days respectively (CPD, 2004). The nutrient-rich silt deposited during the longer duration 1998 flood led to a record *boro* rice crop the next year (BDER, 2004). However, the relatively fast-rising and receding monsoon flood in 2004 resulted in more overbank sand than silt deposition, and there was concern as to the impact this would have on the 2005 rice yields (BDER, 2004).

21.6 SEDIMENTOLOGY OF THE JAMUNA RIVER

The surface geomorphology of the braided Jamuna River, together with descriptions of the numerous cutbanks and more recent use of ground-penetrating radar, allows an insight into the depositional facies of the Jamuna. The principal papers concerning the sedimentology of the Jamuna are those of Coleman (1969), Bristow (1993a) and Best *et al*. (2003) and these are used below to highlight the depositional form of a braid bar within the Jamuna River. The Jamuna River has also been used as an analogue for deposition in other large ancient braided channels (e.g. see Bristow, 1993b; Miall and Jones, 2003) and thus description of a facies model is important for reconstructions of ancient alluvial architecture. Sambrook Smith *et al.* (2019) also examined the sedimentology of river channel confluences and used geophysical data from the Jamuna River to illustrate the internal structure of these bars. Best *et al*. (2003), using a combination of detailed ground penetrating radar (Figure 21.24) and trench/core logging tied into surveys over an evolving, newly formed mid-channel braid bar (Ashworth *et al*., 2000), document four principal depositional facies: (1) large bar-margin slipfaces, up to 8 m high, that are generated as steep avalanche faces at the downstream end of actively migrating braid bars and are often associated with oblique flow over the braid bar; (2) medium-scale dune cross-stratification, 1–4 m high, generated by large-scale dunes within the active channels, or possibly as unit bars; (3) small-scale dune cross-stratification, 0.5–1 m high, generated by sinuous-crested sand dunes; and (4) mud drapes formed in quiet water regions, such as in the lee of mid-channel bars. These four facies were found to generate seven styles of deposition (Figure 21.235):

1. Bar-margin slipface: a dominant style of deposition within mid-channel bars that is created by oblique downstream growth and cross-channel bar-margin accretion. This deposition often occurs through amalgamation of complex sets of dune-scale cross-stratification and bar-margin slipface accretion with both large, low-angle and angle-

of-repose foresets. Large bar-margin slipfaces may become progressively steeper until reaching the angle-of-repose.

2. Vertical accretion in channel: sets of trough cross-stratification, produced by sand dunes within the channels and decreasing in size towards the bar-top, are found in all areas of the bar and formed a significant proportion of the sedimentary facies.

3. Vertical accretion on bar-top: sets of trough cross-stratification are found on the bar-head, bar-tail and along the bar-margin, and are formed from deposition by small (<1.5 m high) three-dimensional dunes.

4. Upstream accretion: restricted to the upper 2–3 m of sediments in the mid-bar region and probably formed in response to dune stacking over the bar-top in shallow flows. The upstream accretion surfaces were separated by small-scale sets of trough cross-stratification, and mirror the observations of bar-top deposition by Bristow (1993a) (Figures 21.25 and 21.26).

5. Lateral accretion: this was documented on one side at the upstream end of the bar studied by Best *et al*. (2003) and attributed to deposition during the falling stage of the hydrograph as flow was diverted around the bar-head. Lateral accretion surfaces were separated by trough cross-stratification generated by small, three-dimensional dunes.

6. Downstream/oblique accretion: occurred on the central and downstream regions of the bar, representing downstream and oblique accretion of dunes across the bar, forming complex downstream-dipping surfaces.

7. Mud drapes: present as low-stage, fine-grained drapes that develop in the bar lee where fine-grained silt and clay are deposited from suspension.

(a)

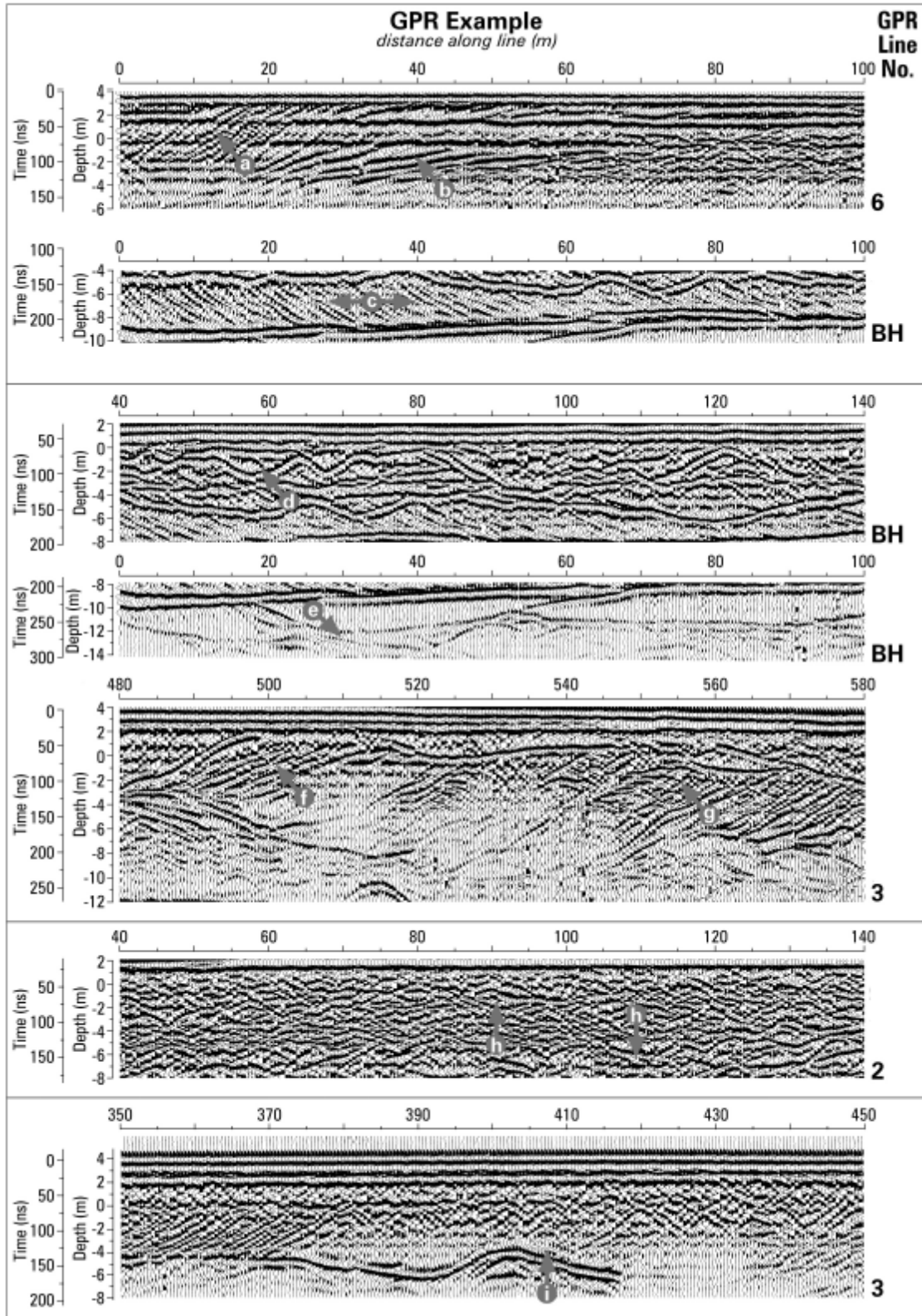| Radar Facies No.	Radar Characteristics	Vertical & Lateral Extent	Sedimentary Characteristics & Interpretation
1	**1a.** Steeply dipping (angle-of-repose) planar or subplanar reflections and low-angle (10 – 15°) planar or subplanar reflections dipping into anabranch channel on western edge of bar.	up to 8 m high and extend laterally for >100 m	1a. Large-scale cross-stratification either at angle-of-repose, with large sets (a) dipping from bar margin into thalweg, or lower angle sets (b) that occur in deeper part of radar profile and on western side of bar, sloping into anabranch channels. May contain internal reactivation surfaces.
	1b. Planar and asymptotic dipping reflections in lens-shaped packages. Sometimes bounded by erosion surface at base or top.	up to 4 m high and extend laterally and downstream up to 100 m	1b. Large-scale cross-stratification (c) caused by deposition at the margins of the barhead by diverging flow.
2	**2a.** Strong, trough-shaped reflections that are laterally discontinuous, often with steeply dipping or low-angle internal reflections.		2a. Medium-scale trough (d) cross-stratification associated with preservation of large dunes.
	2b. Weak undulating reflections at depth often lacking internal dipping reflections (because foresets are beneath radar resolution).	1 – 3 m high; 5 – 300 m lateral continuity	2b. Medium-scale cross-stratification produced by large dunes in the deeper parts of radar profiles are identified from basal erosion surfaces (e) and the lack of discernible foresets.
	2c. Discontinuous sigmoidal packages of concave/convex dipping reflections.	2 – 4 m high; 20 – 200 m lateral continuity	2c. Complex sets of medium-scale cross-stratification (f) due to oblique migration of large dunes and superimposed dunes descending the bar margin. Sets may contain internal reactivation surfaces (g) and variable dip angles.
3	Small discontinuous reflections with weak concavity from trough shaped structures at the limits of radar resolution.	0.5 – 2 m high; 5 – 30 m wide	Small-scale trough cross-stratification (h) produced by dune deposition on the bar flanks. Set size increases with depth, larger sets are found on the bar western side and smaller sets on the eastern side.
4	High-amptitude, continuous, undulating reflections	~ 0.5 m high; ~ 40 m wide	Mud drape (i)

