Mechanisms and Spatio-temporal Variations of Meandering and Erosion-Deposition Statistics of the Dhansiri River, Assam

P. Kotoky and M.K. Dutta

Abstract The highly meandered Dhansiri River, a south bank tributary of the mighty Brahmaputra bears significant geomorphologic importance. Spanning the period 1914–2000, a stretch of the Dhansiri River channel from Dhansirimukh to Nowakota Kachari was studied with an objective to understand the erosion-deposition activities operating within the channel. Owing to its location on an alluvial plain, the river shows conspicuous migration characteristics. It has also imparted unique fluvial landscape in the study area. The river channel within the period under observation has migrated to the tune of 2.85 km towards south at Dhansirimukh in conjunction with the southward migration of the mighty Brahmaputra River channel. The study has revealed a total average annual erosion and deposition covering the entire period were 1.32 and 1.27 km^2/year respectively. The total average rate of erosion and deposition per kilometer length of the river were 0.006375 and 0.00625 km^2/km respectively. Increasing rate of erosion since the year 1914, comparatively higher erosion along the west bank than the right bank have also been observed. The areas around Butalikhowa, Golaghat and Kuruabahi have under gone severe erosion posing a threat to the population in the vicinity.

Keywords Dhansiri river · Brahmaputra · Meandering · Bankline migration · Erosion

---

P. Kotoky (✉)
Council of Scientific and Industrial Research, North East Institute of Science and Technology, Jorhat 785 006, Assam, India
e-mail: probhatk@yahoo.com

M.K. Dutta
Jorhat Engineering College, Jorhat 785 007, Assam, India

Mu. Ramkumar et al. (eds.), *Environmental Management of River Basin Ecosystems*, Springer Earth System Sciences, DOI 10.1007/978-3-319-13425-3_13

1 Introduction

The urge to unravel the mysteries of nature has created a strong group of workers with their own philosophy in different parts of the world since early 17th century, when attention of men was drawn to the mysteries of nature around them. Mention may be made of important contributions in this field by Hutton (1795), Lyell (1872), Gilbert (1887), Powell (1895), Geike (1905), Meinzer (1942), Grover and Harrington (1943), Horton (1932, 1940, 1941, 1945, 1954), Thornbury (1954), Morisawa (1957, 1959,1962), Brice (1964), Chow (1964), Strahler (1964), De-Weist (1965), Dury (1970), King (1970), Temple and Sandburg (1971), Allen (1971), Gregory (1977), Gregory and Walling (1973), Schumm (1977, 1985), Baker et al. (1988), Davies (1989), Goudie (1990), Allen and Allen (1990), Fielding (1993), Simon et al. (1999) and others. During the last few decades the study of river system has become one of the most important areas and gained tremendous momentum throughout the world.

Familiarity and discrete use of the concepts and methods pertaining to the flow and sediment transport in rivers has become a hallmark in geomorphological research in recent times, primarily for two reasons; first, the rivers have been providing sustenance to the ecosystem in which the human race is a part, and provide services and resources for the economic development of the humans and second, these very services and resources provided by the rivers are under threat owing to the indiscriminate use of the resources, and resultant changes in the natural fluvial system. The vastly improved *state-of-art knowledge* about many a natural phenomena of prime geomorphic significance such as hydrological, sedimentological, geomorphic, environmental and human implications of flood (Leopold and Miller 1954; White 1964; Kayastha and Yadava 1977; Ward 1978; Bevan and Carling 1987), mechanism of formation of flood plains (Wolman 1959), development of channel morphology (Schumm and Khan 1972; Leopold and Wolman 1957; Leopold et al. 1964; Yalin 1992) and aggradation and degradation of river valleys and denudation of catchments (Leopold and Miler 1954; Goswami 1985; Duijsings 1987; Dietrich and Gallinatti 1991; Baker 1994) is largely attributable to such approaches in fluvial geomorphic research. However, in most of the developing countries including India, application of ideas and principles, tools and techniques has not yet gained the desired level (Goswami 1998).

In India, the Ganga, the Brahmaputra and the Mahanadi rivers have been among the intensively studied [for example, Ahmed (1969), Coleman (1969), GSI (1977, 1981), Dutta (1980), Barman (1981), Goswami (1985, 1988), Bristow (1987), WAPCOS (1993), Hussein et al. (1993), Naik and Sing (1996), Kale (1998), Goswami et al. (1999), Sarin and Krishnaswami (1984), Sarma and Basumallick (1984), ARSAC (1990), Sarma (1986, 1993, 1995), Bezbaruah et al. (2003), Dutta and Kotoky (2006a, b), Kotoky (2011), Kotoky et al. (1997, 2003, 2005, 2006, 2009, 2011a, b, c, 2012)] fluvial systems. Geomorphologically, the rivers of the Indian subcontinent can be broadly divided into two major fluvial systems (Rashtriya Barh Ayog 1980). The first system includes all the large rivers and their tributaries heading in the Himalayas and the second consist of rivers draining the Deccan Peninsula. The striking differences between the two fluvial systems exist not only in terms of the magnitude of high flows but also in their channel morphology, plan-form and frequency and also the extent of flooding. The Himalayan rivers occupy a highly dynamic environment with profound variability in discharge and sediment load. Shifting of river courses, scouring of bed and banks and disproportionate transportation/deposition of sediments are some of the distinguishing features of the Himalayan Rivers. Conventional hydrological analysis in the Indian subcontinent is hampered by lack of sufficiently long and reliable flood record to evaluate the influence of long term climatic changes on flood magnitude and frequencies. Consequently, attempts are being made to interpret paleofloods from geological records (Baker 1994; Kale 1998). The dynamic Himalayan environment had caused significant impact on the geomorphic development leading to abnormal flow parameters, channel migration, meander growth and avulsion of the river channels draining in the area. Rapid migration of channels or shifting of courses may cause the floodwaters to spill in unexpected areas and may alter the total area flooded by a particular discharge (Dunne 1988). Similarly when meanders grow, rivers are lengthened and the gradient is decreased (Schumm 1985). These conditions in turn may cause the flood to rise (Jorgensen et al. 1994). Avulsion, which is common in rivers with erodible banks, can increase the flood hazards by diverting floodwaters in areas which were formerly above the high flood level (Dunne 1988) and considered to be safe, catching the inhabitants unawares. A case in this regard is the flooding of the Kosi River in the year 2006 that suddenly inundated hundreds of sq.km areas that were thickly populated and were considered to be safe from flooding hazard. In Bangladesh, the Brahmaputra (Jamuna) River has shifted some 70 km during the last half of the 18th century and is still moving at an alarming the rate (Ahmed 1969). Natural changes in the elevation of river channels due to variations in sediment transport can also increase or decrease the flood and/or area affected by floods.

Geomorphic analysis of a river presents unique challenges and requires a systematic and organized approach because of the spatial scale and system complexity involved. Progresses in the study of fluvial geomorphology have been aimed to develop the capability to identify, investigate and understand the continuity and connectivity of the flow processes and fluvial landforms in the river system. This prescribes the need to recognize and explore the links that bind the fluvial system in space and time (Fig. 1). Knowledge on the history and sequence of antecedent events and trends of morphologic evolution during the months, years and decades preceding the study will definitely help to understand the process-form relationships of a river.

River engineers, policy makers and managers recognize the importance of accounting for channel morphology and the dynamics of the fluvial system when dealing with alluvial rivers. Modern approaches to river management require engineers to work with rather than against the natural process-form relationships of the river, by retaining as much as possible of the natural hydraulic geometry of the

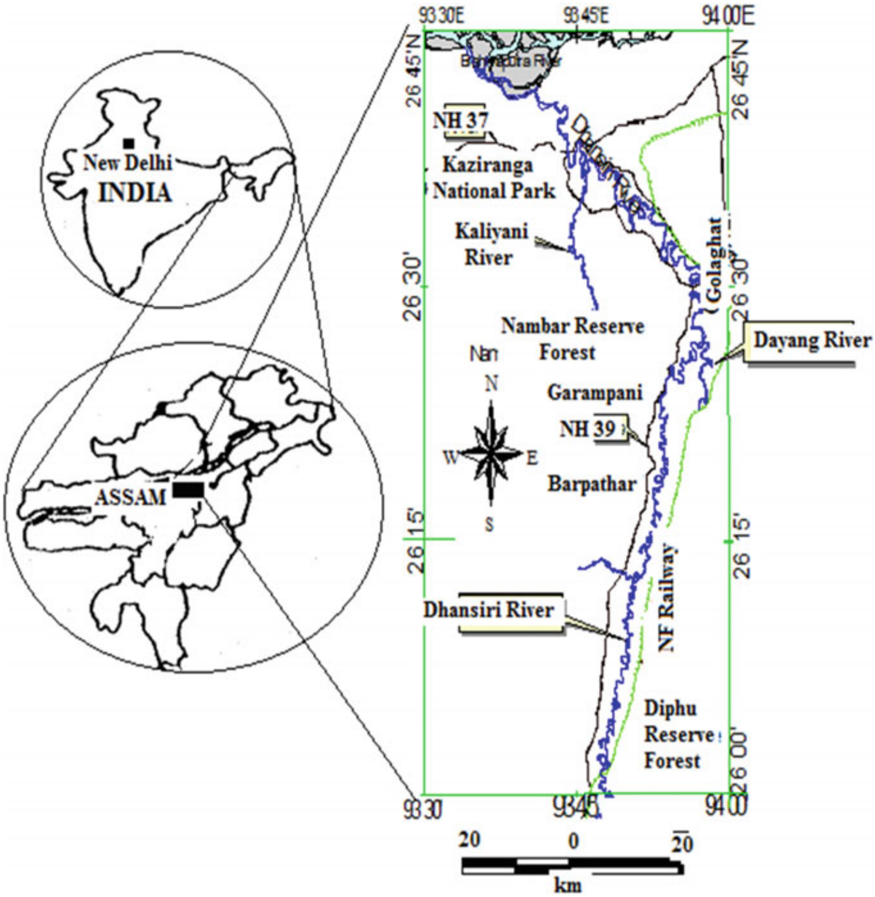


Fig. 1 Location map of the study area

self-formed channel when performing works for river regulation, channel training, navigation, flood defense, and land drainage. For this type of approach to be successful, it is essential to identify correctly the current morphological status of the river and to predict its future development with and without the proposed engineering interventions. This latter need implicitly requires the ability to predict the reaction of the channel to, for example, flow regulation (for hydropower or flood defense), or bank stabilization and training works (to control channel migration). Morphological impacts are known to spread away from the point of disturbance through process-form feedback mechanisms operating in the fluvial system. Hence, predictions of possible impacts cannot be limited to the reach directly affected by engineering works, but must extend along the mainstream and tributaries upstream, and the channel and any distributaries downstream.

Given cognizance to the nature, precepts and requirements for any geomorphic study of fluvial system as reviewed in the preceding paragraphs, this paper study has attempted understanding a unique river system in the Himalayan region, the Dhansiri River, a tributary of the mighty River Brahmaputra.

