JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.92, October 2018, pp.441-448

Morphological Dynamics of the Rivers of Brahmaputra

Rajesh Kumar Sah and Apurba Kumar Das*
School of Sciences, Department of Environmental Science, Tezpur University, Tezpur - 784 028, India
E-mail: *apurba@tezu.ernet.in, apurkdas@gmail.com; rajeshsah110@gmail.com*

ABSTRACT

This study documents the sequential morphological dynamics of rivers of Brahmaputra. Landsat images for the year of 1976 and 1987-2016 (thirty consecutive years) are used in GIS environment to document the activities that have been shaping and reshaping the morphology of the rivers. The use of thirty year consecutive images facilitates an explicit assessment of morphological changes. Apparently, distributary activities, meandering activities, breaches and avulsions, and confluence migrations are the dominant geomorphic agents of morphological changes. A range of distributaries activities are readily noticed in Brahmaputra plain. The plain is densely dissected with numerous rivers and rivulets, and distributaries activities often lead to reorganization in channel network. Considering the frequency of incidence and preserved imprints of abandoned channels, majority of the rivers of Brahmaputra can be categorized as free meanders. Difference in fluvio-geomophic setups of rivers of both the banks is reflected palpably in meandering activities. The upper stretch of Brahmaputra encompassing the rivers Simen, Gai and Jiadhal is found to be the most active in terms of avulsions. High seasonal flow, large sedimentation and absence of distinct river bed in some stretches are presumably leading to these frequent avulsions. The river Simen, further, exhibited repeated confluence migration through avulsion near its confluence with Brahmaputra. The explicit picture of the morphological dynamics of rivers of Brahmaputra at basin scale presented in this work is a key aid in formulating riverine management programs which is conceivably among the most water-troubled region of the country.

INTRODUCTION

River morphological change has been a major area of investigation amongst the researchers all over the world (Hermas et al., 2010; Hosu and Sabo, 2012; Sarker et al., 2013; Willett et al., 2014; Hajek and Edmonds, 2014; Dixon et al., 2015). The common mode of actions through which rivers achieve morphological changes include bankline erosion, accretion, distributary activation and abandonment, meander activities, breaches, avulsions and confluence migrations. Frequency and magnitudes of these actions are largely dependent on the flow regime, lithology, topography, physiography and morphometry of the river system. As far as the Brahmaputra system is concerned, it represents a high energy environment with large monsoonal flow and steep gradients. Many of the rivers originate in high altitudes in the Himalaya. Brahmaputra is a young river with the present configuration shaped only during the Pleistocene and Recent time (Purkait, 2004). The tributaries, particularly the northern (referred as right bank in this paper) ones, carry rapid flow with high sediments (Datta and Singh, 2004). Thus the physical factors including the geological age make the rivers of Brahmaputra system prone towards morphological changes especially in the lithological weak alluvial plain.

Majority of the studies pertaining to morphology of Brahmaputra river system focuses on the channel of the main river- the Brahmaputra (Coleman, 1969; Thorne et al., 1993; Sarma and Phukan, 2006; Lahiri and Sinha, 2012; Sarker et al., 2013; Lahiri and Sinha, 2014), and along a few contiguous stretches of distinctive landscape (Sarma and Phukan, 2004; Sarma, 2005; Lahiri and Sinha, 2012; Lahiri and Sinha, 2014). For tributary rivers, studies are mostly isolated. The available works on tributaries are found selective in terms of stretches covered or parameters studied (Goswami et al., 1999; Sarma et al., 2007; Das et al., 2012; Lahiri and Sinha, 2012). The temporal coverages in the used datasets vary from study to study that retards the possibility of chronological overlapping, therefore, leaving no or little scope for comparison for a basin scale picture. Another vital short fall, found commonly is the use of datasets having years or decadal gap for documenting morphological changes. This acts as a limiting factor in determining morphological dynamics in the intervening period accurately.

As far as the baseline data is concerned, Brahmaputra river system is still one of the most data scarce regions. Though some works are done but they are mostly isolated and do not facilitate a comprehensive understanding. This inevitably demands a holistic study encompassing a complete picture of morphological dynamics of rivers of Brahmaputra. Such a work can be a significant aid in formulating riverine management programs in Brahmaputra rivers system which is conceivably among the most water-troubled region of the country.

