Timespan=All years. Databases=SCI-EXPANDED, CPCI-S, CPCI-SSH, CCR-EXPANDED, IC

can be used to see how China and India have progressed over the recent past as far as their presence in these two journals is concerned. Figure 2 shows the time evolution of India's and China's presence in the two leading journals in the area of computational mechanics. While India has been stagnating after rising initially, China now outpaces India quite significantly.

In this paper, we have used a three-dimensional bibliometric analysis to identify the leading countries, and also the most influential journals in the key area of computational mechanics research. Scholarly performance is broken down into three components – quantity, quality and consistency. The citation data are retrieved from the *WoS* and used to categorize the entities according to these quantities. We see that India plays only a marginal role in this key area and of late this has been stagnating or diminishing.

1. Prathap, G., The Zynergy-Index and the formula for the *h*-Index. *J. Am. Soc. Infor. Sci. Technol.*, 2013; DOI: 10.1002/asi.23046.
2. Prathap, G., Quantity, quality, and consistency as bibliometric indicators. *J. Am. Soc. Infor. Sci. Technol.*, 2013; DOI: 10.1002/asi.23008.
3. Prathap, G., The Energy–exergy–entropy (or EEE) sequences in bibliometric assessment. *Scientometrics*, 2011, **87**, 515–524.
4. Prathap, G., Quasity, when quantity has a quality all of its own–toward a theory of performance. *Scientometrics*, 2011, **88**, 555–562.
5. Laney, D., 3D data management: Controlling data volume, velocity and variety, 2011; http://blogs.gartner.com/doug-laney/files/2012/01/ad949-3D-Data-Management-Controlling-Data-Volume-Velocity-and-Variety.pdf

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A study on channel migration of the Subansiri river in Assam using remote sensing and GIS technology

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The Subansiri is a major Trans Himalayan tributary of the River Brahmaputra, characterized by its extremely dynamic and unstable alluvial channel in Assam. In this study, the pattern of channel shifting as well as various other changes of the Subansiri river have been studied for the period from 1828 to 2011. Five different types of channel shift have been observed in the Subansiri river. They are (i) alternate bar-induced shifting, (ii) neck cut-off, (iii) chute cut-off, (iv) meander shift and (v) avulsion or rapid diversion. The channel pattern of the Subansiri river in Assam changes continuously with large number of channels being abandoned and new channels developed in the course of a few years. Large discharge and heavy sediment load during floods cause the river to be extremely unstable, because of which it consistently migrates laterally from the eastern side to the western side of the basin abandoning the earlier channels.

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Keywords: Channel migration, erosion, flood, sedimentation, Subansiri river.

THE present study was undertaken on the Subansiri river in Assam for assessment of changes in the positions of the channel, resulting from bank erosion as well as various changes in the channel pattern of the river from 1828 to the present. Evidences indicate that the reach of Subansiri in the plain section represents one of the most dynamic and unstable alluvial rivers in the Brahmaputra valley. The reach of the river downstream from Arunachal hills, especially towards its mouth, has a sluggish course subjected to intense braiding and anabranching of the channel. Formation of channel bars and meandering thalwegs is common. Since 1954, the river has been confined between its embankments. This leads to rising of the riverbed. The silt which used to be deposited in the plains, now gets deposited inside the river channel[1]. The map evidence together with records of flood history indicate that recurring large floods have breached the embankments, created areas of bar development and caused bank erosion and channel migration. According to Schumm and Lichty[2], and Schumm[3], floods of very high magnitude may be a contributing factor to channel widening and river bank erosion along with associated changes in the channel pattern. Erosion may be caused either by undercutting of the upper bank materials by channels during the high floods producing an overhanging cantilevered block that eventually fails or by oversteepening of bank materials due to migration of the thalweg closer to the bank during the falling stages[4]. Large-scale slumping of bank during the falling stages of the river was observed in many places, which may be associated with reverse flow from the formation back into the channel causing a lateral flowage of sand and silt into the channel resulting in subaqueous failure[5,6].

It is believed that the Great Assam Earthquake of 1950 and the associated flood episodes are primarily responsible for bringing a major change in the hydrologic regime of the Subansiri river. Before the great earthquake of 1950, the Subansiri was flowing through Bilmukh and this old course was shorter, measuring only 136.77 km. It is learnt that it had a still shorter course two centuries ago, when the Brahmaputra was flowing along the present course of Kherkatia suti and the Lohit Subansiri met