2 Location and Geological Setting of the Dhansiri River

The River Dhansiri, an important southern tributary of the mighty Brahmaputra River is originates from Thimtubum Peak of the Barail range at an altitude of 1,868 m (Sarma 1993). The important tributaries of the river are Dayang, Diphu, Sungajan, Deopani and Nambar. The tributary Dayang is much bigger than the main Dhansiri River. The total catchment's area of the river is about 12,584 km^2, the total length of the river is 352 km, out of which about 215 km falls within the plains of Assam. The river attains a maximum breadth of 132 m near Golaghat and average depth is about 6.20 m. The hydrological station on the river at Numaligarh station indicates its danger level as 77.42 m and maximum, minimum and average water discharges as 209,185, 4.88 and 513 m^3 s^{-1} respectively. The annual discharge of sediment as recorded in the station was reported as 6.28 lakh ha m. The river Dhansiri was reported as one of the highly meandered river of the world (Sarma 1993).

The study area is covered by the agro-eco regions of the Golaghat and Karbianglong districts and adjoining Nagaland. It experiences nearly dry to moist sub-humid climate with a moisture index of 0.2 % and an estimated length of growing period ranging from 270 to 300 days. The average annual temperature, annual precipitation and potential evapo-transpiration are 23.9 °C, 1,223 and 1,219 mm respectively. The area encompasses major physiography and landform types of Purvanchal hills, undulating uplands and plains of Brahmaputra valley.

The soils types present in the study area include relict alluvium developed over sedimentary and metamorphic rocks. The soil profiles are deep, well drained to somewhat excessively drained, loamy to fine textured. The soils are acidic and medium in base saturation and cation exchange capacity (CEC) with appreciable exchangeable aluminium in certain places. The soils were classified as Typic/Umbic Dystrochepts, Typic Paleudalfs, Typic Hapludults in the hills and Typic/Aeric Haplaquepts, Typic aeric Haplaquents, and Typic Udorthents in the Assam plains (NBBS 1999).

The major part of the agro-eco zone is covered with mixed forests. Hilly foothills regions are presently covered by tea and coffee plantation. Major part of the plain areas are used for cultivation of paddy, sugarcane, rotational crops and oil seeds along with varieties of vegetables. The soils of the region also have tremendous potential for horticultural crops. Soil acidity and flooding/water logging in soils of lower topography and/or depressions are the main constraints in potential land use pattern.

3 Materials and Methods

Detailed geomorphologic analysis have been carried out on the Dhansiri River channel, Assam for a stretch of 215 km out of the total length of 352 km within the geographical coordinates 93° 30′E–94° 0′E longitudes and 25° 45′N–26° 45′N latitudes. However, for the study of erosion phenomena, only 95 km of the Dhansiri River channel from Oating to Dhansirimukh was taken into account. The anthropological attributes along the reach, which have got significant impact on the geomorphic behavior of the channel, were also evaluated.

The Survey of India (SOI) toposheets (1914 and 1975) and Indian Remote Sensing (IRS) satellite imagery (1990, 1995 and 2000) were utilized for investigation of spatial changes over available period of time. The IRS black and white (B/W) imagery on band four (wave length 0.77–0.86 μm) with spatial resolution 36.25 m Linear Imaging and Self Scanning II) at 1:50,000 scale were used. The area under study was digitized through the use of Arcview software and geo-referenced in a GIS environment. The meanders were then characterized, quantified and nature of movements was measured to generate database.

Encompassing a period of 87 years starting from 1914 to 2000, the study on erosion phenomena of the Dhansiri River channel from Dhansirimukh to Nowakota-Kachari with potentiality to erosion was considered. Within the logistics and limitation it is attempted to evaluate the bank erosion phenomena with ground check. The erosion intensity along the channel was determined by sequential bank line analysis and the areas of erosion/deposition were determined in a GIS environment. The river course under study has been divided into six sectors to account for the amount of erosion and other related phenomena. Each sector was further sub-divided into smaller segments of 5 km each and studied accordingly.

4 Results and Discussion

4.1 Nature of Meandering

A river is an example of an open system through which matter and energy flow, but within which are inherent tendencies of self-regulation. The interactions between discharge, load, channel shape and other variables of hydraulic geometry in a fluvial system achieve long-term self-regulation in a river channel. Although, in a regional landscape it might take a long period of time, fluvial processes might achieve mutual adjustment in a comparatively shorter time intervals. Developmental activities in the flood plains and in regions adjoining the river courses should take into account this self-regulating mechanism of the rivers. As the rivers have shorter response times than other geomorphic systems, failure to consider this mechanism leads to adverse impacts.

The river Dhansiri is an important south bank tributary of the mighty Brahmaputra River. The river was reported as one of the highly meandered channels of the world. Meandering involves inherent properties of flowing water, as well as size and shape of the channel, erodibility of the stream banks, proportion of suspended and bed loads. In turn, meandering increases the channel length between two points and thus decreases the slope of the stream. Slope influences the velocity and sediment-transporting capacity of the river water. Thus, the formation, migration and removal of meanders in river courses are indicators of the ongoing self-regulation mechanism of rivers. In order to understand this phenomenon, the objective of understanding this mechanism, documentation of spatial and temporal distribution of channels, the degree of their regularity and controls on the pattern and movement is essential.

The characteristics and controls of channel patterns have long been the topics of study in fluvial geomorphology (Jefferson 1902; Friedkin 1945; Durry 1954; Leopold and Wolman 1957). The frequency of types of change in individual bend can be analyzed by comparison with models of movement to obtain a classification. To have an idea of lateral migration, the primary elements of movements have to be identified, defined and the changes have to be established by the vectors of movement of points of inflexion (P) and the apex (A) and by change in the orientation of the apical line. The primary elements of movement are: (a) Translation, (b) Extension, (c) Rotation, (d) Change in wavelength, (e) Lateral movement and (f) Complex change. Each of the movement may have one or two directional movement i.e. up or down, increase or decrease, and to the left or right. Combination of two or three processes in a natural system is also possible (Fig. 2).

In the present study, data from Survey of India (SOI) toposheets (1914 and 1975) and Indian Remote Sensing (IRS) satellite imagery (1990, 1995 and 2000) were collected to investigate spatial changes over time. Thematic maps of different periods were prepared on 1:50,000 scale and were integrated using Arc view GIS. The meanders were then characterized, quantified from individual map and natures of movements were measured by sequential analysis.

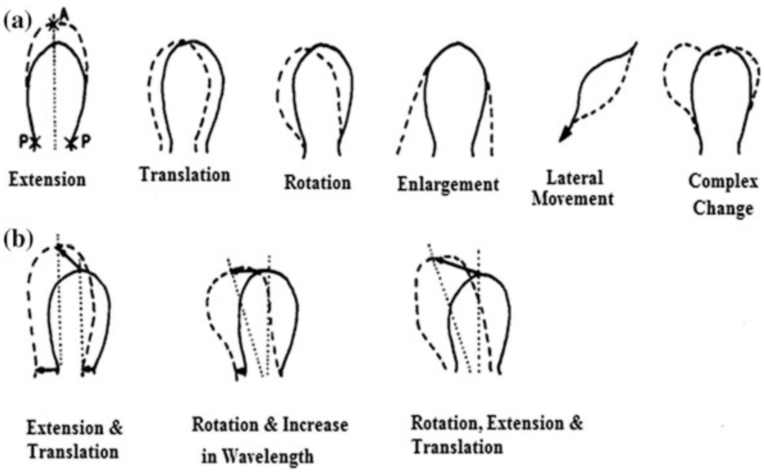


Fig. 2 Types of meandering in a river channel (After Hooke 1977)

The results indicate that out of nine different processes of meander migration, translation type was observed as dominant mechanism throughout the period under study (Table 1, Fig. 3). The order of significance can be represented as translation (49.20 %) > extension (16.04 %) > extension translation (13.37 %) > complex (12.03 %) > rotation (4.55 %) > lateral movement (2.94 %) > enlargement (1.60 %) > rotation and increase in wave length (0.27 %). The maximum number of meander bends (103) was observed in the base map of 1975. The significant rise in the number of meander bends might have a close link with the catastrophic disturbances caused by the Great Assam Earthquake of 1950 with magnitude 8.6 on

Table 1 Types of meander movement in Dhansiri river channel

Types	Periods			
	1914–1975	1975–1990	1990–1995	1995–2000
Translation	40	41	52	51
Extension	8	21	17	14
Rotation	7	5	3	2
Enlargement	1	3	1	1
Lateral movement	8	3	0	0
Complex change	13	16	8	8
Extension and translation	14	14	10	12
Rotation and increase in wave length	1	0	0	0
Total	92	103	91	88

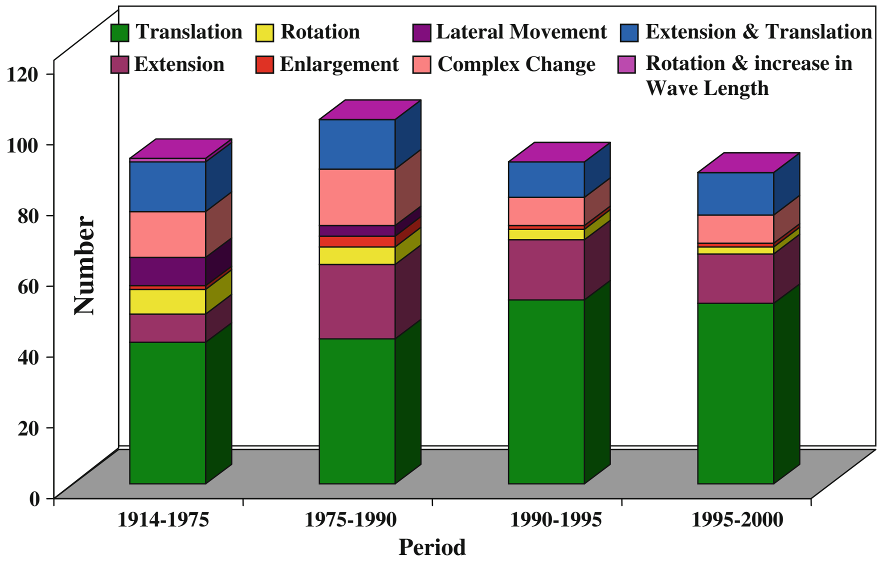


Fig. 3 Types of meander movement

Richter scale along with attendant historic flood. It is established that the earthquake has caused extensive changes to the geomorphology of the Brahmaputra Valley. Migration and abandonment of channels over a short period of time have resulted in the generation of many low-lying areas adjacent to the river system. The existence of significantly higher number of ox-bow lakes in the form of paleo-channels testifies to the transient nature of most of the former channels and the significant geomorphologic changes imparted by the earthquakes of the region. The migration of meanders at different period of time and the resultant generation of lakes (Bils) are shown in Figs. 4 and 5. Figure 6 presents the composite picture of the meander development and migration and formation of Bills for the entire study period (1914–2000).