This work aims to construct an unabridged picture of the whole spectrum of morphological activities of rivers of Brahmaputra and their nature and frequency at the basin scale. In order to determine morphological changes explicitly, images of thirty consecutive years are used in the present study.

STUDY AREA

The work focuses on the plain of Brahmaputra- the most fragile portion of the basin in terms of river mobility (Fig. 1). It covers an area of ~ 120000 sq km. Lithologically, the Brahmaputra plain is mainly comprised of weak alluvial soil with a contrast of relatively coarser sandy beds of the northern tributaries against fine alluvial soil of beds and banks of southern tributaries (Borah, 2004). In plains, the Brahmaputra has overall flat gradient which varies from 0.62 m/km in upper reach to 0.079 m/km along lower reach (Sarma, 2005). As the plain is bounded by high hills (e.g., Eastern Himalaya, Naga-Patkai range and Meghalaya plateau) in majority of its expanse, the high energy flow from hilly catchments causes regular river adjustments in low gradient Brahmaputra plain.

METHODS

As the first step, the rivers of Brahmaputra are identified using topographical maps together with other published maps and reports. The focus of the study is to document the river morphological changes. For this purpose, Landsat images for the year of 1976 and 1987-2016 are used. Layer stacking, masking and finally mosaicking of neighboring scenes are carried out to get images covering the entire Brahmaputra plain for the study periods. Images of thirty consecutive years (from 1987 to 2016) are investigated in GIS platform to document the sequential morphological changes in the rivers of Brahmaputra.

0016-7622/2018-92-4-441/$ 1.00 © GEOL. SOC. INDIA | DOI: 10.1007/s12594-018-1039-y

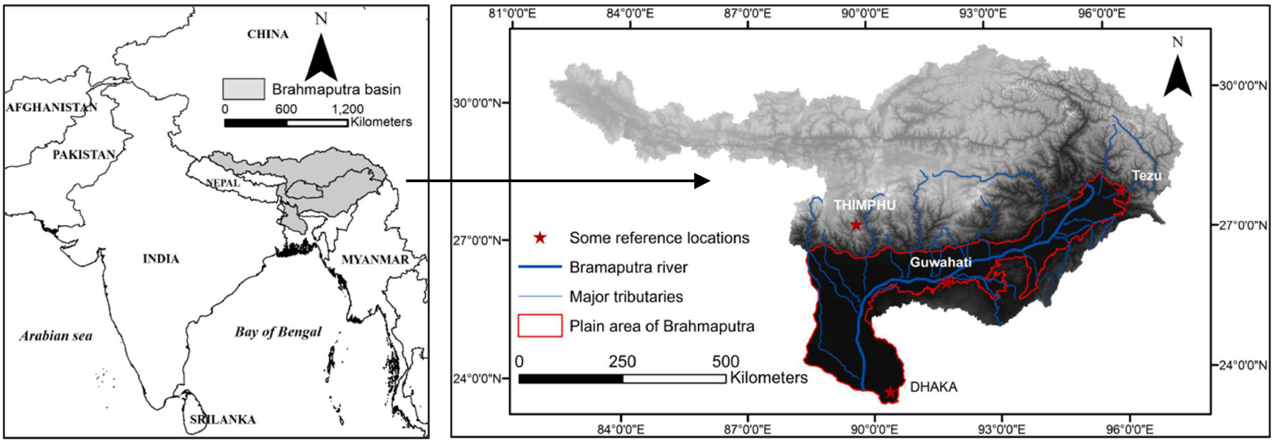

Fig.1. Location map of Brahmaputra plain.

As the morphological changes take place during monsoonal floods, images of subsequent lean phase periods are used for the study.