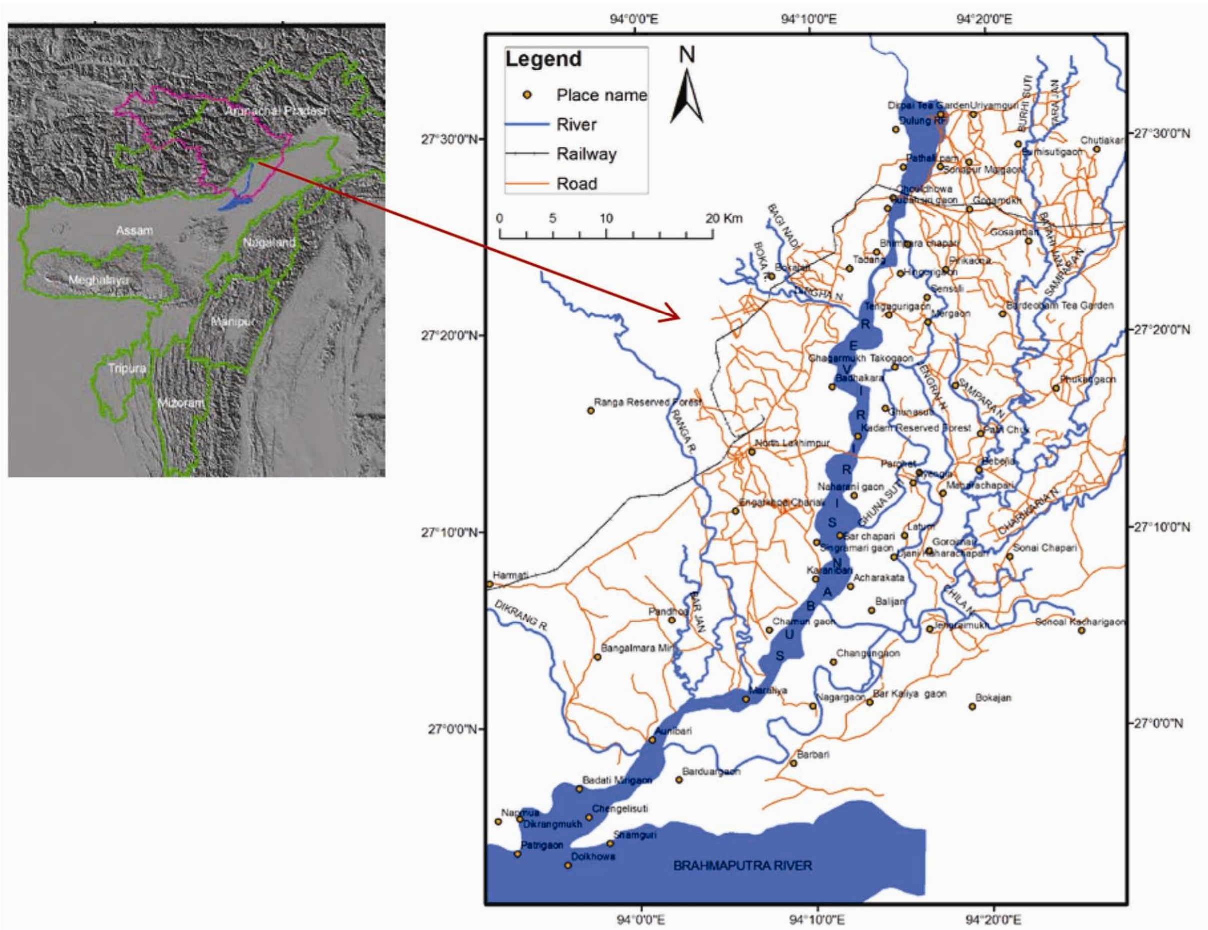

Figure 1. Location map of the Subansiri river in Assam.

the Brahmaputra near Garmur[7]. But after 1950, it had started flowing through the Ghunasuti and changed its bankline several times before it left this channel and started capturing the Ghagar Nala from 2000 onwards. At present, the Ghagar Nala acts as the main Subansiri river. Bankline study shows that it has a tendency to shift its course towards the western side. The River Subansiri, after entering the plains of Assam, spreads out and dissipates its energy causing abrupt reduction of velocity and inducing siltation that results in bank erosion and also frequent changes in its course.

The Subansiri is the biggest tributary of the River Brahmaputra, contributing as much as 11% of the total flow of the river. It originates in Tibet at an altitude of about 5340 m and then flows through the Himalaya and the plains of Assam before reaching its confluence with the Brahmaputra. The length of the river from origin to its outfall is about 468 km. The river after entering the plains of the Brahmaputra valley from the high gradient of the Himalaya, spreads its enormous discharge forming anastomosing pattern in the channel which in the downstream direction takes a meandering course. The Subansiri basin covers an area of 35,771 sq. km. of which 4350 sq. km. falls in Assam. For this study, the reach of the river in Assam is selected (Figure 1), which extends between lat. 26°45′–27°35′N and long. 93°45′–94°30′E.

For the present study, the Survey map of Lieutt R. Wilcox, 1828 (engraved in the office of the Surveyor General of India, July 1830), SOI toposheets and satellite images of 20 different years (Landsat MSS, TM, ETM+ and IRS LISS 3) and published literature currently available on the Subansiri river have been consulted and used for analysis based on remote sensing and GIS techniques. GIS techniques are effective and accurate tool of quantifying channel changes both at medium-term and short-term scales[8].

For the study of channel migration of the Subansiri river, various toposheets and satellite images of different years have been georeferenced using WGS84 datum and UTM projection, and the banklines have been digitized. The overlaid banklines give the overall channel migration pattern of the Subansiri river from 1828 to 2011.