The characteristic nature of meander migration/movement for different periods under comparative study with total number of meanders (figures in parentheses) can be represented as:

1914–1975	Translation (40) > Extension and Translation (14) > Complex (13) > Extension (8) = Lateral Movement (8) > Rotation (7) > Enlargement (1) = Rotation and increase in Wave Length (1)
1975–1990	Translation (41) > Extension (21) > Complex (16) > Extension and Translation (14) > Rotation (5) > Enlargement (3) = Lateral Movement (3)
1990–1995	Translation (52) > Extension (17) > Extension and translation (10) > Complex (8) > Rotation (3) > Enlargement (1)
1995–2000	Translation (51) > Extension (14) > Extension and translation (12) > Complex (8) > Rotation (2) > Enlargement (1)

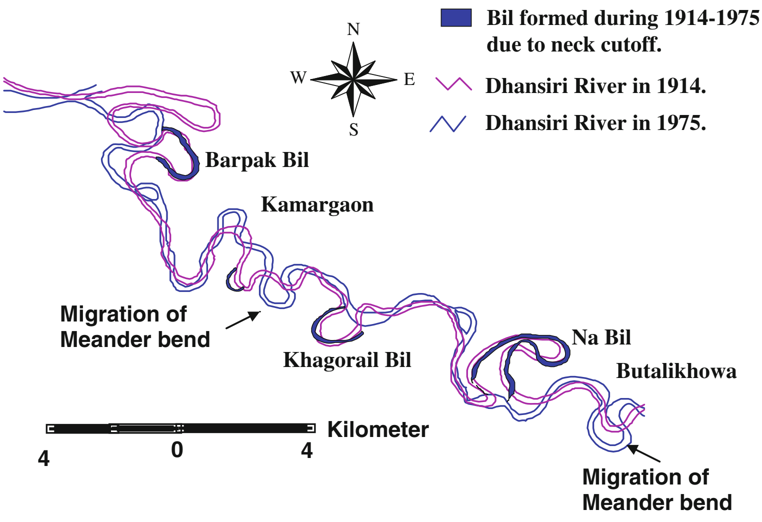


Fig. 4 Migration of meander bends and formation of Oxbow lakes (Bils) during 1914–1975

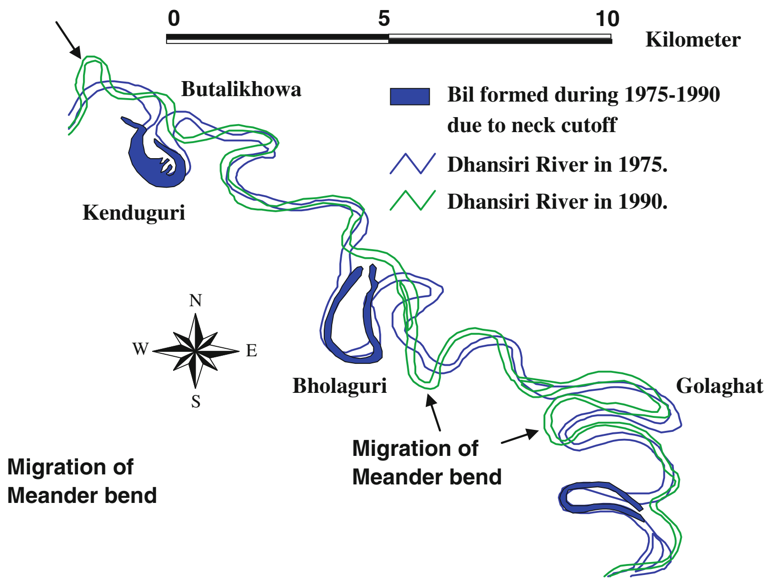


Fig. 5 Migration of meander bends and formation of Oxbow lakes (Bils) during 1975–1990

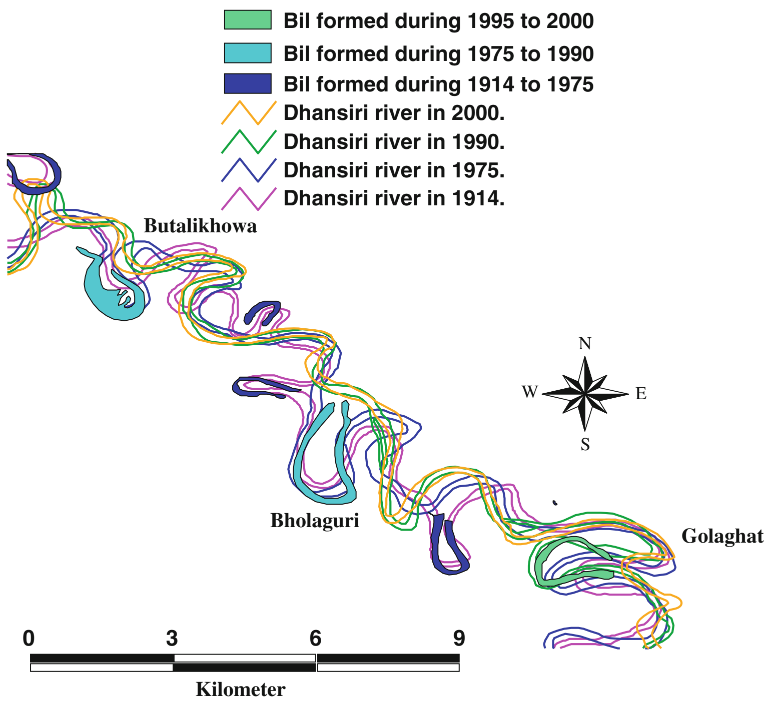


Fig. 6 Migration of meander bends and formation of Oxbow lakes (Bils) during 1914–2000

It can very well be attributed that considerable change in river channel has taken place during the last 87 years. These dynamics could be explained by the variable flow regimes of the channel, which inturn might have been influenced by natural as well as anthropogenic processes. Under constant flow conditions, the channel width stays relatively constant between stable banks, but as the current increases, a neck cutoff can occur. Otherwise, these channels are relatively stable. With mixed suspended and bed loads, however, meandering channels begin to build point bar on the inside of meanders and undercut their outer banks as the thalweg alternately impinges on opposite banks. The total load is usually larger in this type of meandering channel. Channels are wider at sharp bends than along regularly curving reaches. Such channels are quite unstable, with chute cutoffs across the back of the point bars adding to neck cutoffs as a process of shifting.

4.2 Intensity of Meanders and Sinuosity

The alluvial channel changes its position naturally with time. As it flows on erodible sediments and because the stress exerted by the flowing water often exceeds the strength of the sediments forming the bed and banks of the channel, the sediments from the bad as well as bank are mobilized towards downstream and also away from the channel, which results in changing the channel morphology into sinuous and meandering. Dynamism in river channels can very well be observed in terms of its description in plan form, cross sectional and longitudinal forms. Sinuosity represents the irregularity of the channel course and is expressed as the ratio between the channel length, measured along the center of the channel, and the valley length, measured along the valley axis (Leopold and Wolman 1957). Schumm (1963) suggested sinuosity as one of parameters to represent the intensity of meanders.

Decrease in sinuosity values of the Dhansiri River with time in almost all the sectors is recognizable from the Table 2. However, in Sector I the values after 1975 show an increasing tendency. This is also supported by the increase in channel length for different periods (Table 3). In addition, in the sectors I for the period

Table 2 Channel length and sinuosity values at different periods

Sectors	Periods				
	1914	1975	1990	1995	2000
I	2.39	1.97	2.28	2.45	2.60
II	2.98	2.45	2.13	2.17	2.19
III	3.06	3.02	2.95	2.60	2.41
IV	2.20	2.15	2.21	2.18	2.17
V	2.74	2.43	2.06	1.89	1.78
VI	2.55	2.34	1.88	1.91	1.87
Total	2.65	2.39	2.25	2.20	2.17

Table 3 Sinuosity index of the Dhansiri river channel at different periods

Sectors	Periods				
	1914	1975	1990	1995	2000
I	50.2	36	38	38.7	44.15
		(Neck cut off at Sinakangaon, Kamargaon and Barchaparigaon)			
II	43.73	36	31.27	31.84	32.21
		(Neck cut off at Bagariani near Khumtai, Bholaguri and Dhuliagaon)	(Neck cut off at Butalikhowa and Bholaguri)		
II	36.46	36	35.19	36.16	32.29
		(Neck cut off at Dachmuagaon and Thorajan Madhubangaon)	(Neck cut off at Katkatia, Golaghat)		(Neck cut off at Golaghat)
IV	36.86	36	36.95	36.46	36.38
		(Neck cut off at Dibaranigaon near Barpathar)		(Neck cut off at Silanijan)	
V	40.42	36	30.42	28.01	26.3
		(Neck cut off at Deo-pani T.G., Padamani, Jabrajangaon andDilaojan)	(Neck cut off at Sewaguri and Rongagara near Sarupathar)	(Neck cut off at Nagajuri and Kaliabil-gaon)	(Neck cut off at Jabrajan)
VI	39.2	36	29	29.48	28.74
		(Neck cut off near Mohkhuti, Bokajan and Ghorial Dubi)	(Neck cut off at Harihajan, Mara Kardaiguri and Bokajan)		(Neck cut off at Shitoyi Sema
Total length	246.87	216	200.8	200.7	200.1
Average sinuosity	2.76	2.38	2.25	2.22	2.16

1990–2000, increase in channel length was observed signifying enlargement of meander bends and migration of river channel just near the debouching point of river Dahansiri to the Brahmaputra River.

4.3 Erosion-Deposition Along the River

Effective management of rivers against bank erosion and resultant life and property loss requires data on reliable information on the effects of changes in river morphology or bank material characteristics; so that the undesirable impacts of channel changes can be avoided (Odgaard 1987). When extensive lengths of river channel become stabilized, the riverbank erosion can result in considerable riparian land loss and the delivery of large volumes of sediment downstream. The ability to predict the stability and failure geometry of eroding riverbanks is therefore an important prerequisite in estimating the rates of bank erosion and sediment yield associated with bank erosion. Several studies have contributed to the betterment of our understanding on riverbank erosion (Thorne 1982; American Society of Civil Engineers Task Committee on River Widening 1998; Darby and Thorne 1996a, b; Miller and Quick 1997; Simon et al. 1991; Osman and Thorne 1988; Rinaldi and Casagli 1999; Simon et al. 2000). The rate of channel migration (M) is likely to be dependent on stream power (essentially, the product of discharge and slope) per unit area of the bed (w), channel width (W), the force per unit area of the outer (concave) bank which resists channel migration ($Y_{b)}$, the bank height (h), and the radius of curvature (r). Further Y_b is largely a function of the size of sediment at the base of the channel (D_{50}), such that

$$M = f\ (w, W,\ D_{50},\ h,\ r)(\text{Hickin and Nanson 1984})$$

The sediment load, particularly the bed load is known to be strongly correlated to channel migration rate (Neil 1984). Bagnold (1980), however, has shown that the bed load transport is largely a function of stream power operating on particular sediment sizes. Daniel (1971) demonstrated that channel length around a meander loop increases in proportion to the magnitude of the channel-forming discharge, whereas Hickin (1974) demonstrated that the migration operates to maintain a minimum curvature ratio (bend radius to channel width: r/W) of slightly >2. Hickin and Nanson (1975) showed that bend migration reaches a maximum value as the curvature ratio approaches 3 and declines rapidly on either side of this value. Indeed, Carey (1969), and Page and Nanson (1982) have shown that, in very tightly curving bends, deposition will occur around the outer bank and erosion will occur at the convex bank.