Figure 21.24 (a) The four principal ground-penetrating-radar facies documented from the GPR survey lines presented in Best *et al.* (2003), with (b) representative GPR examples and sedimentary interpretation. Vertical
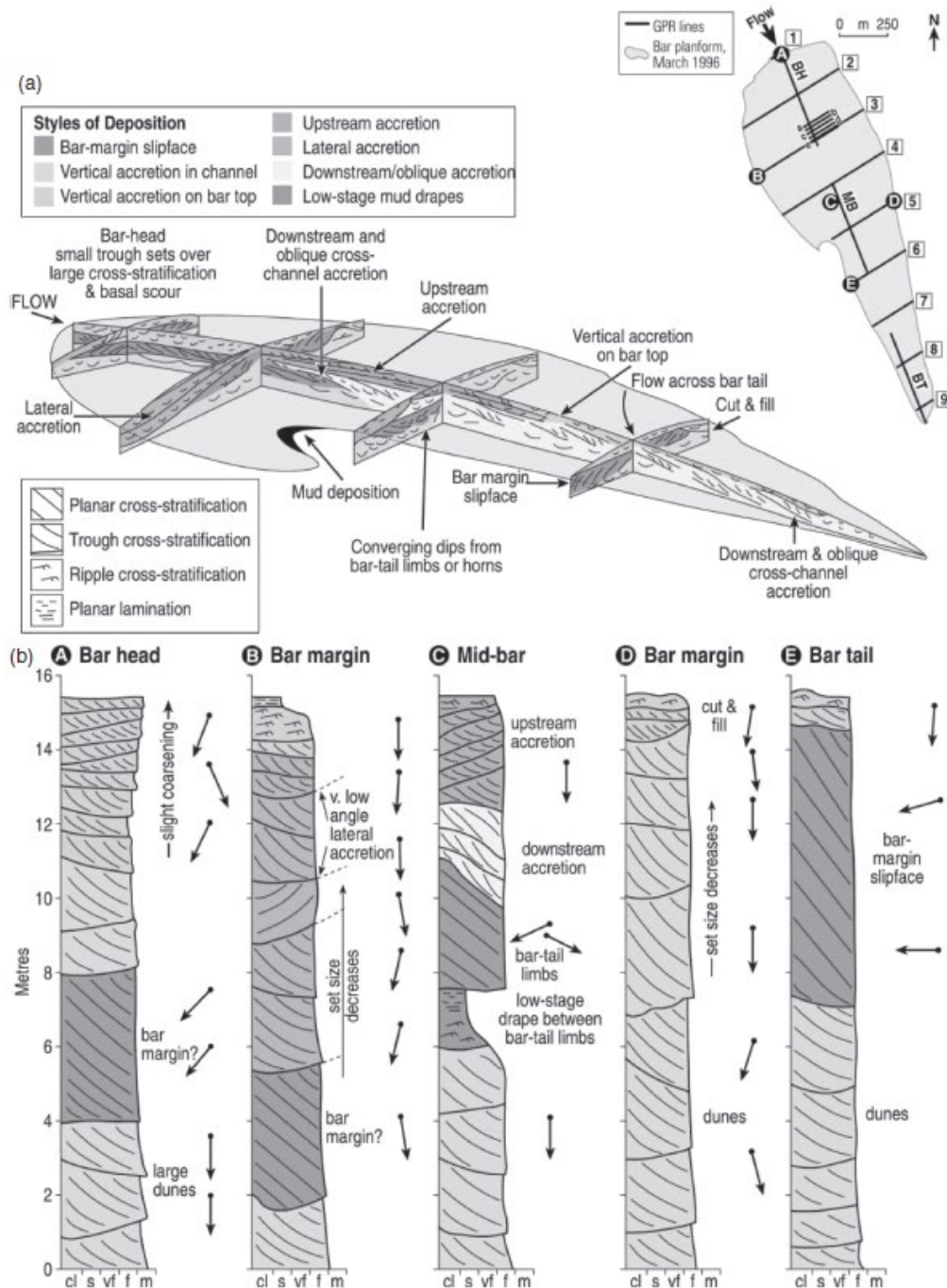
Figure 21.25 (See also colour plates.) Styles of deposition and vertical facies profiles for a mid-channel bar in the Jamuna River. (a) Three-dimensional diagram of the principal styles of deposition quantified within the Jamuna braid-bar (see text for details). The scale of the bar is 3 km long, 1 km wide and 12–15 m high. The different styles of deposition are coloured and the main sedimentary structures are labelled. (b) Schematic sedimentary logs at five localities within the large braid bar (see inset for location), illustrating the characteristic sedimentary structures, large-scale bedding surfaces, and styles of deposition (see a).

