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MEANDER MIGRATION AND CUT-OFF DYNAMICS OF LOWER DISANG RIVER (ASSAM, INDIA)

Abstract: Meander migration and cut-offs are important mechanisms causing changes in river channel morphology. The present work aims at investigating the dynamics of meander migration and cut-offs of the Lower Disang River (Assam, India) and its relation with planform parameters. Channel migration and cut-offs between 1916 and 2017 were studied on an approximately 203.89 km long meandering alluvial reach of the Lower Disang River. Topographical sheets, satellite imageries and Google Earth images (1916, 1969, 1990, 2005 and 2017) have been used to map, quantify, and analyse the development pattern of the meander bends. Only five natural cut-offs occurred during the 101-year time span in the study area. However, numerous cut-offs have occurred in the pre-1916 period, which is seen in the form of traces of oxbow lakes on its floodplain. No cut-off has been formed in the post-2005 period. For the period between 1916 and 2017, the average rate of lateral channel migration has been 1.35 $m \cdot y^{-1}$ due to the combined process of progressive migration and cut-off. An average of 2.98 % of the total channel length changed via cut-off while 97.02 % of the channel length changed by gradual migration. As a result, of low cut-off frequency and progressive increase in channel length through migration, there is a steady build-up of sinuosity and increasing complexity in meander forms. Thus, cut-off has been less dominant mode of channel change than progressive migration.

Keywords: meander migration, cut-off dynamics, channel centerline, sinuosity, meandering planform, Lower Disang River

INTRODUCTION

The migration of meanders is a distinct characteristic feature of alluvial rivers and one of the most conspicuous changes affecting fluvial landscapes (Ferguson 1977). Meander migration and cut-off processes drive changes in channel morphology, sediment load, and habitat attributes of alluvial rivers (Micheli, Larson 2010). Meandering rivers display a wide range of behaviour. While some of the meanders exhibit instability and high migration rates, some experience low rates of mobility or are stable. The explanations for such varied behaviour vary from assumptions of equilibrium, with change as adjustment to external alterations (exhibited by stable relations of morphology to discharge), to attribution of meandering as inherent and autogenic and evolution being due to intrinsic factors (Hooke 2003). The rate of meander migration is controlled by various factors under different environmental conditions. Geological structures are critical control on the downvalley translation in confined meandering rivers (Nicoll, Hickin 2010). Cohesive bank sediments or clay plugs may resist bank erosion (Wolman, Leopold 1957; Hudson, Kesel 2000). In his study on the Darjeeling Himalaya in 1968, L. Starkel has observed the geomorphic impacts of extreme rainfall events on channel processes such as increase in bedload and changes in channel geometry (Froehlich et al. 1990). On the other hand, migration rate increases with increase in drainage area (Brice 1984; Hooke 1980, 2008) which represents a surrogate for discharge (Hudson, Kesel 2000), bankfull width (Nanson, Hickin 1986; Richard et al. 2005; Nicoll, Hickin 2010), channel slope and stream power (Nicoll, Hickin 2010). A strong relation was seen between migration rate and bankfull width in Rio Grande River (Richard et al. 2005), a sample of western Canadian rivers (Nanson, Hickin 1986) and a sample of 23 confined meandering rivers in Canadian prairies where width explained 50%, 44%, and 31% of the migration rate variance respectively. Change in supply of sediment load also plays an important role in determining the movement of meanders. An increase in sediment load could trigger the initiation of meanders in a formerly straight channel and also lead to an increase in its sinuosity (Ackers, Charlton 1975; Neill 1984). Besides, an increase in the proportion of fine material (silt/clay) in the bed and banks results in greater resistance to erosive forces (Schumm 1968; Hooke 1980). Human interventions on river channels such as revetments and bank protection, cut-offs, dams and diversions, as well as land-use have significant direct and indirect impact on rates of migration. J. Cebulski (2016), in his study on Łapszanka stream, has shown how human beings indirectly bring about changes in the direction of natural migration by triggering a landslide on its bank resulting in damming the flow of the stream. Some meandering rivers such as the lower Mississippi River, USA (Hudson, Kesel 2000), and Cann River in Australia (Brooks et al. 2003) have recorded a very high average migration rate. According P.F. Hudson and R.H. Kesel (2000) study of the lower Mississippi River, migration rates increase with increasing drainage area whereas A.P. Brooks et al. (2003) have attributed the removal of riparian vegetation and in-channel wood from the Cann River as the cause of high migration rates. On the other hand, some rivers, like Ohio River (Alexander, Nunnally 1972), Ouchita River in Arkansas and Louisiana (Biedenharn et al. 1984), the Klip River in

South Africa (Rodnight et al. 2005), the Cher River in France (Dépret et al. 2017) or the Usuktuk River in Alaska (Matsubara et al. 2015) have displayed low mobility. D.S. Biedenharn et al. (1984) have attributed low stream energy, cohesive banks and dense vegetation as the causes of planform stability of the Ouchita River between 1820 and 1980. In Y. Matsubara's (2015) study, vegetation mantled banks of the Usuktuk River appear to offer resistance to fluvial erosion. T. Dépret et al. (2017) have attributed low rate of meander migration of the Cher River to the presence of bank protection measures and constraints imposed by the engineering works installed in the bed of the river. In numerous studies, a non-linear relationship has been recognized between migration rate and the radius of curvature in which the migration rates are highest when R_c/w is between 2 and 3 (Bagnold 1960; Harvey 1978; Hickin, Nanson 1984; Nanson, Hickin 1986; Hooke 2007; Nicoll, Hickin 2010).

C. Camporeale et al. (2008) have described the evolution of a meandering planform by three basic processes: the continuous elongation of the river axis, with single or compound lobe formation, the downstream (sometimes upstream) migration of the meander loops, and the occurrence of cut-off events. Cut-off events are considered signs of instability (Quick 1974; Knighton 1984), and they not only reduce the sinuosity but also affect the adjacent meander bends upstream or downstream of the cut-offs (Larsen, Shen 1989; Hooke 1995). Cut-offs cause alteration in distribution of stream power and increases the channel gradient and in order to accommodate these changes, local morphological adjustments take place in adjacent bends. J.M. Hooke (1995) has demonstrated in her study on the Bollin and Dane rivers that although much of the adjustments of gradient and energy takes place within the cut-off channel by modification of width, pool and riffle configuration, in Bollin River, a cut-off resulted in steepening and destabilization of the adjacent upstream section of the cut-off. However, in the Dane River, the downstream section of the cut-off was eroded due to new patterns of current through the breach. Migration rate and cut-offs are not only determined by complex interactions between discharge, bed material mobility, sediment supply, bank erodibility, riparian vegetation, bank geotechnics and human interventions (Lagasse et al. 2004), but also by sinuosity and planform complexity (Li et al. 2016).