A different approach to the problem of channel migration has been developed by those focusing on the details of bank erosion without specific regard to channel planform. The role of frost action and ground ice has been considered by Wolman (1959), Walker and Arnborg (1966) and Outlet (1974). Knighton (1973) found that bank erosion at a cross section was largely determined by the magnitude and variability of discharge and by the degree of asymmetry in the velocity field, bank wetting being a particularly important preconditioning process. Hooke (1979, 1980) has attempted to develop predictive statistical relationships and found that erosion rate is related to catchment area (discharge) and the percentage of silt and clay in the banks.

Global estimates of erosion and sediment transport in major rivers of the world vary widely, reflecting the difficulty in obtaining reliable values for sediment concentration and discharge. Milliman and Syvitski (1992) estimate global sediment load to oceans in the mid-20th century at 20,000 million t/year, of which about 30 % comes from rivers of southern Asia (including the Yangtze and Yellow Rivers of China). Significantly, they believe that almost 50 % of the global total comes from erosion associated with high relief on islands of Oceania—a phenomenon which has been underestimated in previous estimates of global sediment production. While erosion on mountainous islands and in upland areas of continental rivers reflects natural topographic influences, Milliman and Syvitski (1992) suggested that human influences in Oceania and southern Asia cause disproportionately high sediment loads in these regions.

Erodibility and Erosivity are two important physical factors that affect the magnitude of erosion. Erodibility is a measurable characteristic, susceptible to detachment and transport by the agents of erosion. Erosivity is an expression of the ability of erosive agents. Quantification of these two factors is basic to an understanding erosional process.

4.3.1 Bank Line Migration

The sequential analyses of geomorphological maps (Fig. 7) for the period from 1914 to 2000 have shown that the total length of the channel during 1914 measured to be 246.87 km has undergone changes over the period of time and the channel configuration of 1914 was considered as the base line for evaluation of bank line migration during the period 1914–1975. The bank line migration from 1914–1975 is presented in the Fig. 8. The maximum migration was observed on both the bank lines near Dhansirimukh for a distance of about 3.0 km towards south. This information along with the field investigation revealed that, migration in this area followed the pattern of migration of the Brahmaputra River. In some other sectors the rate of migration could not be measured as the migration of meanders in the resulted development of neck cutoffs.

A significant change in the migration of bank line towards east for a distance of about 1.5 km at Dhansirimukh has been observed during the period between 1975 and 1990 (Fig. 9). Near Dighali Ati area both the banks of the river witnessed a shift towards east up to maximum of 0.6 km. The period during 1990–1995 has shown the migration of the channel towards its original configuration. The locations on the bank of the river viz., near Golaghat and Numaligarh areas, the bank lines of the river migrated towards west and east respectively (Fig. 10). Significant migration is noticed near Elengmari gaon during the 1995–2000 period. The west bank line during this period evidenced significant migration towards west near Deopani area (Fig. 11).

The river channel has migrated for a distance of about 2.5 km towards east (Fig. 12) during the entire study period from 1914 to 2000. Higher rates of migration were prevalent near Numaligarh and Butalikhowa-Bholaguri areas. Near Bholaguri, the bank line had migrated towards west and near Numaligarh it migrated towards east. From the overall migration trends of the bank line, it can stated that there has been a continuous shifting of the Dhansiri River channel towards east for a distance of about 2.5 km at Dhansirimukh. The channel course from Dhansirimukh to Golaghat has shown significant changes in the bank line whereas, beyond Golaghat till Nowakota-Kachari, the channel remained stabilized,

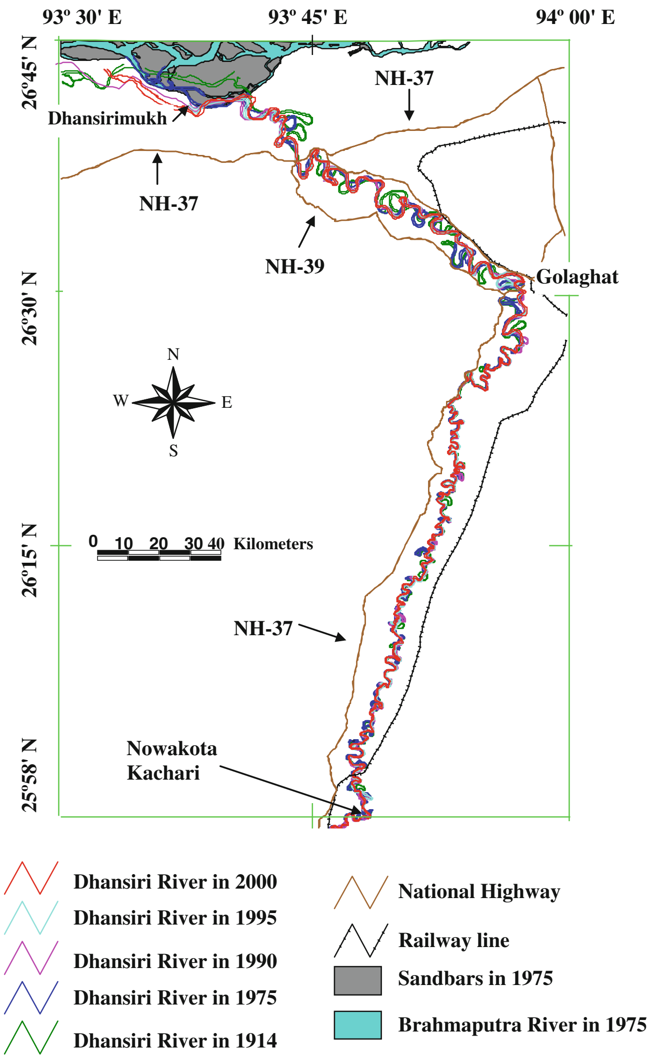


Fig. 7 Dhansiri river channel within the studied reach during 1914–2000

perhaps as a result of NS-trending fault located in the vicinity (ARSAC 1990). In other areas, the gradient of the terrain and nature of alluvium within the course might have played a crucial role in morphological adjustment of river channel.

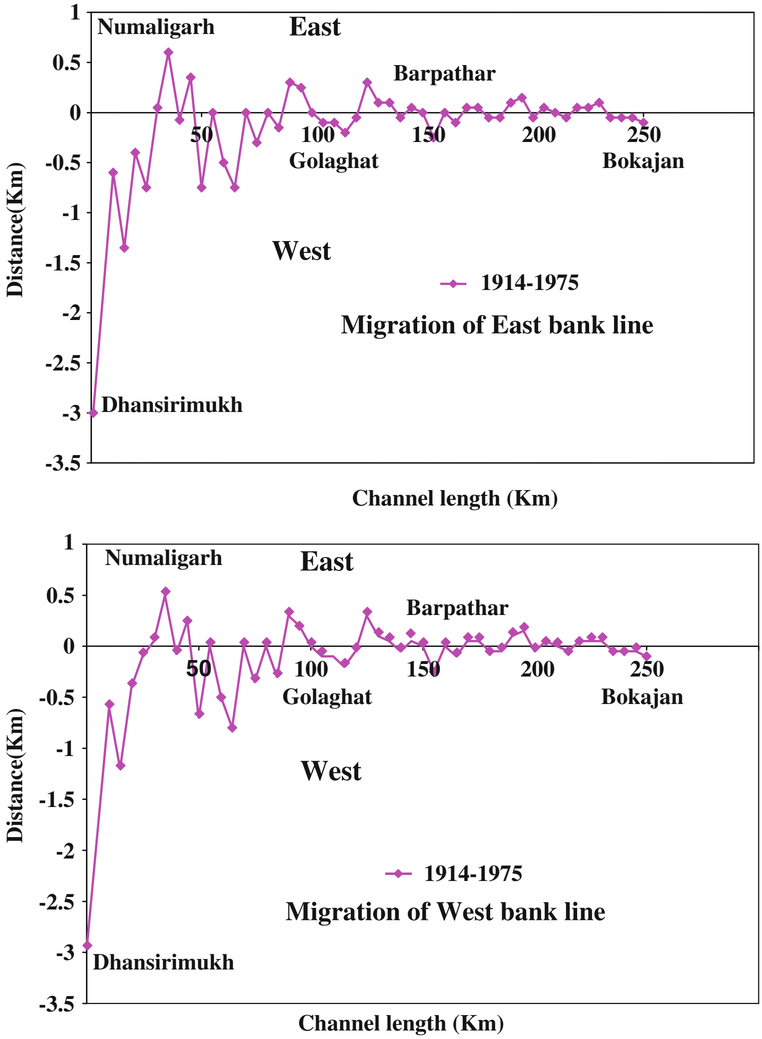


Fig. 8 Bank line migration of the Dhansiri river during 1914–1975

4.3.2 Erosion/Deposition

The erosion-deposition prevalent at different sectors during different time periods are presented in the Tables 4 and 5. From these tables, it follows that the intensity of erosion-deposition increases over time since the year 1914. From the Fig. 13, it is revealed that, the Dhansiri river experienced a higher rate of erosion along its western bank than the eastern bank. Near Butalikhowa at a distance of 60 km from Dhansirimukh the river had eroded an area measuring 1.34 km^2. However, the area

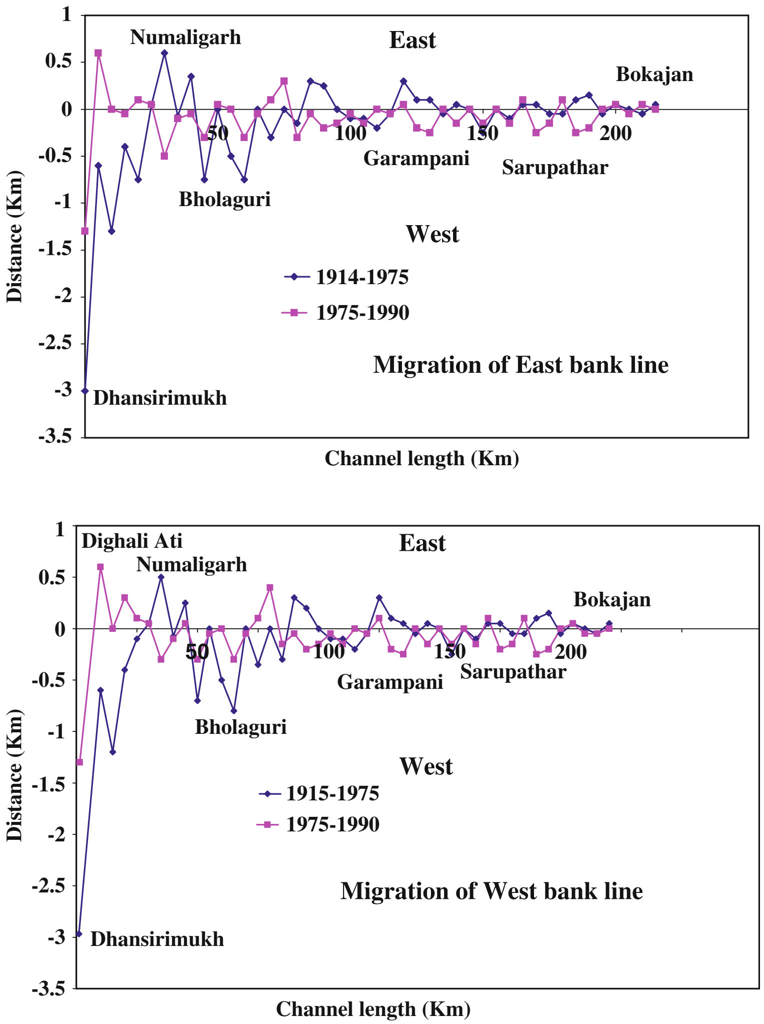


Fig. 9 Bankline migration of the Dhansiri river during 1975–1990

near Golaghat suffered significant erosion on its western bank and deposition on its eastern side. During the period 1914–1975, the total average annual erosion and deposition were estimated to be 0.37 and 0.25 km^2/year respectively, signifying a net loss of sediment/land area.