Apart from this model of deposition within the entire braid bar, Bristow (1993a) presents a model of bar-top sedimentation in the Jamuna (Figure 21.26) which matches well with the later GPR surveys of Best *et al*. (2003) and is characterized by: (1) upstream accretion on the upstream part of the bar-top, that is formed from trough cross-stratification and rare upper-stage plane beds. The upstream part of the bar-top was found to sometimes be erosional with cantilever bank failures; and (2) the central section of the bar-top was characterized by both vertical and lateral accretion, containing dune-scale trough cross-stratification, upper-stage plane beds, and ripple cross-lamination. Bristow (1993a) proposed a characteristic vertical sequence of upper stage plane beds to trough cross-stratification and then ripple lamination, which reflects declining flow velocities and increasing aggradation rates within these bar-top sediments. The downstream ends of the bar-top were found to be more variable in composition, with dunes and scroll-bars (unit bars) migrating around the downstream bar margin (see also model of braid bar growth, Figure 21.17). Bristow (1993a) found that the downstream bar margins may become steepened to form avalanche faces and that flow separation/reduced velocities in the bar-lee can lead to deposition of current ripples and fine-grained drapes. Bristow (1993a) also highlights the role of falling-stage modification in forming bar-top channels, with low-stage flow being unable to rework the bar-surface.
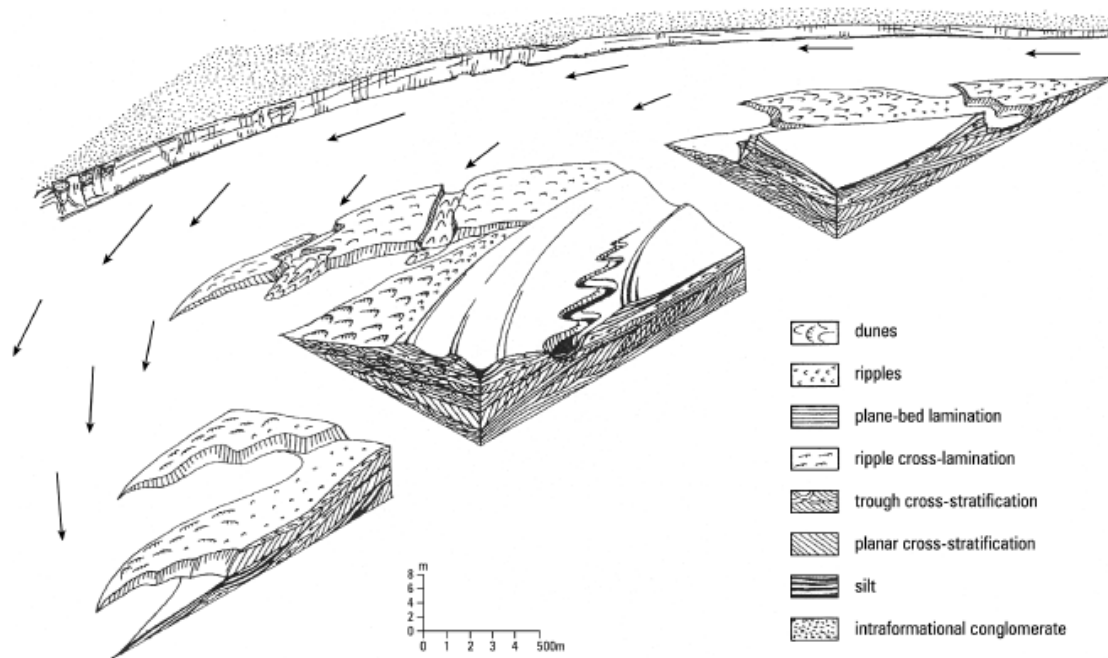
Figure 21.26 Facies model for bar-top deposition in the Jamuna River. Reprinted from Braided Rivers, Eds Best, J.L. and Bristow, C.S., Bristow, C.S. Sedimentary Structures in Bar Tops in the Brahmaputra River, Bangladesh, pp. 277–289, 1993, with permission from Geological Society of London

In a study examining the sedimentology of river channel confluences, Sambrook Smith *et al.* (2019) used a Boomer system to collect seismic reflection profiles at the junction of the Jamuna and Ganges rivers (Figure 21.27). This seismic data was georeferenced to the 1973-2014 Landsat imagery of Dixon *et al.* (2018), as well as the earlier bathymetric analysis of Best and Ashworth (1997). Rather than showing the dominance of depositional surfaces produced by the uninterrupted migration of bars into the confluence scour, as suggested in other models of junction sedimentation (Bristow *et al.,* 1993), these seismic sections show the dominance of low-angle (*c.* 2-4°) erosion surfaces (labelled R1-R3 in Figure 21.27A) down to a depth of *c.* 14m, which represent reworking of the bar surfaces over a distance of up to 1-2 km. In a section towards the base of the scour (Figure 21.27B), although the same reflections R1-R3 are present, more of the reflections show clear truncations, and are only *c.* 400m in length. Sambrook Smith *et al.* (2019) interpret these shorter, and more complex, reflections to likely be the product of the channel thalweg moving back across a location, as revealed in the satellite imagery of Dixon *et al.* (2018), and reworking its deposits.
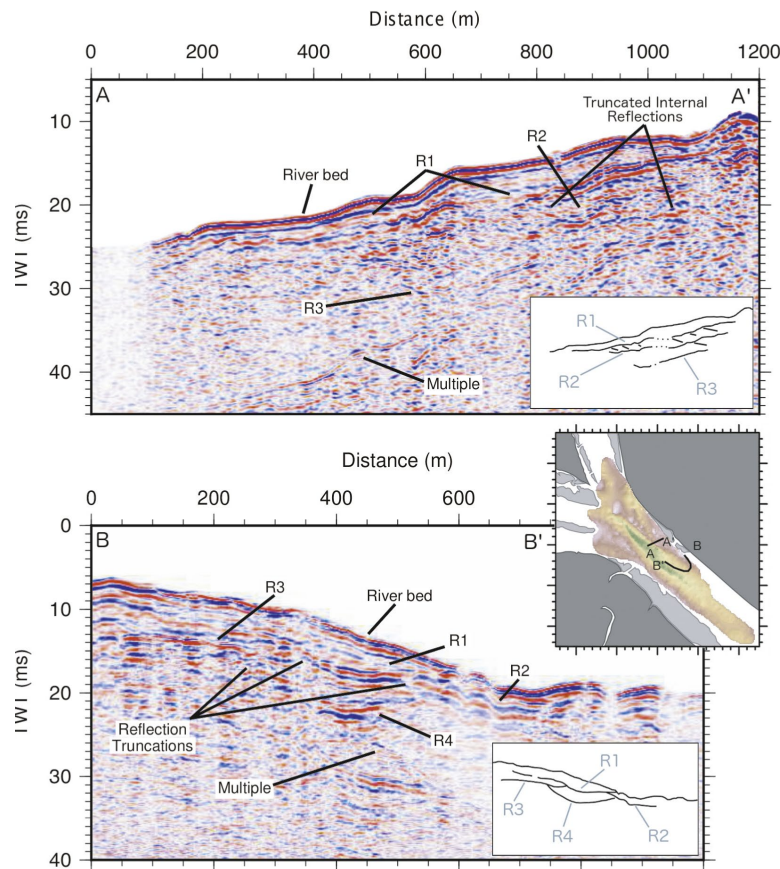
Figure 21.27 Seismic data and interpretations from the Jamuna–Ganges junction (see inset for bathymetry and location of seismic line at the site). (A) Seismic section A-A′. The three broadly parallel reflections, labelled R1 to R3, were interpreted as erosion surfaces that could be traced across the east side of the confluence. (B) Seismic section B-B′, showing a series of relatively short cross-cutting reflections (R1 to R4) that are show migration and reworking of sediment by the scour zone. Reflections R1 to R3 refer to the same feature in both (A) and (B). Reprinted from *Sedimentology*, Vol. 66, Sambrook Smith *et al.,* The sedimentology of river confluences, pp. 391-407 (2019).

Sambrook Smith *et al*. (2005) considered the morphology and depositional facies of a range of braided rivers, including the Jamuna River, and have found that the surface planform morphology of braid bars, and the maximum relative depth of confluence scour, displayed a scale invariance over many different types and sizes of braided river. They also concluded that the subsurface sedimentary facies of three sandy braided rivers, which covered a twofold order of magnitude in channel width, exhibited a degree of scale invariance with the ubiquitous occurrence of trough cross-stratification associated with migrating dunes. However, the occurrence of bar-margin, high-angle planar cross-stratification and low-angle stratification was variable both between rivers and between bars within the same river. Sambrook Smith *et al*. (2005) concluded that the relative presence of these two facies within the stratigraphy is related to a wide range of factors, including the discharge regime, local bar/channel topography, the channel width : depth ratio and the presence and abundance of vegetation. Hence, although the models described above for the Jamuna may share common characteristics with many other braided rivers, much work remains to be conducted to document and quantify the full range of depositional facies within large sandy braided rivers, especially in bars that are a complex product of successive periods of erosion and deposition.