The upper reach of the Brahmaputra River flowing through the plains of Assam (India) has three major south bank tributaries, namely, Burhidihing, Disang, and Dikhow rivers, all of which have sinuous planform. A close look at the topographic maps and satellite imageries reveals the presence of several oxbow lakes and cut-off scars, most of which predate the available historical maps. It shows that the river has undergone frequent cut-offs, which are driven by migration processes. The Disang basin is located in geologically unstable and fragile rock formations falling under a zone of very high seismicity (Zone V- Very Severe Intensity Zone) (IS:1893, 2002). The basin falls in the sub-tropical monsoon region with heavy precipitation in its hilly catchment. The Disang River flows through regions having both rural and urban settlements. The vegetation along the rivers have been cleared to make agricultural fields. The middle and lower portion of the river plain has high density of settlements with extensive agricultural fields whereas in the foothill region and in other areas of relatively higher lands and isolated hillocks tea plantations are common. Recurring floods of different magnitude and durations are annual events especially during monsoons, which pose a major problem to both man and animal lives along the river banks. The migration of meanders as well as cut-offs result in loss of agricultural lands as well as their hearth and homes. Poor means of transport and communication further adds to the problem, particularly in rural areas settled by different ethnic groups. Breaches of embankments due to bank erosion also lead to siltation of the low lying areas as a result of which natural water reservoirs are decreasing in size. Although P. Buragohain (2010) has done a pioneering fluvio-geomorphological study of the basin, a detailed long-term geomorphological investigation of the Disang River is still missing. Thus, empirical research spanning over 100 years will help us in our understanding of the processes driving meander migration and cut-offs as well as in quantification of their current mobility, thereby helping in the prediction of potential meander migration bends and cut-offs. The objectives of the present paper are (i) to analyse the meandering planform of the Lower Disang River, (ii) to assess the relation of migration rate and cut-offs with planform parameters from 1916 to 2017.

THE STUDY AREA

The Disang River is a south bank tributary of the Brahmaputra River in Assam, India (Fig. 1). The river originates in the hilly ranges of Naga Patkai (Lahiri, Sinha 2012) at an elevation of 2,200 m a.s.l. in the Tirap district of Arunachal Pradesh. The river is known as the Tisa at its source, as Dilli in the middle part, and as Disang in its lower part (Buragohain 2010). The present study area is located on the lower reach of the river from its point of debouching onto the plains near Dilli Tea Estate in Namrup to its confluence with the Brahmaputra River at Disangmukh. Having an area of 3,845.98 km^2 the river basin is bounded by the latitudes of 26°36’20” N and 27°18’ 50” N and longitudes of 94°34’35” E and 95°32’45” E. The study focuses on the reach stretching from 27°08’12.27” N and 95°22’02.42” E to 27°03’01.25” N and 94°31’48.12” E,

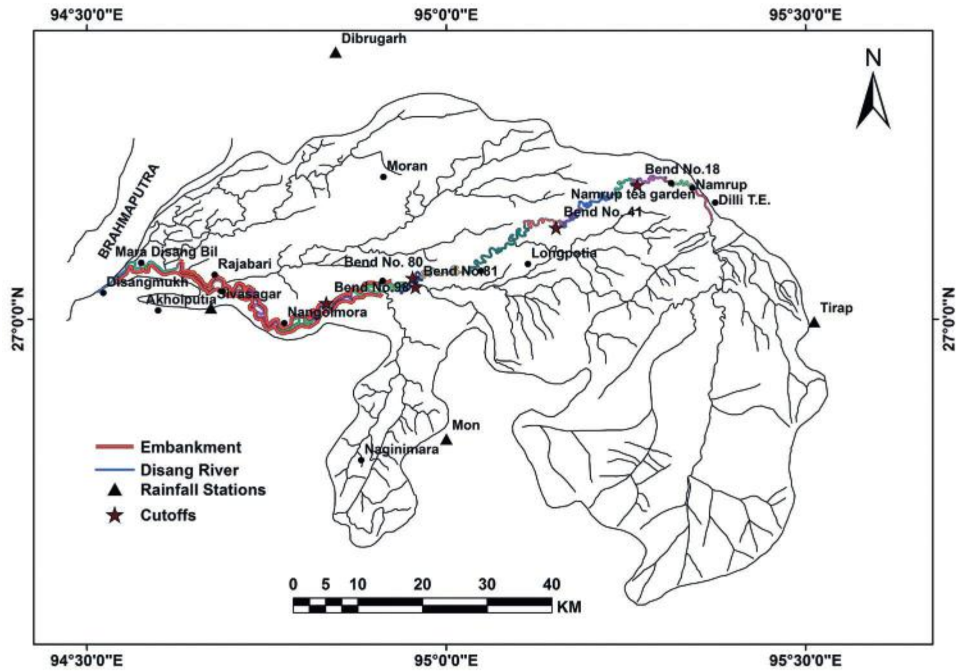

Fig. 1. Location map of the Disang River basin

which has been further divided into 18 sub-reaches. The river is a single thread channel freely meandering through the valley composed of recent alluvium of Holocene age for approximately 203.89 km from north-east to south-west and then towards the north-west, ultimately discharging itself into the Brahmaputra River. The existing lithology of the area has shown in Figure 2. The Disang River has a perennial flow regime with most of the high flows occurring between May to September. Mean annual discharge of the Disang River is 245.41 $m^3 \cdot s^{-1}$ and mean water level is 89.423 m. The mean sediment load is 82,327.98 tons. The relation between discharge and sediment load is nearly linear (Fig. 3). The mean width and depth of the river is 84.16 m and 8.62 m respectively. The basin is characterized by wet tropical monsoon type of vegetation. Along the river, the vegetation comprises of long grasses, canes, reeds, bamboo, ferns and plantains. Most of the vegetation has been cleared for making agricultural fields, tea gardens, and settlements. Vegetation is also lost due to bank erosion during floods. In the upper reaches where the river debouches onto the plains, bank and bed materials are mined extensively. This also makes the river vulnerable to erosion. General hydrological characteristics of the Lower Disang River is summarized in Table 1.

Table 1.
Hydrological characteristics of the Lower Disang Rriver

Discharge ($m^3 \cdot s^{-1}$)	Sediment load (tons)				Channel characteristics			
Q_m	coarse	medium	fine	Q_s	W_m (m)	D_m (m)	channel gradient ($m \cdot km^{-1}$)	mean sinuo-sity
245.41	35,543.39	25,612.78	21,171.80	82,327.98	84.16	8.62	2.79	2.06

Q_m = annual mean discharge, data series: 1985-2003; Q_s = annual mean sediment load, data series: 1985-2003; W_m = mean channel width; D_m = mean channel depth.