River channel migration is the lateral movement of an alluvial river channel across its floodplain due to processes of erosion and deposition on its banks and bars. In meandering streams, channel migration typically takes

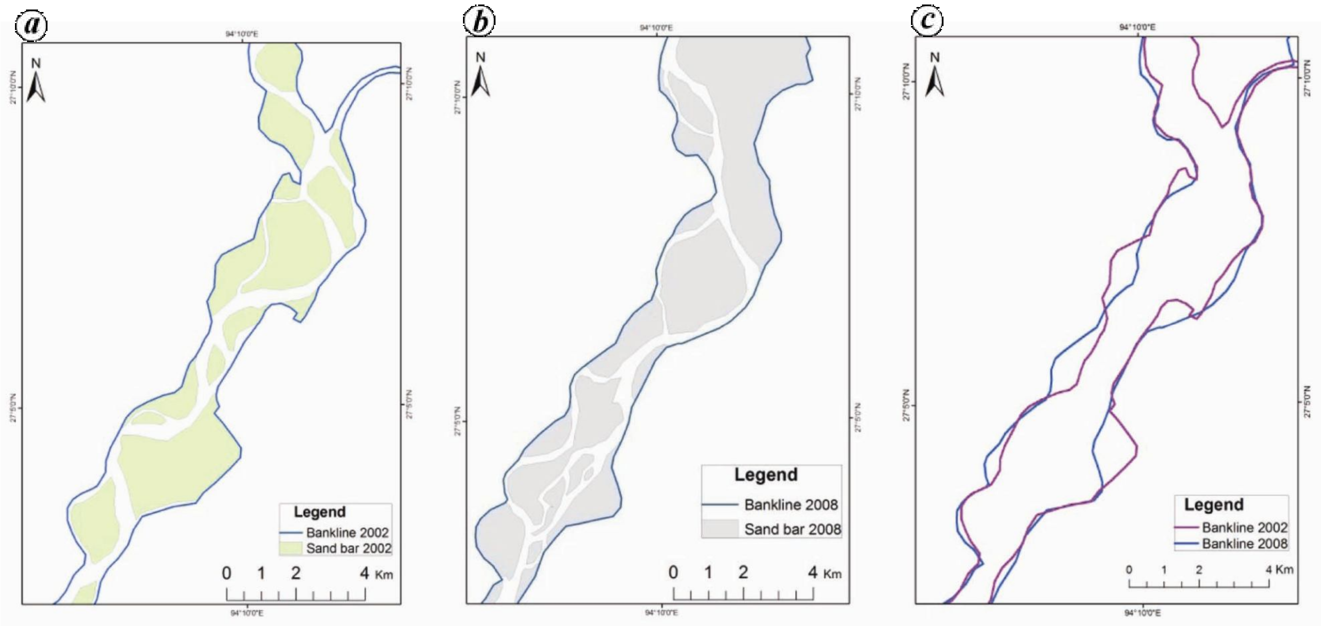

Figure 2 *a–c*. Channel shifting due to bar development.

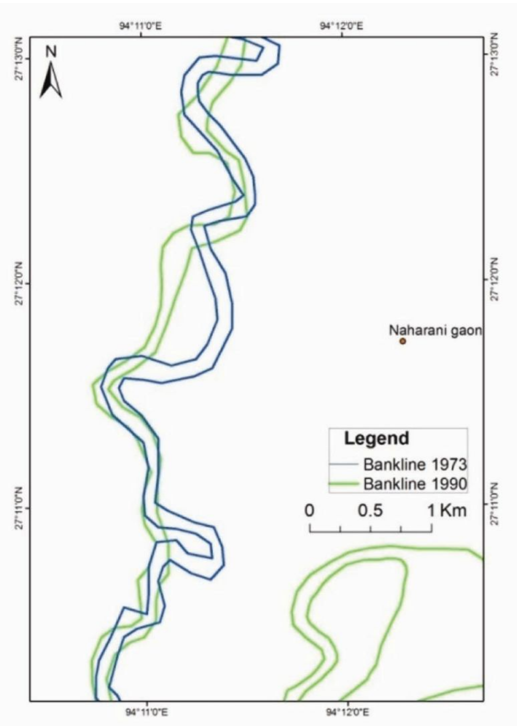

Figure 3. A well-defined neck cut-off seen in the Ghagar Nala between 1973 and 1990, which later becomes the main active channel of the Subansiri river.