The pattern of erosion-deposition has been different during the period of 1975–1990 (Fig. 14). Fourfold increase in erosional intensity and fivefold increase in deposition are observed during this period. The region 20–30 km near Numaligarh-Kamargaon and the region 75 km near Golaghat on the eastern bank of the channel

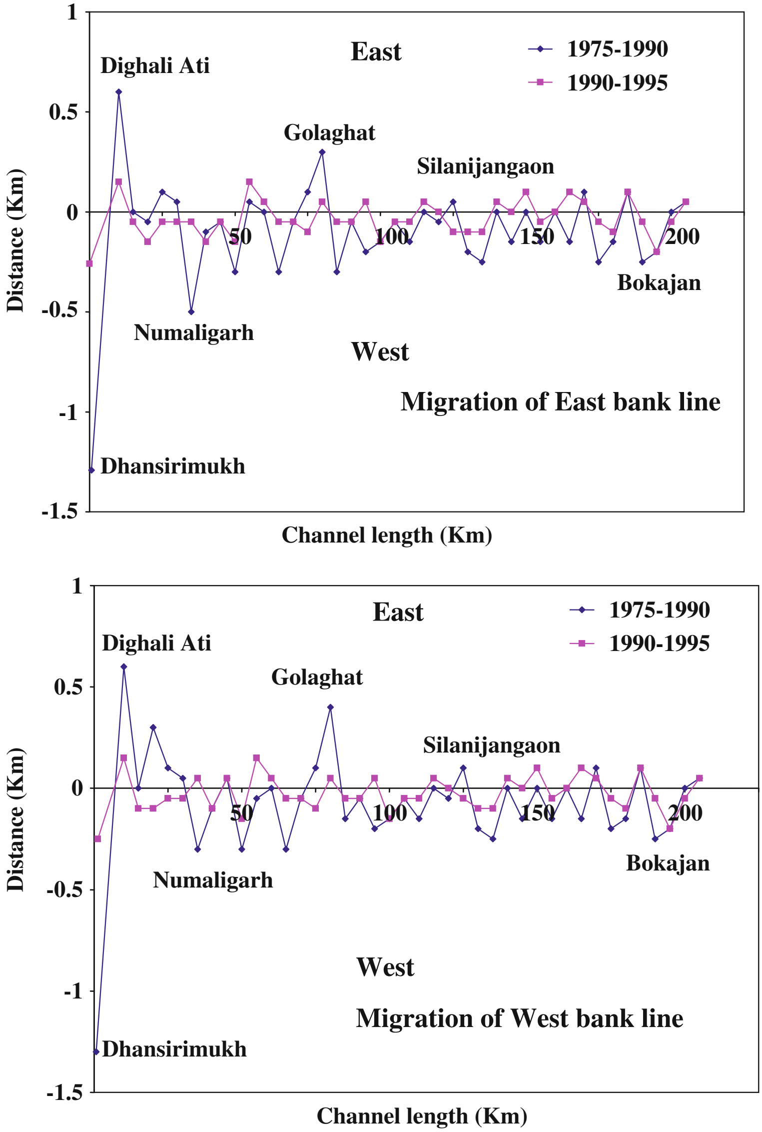


Fig. 10 Bankline migration of the Dhansiri river during 1990–1995

experienced severe erosion and lost land to the tune of 1.2 km^2. Surprisingly, the region located 65–75 km near Golaghat on the eastern bank exhibited deposition of 1.16 km^2 with concomitant erosion of 0.73 km^2 area. Net annual erosion and deposition during this period are estimated to be 1.31 and 1.25 km^2/year respectively. The period 1990 to 1995 shows average total annual erosion and deposition

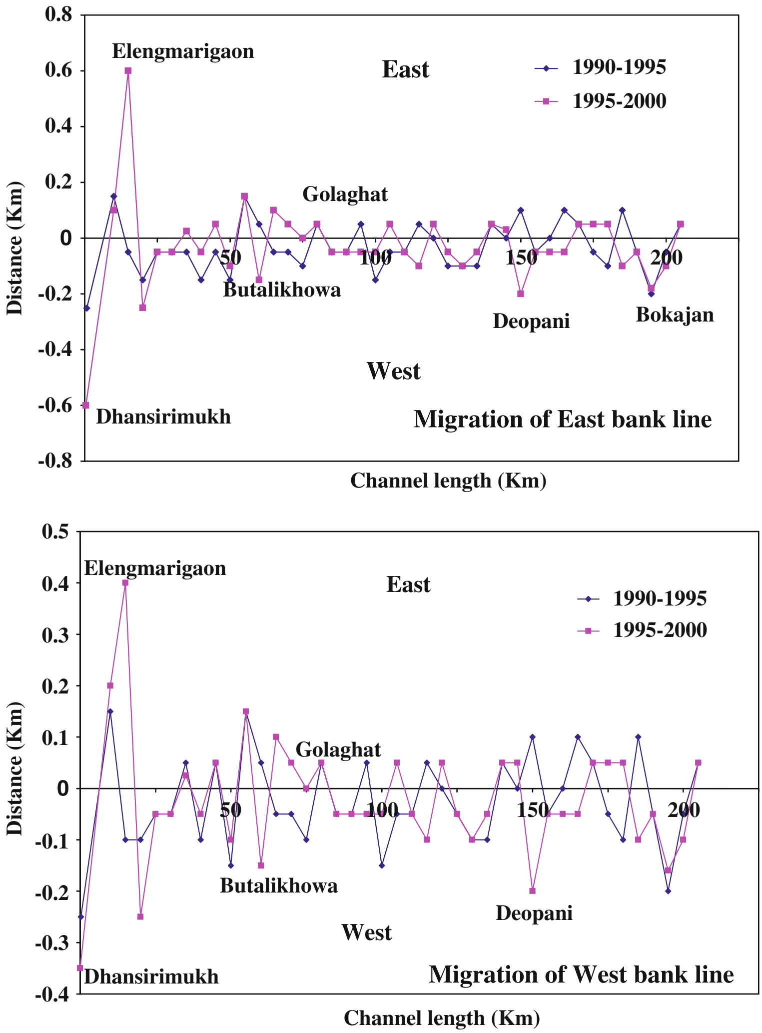


Fig. 11 Bankline migration of the Dhansiri river during 1995–2000

as 1.78 and 1.93 km^2/year respectively. The period has also represented an increase in the intensity of deposition than erosion (Fig. 15). More specifically, during this period, the eastern bank experienced consistent depositional episodes than the western bank.

The period 1995–2000 has shown phenomenal increase in erosion as well as deposition (Fig. 16). In a stretch from Kuruabahi up to Butalikhowa-Bholaguri areas, both the banks show erosional characteristics. The areas around Bholaguri on

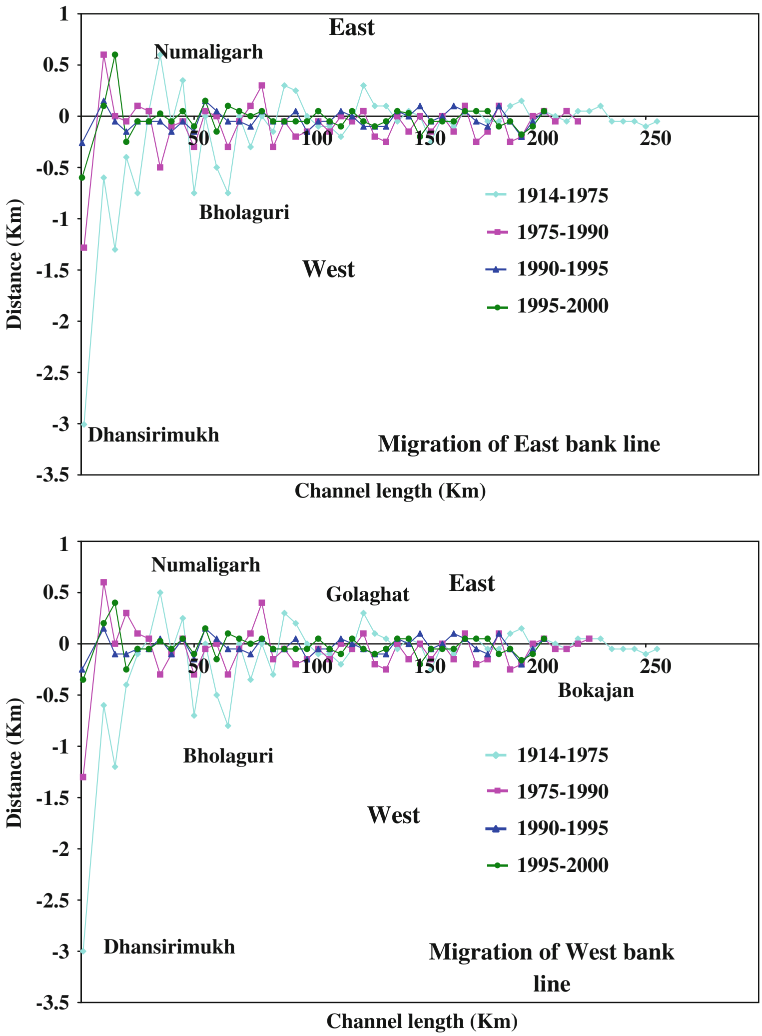


Fig. 12 Bankline migration of the Dhansiri river during 1914–2000

Table 4 Average annual erosion and deposition along with its rate within the studied reach of Dhansiri River channel