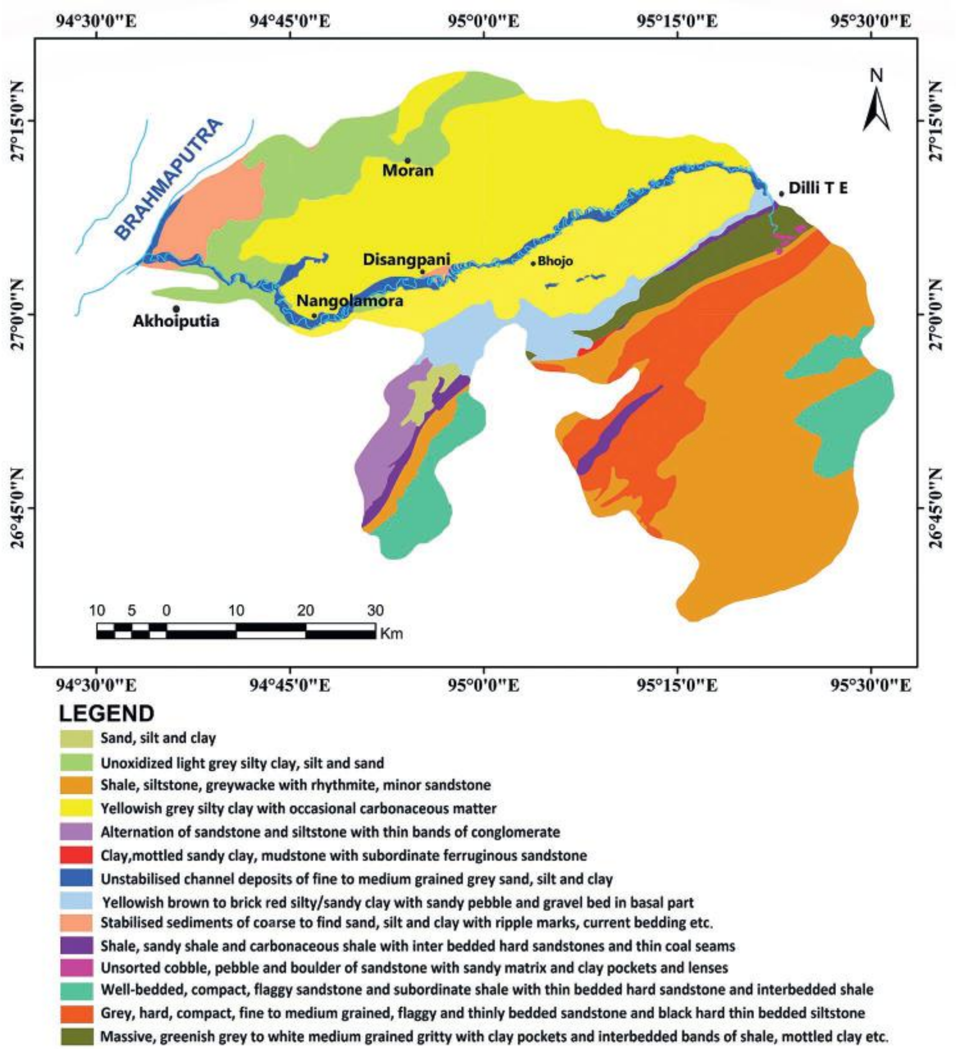

Fig. 2. Lithology of the Disang River basin (Source: Geological Survey of India, Shillong)

The hill section of the Disang River has a very steep gradient which abruptly gives way to a very gentle channel gradient as it debouches onto the plains in Assam as evident in Figure 4. The soils of the hill portion of the basin are composed of red loams and laterites mixed with boulders, pebbles, cobbles and gravels with high organic compounds (Buragohain 2010). New alluvial soils of Holocene age are found in the active floodplain of the basin. Numerous ox-bow lakes, swamps and marshes made the river belt and flood plain heterogeneous in character. In order to mitigate the problem of floods, embankments along both the banks has been constructed. However, during floods, breaches and overtopping have occurred on several occasions. The total length of the embankment on Disang River is 93.25 km of which 47.20 km is along its left bank and 46.05 km on its right bank. The lowermost reach on the right bank is not embanked.

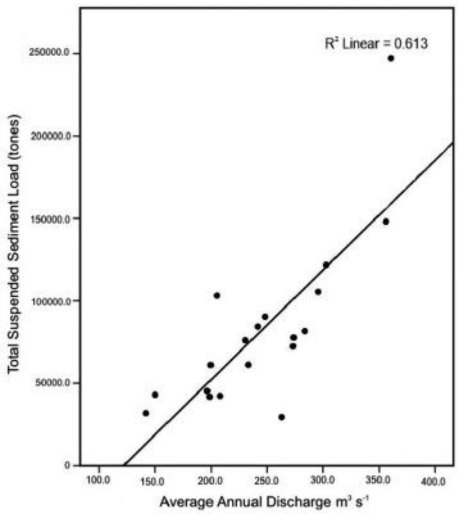

Fig. 3. Relation between average annual discharge and total suspended sediment load

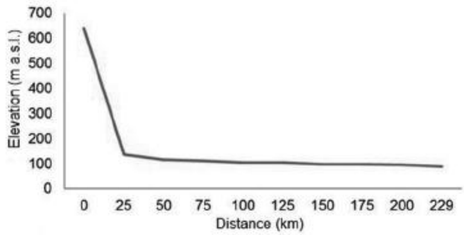

Fig. 4. The longitudinal profile of the Disang River

DATABASE AND METHODOLOGY

The database of the present has been prepared based on the maps, satellite imageries and data collected from different sources (Tab. 2).

MEANDER PLANFORM GEOMETRY

Different parameters of meander planform geometry, symbols, definitions and their techniques of measurement is given in Table 3. All of these parameters including channel orientation is also shown in Figure 5. About 130 meander bends of the river have been considered for studying these parameters.

Table 2.
Maps, satellite imageries and data for the present study

	Year	Number	Source	Scale
Topographic maps	1916	83 I/12, 83 J/13, 83 I/16, 83 M/04, 83 M/08, 83 N/05	Survey of India (SOI)	1: 63,360
	1969 –1970			1: 50,000
Satellite data	1990	Landsat 5 TM		30m resolution
	2005	Landsat 7 ETM+		
Google Earth Pro Images	2017			
Geological maps	1992–1993		Geological Survey of India	1: 50,000
Hydrological data	1985–2003	annual/ peak discharge, water level	Water Resource Department, Jorhat, Assam	
		sediment load		
	1982–1994	flood duration	Brahmaputra Board, Guwahati, Assam	
Precipitation data	1960–2005		India Meteorological Department portal, Ministry of Earth Sciences, Govt. of India	
Depth	2017 and 2018	cross sections taken at field survey		

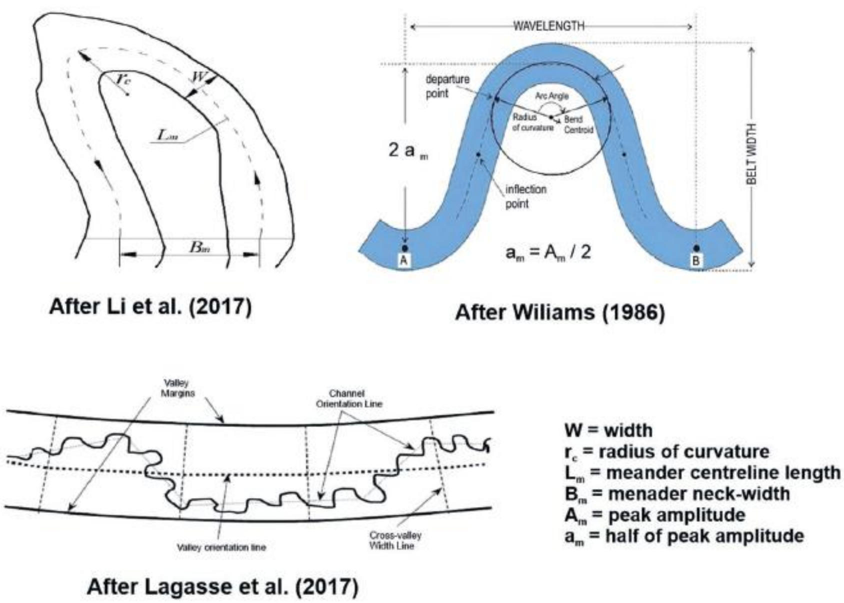

Fig. 5. Meander parameters

Table 3.
Parameters of meander planform geometry and techniques of their measurement