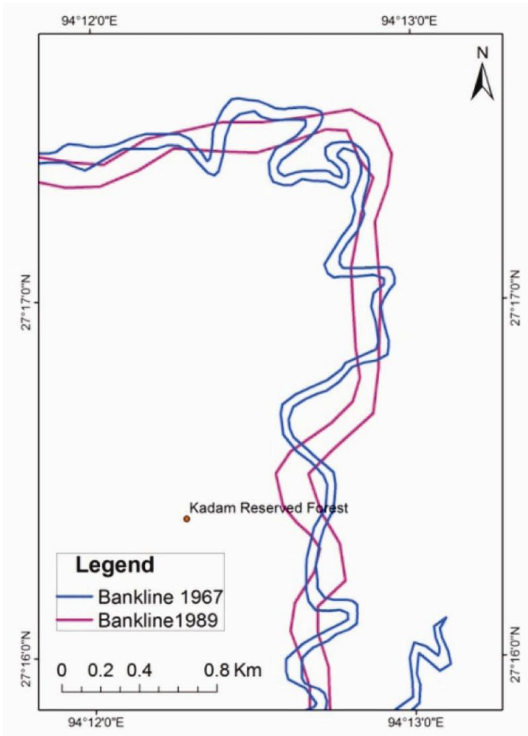

Figure 4. Chute cut-off seen in the Ghagar Nala, which is at present the main active course of the Subansiri river.

place by erosion of the cut bank and deposition on the point bar. In braided streams, channel change may occur due to high rate of sediment transport, weak bank materials and the movement of bedforms through the channel. According to Hicking and Nanson[9], the factors which are responsible for changes in alluvial channels and rate of meander migration include water discharge, character of the bank material, height of the concave bank, vegetation and sediment supply, etc.

The channel pattern of the Subansiri river in Assam changes continuously, where large channels being abandoned and new channels being developed in a few years

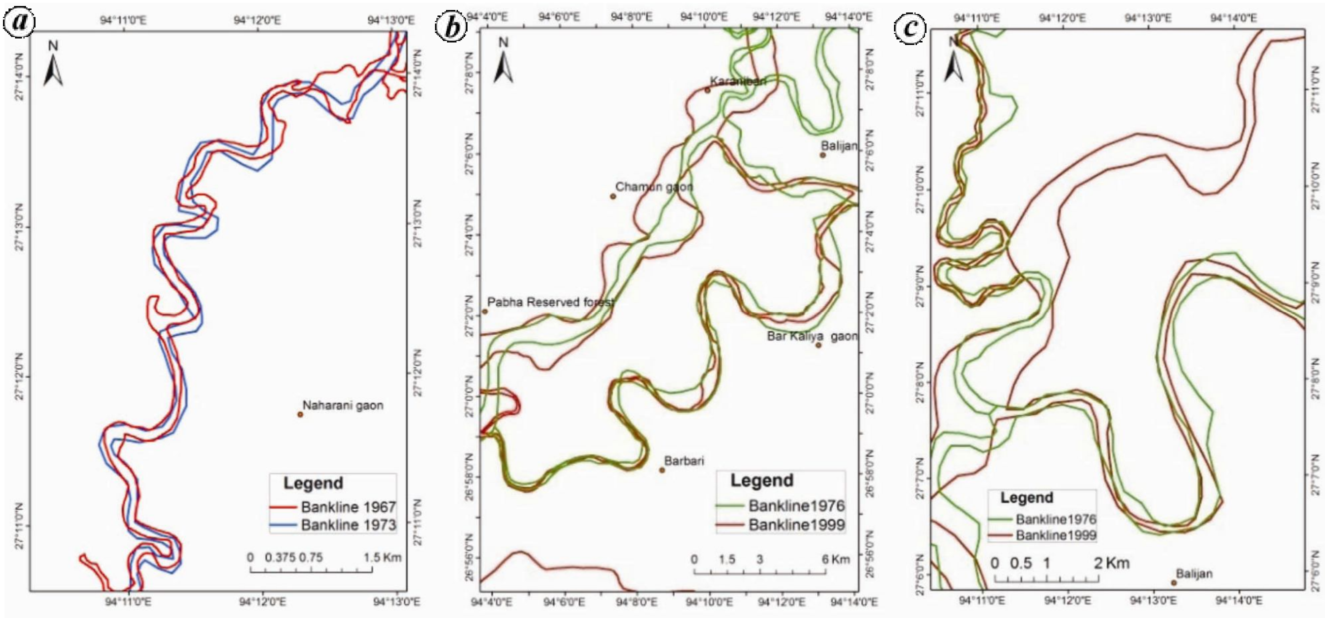

Figure 5 ***a–c***. Shifting of the meander bends.