21.7 APPLIED GEOMORPHOLOGY AND ENGINEERING IN THE JAMUNA RIVER

21.7 APPLIED GEOMORPHOLOGY AND ENGINEERING

The Jamuna River is one of the most dynamic rivers in the World with little to stop sustained channel migration, bank erosion, bar creation and destruction. The banks of the Jamuna consist of weakly cohesive sand and silts, commonly with less than 1% clay and hardly any deep-rooted vegetation to bind the soil (FAP24, 1996h). However, even deep roots would be insufficient to stop bank erosion along the 20 to 30 m deep channels of the river. Banks erode usually through large-scale slab failure due to toe scouring (Figure 21.28), and the slump blocks disintegrate rapidly after failure, so there is no potential for temporary stabilization of the bank through the accumulation of bank failure debris at the toe (Thorne *et al*., 1993). This bank erosion is a major source of poverty (Elahi *et al.,* 1991). Banks along the Brahmaputra-Jamuna can retreat hundreds of metres in a single flood season (Ashworth *et al.,* 2000), devouring property and infrastructure on their way. The stabilization of riverbanks is thus of vital importance for alleviating poverty. In cost-benefit analyses, the major benefit of stabilization is derived from avoiding erosion and the collapse of embankments that protect land and infrastructure from flooding, such as the Brahmaputra Right Embankment built in the 1960s. Other benefits arise from the stabilization of the distributary river offtakes of the Old Brahmaputra and Dhaleshwari that supply water to the capital city Dhaka. Riverbank stabilization projects along the Jamuna River also encounter pressures from sand mining and efforts to narrow the river to reclaim

land and improve navigability, sometimes framed as if the Jamuna River needs to be cured from an abnormal width and an excessive sediment load. These additional interventions, however, are not justified by cost-benefit analyses. Rather, they give rise to concerns about adverse effects, which can be expected within Bangladesh as well as upstream in India.

Figure 21.28 Large-scale slab failure by bank undercutting near Shailabari (~4 km upstream of Sirajganj). Photograph taken at low flow. During seasonal floods the water level would be up to bankfull.

Bank protection systems have been developed along the Jamuna-Brahmaputra River since the 1990s. Although several systems built between 1998 and 2004 failed (BDER, 2004), earlier and later projects have also been successful. Flood Action Plan projects FAP1 and FAP21/22, as well as river training works for the Bangabandhu Bridge, were realized in the 1990s. FAP1 stabilized banks to protect the Brahmaputra Right Embankment, thus preventing avulsion into the Bengali River, securing the city of Sirajganj and the Fulchari railway ferry terminal, and preventing future outflanking of the Bangabandhu Bridge. FAP21/22 piloted new designs and new materials for more affordable structures: permeable groynes on the right bank at Kamarjani and revetments on the left bank at Bahadurabad and Ghutail (Mosselman, 2006). Figure 21.29 shows that the revetments are still in place after 25 years, despite heavy fluvial attack. The project

concluded that revetments are to be preferred for works that merely aim to stabilize the banks. Groynes and spurs require more material and create deep scour holes that threaten the stability of the structures.

In addition, the Bangabandhu Bridge, 5 km south of Sirajganj (Figures 21.30 and 21.31), is the first and at present only bridge to span the Jamuna River. Built at a cost of *c.* US$ 550 million and completed in 1998, the bridge is 4.8 km long with 49 spans and used 80 m long piles driven 60 m into the river bed. The bridge deck is 18.5 m wide with four road lanes and a wide-gauge railway track, as well as a 600 mm diameter gas pipeline attached underneath. Concrete pylons above carry power and telecommunication lines. The Bangabandhu Bridge is located at a position where the Jamuna River braid belt narrows. This was one of the narrower, and deeper, reaches that Coleman (1969) identified as a nodal point, although these points were later found to be transient, and not permanent, nodes (Klaassen & Masselink, 1992).

The major challenge in constructing bridges across dynamic braid belts is to prevent the migrating channels eroding the approach embankment, and thus outflanking the bridge. In the 19th century, Horace Bell and Francis Spring developed a system based on guide bunds, originally termed 'guide banks' or 'Bell's bunds', to protect the bridge abutments, and the roads or railways on the approach embankments, against erosion (Spring, 1903). These arcuate embankments extend far enough upstream to prevent sinuous bends from breaching the approach embankment, whilst the upstream head of a guide bund is curved so that it can cope with channel and flow approach from different directions. The downstream tail is also curved, in order to locate the vulnerable termination of the structure outside any zone of deep scouring. The guide bunds of the Bangabandhu Bridge (Figure 21.30 and 21.31) are 2.1 km (West) and 2.2 km (East) long in upstream direction, and their slopes are relatively flat (1V:5H and 1V:6H) in order to reduce potential scour.