Parameter	Symbol	Definition	Technique of measurement
Wavelength	λ	distance over which shape of the waves repeats (Hecht 1987)	a line defining the valley axis split up at each inflection point of the channel centreline
Amplitude	a_m	vertical distance between the crest and the trough	a perpendicular distance from the wavelength to the apex of the bend centerline. In this study, the term amplitude means half of the peak-amplitude (Williams 1986) (Fig.5)
Radius of curvature	R_c	R_c of a curve at a point is a measure of the radius of circular arc which best approximates curve at that point	radius of the circle that best fits the meander centreline
Average meander width	w	distance across the channel between vegetation boundaries	arithmetic average of the measurement of the width: one at the apex, one each at the inflection points, and between the inflection points and the apex
Sinuosity	SI	ratio of the channel length (CL) to the valley length (VL) over a given reach	reach-wise sinuosity index has been obtained by measuring the length of the channel orientation line between two points and then measuring the channel centreline between the same locations; the channel orientation line defines the direction along which the channel is flowing across the valley (Lagasse et al. 2004); for individual meander bends, the sinuosity index has been calculated as the ratio of meander bend length to the meander wavelength.
Meander neck width	B_m		width from the channel centrelines at the narrowest point in each meander loop
Bend curvature	C		the ratio of the channel centreline length L_m to the neck channel width B_m
Channel gradient			channel gradient obtained from maps by dividing the elevation change between successive contour crossings by the distance measured along the centerline of the river between the contour crossings.
Non-dimensional neck width	B_m/w	non dimensional measure of the neck width	ratio of neck channel width to average channel width (Li et al. 2016).
Bend centroid		location of the center of bend radius	
Bend orientation		orientation of the bend with respect to the valley	the angle between the meander axis and the straight line between two inflection points. A line that extends from the bend centroid to the apex (Fig. 5)

CHANNEL CENTRELINE ANALYSIS

One of the tested methods for discerning changes in a river channel for identifying bends that migrate either progressively or by cut-off is through temporal analysis of channel centrelines (Micheli, Larson 2010). The river channel outline has been digitized using the wetted boundaries of the valley to determine the channel centreline. The digitized channel boundary lines have been used to generate a channel centreline using ArcGIS (line connecting the locus of points equidistant from the two channel boundaries) software for subsequent analysis. According to T.J. Nicoll and E.J. Hickin (1986), this protocol has an averaging effect that minimizes the error associated with any change in the water stage. Both increase in channel length by means of extension or expansion as well as decrease in length by means of cut-offs have been measured.

MEANDER MIGRATION AND CUT-OFF

The methodology for studying channel migration and cut-off has been obtained based on the methodology adopted by J.R. Wallick et al. (2007) on the Willamette River, E.R. Micheli and E.W. Larson (2010) on the Sacramento River, R.J. Giardino and A.A. Lee (2011) on the Brazos River. It involves the generation of migration polygons by superimposing successive channel centrelines in a GIS environment. The respective total area of migration polygon is then divided by semi-perimeter of that polygon. Migration polygons have been classified as either progressive migration or cut-off based on inspection of the source aerial photograph. The two have been distinguished by examining whether or not the affected area had been 'reworked' via progressive migration using indicators such as the condition of the floodplain vegetation and the presence of scroll bars (Micheli, Larson 2010). The mode of movement of meander loops were determined by measuring changes in the centroid, radius and orientation of the meander loops (Hooke 1984; Lagasse et al. 2004), (Fig. 6). Extension or across-valley migration and translation or

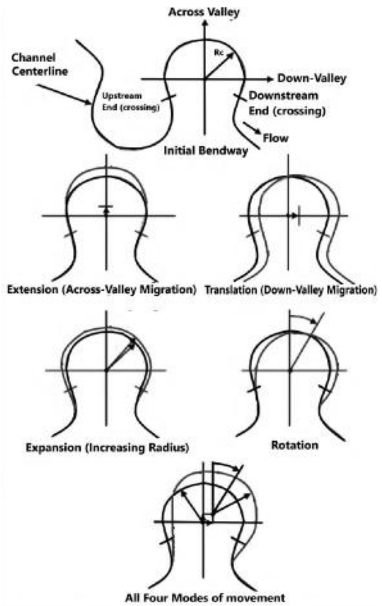

Fig. 6. Measuring meander migration (after Lagasse et al. 2004)

down-valley migration has been measured at the bend centroid. Expansion or contraction has been determined by measuring the change in the radius of curvature (R_c). Rotation has been determined by examining the change in the orientation of the meander with respect to the valley alignment.

RESULTS

PLANFORM ANALYSIS

SINUOSITY AND CHANNEL LENGTH

Table 4 shows the temporal changes in the sinuosity of the river channel and its consequent effect on the channel length. The sinuosity has steadily increased with a corresponding increase in channel length by 17.36 % or approximately 30.16 km. The growth rate of the channel has been highest (7.49 %) during 1969–1990 periods and lowest (1.12 %) during 1990–2005. Both sinuosity and channel length has increased during the 101-year time-span from 1.79 to 2.06 and from 173.73 km to 203.89 km respectively.

Table 4.
Sinuosity index and channel length

Year	Channel length (km)	Sinuosity index	Channel length growth rate (%)
1916	173.73	1.79	
1969	183.83	1.89	5.81
1990	197.6	1.96	7.49
2005	199.81	2.01	1.12
2017	203.89	2.06	2.04

BEND CURVATURE RATIO C

The bend curvature ratio (*C*) of the 103-meander bends for the year 1916, 1990, and 2017 has been studied (Fig. 7). It shows that in 1916, about 81.73 % of the studied meander bends have *C* values <4, which has drastically reduced by 20 % in 1990. The category having *C* values between 4 and 5 has remained relatively stagnant. In 1990, the category with *C* values >5 has multiplied 4-times the values observed in 1916. The average *C* values have increased from 2.72 in 1916 to 4.39 in 2017.

MEANDER NECK WIDTH-AVERAGE CHANNEL WIDTH RATIO B_m/W

A temporal analysis of B_m/w value shows that the percentage of meander bends with B_m/w <3 increased during 1916–1990 period followed by subsequent reduction in 1990 due to natural cut-offs (Fig. 8). It is noticed that the bends with high B_m/w (>5) have gradually decreased by 5.88 % between 1916 and 2017.