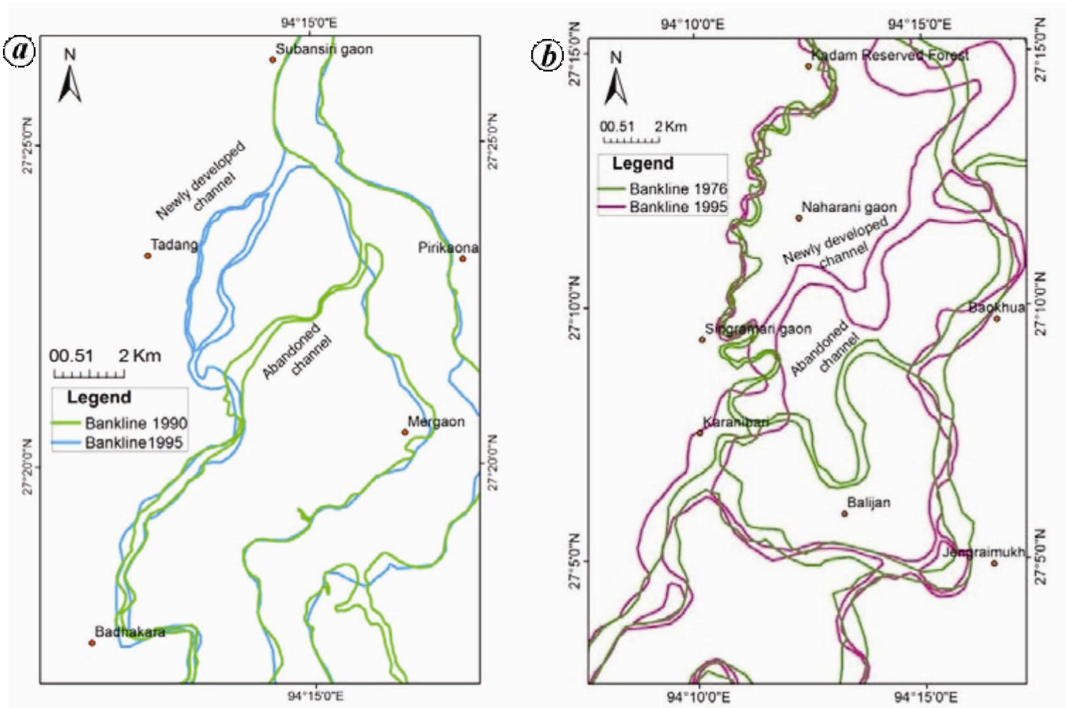

Figure 6 ***a*, *b***. Avulsion process in the Subansiri river, where one channel is abandoned forming another channel.

are common features. Coleman[5] refers to this process as ‘sudden shifts’. A channel shift is accomplished by the development of a completely new channel, or, more commonly, a pre-existing channel takes over the conveyance function of another channel. The new channel may flow through the original channel deposits or through the floodplain[10]. Goswami *et al.*[11] have studied the changes of the Subansiri river over a period of 70 years based on toposheet and satellite imageries for the years 1920, 1970 and 1990 and grouped the types of changes into four categories, viz. (i) alteration of the direction of flow due to neck cut-off, (ii) widening of channel resulting from bar development, (iii) development (and subsequent abandonment) of anabranches, and (iv) progressive shifting of meander bends. However, in the present study, the different types of channel shifts observed in the Subansiri river are as follows.

(i) Alternate bar-induced shifting: Sand bar-induced channel shifting is a common process in the Subansiri river. Different types of channel bars, point bars and side