Period	Average annual erosion (km^2/year)	Average annual deposition (km^2/year)	Rate of average annual erosion (km^2/km)	Rate of average annual deposition (km^2/km)
1914–1975	0.37	0.25	0.0015	0.0010
1975–1990	1.31	1.25	0.0061	0.0058
1990–1995	1.78	1.93	0.0089	0.0096
1995–2000	1.81	1.65	0.0090	0.0082
Mean	1.32	1.27	0.006375	0.00615

Table 5 Erosion and deposition along the studied reach of Dhansiri river channel at different time and space

Sectors	Erosion (km^2)					Deposition (km^2)				
	1914–1975	1975–1990	1990–1995	1995–2000	Total	1914–1975	1975–1990	1990–1995	1995–2000	Total
I	5.59	3.92	2.59	1.99	14.09	3.65	3.44	2.46	1.67	11.22
II	7.55	5.98	1.96	2.52	18.01	5.07	5.52	2.62	2.09	15.30
III	3.44	1.96	1.34	1.23	7.97	2.53	2.22	1.46	1.01	7.22
IV	2.10	1.81	1.61	1.56	7.08	1.63	1.66	1.67	1.46	6.42
V	1.91	3.12	1.39	1.97	8.39	1.04	3.12	1.43	2.39	7.98
VI	1.90	2.92	1.81	1.58	8.21	1.24	2.73	1.95	1.56	7.48

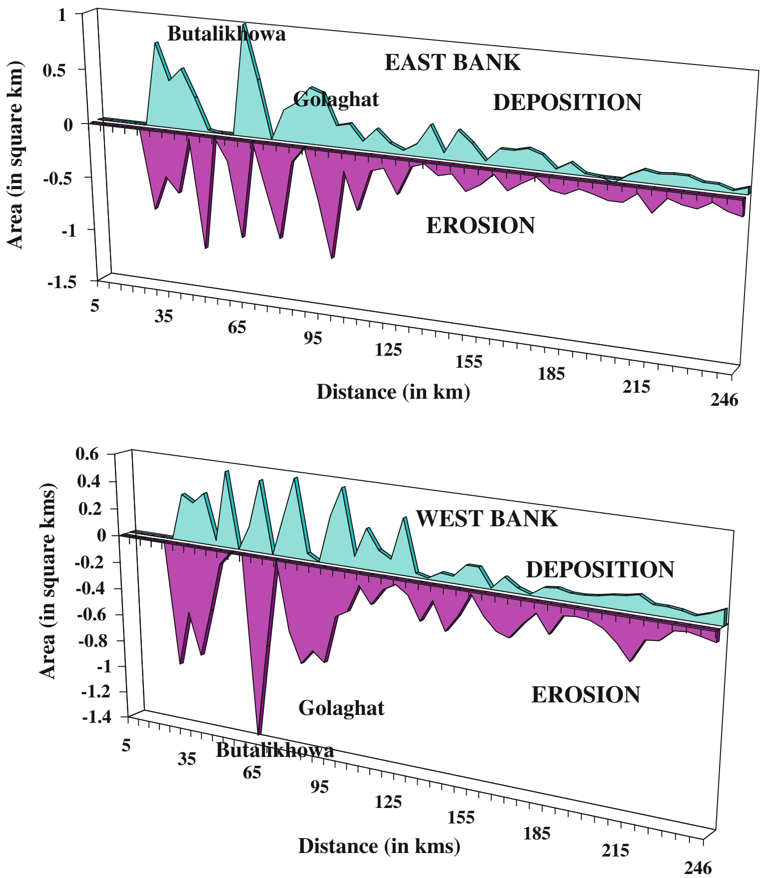


Fig. 13 Erosion and deposition in the studied reach of the Dhansiri river during 1914–1975

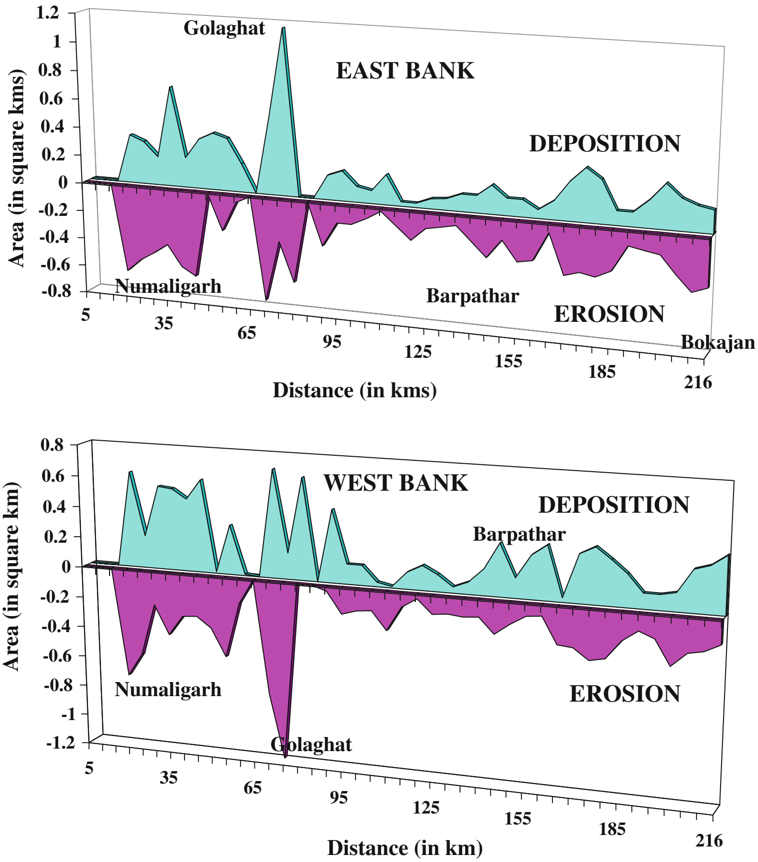


Fig. 14 Erosion and deposition in the studied reach of the Dhansiri river during 1975–1990

the east bank, depositional episodes predominate. The total average annual erosion and deposition during this period was evidenced as 1.81 and 1.65 km^2 respectively.

The erosion/deposition patterns along the Dhansiri River with average annual rate are presented in Table 4. The total average annual erosion and deposition calculated from the available data during the period from 1914 to 2000 within the studied stretch are represented as 1.32 and 1.27 km^2/year respectively. It is also observed from the available data (Table 5) that the erosion was maximum (18.01 km^2) in Sector II, whereas, it was least in the Sector IV (7.08 km^2). In addition, this sector has also evidenced the lowest amount of deposition (6.42 km^2). The total average annual erosion and deposition range from 0.37 to 1.81 km^2/year and 0.25 to 1.93 km^2/year respectively (Table 4). The nature of soft alluvial bank and contribution from the major tributaries might have played a major role in

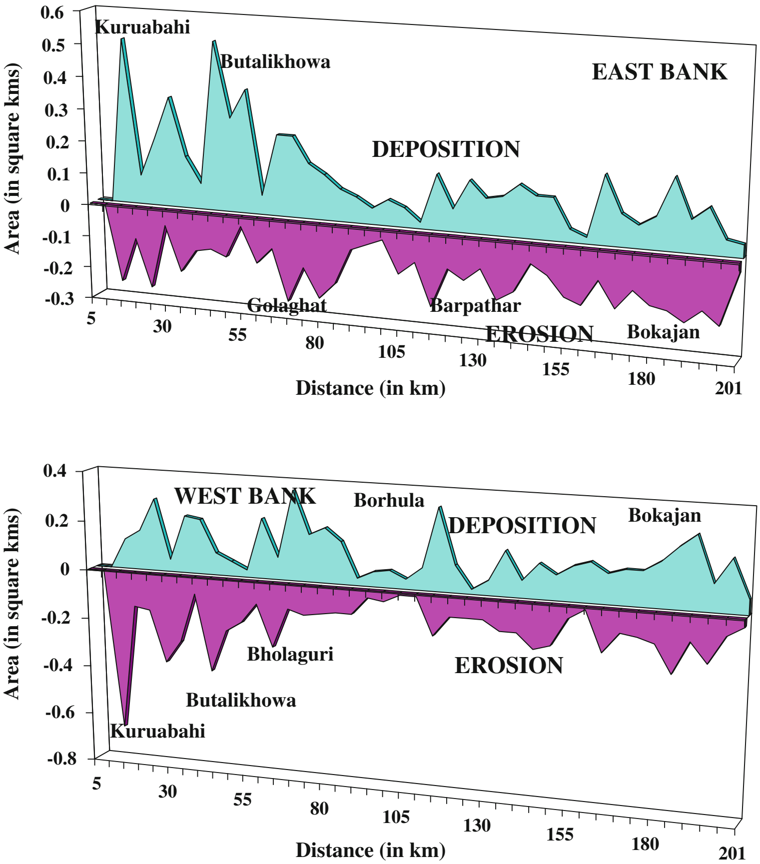


Fig. 15 Erosion and deposition in the studied reach of the Dhansiri river during 1990–1995

inhomogeneous natures of erosion/deposition activities operating within the basin. From the data of the Table 4, it is clear that the rate of bank erosion per km length of the river course ranges from 0.0015 to 0.0090 km^2/km. whereas, the rate of average annual deposition per km length of the river ranges from 0.0010 to 0.0096 km^2/km. The average rate of bank erosion and deposition per km length of the river channel, for the entire period of study, are found to be 0.006375 and 0.00615 km^2/km channel length respectively. The rate of average annual erosion and deposition for different periods are represented in the Fig. 17.