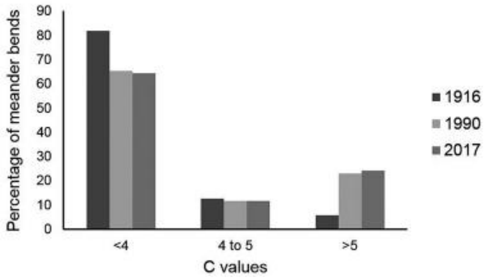

Fig. 7. Temporal changes in the bend curvature ratio C

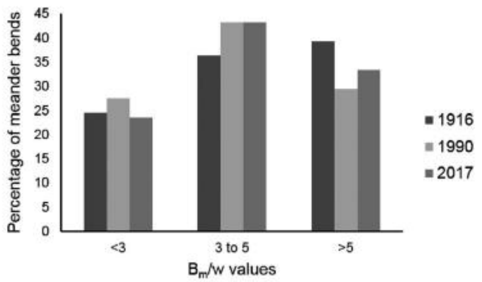

Fig. 8. Temporal changes in non-dimensional neck width B_m/w

Correlations have been established between ratio C values and B_m/w for the years 1916, 1990, and 2017 (Fig. 9). There exists significant inverse relationship between the two variables, r (101) = –0.296, –0.425, and –0.452 for 1916, 1990, and 2017 respectively, and $p<0.01$.

The study of the trends in planform evolution during the period 1916–1990 and 1990–2017 shows that translation, extension, and compound development are the most common types of loop evolution (Tab. 5). During 1916–1990, downstream translation, extension, rotation, and translation have been a common form of meander loop evolution along the entire length of the Lower Disang River. There has been the formation of new meander bends (7.14 %) while 3.17 % of the total number of meander bends along the river has been between 1990 and 2017 the meander loops evolved mainly through the process of translation, expansion and translation, and compound development. The percentage of stable bends has also increased to 11.36 %. The descriptive statistics showing the temporal evolution of planform parameters such as wavelength, amplitude and radius of curvature have been shown

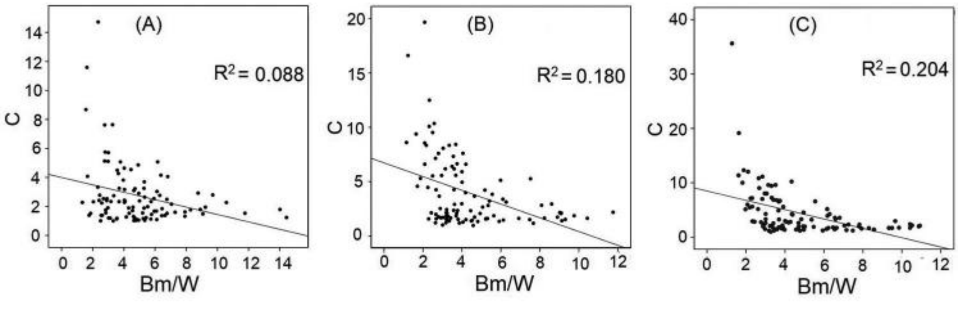

Fig. 9. Relation between bend curvature ratio (C) and non-dimensional neck width (B_m/w) values in year: A – 1916, B – 1990, C – 2017

Table 5.
Changes in meander loops

Changes in meander loops	% of total meander loops	
	1916–1990	1990–2017
Translation	27.78	16.67
New bend	7.14	0.0
Extension	16.67	8.33
Expansion	4.76	13.64
Rotation	1.59	0.76
Lobing	3.97	1.52
Stable	3.17	11.36
Cut-off	0.79	3.03
Extension and expansion	4.76	3.03
Translation and lobing	1.59	0.0
Extension and rotation	1.59	3.79
Extension and translation	7.14	7.58
Expansion and rotation	1.59	2.27
Expansion and translation	0.0	15.15
Rotation and translation	15.08	0.0
Compound development	2.38	12.88

in Figure 10. It shows a reduction in variation of wavelength. The radius of curvature has decreased substantially although the variation remains high throughout the study period. The median wavelength has been lowest during the year 1990. The amplitude shows a considerable increase in its length. However, it shows only a slight temporal variation during 1990–2017 periods. The average radius of curvature (R_c) and average wavelength have reduced by 25.75 % and 4.35 % respectively, while the average amplitude (a_m) has notably increased by 33 %.

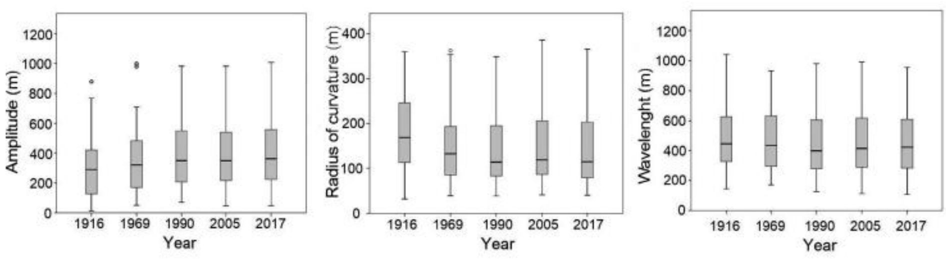

Fig. 10. Temporal evolution of planform parameters

Average bend migration rate (M) from 1916 to 2017 varies from 0.53 m·y^{-1} to a maximum of 2.89 m·y^{-1}, with a mean value ($\bar{x}$) of 1.35 m·y^{-1} and a standard deviation of 0.46 of which about 57.7 % of the meander bends have migration rates below the mean migration rate (Tab. 6). It is worth mentioning here that while carrying out statistical analysis of the meander migration rates, cut-offs and nearly stable bends were treated as outliers to avoid a misleading value of mean migration rate and standard deviation. The mean migration rate of cut-off bends is 3.92m·y^{-1} (Tab. 8). From the statistics of lateral migration rate of the meander bends of the Disang River of four-time intervals it is found that the highest mean migration has taken place during 1969–1990 (Tab. 6). The migration rate has gradually reduced since 2005 having a very low mean migration rate of 0.824 m·y^{-1} and standard deviation ($\sum$) of 0.364. The relation between R_c/w and migration rates of the meander bends of the Lower Disang River between 1916 and2017 is slightly negative (Fig. 11). The maximum migration rates occur where R_c/w is between 0.5 and 2.0.

Table 6.
Analysis of lateral migration rate

Lateral migration rate (m·y^{-1})	$\bar{x}$ (mean)	Σ (standard deviation)
1916 to 1969	1.249	0.645
1969 to 1990	2.05	0.989
1990 to 2005	1.228	1.027
2005 to 2017	0.824	0.364
1916–2017 (min. 0.53, max. 2.89)	1.35	0.46

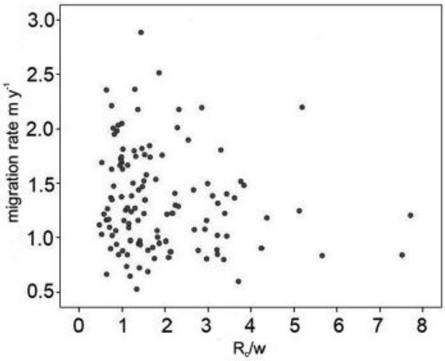

Fig. 11. Relation between lateral migration rates and bend curvature Rc/w between 1916 and 2017.