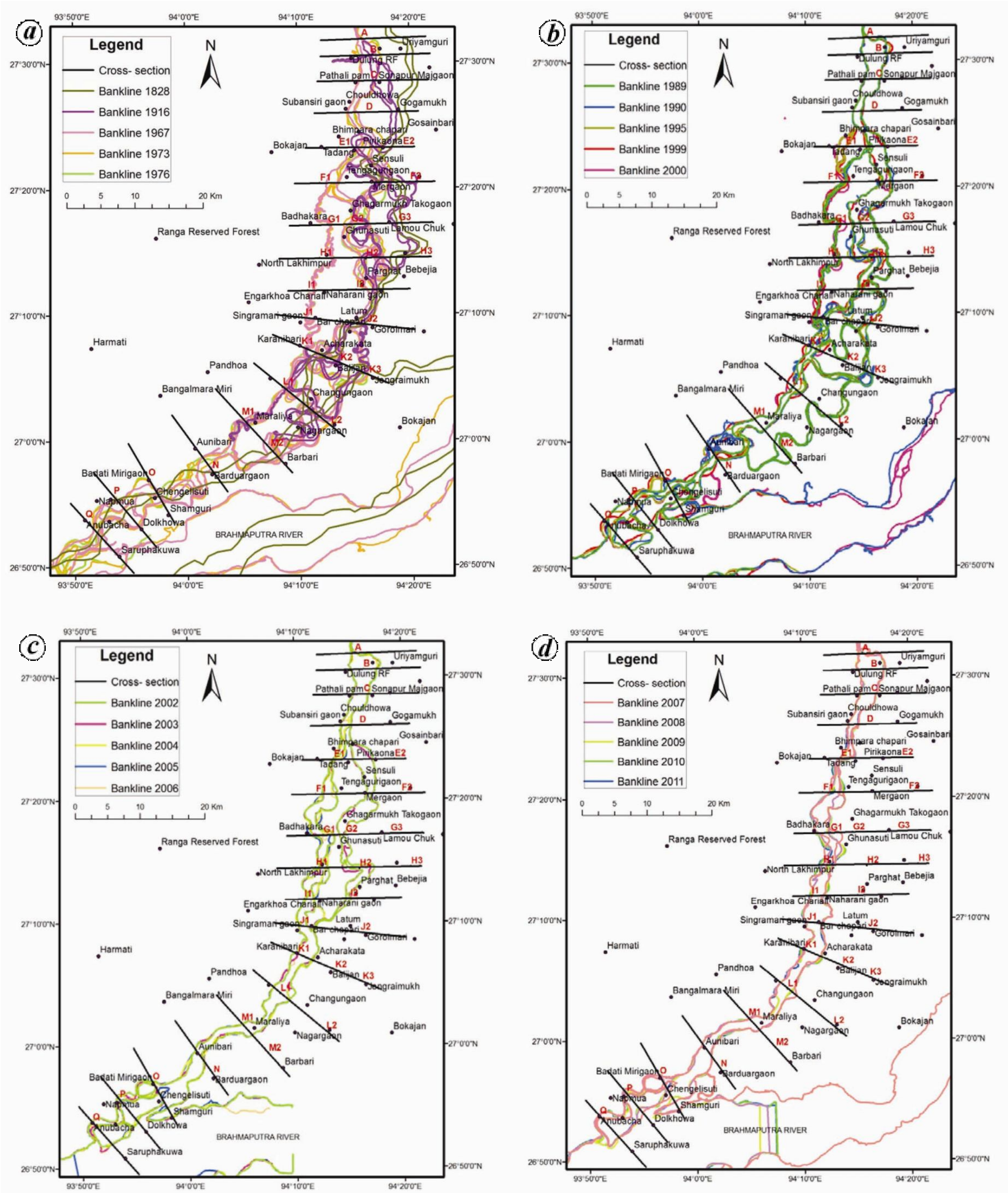

Figure 7 *a–d*. Channel migration of the Subansiri river from 1828 to 2011. The locations A, B, C, E1, E2... Q represent the different positions of the cross-sections where shifting of different branches of the river was measured.

bars are developed and their size increases, decreases and sometimes diminishes inducing shifting of the channel. Figure 2 shows the shifting of the channel due to bar development.

(ii) Neck cut-off: Well-defined neck cut-off in an alluvial meandering river is a typical way of channel shift (Figure 3). In neck cut-off, a stream in a meander loop cuts a new channel through the narrow neck between two meander loops to straighten the channel[12].

(iii) Chute cut-off: Meander grows and migrates by erosion on the outside and downstream side of the bend and by deposition on the inside. This deposition leaves

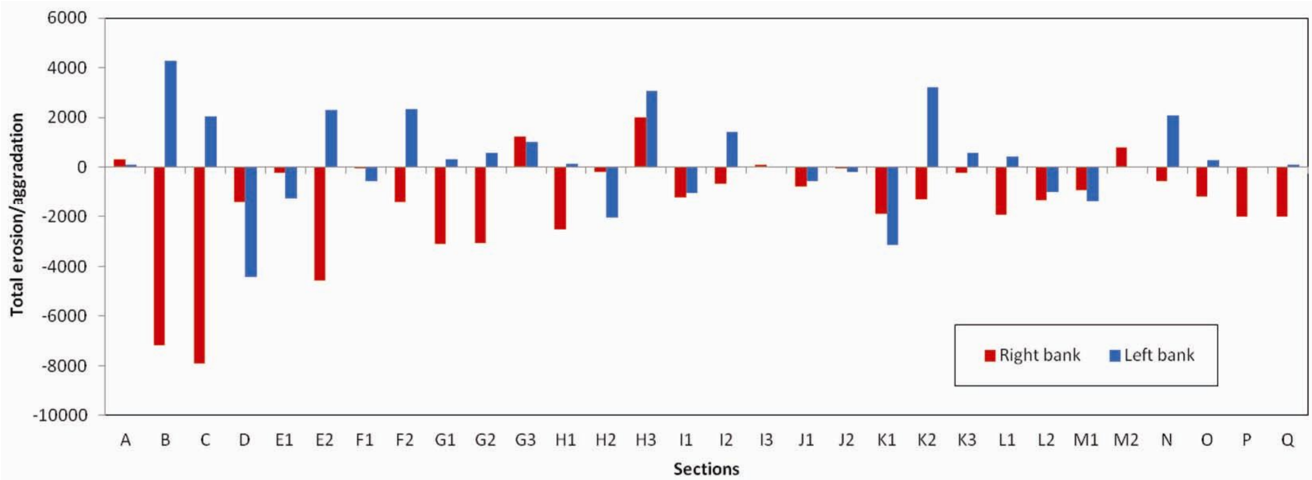

Figure 8. Shifting of banks due to erosion/aggradation along different sections of the Subansiri river (negative value indicates shifting of the channel due to erosion and positive value indicates shifting of the channel due to aggradation).

behind a series of low ridges and troughs, which are known as point bars. During floods, the river may develop an alternate channel through one of the troughs to straighten its course and this channel is called chute cut-off (Figure 4).

(iv) Meander shift: Shifting of meander bends from one place to another to maintain equilibrium in energy distribution is a common phenomenon in an alluvial river. Erosion in one bank may lead to aggradation in the other bank, which changes the position of the bank line. Figure 5 shows the shifting of meander bends in different places and different years.

(v) Avulsion or rapid channel diversion: 'Avulsion' is the situation where a river, at a particular point, abandons its original channel and starts flowing in another channel and, in the course of time, the newly formed channel develops the pattern of the original one (Figure 6). Shifting due to avulsion is aided by the successive growth of the meander scrolls. By this, each meander loop of a stretch of the river gradually shifts and thereby, with the passage of time, that stretch deviates much from its original position. Migration may not necessarily follow any preferred direction along the entire channel length.