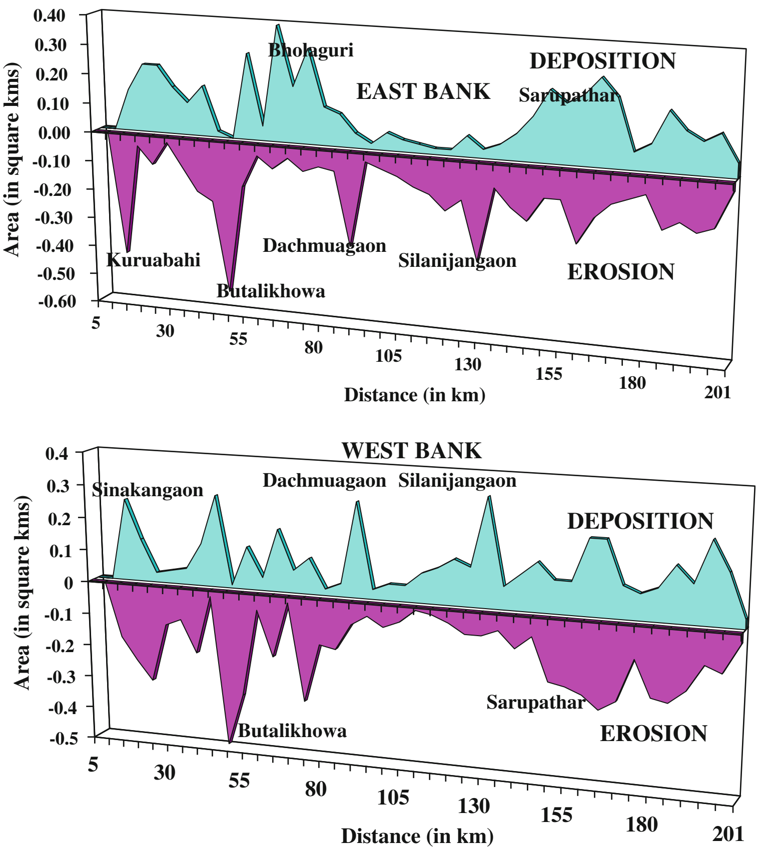
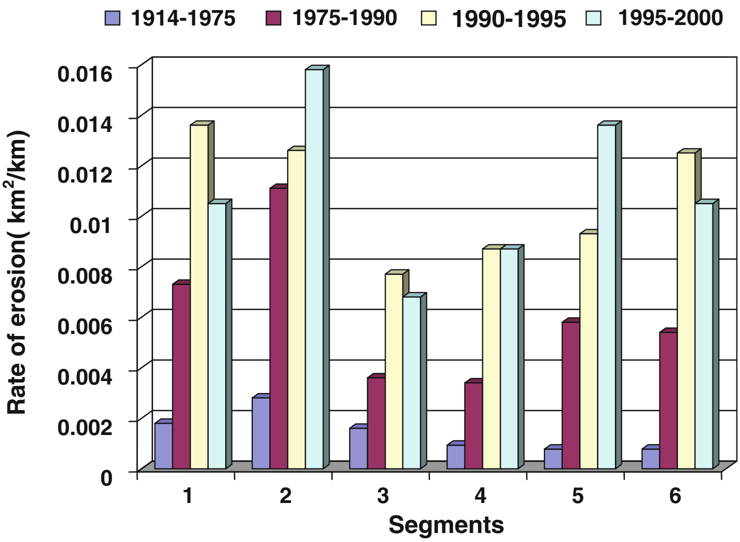


Fig. 16 Erosion and deposition in the studied reach of the Dhansiri river during 1995–2000



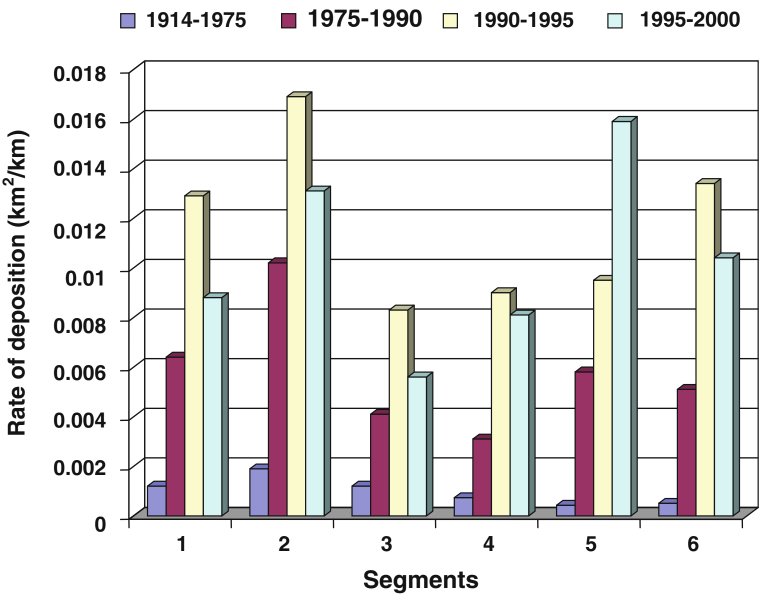


Fig. 17 Rate of average annual bank erosion and deposition along the studied reach of the Dhansiri river channel

5 Conclusions

- The highly meandered Dhansiri River channel, a south bank tributary of the Brahmaputra River has shown the predomination of translation mechanism of meander migration followed by extension and extension-translation mechanisms.
- Occurrences of abundant number of oxbow lakes and paleochannels indicate significant dynamic nature of the river during geologic past. A drop in the total number of meander bends from 1914 to 2000 was observed. The shortening of the river course from 246.87 to 200.07 km, has also supported the decrease in meander bends. The total mean sinuosity index studied for different periods have shown a decreasing tendency from 2.65 to 2.15.
- The river channel during the period of observation has evidenced a migration of 2.85 km. towards south at Dhansirimukh in conjunction with the southward migration of the mighty Brahmaputra River channel.
- The total average annual erosion and deposition during the entire period of study were 1.32 and 1.27 km^2/year respectively. Comparatively higher erosion was experienced by the west bank of the river than the east bank. The locations of the river channel in a soft alluvial plain and contribution of larger volume of water to the main channel by the larger tributaries (viz. Dayang River) might have played a major role in increasing the intensity of the erosion/deposition processes.
- The erosion/deposition processes within the studied stretch have evidenced increasing intensity from 1914 to 2000. The total average rate of erosion and deposition per kilometer length of the river were estimated to be 0.006375 and 0.00625 km^2/km respectively. The areas around Butalikhowa, Golaghat and Kuruabahi pose a threat demonstrating more erosion potentiality.
- The undercutting of soft alluvial banks ultimately lead to shearing from the bank material by its own weight. The generation of pad fabric in relation to the associated moisture content of the fine-grained bank materials has also contributed significantly towards the enhancement of bank erosion responses.

References

Ahmed F (1969) Maximum discharge of major rivers in large flood plains in East Pakistan. Floods and their computation. IAH-UNESCO-WHO Publication, Leningrad, pp 349–364

Allen JRL (1971) Changeable rivers: some aspects of their mechanics and sedimentation

Allen AP, Allen JR (1990) Basin analysis, principles and applications. Blackwell Scientific Publication, London, pp 445–470

American Society of Civil Engineers Task Committee on River Widening (1998) River width adjustment. I: Processes and mechanisms. J Hydraul Eng ASCE 124:881–902

ARSAC (1990) Landuse/landcover maps and reports of Assam. Assam Remote Sensing Application Centre, Gauhati (Unpublished Report)

Bagnold RA (1980) An empirical correlation of bedload transport rates in flumes and natural rivers. Proc Roy Soc Lond A372:453–473

Baker VR (1994) Geomorphological understanding of floods. Geomorphology 10:139–156
Baker VR, Kochel RC, Patton PC (1988) Flood geomorphology. Wiley, New York, p 503
Barman G (1981) Geomorphology of the Brahmaputra basin. Its floods problem and possible remedial measures. Geol Surv India Misc Publ 46:21–31
Bevan K, Carling P (eds) (1987) Floods: hydrological, sedimentological and geomorphological implications. Wiley, New York, p 290
Bezbaruah D, Kotoky P, Baruah J, Sarma JN (2003) Geomorphological explanation of swamps in geomorphological explanation of swamps along the Brahmaputra river channel, Assam. J Geol Soc India 62:605–613
Brice JC (1964) Channel patterns and terraces of Loupe river in Nebraska. US Geol Surv Prof Paper 422-D:1–41
Bristow CS (1987) Brahmaputra river: channel migration and deposition (In: Ethridge FG, Flores RM, Harvey MD (eds) Recent development in fluvial sedimentology). Soc Econ Paleontol Miner Spec Pub 39:63–74
Carey WC (1969) Formation of floodplain lands. Am Soc Civ Eng Proc 95(HY3):981–944
Chow VT (Ed) (1964) Handbook of applied hydrology, vol 15. McGraw Hill Inc, New York, pp 1–41
Coleman JM (1969) Brahmaputra river: channel processes and sedimentation. Sed Geol 8:131–237
Danial JF (1971) Channel movement of meandering streams. US Geol Surv Prof Pap 732-A:A1–A18
Darby SE, Thorne CR (1996a) Modelling the sensitivity of channel adjustment in destabilized sandbed rivers. Earth Surf Proc Land 21:1109–1125
Darby SE, Thorne CR (1996b) Development and testing of riverbank-stability analysis. J Hydraul Eng ASCE 1222(8):443–445
Davies WM (1989) The rivers and valleys of Pennsylvania. Nat Geog Mag 1:183–253 (also in Geographical Essays Ginn and Co, New York, pp 413–484)
De Wiest RJM (1965) Geohydrology. Wiley, New York, p 712
Dietrich WE, Gallinatti JD (1991) Fluvial geomorphology. In field experiments and measurement programs in geomorphology. Earth Surf Proc Land 12:173–184
Duijsings JJHM (1987) A sediment budget for a forested catchment in Luxembourg and its implication for channel development. Earth Surf Proc Land 12:173–184
Dunne T (1988) Geomorphological contribution to flood control planning. In: Baker VR, Kochel RC, Patton PC (eds) Flood geomorphology. Wiley, Chichester, pp 421–438
Durry G (1954) Bedwidth and wavelength in meandering valleys. Nature 176:31
Dury GH (ed) (1970) Rivers and river terraces. Macmillan Publication Co, London, p 277
Dutta SK (1980) The geomorphic history of Brahmaputra. J Palaeontol Soc India 23, 24:24–29
Dutta MK, Kotoky P (2006a) Wetlands along the Dhansiri river channel, Assam. GIS Development, Asia, pp 1–12
Dutta MK, Kotoky P (2006b) Nature of meandering in the Dhansiri river channel, Assam. National Seminar, Geological Society of India, Nagaland University, Kohima 9–11 Nov 2006
Fielding CR (1993) A review of recent research in fluvial sedimentology. Sed Geol 85:3–14
Friedkin JF (1945) A laboratory study of the meandering of alluvial rivers. United States Waterways Experiment Station, Vicksburg
Geike SA (1905) The founders of geology. Macmillan and Co Ltd, London, p 297
Geological Survey of India (1977) Contribution of geomorphology and geohydrology of the Brahmaputra valley. Geol Surv India Misc Publ 32:105–110
Geological Survey of India (1981) Proceedings of the seminar on fluvial processes and geomorphology of the Brahmaputra River basin, vol 46. Miscellaneous Publ, p 141
Gilbert GK (1887) Report on the geology of the Henry mountain. Washington, p 160
Goswami DC (1985) Brahmaputra river, Assam, India: physiography, basin denudation and channel aggradation. Water Resour Res 21(7):959–978
Goswami DC (1988) Magnitude and frequency of fluvial processes in the Brahmaputra Basin, Assam: some observations. In Singh S, Tiwari RC (eds) Geomorphology and Environment. The Allahabad Geographical Society, Allahabad, India, pp 203−211