Whilst the Bangabandhu Bridge has withstood several years of high flows, including the largest flood of the twentieth century in 1998, the bridge site requires continual and sustained river engineering management, as revealed in satellite imagery over the period 1999-2019 (Figures 21.30 and 21.31). Klaassen *et al.* (2012) reviewed the performance of the river training works at the bridge in the period 1997-2009. They found the local bed scour depth at the western guide bund was almost 45 m below the average
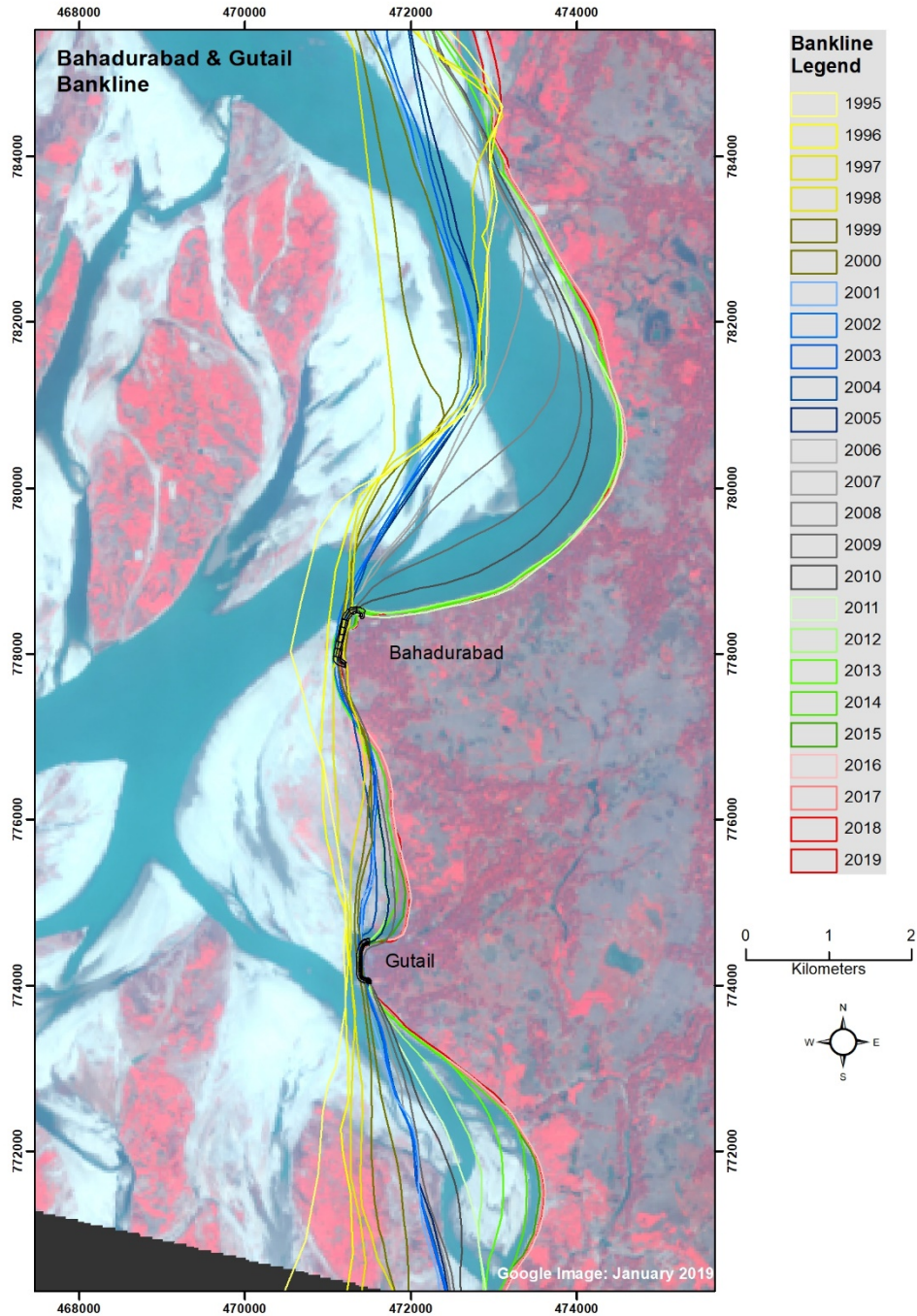
Figure 21.29. Bankline positiosn on the east (left) bank of the Jamuna River over 25 years near Bahandurabad, showing the success of revetments at Bahadurabad and Gutial in preventign bank erosion at these key sites.
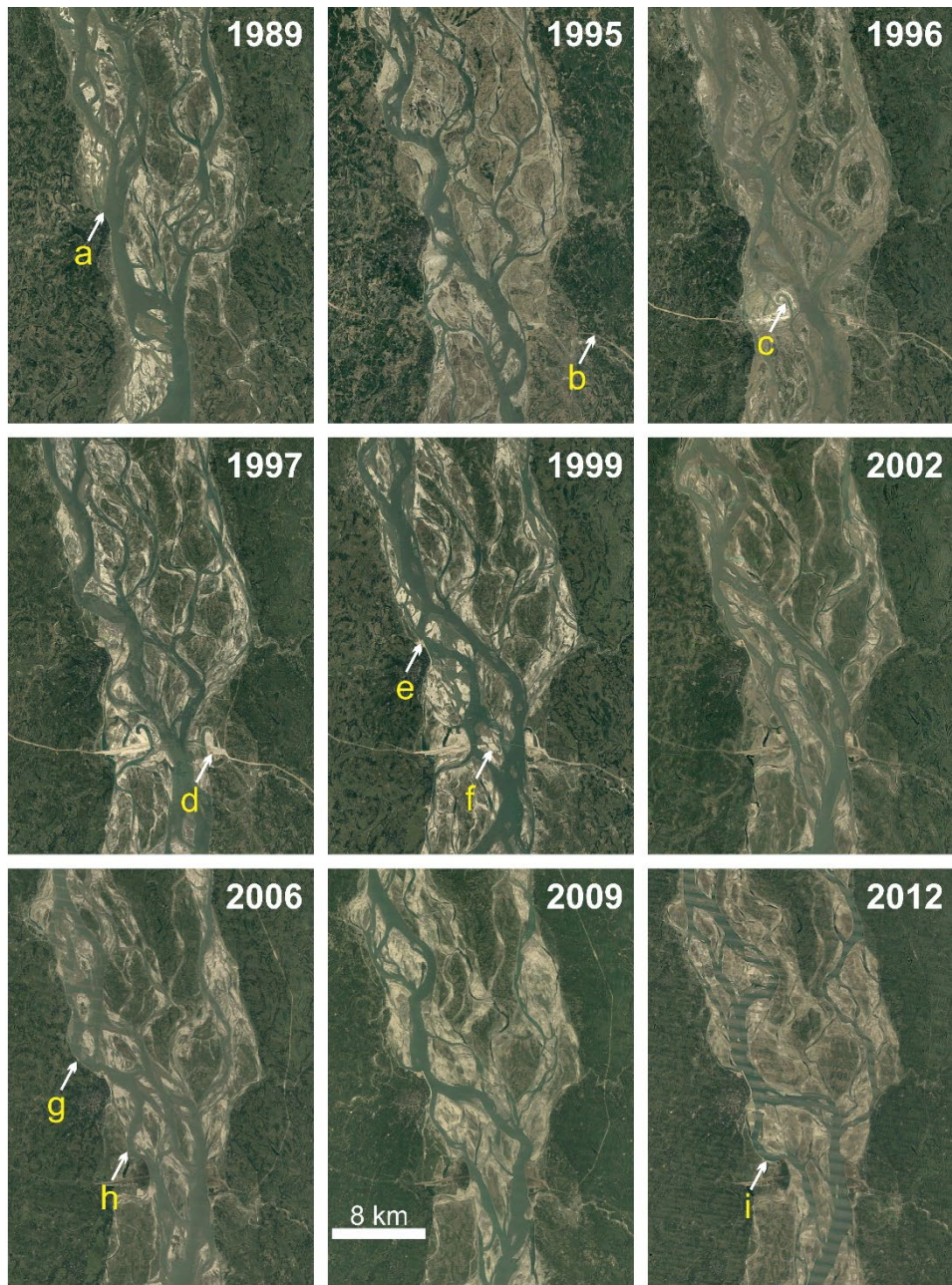
Figure 21.30. Landsat images of the Jamuna River in the vicnity of Sirajganj (B2 hardpoint) and the Bangabandhu Bridge, 1989-2012. Images courtesy Google Earth.
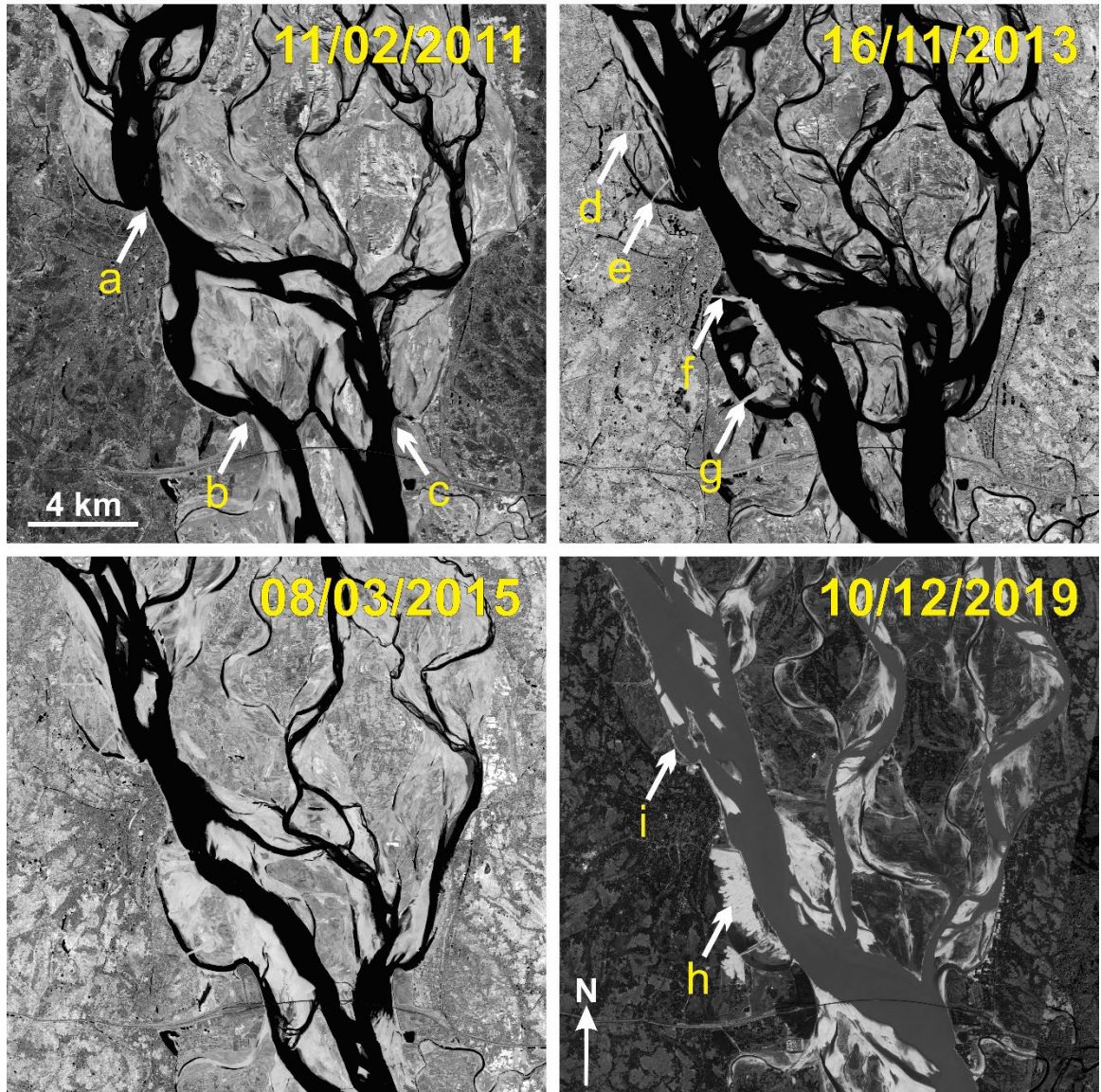
Figure 21.31. CubeSat images of the Jamuna River in the vicnity of Sirajganj (B2 hardpoint) and the Bangabandhu Bridge, 2011-2019. Images courtesy Planet Labs.