This work carries tables which enumerate events leading to sequential morphological changes in the rivers of Brahmaputra in the past 30 years. Only the most common morphological activities i.e. meander cut-off, avulsion and confluence migration are included. Keeping in mind the fragmental nature inherent in such enumeration, it is important to mention the criteria followed while counting the events. In order to identify meander cut-offs both neck as well as chute cut-offs are considered. In case of large braided rivers of Brahmaputra where absence of well-defined imprints of such true meanders cut-offs are noticed, careful reasoning based on traslatory movement of bends that led to abandonment of meanders are considered for counting. This was possible due to the usages of data sets of consecutive years. For counting the avulsions only relatively sudden displacements of river channel are considered (Jones and Schumm, 1999). Avulsion may be full or partial (Slingerland and Smith, 2004). Full avulsions are counted which have taken place either in stages (sequentially) or during a single flood year. Rivers of Brahmaputra, mainly the right bank tributaries, adjust confluences very frequently. Therefore to be categorical, alteration of confluence point for more than 1 km between two successive years are considered. Well deciphered confluence migrations are only counted which do not include channel migration within the confine of a channel. All the event counts are done only along the main channels of the rivers.

RESULTS

The results are presented in two subsections covering the right and left bank tributaries of Brahmaputra.

Right bank Tributaries

Apart from the precursor stream Dihang, the major tributaries that Brahmaputra receives on its right bank are Simen, Subansiri, Jiabhareli, Panchnoi, Dhansiri(R), Puthimari, Pagladia, Manas-Beki-Aie, Sankosh, Torsa, Jaldhaka, Teesta and Atrai/Hurasagar.

Dihang

Dihang is characterized by braiding in plain. Except minor channel widening, Dihang did not show any distinct morphological change till 1997. During 1998-2001, Dihang experienced a series of changes in the form of distributary activities. The floods of 1998, 2000 and 2001 transformed Sibia-the lean distributary of Dihang- into a major distributary. This was achieved first by widening Sibia in 1998 and later by developing connecting channels from Dihang in 2000 and 2001. Finally in 2002, Sibia evidently has become a channel of similar width with that of Dihang (Fig. 2a).

Simen

Simen is known for its frequent channel shifts (Hazarika et al., 2015). The river experienced major shift in its bankline during the floods of 1988. Levee crevassing and avulsions are common in Simen (Fig. 2b$_{i-ii}$). In a recent avulsion which took place near Somkong in 2013, Simen captured Narad river temporarily and resulted in large scale sedimentation in the nearby locality (Fig. 2b$_{ii}$). Most of the avulsions in Simen took place near its confluence with Brahmaputra which have resulted in confluence migration on several occasions.

Subansiri

Subansiri is the largest tributary of Brahmaputra and is a sizable river system by itself with several major rivers as its tributaries. Such two major eastern tributaries of Subansiri are- Gai and Jiadhal. The river channels of these two tributaries are highly migrating in nature. Two tributaries have migrated for about 15 times each during last three decades (1987-2016). Frequent avulsions have led to such adjustments in these rivers (Fig. 2c$_{i-ii}$, d$_{i-ii}$).

The trunk channel of Subansiri is known for its regular channel migrations (Goswami et al., 1999; Das et al., 2012). The river exhibited three major avulsions during the study period. The first is in the middle portion of Subansiri (near Bebejia) in initial decades (the period of 1976 to1987 is refereed as initial decade here as well as subsequent sections of the paper) (Fig. 2e$_i$). Other two are the sequential river shift to Ghaghar river (tributary of Subansiri) and channel migration near Dunabari (Fig. 2e$_{ii}$). Apart from these avulsions, meander activities, breaches and confluence migrations are also noticed in the river Subansiri.

Ranganadi and Dikrong are two major western tributaries of Subansiri. Similar to Subansiri, breaches and avulsions are common in Ranganadi (Fig. 2f$_{i,ii}$). The avulsion in 1990 had changed its confluence with Subansiri. Four more devastating breaches are noticed along the main channel of Ranganadi- one each in 1998, 1999, 2002 and 2008 near Jorhat Kanigaon, Balijan, Ujani Khamti Mirigaon and Ujani Khamti Ranigaon respectively. Dikrong, on the other hand, had undergone river straightening due to meander cut-offs in upper reach during 1990-1991 and near its confluence in 1993. During the floods of 2004, Dikrong further reduced its length with alteration of its confluence with river Subansiri (Fig. 2g). Dikrong had major breaches-one each in 1990, 1998 and 2008 near Bangalmara, Napaligaon and Pithaguri respectively (Fig. 2h$_{i,ii}$).