Goswami DC (1998) Fluvial regime and flood hydrology of the Brahmaputra river, Assam. Mem Geol Surv India 41:53–75
Goswani U, Sarma JN, Patgiri AD (1999) River channel changes of the Subansiri in Assam, India. Geomorphology 30:227–244
Goudie A (1990) Geomorphological technique, 2nd edn. Unwin and Hyman, London, 570 pp
Gregory KJ (1977) River channel changes. Wiley, New York, p 443
Gregory KJ, Walling DE (1973) Drainage basin form and process, a geomorphological approach. Edward Arnold, London, p 447
Grover NC, Harrington AW (1943) Stream flow: measurements, records and their uses. Dover publication Inc. New York, p 363
Hickin EJ (1974) The development of meanders in natural river channel. Am J Sci 274:414–442
Hickin EJ, Nanson GC (1975) The character of channel migration on the Beatton river, Northeast British Columbia, Canada. Geol Soc Am Bull 86:487–494
Hickin EJ, Nanson GC (1984) Lateral migration rates of river bends. Am Soc Civ Eng, J Hydraul Eng 110, 11:1557–1567
Hooke JM (1977) The distribution and nature of changes in river channel patterns: an example from Devon. In: Gregory KJ (ed) River channel changes (British Geomorphological Research Group). Wiley, New York, pp 265–279
Hooke JM (1979) An analysis of the processes of the river bank erosion. J Hydraul 42:39–62
Hooke JM (1980) Magnitude and distribution of rates of river bank erosion. Earth Surf Process 5:143–157
Horton RE (1932) Drainage basin characteristics. Trans Am Geophys Union 13:350–361
Horton RE (1940) An approach towards a physical interpretation of infiltration capacity. Pract Soil Sci Soc Am 1:899–917
Horton RE (1941) Sheet erosion, present and past. Trans Am Geophys Union 22:299–305
Horton RE (1945) Erosional development of stream and their drainage basins, hydrophysical approach to quantitative morphology. Bull Geol Soc Am 56:275–370
Horton RE (1954) Erosional development of streams, quantitative physiographic factors. In Dury GH (ed) Rivers and rivers terraces. Misc, V 1, London
Hussein I, Choudhury JN, Ghani MU (1993) River bank erosion of Majuli Island as deciphered from the IRS imagery. In: Proceedings of national symposium on remote sensing application and resource management with special reference to NE-India region, Guwahati, pp 31–35, 25–27 Nov 1993
Hutton J (1795) Theory of the earth, Edinburgh. In: Horton RE (1945) Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Bull Geol Soc Am 56:275–370
Jefferson M (1902) Limiting width of meander belts. Nat Geog Mag 13:373–384
Jorgensen DW, Harvey MD, Flamm L (1994) Morphology and dynamics of the Indian river: implication for the Mohen Jo Daro site. In: Shroder J, Kazmi (eds) Himalayas to the sea: geology, geomorphology and quaternary. Routledge, London, pp 288–326
Kale VS (1998) Flood studies in India. Geol Soc India Mem 41:27–52
Kayastha SL, Yadava RP (1977) Human perception and adjustment to environmental hazards: a case study of three villages of the Ganga flood plain. In: Robert C (ed) Man, culture and settlement. Kalyani Publishers, New Delhi
King CAM (1970) Techniques in geomorphology. Edward Arnold, London, p 342
Knighton AD (1973) Riverbank erosion in relation to stream flow conditions, River Bollin-Dean, vol 5. East Midlands Geographer, Cheshire, pp 416–426
Kotoky P (2011) Geoenvironmental perspectives. Sci Cult 77:474–479
Kotoky P, Baruah J, Baruah NK, Sarma JN (1997) Geoenvironmental studies of river Jhanji, Assam. J Hum Ecol 6:55–67
Kotoky P, Bezbaruah D, Baruah J, Sarma JN (2003) Erosion activity on Majuli- the largest river island of the world. Curr Sci 84(7):929–932
Kotoky P, Bezbaruah D, Baruah J, Sarma JN (2005) Nature of bank erosion along the Brahmaputra river channel, Assam. Curr Sci 88(2):634–640

Kotoky P, Bezbaruah D, Baruah J, Sarma JN (2006) Characterisation of clay minerals along the Brahmaputra river channel, Assam. Curr Sci 91(9):1247–1250

Kotoky P, Bezbaruah D, Borah GC, Sarma JN (2009) Do node points play a role in flood proliferation? Curr Sci 96:1457–1460

Kotoky P, Dutta MK, Goswami R, Borah GC (2011a) Geotechnical properties of the bank sediments along the Dhansiri river channel, Assam. J Geol Soc India 78:175–183

Kotoky P, Dutta MK, Borah GC (2011b) Wetland ecology along the Dhansiri river channel, Assam, India. In: Kosygin L (ed) Ecology and biodiversity of rivers and streams of NE-India. Akansa Publishing House, New Delhi, pp 185–202. ISBN: 978-81-8370-26-8

Kotoky P, Bordoloi RK, Baruah NK, Borthakur KK, Borah GC (2011c) Water chemistry of the rivers around Jorhat, Assam, India. In: Kosygin L (ed) Ecology and biodiversity of rivers and streams of NE-India. Akansa Publishing House, New Delhi, pp 203–243. ISBN: 978-81-8370-26-8

Kotoky P, Dutta MK, Borah GC (2012) Changes in landuse/landcover along the Dhansiri river channel, Assam—a remote sensing and GIS approach. J Geol Soc India 79:61–68

Leopold LB, Miller JP (1954) Apost-glacial chronology for some alluvial valleys in Wyoming. USGS water supply paper, vol 1261, p 89

Leopold LB, Wolman MG (1957) River channel patterns: braided, meandering and straight. US Geol Surv Prof Pap 282-B:39–85

Leopold LB, Wolman MG, Miller JP (1964) Fluvial processes in geomorphology. WH Freeman, San Francisco, 522 pp

Lyell SC (1872). Principles of geology, 11th edn, Chaps 2, 3 and 4D. Appleton and Co, New York

Meinzer OE (1942) Hydrology. Dover Publication Inc, New York, 712 pp

Miller RG, Quick MC (1997) Discussion on Development and testing of riverbank stability analysis by Stephen Darby and Colin Thoene. J Hydraul Eng, ASCE 123(11):1051

Milliman JD, Syvitski JPM (1992) Geomorphic/Tectonic control of sediment discharge to the ocean: the importance of small mountain rivers. J Geol 100:525–544

Morisawa ME (1957) Accuracy of determination of stream length from topographic maps. Trans Am Geogr Union 38:86–88

Morisawa ME (1959) Relation of quantitative geomorphology to stream flow in representative watersheds of the Appalachian plateau province. Project NR 389-042, Technical report 20, Columbia University, Department of Geology. ONR, Geography Branch, New York

Morisawa ME (1962) Relation of quantitative geomorphology to stream flow in representative watersheds of the Appalachian plateau province. Bull Geol Soc Am 73:1025–1046

Naik SD, Singh RKS (1996) Bank erosion at Majuli Island, Assam—a study on multitemporal satellite data. Project Report SAC/RSAM/ RSAG/ WSP/96/2, p 51

NBBS (1999) Soils of Assam for optimizing landuse. Indian Council of Agricultural Research, Nagpur Publ, pp 66, 43

Neil CR (1984) Bank erosion versus bedload transport in a gravel river: rivers 83. In: Proceedings of American society civil engineer, New Oreland, pp 204–211

Odgaard AJ (1987) Streambank erosion along two rivers in Lowa. Water Resour Res 23:1225–1236

Osman AM, Thorne CR (1988) Riverbank stability analysis-I, theory. J Hydraul Eng, ASCE 114 (2):134–150

Outlet DN (1974) Progress report on bank erosion studies in the Mackenzie river delta. Northern oil development report, Report No 74–12, pp 303–345

Page K, Nanson GC (1982) Concave bank benches and associated floodplain formation. Earth Surf Proc Land 7:529–542

Powell JW (1895) The exploration of the Colorado valley and its canyons. Dover, New York

RAB (1980) Report of the Rashtriya Barh Ayog. Government of India, New Delhi, I and II

Rinaldi M, Casagli N (1999) Stability of streambanks formed in partially saturated soils and effects of negative pore pressure: the Sieve river, Italy. Geomorphology 26:253–277

Sarin MM, Krishnaswami S (1984) Major ion chemistry of the Ganga Brahmaputra river systems, India. Nature 312(5994):538–541

Sarma JN (1986) Sediment transport in the Burhi dihing river, India. IAHS Publication, Wallingford, p 159
Sarma JN (1993) Axamar Nad Nadi, Axam Sahitya Sabha, In Assamese, 335 pp
Sarma JN (1995) A study of the hydraulic characteristics of the Noa Dihing- Burhi Dihing river sytem in Eastern India. Colloquium in floods, slopes and river beds. University of Paris, France 22–24 March 1995
Sarma JN, Basumallick S (1984) Bankline migration of the Burhi Dihing river, Assam, India. Indian J Earth Sci 11(3, 4):199–206
Schumm SA (1963) Sinuosity of alluvial rivers in Great Plains. Geol Soc Am Bull 74:1089–1100
Schumm SA (1977) The fluvial systems. Wiley, New York, 388 pp
Schumm SA (1985) Patterns of alluvial rivers. Ann Rev Earth Sci 13:5–27
Schumm SA, Khan HR (1972) Experimental study of channel pattern. Geol Soc Am Bull 83:1755–1770
Simon A, Wolfe WJ, Molinas A (1991) Mass wasting algorithms in an alluvial channel model. In: Proceedings of the 5th federal interagency sedimentation conference, Las Vegas, Nevada, p 2, 22–29 Aug 1991
Simon A, Curini A, Darby S, Lagendoen EJ (1999) Stream bank mechanics and the role of bank and near- bank processes in incised channels. In: Darby SE, Simon A (eds) Incised river channels. Wiley, Chichester, pp 123–152
Simon A, Curini A, Darby SE, Langendoen EJ (2000) Bank and near bank processes in an incised channel. Geomorphology 35:193–218
Strahler AN (1964) Quantitative geomorphology of drainage basins and channel networks. In: Chow VT (ed) Handbook of applied hydrology. McGraw Hill Book Company, New Delhi, pp 4.39–4.76
Temple H, Sundborg AKE (1971) The Rufiji river, Tanzania, hydrology and sediment transport. Geografirka Annaler 54(3–4):1972
Thornbury KD (1954) Principles of geomorphology. Wiley Eastern Ltd, New Delhi
Thorne CR (1982) Processes and mechanisms of vegetation on river bank erosion. In: Hey RD, Bathurst JC, Thorne CR (eds) Gravel bed rivers. Wiley, Chichester
Walker HJ, Arnborg L (1966) Permafrost and ice-wedge effect on riverbank erosion. In: Proceeding of Conference Permafrost, Washington DC, pp 164–171
WAPCOS (1993) Morphological study of the river Brahmaputra. Water and Power Consultancy Services (India) Ltd, New Delhi
Ward RC (1978) Floods: a geographical perspective. The Macmillan Press Ltd, London
White GF (1964) Choice of adjustment to floods. Department of Geography, University of Chicago, Research paper, p 93
Wolman MG (1959) Factors influencing erosion of a cohesive river bank. Am J Sci 257:204–216
Yalin MS (1992) River mechanics. Pergamon Press, Oxford, 23 pp