flood level, deeper than anticipated in the original design and tentatively ascribed to flow separation near the head of the guide bund. Such flow separation can create increased local flow velocities and turbulence, thereby aiding bed scour. Islam *et al.* (2017) examined the changing bar morphology 35km upstream and downstream of the Bangabandhu Bridge, finding that the bridge construction induced an increase in both the area of bars and bar migration rates, which subsequently also generated problems with local bank erosion (see below).

The narrower river channel between the guide bunds hinders downstream migration of meander bends. Such migrating bends jam against the narrowed section and increase in amplitude: they become wider. Therefore, hard points were created upstream of the Bangabandhu Bridge in a funnel-shaped planform alignment, in order to guide migrating bends under the bridge without widening. Without such hard points, a danger would remain that bends would outflank the guide bunds, despite the upstream lengths of the bunds. The hard point at Sirajganj is one of the largest fixed, hard engineering structures on the Jamuna River, and its 2 km long embankment, termed the 'B2 hardpoint' (Figures 21.30 and 21.31), was constructed at an approximate cost of US$ 65 million to protect the large ferry terminal and market town. The B2 hardpoint was constructed of a ridge of locally dredged river sand and silt covered by a plastic and geotextile membrane, then superimposed by broken bricks and topped with 0.45 m^3 or 0.65 m^3 concrete blocks (Figure 21.32). Although largely successful, the B2 hardpoint suffered a major failure during the 1998 flood season (Figure 21.33) when construction was 94% complete. A 32 m deep scour hole developed immediately downstream of the hardpoint 'nose', reaching a maximum during the height of the monsoon flood that was especially prolonged in 1998, and caused collapse of at least four sections of the embankment. Repair costs were estimated in excess of US$ 10 million. Although now repaired and functioning well, the scale and cost of the damage that was inflicted on the B2 hardpoint illustrates the erosional threat of the Jamuna River and the magnitude of the problem faced by river engineers and geomorphologists working in such a dynamic alluvial environment. Similar to the diagnosis outlined by Klaassen et al. (2012) for unexpectedly deep scour at the head of the western guide bund, flow separation was an important factor in generating the deep scour near the 'nose' of the B2 hardpoint. In addition, the changing planform configuration of the channels upstream of the nose of the hard point over the construction period in 1995-1999 (Figure 21.30), resulted in very different flows across the hard point nose that exacerbated the size, and erosive potential, of flow separation. This illustrates the key role of assessing the changing channel planform when assessing likely scour around such structures. However, contrary to the exacerbation of morphological conditions upstream of the river training works at Siraganj, the guide bunds at the Bangabandhu Bridge appear to have stabilized the channel pattern downstream of the bridge.

The complexity of morphological change, and the continuous need to assess channel change when managing large-scale infrastructure in the Jamuna River, is clearly shown over the last thirty years at the site of the B2 hardpoint and Bangabandhu Bridge (Figures 21.30 and 21.31). Once construction of the Bangabandhu Bridge had begun in 1995-1996, sedimentation underneath the main bridge span generated a mid-channel bar (Islam *et al.,* 2017) that deflected flow to each side and caused erosion towards the west

and east guide bunds (see 1999 image in Figure 21.x). Continuing sedimentation in the vicinity of

Figure 21.32 Construction of the B2 hardpoint at Sirajganj showing: (a) dredged river silt covered with geotextile membrane filter, then covered by broken brick and concrete cubes (photograph courtesy of Mr Bob Courtier, W.S. Atkins Ltd) and (b) 0.45 m^3 concrete blocks in place, view looking downstream from the hardpoint 'nose'

Figure 21.33. Image of the B2 hardpoint in 1998 showing the multiple failures formed at the height of the 1998 flood (photograph courtesy of Mr Bob Courtier, W.S. Atkins Ltd).

the bridge also formed a large bar complex immediately upstream and adjacent to the bridge (see label f, Figure 21.30), which resulted in bank erosion on the west bank that threatened to outflank the bridge. As detailed above, erosion adjacent to the B2 hardpoint was caused by the changing alignment of the upstream channel, which was still causing flow to run across the hardpoint in the period 2006-2009 (see label 'g' in Figure 21.30). These two sites have been the location of major engineering works since 2013 (Figure 21.31) that have sought to reclaim land, and protect the west bank upstream of the B2 hardpoint and Bangabandhu Bridge, in order to lessen erosion problems in this region. In 2011, the B2 hardpoint and western guide bund (see labels 'a' and 'b' respectively in Figure 21.31) were exposed and vulnerable, and led to beginning of construction of four groynes (labels d-g, Figure 21.31) in 2013. These presence of these groynes, and infill by sand that was pumped from adjacent channels and bars, allowed infill of these two regions, such that by 2015 these two areas were far better protected and the reclaimed land was already being farmed. An image from December 2019 shows that infilling by dredged sand is still ongoing in the southern area just north of the Bangabandhu Bridge (see label 'h', Figure 21.31) but that the B2 hardpoint and western guide bund are more stable. However, it is clear that monitoring and maintenance of these sites will be a continual practice, for even areas of recently reclaimed land are subject to continued erosion (label 'i', Figure 21.31). The images shown in Figure 21.31 over a period of 8 years also illustrate the rapidly changing nature of sedimentation underneath the bridge (see Islam *et al.,* 2017), and thus the changing velocities experienced at the guide bunds as flows are deflected by these bars.

Bank revetments and guide bunds are made of rocks or concrete cement blocks ("CC blocks"). However, rocks are expensive as they need to be imported, and producing concrete blocks consumes precious river sand and emits CO_2. Geobags are thus a cost-effective alternative (Oberhagemann & Hossain, 2010). The Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP) has applied geobags successfully for riverbank stabilization along the Jamuna River at Chauhali (Figure 21.34). Irrespective of the material used, all bank stabilization and river training structures require monitoring and, wherever necessary, repairs by dumping additional rocks, blocks or geobags.