MEANDER CUT-OFFS

Five meanders bends have converted into cut-offs during the 101 years out of which one cut-off occurred between 1916 and 1969 and the remaining four cut-offs between 1990 and 2005 (Fig. 12). The entire study period has been grouped into four-time intervals. There has been only one cut-off in the time interval between 1916 and 1969, no cut-off during 1969–1990 period, four cut-offs in the 1990–2005 period followed by a period of no cut-off in the 2005–2017 time interval. Thus, the cut-off frequency has been 0.79 % in the 1916–1969 period and 3.03 % in the 1990–2005 period. In rest of

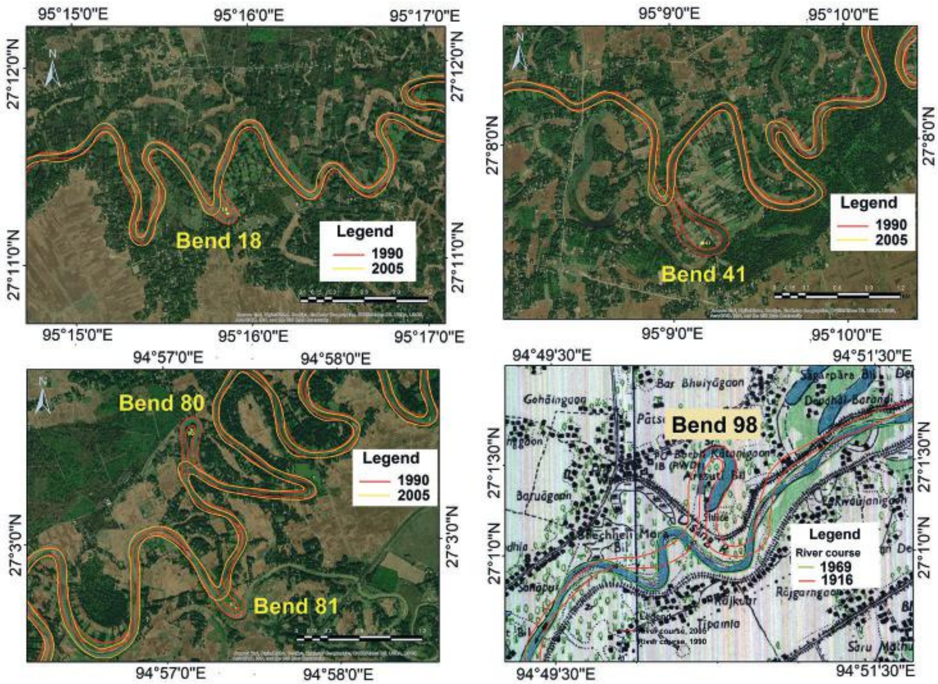

Fig. 12. Google Earth imageries (1990–2005) and topographic map (1916–1969) showing evidences of cut-offs

the periods, there were no cut-off formation. The length of the river channel increased from 173.3 km in 1916 to 203.89 km in 2017 showing that the rate of shortening by meander cut-offs has been less than the rate of lengthening by meander growth. The cut-offs recorded were all neck cut-offs except one which has been a partial cut-off that occurred in the 1990–2005 period (Bend 18).

COMPARISON OF A LATERAL CHANNEL CHANGE BY CUT-OFF VERSUS PROGRESSIVE MIGRATION

In the Lower Disang River, the significant portion of the river channel has changed via progressive migration rather than by cut-offs (Tab. 7). On an average 97.02 % of the total channel length has moved through progressive migration and only 2.98 % of the channel has moved through meander cut-offs. An average amount of 4,298.55 $m^2 \cdot y^{-1}$ of floodplain has been affected by progressive migration, whereas cut-offs have affected an average of only 95.87 m^2. However, in case of the rate of lateral migration, it is seen that cut-offs result in a more significant increment of lateral change at the rate of 1.48 $m \cdot y^{-1}$ when compared to 1.29 $m \cdot y^{-1}$ due to progressive migration.

Table 7.
A comparison of lateral channel change by cut-offs versus progressive migration

Time interval	Lateral migration rate ($m \cdot y^{-1}$)		Floodplain area affected (m^2)		Percentage length moved via (%)	
	progressive migration	cut-offs	progressive migration	cut-offs	progressive migration	cut-offs
1916–1969	1.21	2.80	8291.43	148.31	98.24	1.76
1969–1990	2.03	0.00	5549.87	0.00	100.00	0.00
1990–2005	1.11	3.14	2077.07	235.18	89.83	10.17
2005–2017	0.82	0.00	1275.84	0.00	100.00	0.00
Average	1.29	1.48	4298.55	95.87	97.02	2.98

GEOMETRIC ATTRIBUTES OF CUT-OFF BENDS VERSUS HIGH SINUOUS BENDS

A comparison of meander geometry of cut-off bends with other high-sinuosity bends (SI>1.85) provides a starting point for evaluating the utility of centre-line data for prediction of potential cut-offs (Michelli, Larson 2010). Meander bends that developed cut-offs had an average sinuosity of 6.12; an average radius of curvature of 75.40 m; an average wavelength of 179.29 m (Tab. 8). On the other hand, the average values for high-sinuosity bends migrating progressively for the above parameters are 3.28, 123.67 m and 400.32 m, respectively. Thus, the cut-off bends are reasonably distinct from the other high-sinuosity bends in terms of wavelength (55% lower), amplitude (49% higher), sinuosity (86% higher) and radius of curvature (39% lower). Thus, a careful analysis of bend geometries along with other bend parameters will help in the identification of bends that may undergo cut-off processes.

Table 8.
Geometric characteristics of cut-off bends versus high sinuosity bends

Geometric characteristics	Cut-off bends	High sinuosity bends (>1.85)
Average wavelength (m)	179.29	400.32
Average amplitude (m)	704.92	472.39
Average sinuosity index	6.12	3.28
Average radius of curvature (m)	75.4	123.67
Average migration rate ($m \cdot y^{-1}$)	3.92	1.23

DISCUSSION

An inverse relation exists between sinuosity and channel gradient. The present sinuosity index 2.06 shows that the length of the channel is about twice the valley-length of Disang River. With an increase in sinuosity, the possibility of cut-off increases. This instance is seen in the 1990–2005 period when SI is 1.96, which has been followed by cut-offs.