In the present study, shifting of the channels of the Subansiri river has been measured in 17 cross-sections across the river. Shifting of the banklines of different anabranches in the right and left banks and the change in total width were measured in 30 different positions of the cross-sections.

From Figure 7, it can be seen that after entering into the plains of Assam, the Subansiri river is characterized by typical braiding with numerous mid-channel bars, but the overall pattern of the river is a meandering one with many sinuous bends and point bars. For the period prior to the great earthquake of 1950, two years of data were available. The Survey map of 1828 shows that the river was then flowing through Kachutoli, upstream near Gogamukh to Bebejia and Changungaon before it debouched to the Brahmaputra. The SOI toposheets of 1916 show that the river was flowing in the vicinity of the present Gogamukh Chariali, where the old channel is still present. After Gogamukh, it flowed in a single channel up to Sensuli, but after Sensuli it started flowing in two equal branches separated by an island before they met again near Parghat. It again separated into two different branches near Latum, one through the present Kherkatiya suti and the other through the present Subansiri before they met near Nagargaon.

After the great Assam earthquake of 1950 and the associated floods, the morphology of the river has changed a lot. Because of the earthquake, landslides occurred and blocked the river forming a natural dam in the higher gorge section at Sipoumukh, 9 km upstream from Gerukamukh. It blocked the river for almost three days and after the third day, the dam breached and the sudden release of the stored water washed away a large portion of the Pathalipam Tea garden located near the river in the foothills zone and several villages, killing hundreds of people and innumerable cattle by the surging waters downstream. During the flood, the river got charged with enormous amount of silt which in its movement down the river altered the conditions of flow and changed the river course[7]. It also considerably raised the riverbed[13]. From the SOI toposheet of 1967, it can be seen that the river had shifted its course after the 1950 earthquake. It left the original channel near the Gogamukh Chariali and started flowing almost 5 km away towards east near Chouldhowa. From Katari chapari to Ayengia, the river was flowing along two equal branches. The channels of the river were more or less stable till 1989. In later years the channel pattern has changed and the right branch, i.e.

Table 1. Variation in width (m) of the channels at different positions of cross-section of the Subansiri river

Section	1828	1916	1967	1973	1976	1989	1990	1995	1999	2000	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
A				672	576	744	766	723	3867	678	816	801	759	1522		1480	885	814	775	
B	926	579	2208	3306	3142	3510	3649	3879	2461	4001	3988	3907	3938	3965		4013	3953	3942	3999	
C	823	2448	2496	2535	2447	2446	2453	2356	1444	2496	2505	2393	2501	2445		2496	2568	2556	2570	2562
D	823	790	1433	1140	971	1180	1256	1251	1439	1498	1537	1514	1220	1538	1544	1566	1476	1539	1540	1476
E1								240	252	219	366	394	530	520	1036	514	2267	1804	1766	1741
E2	1245	542	2776	2813	2766	2611	613	2670	3066	2819	2988	2856								
F1	887	288	1402	280	301	98	100	228	498	719	2170	1970	2027	2161	1271	1333	1664	1679	2076	1423
F2				1374	1485	1274	1597	1688	1769	1221	1035	1114								
G1	691	586	3109	119	173	123	127	222	397	1126	3392	2643	2649	2841	2045	3191	1956	1776	2093	2097
G2				1282	933	779	994	1196	1255	1314	656	576								
G3				442	455	153	178			100										
H1				108	158	224	263	220	240	950	1244	1218	1067	1143	1179	1271	1646	1809	2136	1695
H2				106	737	1649	4400	5262	4943	4922	3997	4443								
H3	977	493	2423	3503	187	105	97			121										
I1				126	134	59	117	166	656	888	1254	1276	1227	1421	1484	1478	1811	1883	2193	2316
I2	645.29	619	1155	850	1083	2787	2895	3112	3132	848	821	845								
I3										44										
J1				107	170	96	187	196	660	845	1272	1478	2499	2529	2416	2455	2467	2479	2449	2736
J2	2596.52	1668	596	690	698	788	1005	946	302	114										
K1	1646.09	2586	1017	143	277	1123	1425	1372	2469	2764	2624	2236	2398	2557	2722	2609	2855	3076	3322	3299
K2				522																
K3				1193	622	298	255	207	225	186										
L1	983.31	1130	771	921	1121	1424	1506	1519	2651	2721	3071	3003	3033	3107. 90	3113	3091	3106	2039	2053	2151
L2							194	126	139	141										
M1		157	871	572	1084	2209	2257	2260	2249	2218	2334	2296	2209	2252	2307	2260	2339	2360	2349	2423
M2				432	377	89	103	103	79	121										
N			2091	1263	612	914	1010	2562	2854	1827	2246	2232	1760	2210	2298	2259	2323	2295	2312	2326
O			2741	2486	2805	3656					4881	4739	9445	4757	4478	4824	4604	1789	1775	1860
P			4765	1141	1221															
Q			1129	1813	1063															

Ghunasuti has become the major channel in terms of flow. This change in the flow regime in the right branch has renewed its pressure on the bed as well as the banks. It has straightened its course through Ghunasuti, abandoning the left branch. One new channel has developed between Barchapari and Ayengia due to avulsion, abandoning the earlier channel (Figure 6 *b*). Another channel which was formed due to avulsion is seen in the satellite image of 1995 in the upper part of the river in Assam, where it abandoned the earlier channel near Hingurigaon and captured the Ghagar Nala near Bhimpara chapari to form a new channel (Figure 6 *a*). The satellite image of 2002 shows that the river had already abandoned the right branch, making the left branch the only active channel.