Jia Bhareli

Jia Bhareli is a Trans-Himalayan river. In plains, Jia Bhareli near the confluence with Bor Dikorai (tributary of Jia Bhareli) has a network

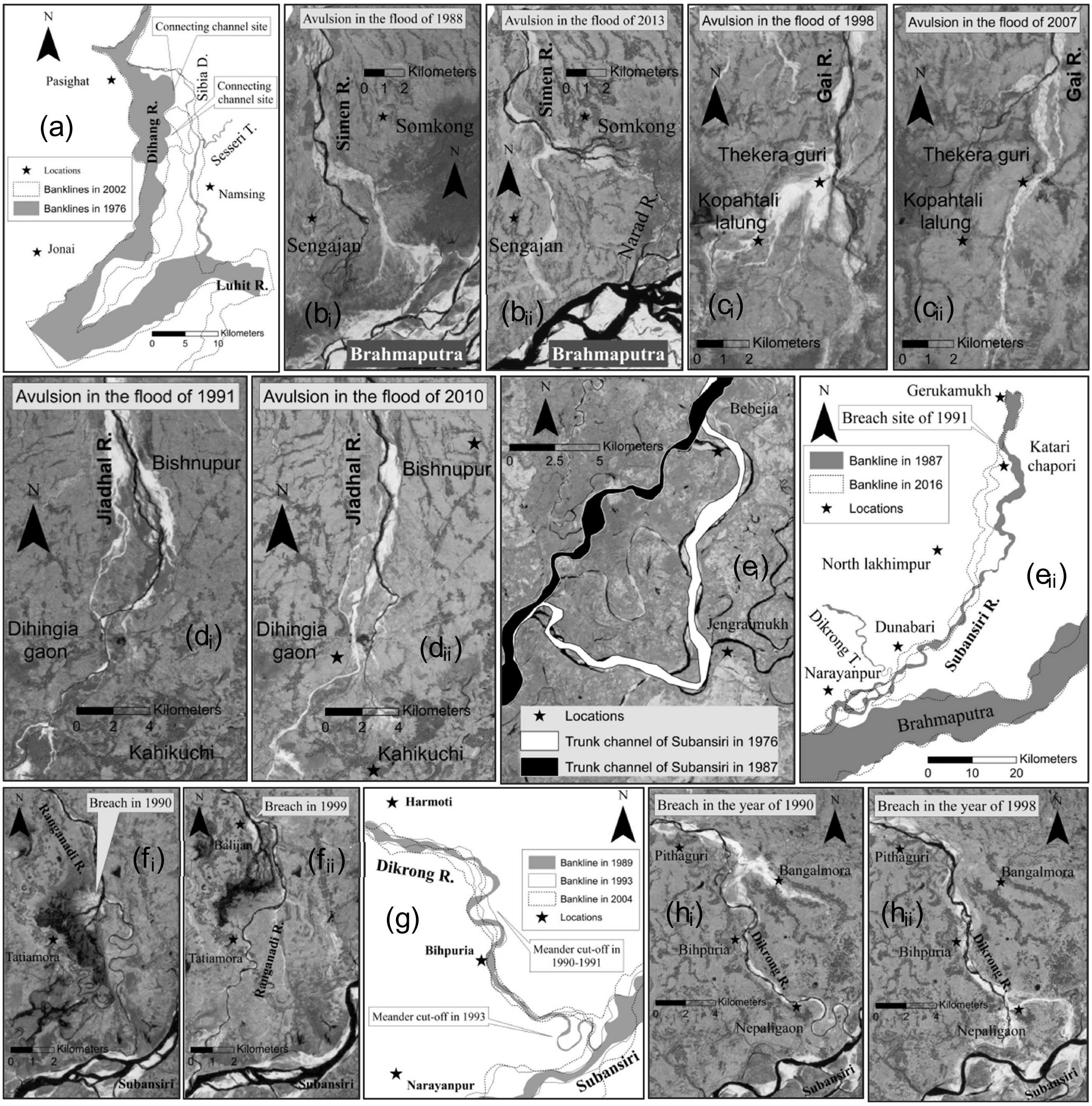

Fig.2. Distributary activities in Dihang (a); and selective avulsions in Simen (b_{i-ii}), Gai (c_{i-ii}), and Jiadhal (d_{i-ii}); Geomorphic activities in Subansiri ($e_{i,ii}$); selective breaches in Ranganadi ($f_{i,ii}$); and meander cut offs, confluence migration and avulsion in Dikrong (g and $h_{i,ii}$).

of anabranches which shuffled several times. In the contiguous downstream, Jia Bhareli exhibits braiding. The braided stretch has been active in terms of bankline change. Changes in the bankline took place in the initial decade as well as in the years 1991 and 1998. After 1998, the channel has the tendency to move westward and generated stress on its right bank in its lower reach which resulted in a devastating breach in 2004 (Fig. 3a).

*Panchnoi and Dhansiri(R)**

To the west of Jia Bhareli, Brahmaputra receives two major tributaries viz., Panchnoi and Dhansiri(R). Panchnoi, in contrast to other rivers, added meanders in the initial decade though many disappeared later during the floods of 1988 and 1989 through cut-offs. The main stream continued its action of meander transformations along with bankline adjustments. The flood of 1990 brought a major avulsion in Panchnoi that led to rearrangement of its confluence with Pagla river (Fig. 3b). Dhansiri(R) enters the plain from Bhutan near Bhairabkunda. Dhansiri(R) exhibited frequent transformations in its bankline in the lower reach. Meander cut-offs are also commonly found in the river during the study period (Fig. 3c).

Puthimari

Puthimari is a Trans-boundary river which originates in lower Himalaya. The river exhibited many meander cut-offs during the study period (Fig. 3d). The river experienced several breaches including two large ones that occurred in the year 2004 and 2012 near Dhepar Gaon (Fig. 3$e_{i,ii}$). Repeated activation and deactivation of distributary that joins Baralia (tributary of Pagladia) is also noticed. Another marked

*Two of the tributaries, one each in the right and the left bank, of Brahmaputra carry the same name Dhansiri. For clarity of identification the "(R)" for the right and "(L)" for the left bank Dhansiri are suffixed to their names in this work.