The trend of *C* values reveals an increase in the number of bends nearing cut-off stage. A high B_m/w value is indicative of a meander in its early development stage (i.e., U-type), which means that the bend apex is primarily laterally migrating, and upstream and downstream adjacent bends do not erode the neck. A low B_m/w value indicates that the meander is in its late development stage (i.e., Ω-type) in which the adjacent necks are closing, and meander may be approaching neck cut-off stage (Li et al. 2016). It is thus inferred that the number of meander bends approaching late development stage has increased by gradually narrowing down their neck-widths, making them susceptible to cut-offs. The B_m/w proves to be a good indicator for neck-cut-off prediction. Bend No. 98, which had the lowest B_m/w, underwent a cut-off between 1916 and 1969. Cut-offs also occurred in Bend Nos. 80, 41, and 81 with B_m/w 1.15, 1.23, and 1.87 respectively. While the meander Bend Nos.104 and 85 having B_m/w 1.64 and 1.28 respectively in 2017 are approaching cut-off (Ω-type) stage. Bend No.104 is separated by a distance of ~16.97 m at the neck, making it vulnerable to cut-off (Fig. 13). This relationship has become stronger over time, signifying the meander bends tendency to attain a mature stage. Thus, the planform geometry evolution reveals a defined temporal behaviour of steady elongation of the meander bends.

Most of the empirical studies done on freely meandering rivers have recorded a high rate of lateral mobility in the form of cut-offs and migration (Gilvear et al. 2000; Hooke 2007, 2008). Whereas meanders exhibit stability or low mobility have been less extensively studied (Biedenharn et al. 1984; Dépret et al. 2017). The migration rate has shown a decreasing trend over the studied period (Tab. 7). The river has migrated down-valley through translation. Spatial analysis of meander migration along the river shows that migration has been more intense in the upstream part of the lower course of the river without embankment while the down-stream part has been relatively stable because it is controlled by embankments along both sides of the river. The section between Dilli and Namrup Tea Garden has registered a high mean migration rate of 1.873 $m \cdot y^{-1}$ between 1916 and 2017. There was formation of two new meander bends in this reach between 1969–1990 period and had a mean migration rate of approximately 3.61 $m \cdot y^{-1}$ during this period. Mining of bed materials in certain sections, particularly in the upstream section

Fig. 13. Meander bends with low B_m/w values approaching cut-off stage

near the point of debouchments of the river, has rendered the banks unstable and vulnerable to erosion (Fig. 14, I and III). Along the down-stream section, construction of embankments such as porcupine systems (Fig. 14, II and IV) has resulted in relatively lower erosion rates and hence lesser movement of bends compared to the upper reach of the river (Fig. 1). However, the bank protection measures have suffered from breaching in many parts over time. In the absence of renovation of these measures, even these banks are vulnerable to erosion and floods. The floodplain is composed of loam-silt-clay sediment (Buragohain 2010) which offers considerable resistance to erosion that explains the relatively moderate rate of migration for the studied period.

R.A. Bagnold (1960), D.J. Furbish (1988), M.R. Leeder and P.H. Bridges (1975) and G.C Nanson and E.J. Hickin (1983, 1986) have demonstrated the correlation of migration rate of meanders with the radius of curvature of the meander bends. E.J. Hickin and G.C Nanson (1975) showed that the rate of migration has been the highest when the R_c/w value has been between 2.0 and 3.0, with decreasing migration rate on either side of this range. This model has been validated in several other studies (Nanson, Hickin 1983, 1986; Hooke 1997; Knighton 1998). However, according to

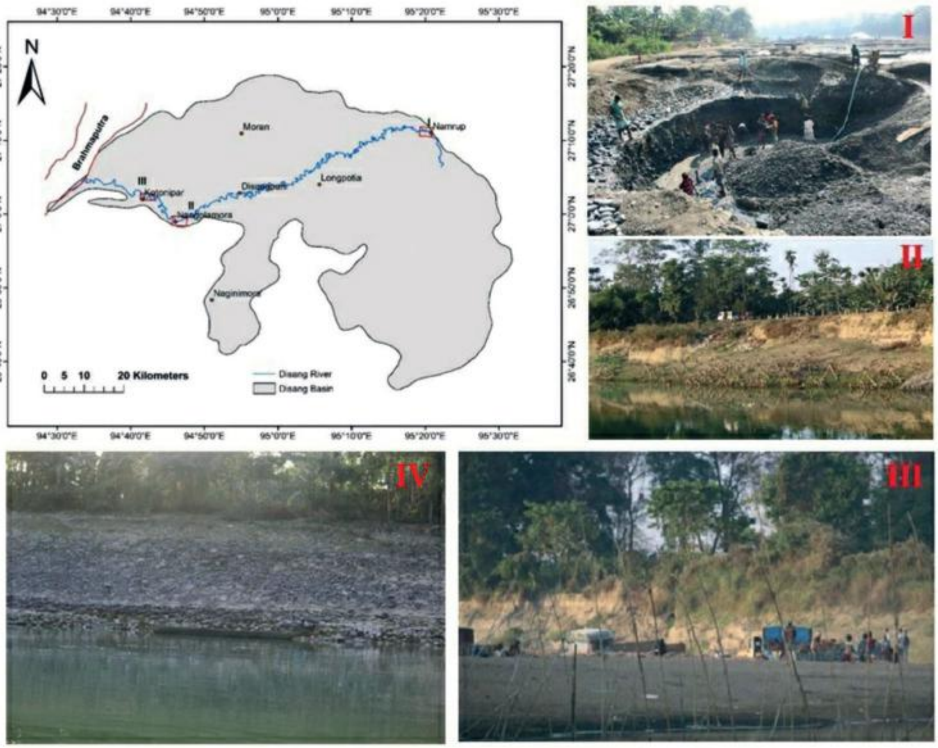

Fig. 14. Human influence in the Disang River. I: Mining of bed material near Namrup (about 5 km from the debouching point), II: Embankment along the river channel near Kotonipar, III: Mining of bed material near Kotonipar, IV: Porcupine system along the channel near Nangolmora

P.F. Hudson and R.H. Kesel (2004), there are a few studies from river channels, large rivers in particular, which do not agree with this model. In contrast to the findings reporting the highest migration rates where R_c/w is between 2.0 and 3.0, in the present study, the maximum migration rates have occurred with R_c/w values <2.0 with the gradual decrease in migration rates towards higher R_c/w values. This pattern is similar to that of lower Mississippi River (Hudson, Kesel 2000) and River Dane (Hooke 1987) which recorded peak migration rates at $R_c/w \sim 1.0$ and gradually declining rate of migration with increasing R_c/w values. PF. Hudson and R.H. Kesel (2000) attributed this behaviour to heterogeneous floodplain characteristics, which may be right for this study as well. However, further attention is necessary to understand the floodplain characteristics of the Disang River.