The river had undergone major changes during the period from 1995 to 2004 to form the present channel pattern. The channel along the Ghagar had started to flow as the main channel of the Subansiri and straightened its course abandoning its original channel along the Ghunasuti. Presently, this channel usually disappears during winter and gets activated with rising water during floods. The width of the channel through Ghagar is increasing year after year, eroding a large part of land along both banks of the river. The satellite images of consecutive years from 2002 to 2011 show the gradual shifting of the bankline of the Subansiri river, where processes of erosion and aggradation through bar formation play the main role in bankline migration.

Figure 8 shows the overall shifting of the river towards west due to dominant erosion along the right bank and aggradation along the left bank during the period from 1828 to 2011. Shifting due to erosion is highest in sections C (7894.61 m) and B (7190.14 m) along the right bank and shifting due to aggradation is highest in section B along the left bank (4267.11 m) of the Subansiri river.

Table 1 shows the variation of width of different branches/sub-channels of the Subansiri river at 30 different positions of the 17 cross-sections. The channels along the eastern side of the river become narrower due to heavy siltation and are abandoned within a few years. However, the channels on the western side become wider with the passage of time and form the active channels of the Subansiri river. This process resulted in an overall shift of the river towards the west.

The present study highlights the overall migration pattern of the Subansiri river due to alternate bar-induced shifting, neck cut-off, chute cut-off, meander shift and avulsion or rapid diversion. Development of anabranches is a characteristic feature of the Subansiri river. The river develops and abandons anabranches quite abruptly. Floods and erosion are the main driving forces for channel migration. Large discharge and heavy sediment load during floods cause the river to become extremely unstable because of which it consistently migrates laterally. From 1828 to 2011, a period of 184 years, the Subansiri river has been migrating from the eastern side towards the western side of the basin. This may be suggestive of a post-Pleistocene tilt in the basin that needs further studies[14].

1. Agarwal, A. and Narain, S. (eds), CSE Report, Annual Mayhem in Assam, Floods, flood plains and environmental myths. Centre for Science and Environment, New Delhi, 1991, p. 87.
2. Schumm, S. A. and Lichty, R. W., Channel widening and flood-plain construction along Cimarron river in southwestern Kansas. *U.S. Geol. Surv. Prof. Pap.*, 1963, **352-D**, 71–88.
3. Schumm, S. A., River adjustment to altered hydrologic regimen – Murrumbidgee River and palaeochannels, Australia. *U.S. Geol. Surv. Prof. Pap.*, 1968, **598**, 65.
4. Goswami, D. C., Channel pattern, sediment transport and bed regime of the Brahmaputra river, Assam. In *Recent Advances in Geomorphology, Quaternary Geology and Environmental Geosciences: Indian Case Studies* (eds Tandon, S. K. and Thakur, B.), Manisha Publications, New Delhi, 2002, pp. 143–156.
5. Coleman, J. M., Brahmaputra river: channel process and sedimentation. *Sediment. Geol.*, 1969, **3**, 129–239.
6. Goswami, D. C., Brahmaputra River, Assam, India: physiography, basin denudation and channel aggredation. *Water Resour. Res., Am. Geophys. Union*, 1985, **21**, 959–978.
7. District Gazetteers, Lakhimpur district, Government of Assam, 1976, p. 21.
8. Winterbottom, S. J., Medium and short-term channel planform changes on the rivers Tay and Tummel, Scotland. *Geomorphology*, 2000, **34**, 195–208
9. Hicking, E. J. and Nanson, G. C., The character of channel migration on the Beatton River, N.E. British Columbia, Canada. *Bull. Geol. Soc. Am.*, 1975, **86**, 487–494.
10. Klaassen, G. J. and Masselink, G., Planform changes of a Braided River with fine sand as bed and bank material. In 5th International Symposium on River Sedimentation, 1992.
11. Goswami, U., Sarma, J. N. and Patgiri, A. D., River channel changes of the Subansiri in Assam, India. *Geomorphology*, 1999, **30**, 227–244.
12. Reineck, H. E. and Singh, I. B., *Depositional Sedimentary Environment*, Springer, Berlin, 1975, p. 439.
13. Poddar, M. C., Preliminary report of the Assam earthquake, 15th August 1950. *Bull. Geol. Surv. India*, 1952, **2**, 11–13.
14. GSI, *Contributions to Geomorphology and Geohydrology of the Brahmaputra Valley*, Geological Survey of India, Miscellaneous Publication No. 32, 1977, p. 291.

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