Engineers in South Asia have longstanding experience with using relatively light structures in the dry season to create, and deepen, navigation channels that connect ports and ferry landings to the main channels of the river. This annually repeated improvement of navigation channels is called 'bandalling'. Bandals refer to screens placed on poles under an angle with the flow, and oriented towards the channel axis downstream. These bandals aim to concentrate the upper, fast flows in the centre of the channel while generating sediment transport underneath towards the channel margins. They were originally called 'jhámp', whereas the present term 'bandal' referred to brushwood fascines that were placed in channels to favour erosion of another, parallel channel. Spring (1903) therefore conjectured the word 'bandal' to be a vernacular corruption of the English word 'bundle' for 'fascine', used by crew members of steamers plying the rivers of British India. FAP21/22 piloted a similar type of screen on poles for flood conditions (see Mosselman, 2006), but this high-water bandal became so massive that it lost the advantage of a light and flexible recurrent structure. Moreover, the functioning of bandals depends sensitively on their orientation with respect to the flow, which may vary considerably due to morphological changes occurring in the flood season. Bandals thus remain excellent for correcting the river bed at low flows but are not well suited for flood conditions.

Figure 21.34. Sand-filled geotextile bags, or geobags, used for bank protection at Chauhali, Jamuna River. View looking upstream.

Prioritization, planning, design, and implementation of river training and bank stabilization works require predictions of morphological development 2 to 3 years ahead, when the river may still be hundreds of metres away from the future structure (see example of B2 hardpoint above; Figure 21.30). For forward planning, land thus needs to be acquired, the population must be relocated, a construction camp set up, and equipment and materials imported to the area. Meanwhile, the river should not erode the site during these preparations. Moreover, a requirement within the FAP21/22 project was that the structure would be subjected to fluvial attack immediately after completion, and within the monitoring period of the project so that its effectiveness could be assessed. These planning needs thus pose a great challenge to forecasting morphological developments. FAP21/22 developed an empirical prediction method, based on studying the year-to-year changes of the dry-season braided-anabranched channel pattern visible on satellite images. The method produced predictors for channel width changes, bend migration and bifurcation development, including channel creation and abandonment (Klaassen & Masselink, 1992; Klaassen et al, 1993; Mosselman, 1995; Mosselman *et al.,* 1995). The method was formulated in a probabilistic way, assigning probabilities of exceedance to rates of bank retreat and elaborating different cascades of downstream effects depending on the probabilities of channel creation and channel abandonment.

Jagers (2001, 2003) subsequently coded the empirical prediction method into a computer program that he called the "branches model". He also trained an artificial neural network on a set of dry-season satellite images of consecutive years, and compared the predictions from this network and the branches model with the erosion that occurred in

reality (Figure 21.35). Although the agreement may seem poor at first sight in terms of the magnitude of change, the models are successful in identifying the locations where the predictability of erosion was relatively good. This approach was successful in aiding the selection of suitable sites for pilot projects under FAP21/22.

The FAP19 project of the Flood Action Plan developed another empirical prediction method for riverbank erosion, also based on satellite images, but valid for shorter time spans. This method relies on the identification of a series of key sedimentary features, or bar forms, which are indicators for the ongoing morphological development of the Jamuna River planform. EGIS (2002) terms these features "contraction bars", "sharpened bars", "sand wings", "sand tongues" and "bankside bars". The lengths of downstream wings on either side of a bar, for instance, indicated on which side the river was the most active. EGIS (2002) merged the FAP19 and FAP21/22 methods into a single prediction method that is still operational at the Center for Environmental and Geographic Information Services (CEGIS) in Dhaka. Figure 21.36 shows an example flow chart using this type of methodology that may be used to predict the rate of bank erosion on the outer banks of the Jamuna River. The empirical prediction depends strongly on the presence/absence of a bar ('sedimentary feature') downstream of the channel and the radius of curvature of the channel (ratio of the radius of the outer bank of the curved channel to the low flow width of the channel). Data on channel radius of curvature, channel width, and rate of annual bank erosion were derived from Landsat images for the period 1992–2000 to build upon earlier data reported by Klaassen and Masselink (1992) and Klaassen *et al.* (1993).

In parallel to the development of empirical prediction methods, Enggrob & Tjerry (1999) and Jagers (2003) pioneered the application of physics-based numerical models of fluvial morphodynamics to the Jamuna-Brahmaputra River. The Institute of Water Modelling (IWM) in Dhaka and several consultancy firms now use such models routinely to assess the effectiveness and impacts of interventions in the rivers of Bangladesh. For example, Schuurman *et al.* (2013, 2015) systematically studied numerical simulations of the morphological evolution of the Jamuna River, finding that their models reproduced the cascades of effects of the FAP21/22 method and the relation between sand wings and morphological activity of the FAP19 method. However, shortcomings remain. Because the numerical models are depth-averaged, and their computational cells are larger than the water depth, this means they do not represent the relevant details of subgrid processes such as bank erosion and structure-induced local scour. These shortcomings form key areas for further research and development.

Riverbank stabilization in the past 25 years, and the development of a variety of prediction methods, have shown that predicting and influencing channel change is possible in even the largest and most mobile of sand-bed braided rivers. Further development of our understanding and modelling of the controlling morphodynamic processes holds great potential for helping to maintain and implement bank protection structures along the Jamuna River.
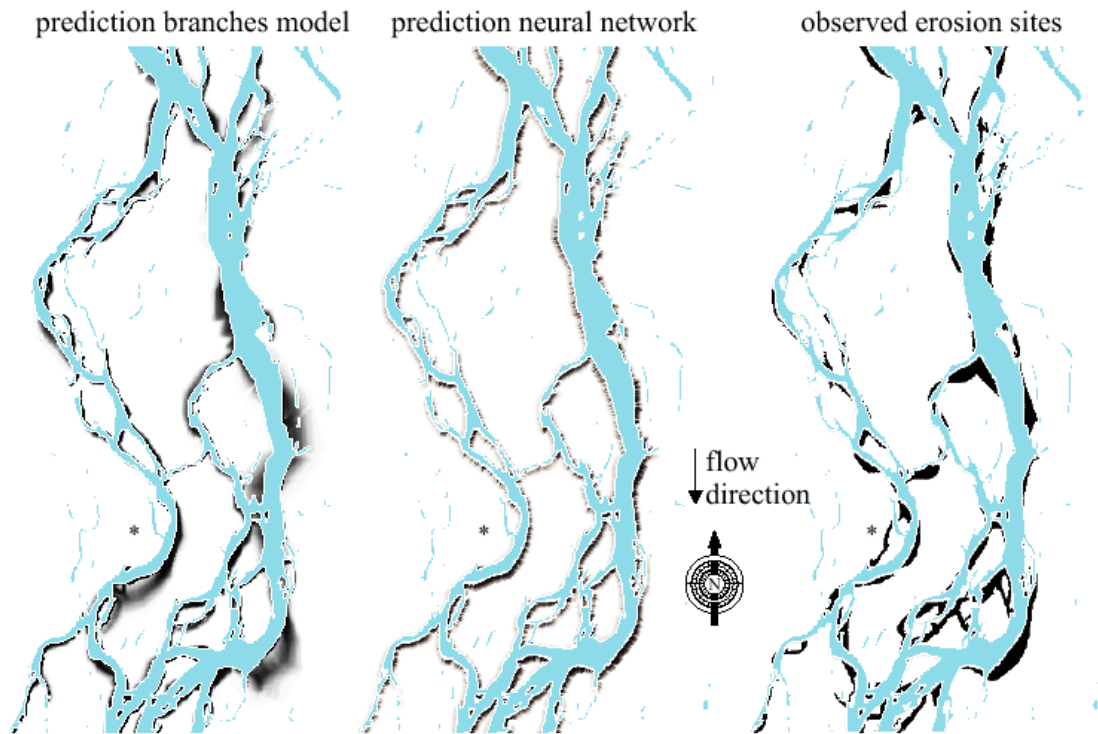
prediction branches model   prediction neural network   observed erosion sites