The cut-off events can be explained to have occurred due to incidents of high discharge and precipitation and sediment concentration. The 1990–1991 period has been marked with very high mean annual and peak discharge and suspended sediment load and high precipitation (Figs 15, 16). Although meander bend geometry governs whether or not a bend is ripe for cut-off, the distribution of subsequent stream flows determines when cut-off may occur (Hooke 2008). The high discharge, precipitation, and long flood duration can be regarded as the possible trigger to initiate the cut-offs of the meander bends. The examination of the duration of flood level in the year 1991 shows that the number of days having floods have reached as high as

Fig. 15. Changes of total suspended sediment load in the period 1985–2003

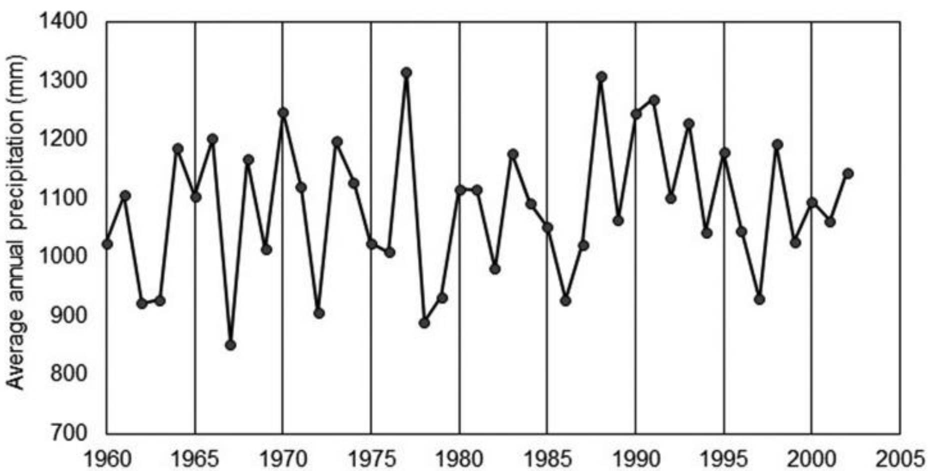

Fig. 16. Average annual precipitation for the Disang River basin, 1960–2005

80 days (Rajabari) (Fig. 17). Analysis of mean peak discharge and sediment concentration from gauging station of NH 37 Road Crossing (near Rajabari) for the period 1985–2003 indicates that an unusually high flow (Fig. 18) occurred in July,1991 with exceptionally high sediment concentration (Fig. 14). It is, therefore, possible to explain the cut-offs through the occurrence of floods or as an adjustment of the channel morphology to high discharge and sediment load. Thus, the analysis points to the coincidence of the cut-offs with

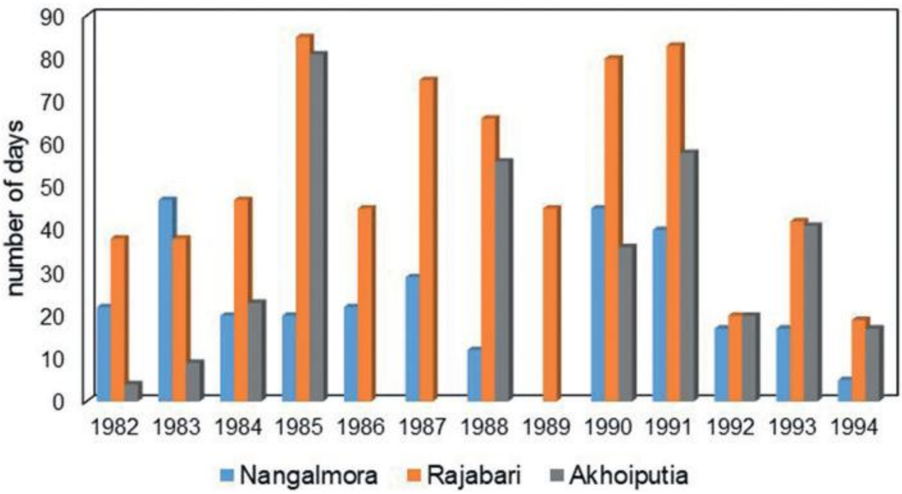

Fig. 17. Duration of floods in the Lower Disang River, 1982–1994

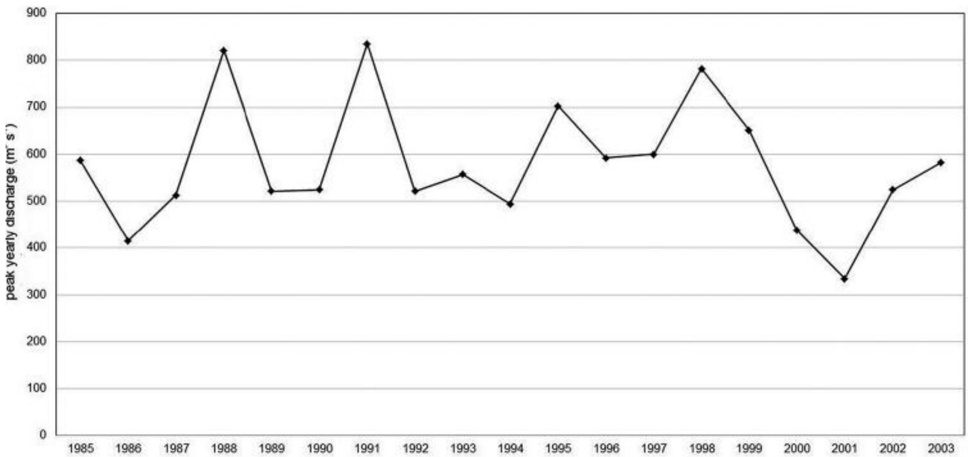

Fig. 18. Peak Yearly Discharge, 1985-2003

high discharge period in the river in conjunction with high sinuosity and low B_m/w value of the meander bends.

Another perspective of cut-offs explanation is that these cut-offs occurred because of the natural evolution of its meandering planform. The Lower Disang River has shown a steady increase in channel length and sinuosity and a decrease in bend curvature along with a reduction in widths of the meander necks. Besides, it is seen that the cut-offs in the river are isolated and random. The meander bends, which underwent cut-off, were in the late development stage having distinct planform geometries. The absence of chute cut-offs along the river shows that the meanders had reached the stage of neck cut-off through the gradual evolution of their planform. Thus, the meanders may not owe their cut-off to high discharge level or floods but their distinct planform characteristics in terms of high sinuosity and bend curvature. Therefore, these cut-offs can be regarded as part of the natural evolution of a meandering planform.

CONCLUSION

Migration and cut-offs play a vital role in the evolution of meandering planform of a river channel. The Lower Disang River has undergone a steady increase in sinuosity and channel length. A century-scale analysis of the meander migration and cut-offs of the Lower Disang River shows that it has a relatively low rate of migration during the studied period and low cut-off frequency, except between 1990 and 2005 during which a few, isolated cut-offs took place, along a 203.89 km reach. The relatively higher erosion in the upper reach may be attributed to bed material extraction, whereas the presence of embankments in its lower course acts as a deterrent to erosion. The meanders have migrated largely through extension, expansion, translation, and compound development resulting in high-amplitude meander bends and their down-valley translation. It is found that progressive migration has been the dominant mode of meander migration rather than cut-off processes. The study also indicates coincidence of the cut-offs with the occurrence of floods, heavy precipitation, high mean and peak annual discharge, and high sediment load in the river. However, these alone do not account for the occurrence of cut-offs. In the absence of long-term data on flood, discharge and sediment load, it is difficult to attribute the occurrence of cut-offs to these factors alone. The cut-off bends display distinct planform geometries when compared with other high-sinuosity meander bends of the river, which suggest that these cut-offs, could have occurred because of their distinct planform characteristics. Thus, an analysis of planform characteristics along with the geomorphic activity can help us in our understanding and prediction of potential cut-offs.

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