flow
direction

Figure 21.35. Comparison of bank erosion predictions by the branches model (left), the neural network (centre) with observations (right). Erosion of high mainland and island banks appears to be more predictable than the erosion of the margins of low chars (after Jagers, 2001).
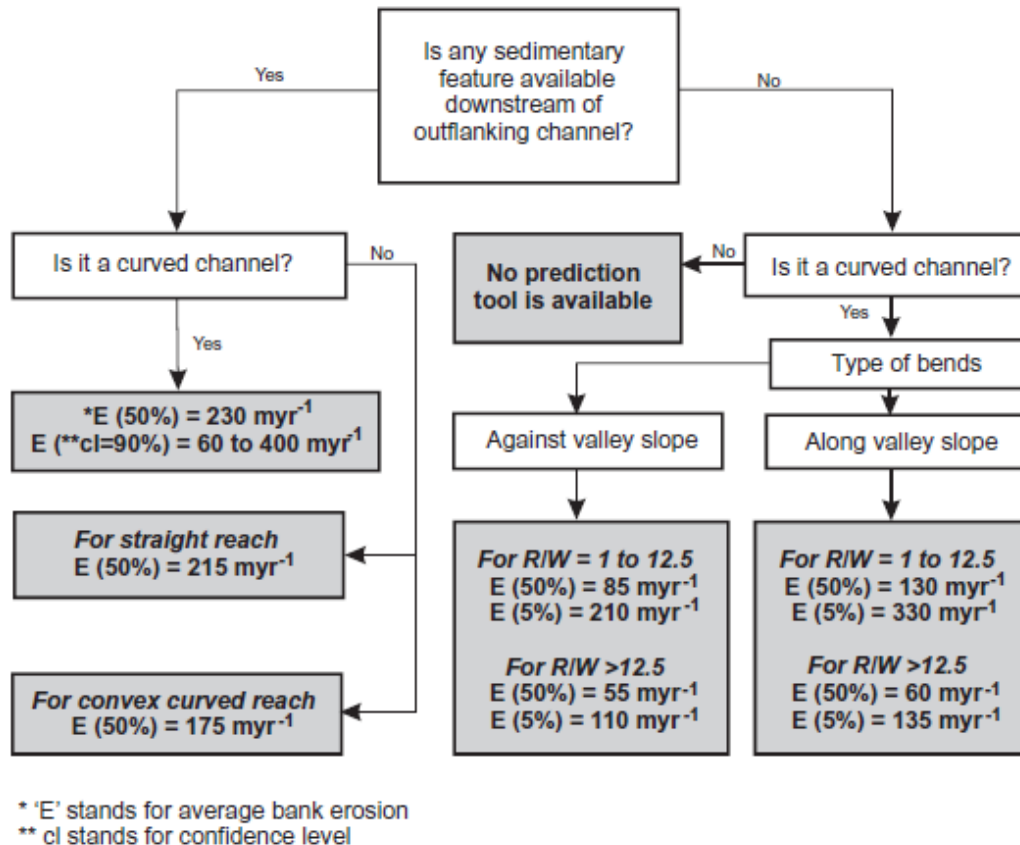
Is any sedimentary feature available downstream of outflanking channel?

Yes   No

Is it a curved channel?   No

No prediction tool is available   No   Is it a curved channel?

Yes   Yes

Type of bends

*E (50%) = 230 myr^{-1}
E (**cl=90%) = 60 to 400 myr^{-1}

Against valley slope   Along valley slope

For straight reach
E (50%) = 215 myr^{-1}

For R/W = 1 to 12.5
E (50%) = 85 myr^{-1}
E (5%) = 210 myr^{-1}

For R/W >12.5
E (50%) = 55 myr^{-1}
E (5%) = 110 myr^{-1}

For R/W = 1 to 12.5
E (50%) = 130 myr^{-1}
E (5%) = 330 myr^{1}

For R/W >12.5
E (50%) = 60 myr^{-1}
E (5%) = 135 myr^{-1}

For convex curved reach
E (50%) = 175 myr^{-1}

* 'E' stands for average bank erosion
** cl stands for confidence level

Figure 21.36 Flow diagram for predicting bank erosion along the outflanking channels of the Jamuna River. Data were obtained from 213 bends from sequential dry-season satellite images from 1992 to 2000. R and W are the radius of curvature to the outer bank line and the channel wetted width at low flow, respectively. Reprinted from EGIS, Developing and updating the empirical methods for predicting the morphological changes in the Jamuna River, 2002, with permission from CEGIS

21.8 SUMMARY: WHAT DOES THE FUTURE HOLD?

The Jamuna-Brahmaputra is one of the World's truly great rivers and forms a dynamic and highly variable alluvial environment that has a huge impact on the daily lives of the growing population of Bangladesh. The past three decades have seen a massive increase in our knowledge of the behaviour of this dynamic river, and a growing realization that a holistic management approach is required to plan for, cope with, and benefit from floods (Yang *et al.,* 2016; Barua, 2018; Ferdous *et al.,* 2018, 2019). The early plans for large-scale engineering works along the Jamuna (see reviews in Hossain, 1994; Yakub, 1994) have been shown to be inappropriate from a community and environmental perspective, let alone considerations of costs, but have set the agenda for some key schemes and approaches that have borne great benefits. Although the Flood Action Plan has had many critics and the nature of FAP changed greatly over the years (see papers in Haggart *et al*., 1994), hindsight now shows many highly valuable products of the FAP projects, including both a far improved understanding of the processes and dynamics of the rivers of Bangladesh (Jagers, 2003), and establishment of long-lived remote sensing, field survey and modelling capabilities that have led to better predictive tools for assessing channel change (EGIS, 2002; Jagers, 2003; Schuurman *et al.,* 2015). This will be increasingly important in key

infrastructural protection works, such as shown herein for the Bangabandhu Bridge, as well as bridges such as the Muktarpur Bridge across the Dhaleswari River and the multipurpose bridge across the Padma River, which is due for completion in 2020. Such remote sensing, field surveys and numerical models will also better assessment of the impact of future river planform change, such as the potential movement of the Jamuna River into the channel of the Bangali River, near Sariakandi and Mathurapara (Figure 21.1).

It is also evident that the hydrology of the Ganges-Brahmaputra-Meghna basin will change in the future, with most models indicating an increased frequency and intensity of flood events (Arnell and Gosling, 2016; Ali *et al.,* 2019; Best, 2019), with reductions in the return period of the current 100-year magnitude flood event (Hirabayashi *et al.,* 2013). This change in river hydrology, and thus sediment transport and morphological change, will also have to be set in the context of human interventions as regards hydropower construction, water abstraction and diversions (Yang *et al.,* 2016; Best, 2019), which could severely change the amount of water routed along the Jamuna, with potential detrimental downstream effects as have been realized by construction of the Farraka Barrage across the Ganges River (Mirza, 1998). The Jamuna River will also face increasing pressures from pollution, both from agricultural and urban sources, as well threats to its natural ecology, and fish yield.

Thus on a large spatial and temporal scale, Bangladesh faces many challenges in coping with changing water resources dictated by decisions taken outside its borders, and the potential effects of climatic change on the monsoon and sea-level. The sustainable development of this transboundary river thus calls for an integrated approach across the climate-water-energy and food nexus, with major implications for security and international relations (Yang *et al.,* 2016) and one in which transnational water diplomacy will be vital (Barua, 2018). Barua (2018) views multitrack diplomacy as being essential to develop inclusive governance within the Brahmaputra River Basin, and further progress in the 'Brahmaputra Dialogue' as being vital in the sustainable development of water resources that will play a vital role in poverty alleviation and raising living standards. The past twenty years have witnessed the immense benefits of adopting a multidisciplinary approach to studying these large rivers in Bangladesh. With the successful and continued development of infrastructure and expertise in Bangladesh [e.g. CEGIS, Institute of Water Modelling (IWM), Bangladesh Water Development Board (BWDB)], working in close collaboration with Government policy (i.e. WARPO), and developing technologies for monitoring river and sediment flows from space (Best, 2019), the future for assessing, predicting and managing river channel change should become more sustainable and environmentally acceptable.

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