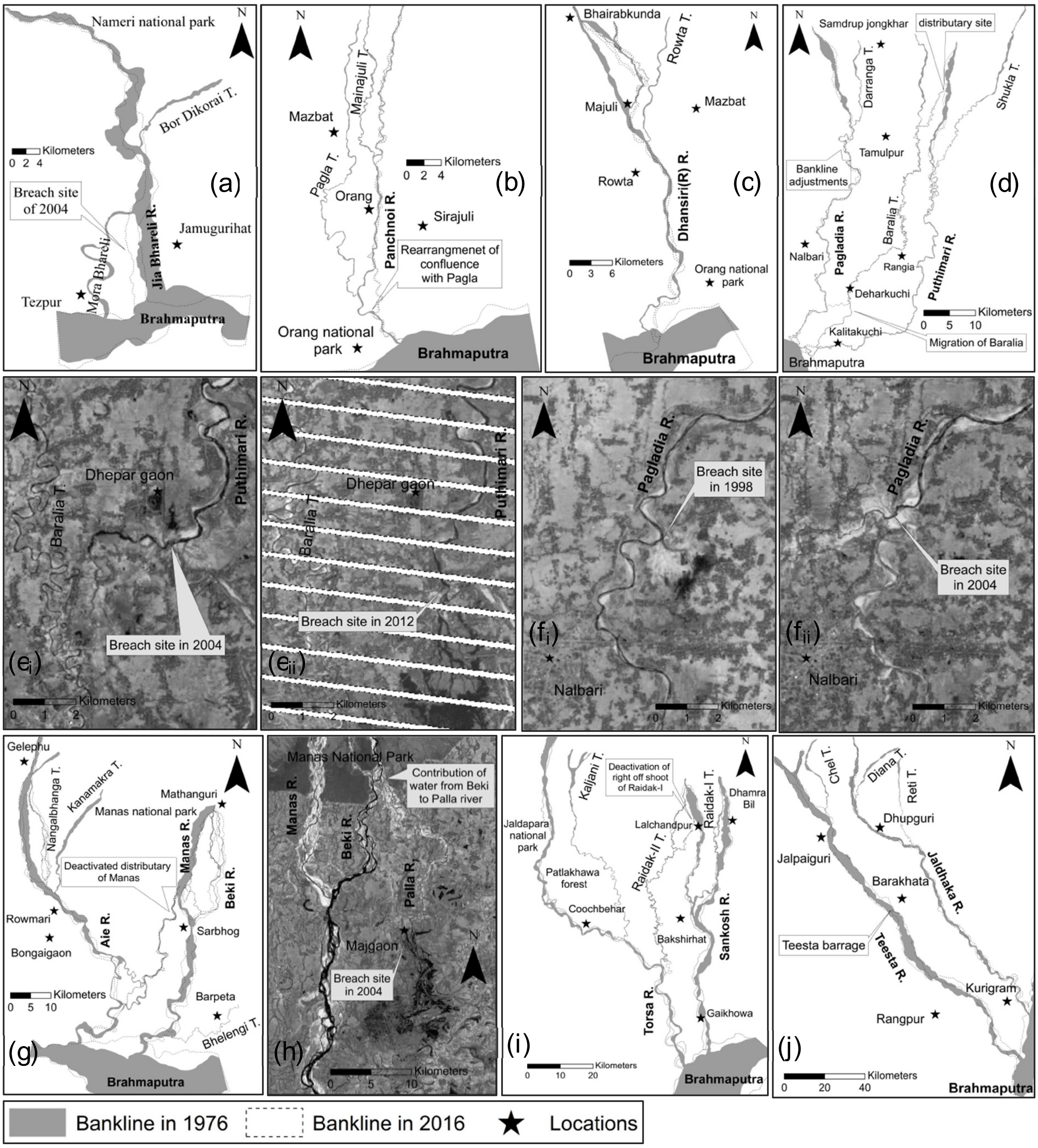

Fig.3. Geomorphic activities of Jia Bhareli (a), Panchnoi (b), Dhansiri(R) (c), and Puthimari and Pagladia (d); major breaches in Puthimari ($e_{i,ii}$) and Pagladia ($f_{i,ii}$); distributary, meander and confluence activities in Manas-Beki-Aie system (g); the increased flow through Beki that led to a breach on Palla river (h); distributary, meander and confluence activities in Sankosh and Torsa (i); and bankline adjustments in Jaldhaka and Teesta (j).

change is the shift in the confluence of Baralia river. Baralia had its outlet to Pagladia in the initial years but had shifted its flow (near Deharkuchi) gradually to Puthimari during 90's (Fig. 3d).

Pagladia

Pagladia is known for its frequent morphological dynamics in the past. During its passage, middle portion of Pagladia especially the stretch immediately downstream of the confluence with Darranga (tributary of Pagladia) showed considerable bankline alteration during the initial decade. In the later periods the river exhibited several meanders cut-offs, expansion and transformation. Breaches are also noticed commonly in the banklines of Pagladia during the study period. Larger ones occurred in the flood years of 1998, 2002-03 and 2004 (Fig. 3$f_{i,ii}$).

Manas-Beki-Aie

Manas-Beki-Aie collectively with anabranches, tributaries and distributaries (particularly in the reaches from foothills to Sarbhog) represents a system where river reorganizations have been active during the last four decades. Manas bifurcates into Beki and Manas as soon as it enters into the plain near Mathanguri and flow for a considerable distance before they rejoin. In the early image of 1976 Manas clearly was the major branch with lean flow through Beki. The floods in succeeding years switched Beki as the trunk channel (Fig. 3g). Greater flow pressure on Beki led to activation of a distributary channel which started contributing water to Palla river (tributary of Manas system) in 2004. The combined flow caused a devastating breach on the left bank of Palla river near Majgaon (Fig. 3h). For Manas anabranch, this shift in trunk channel led to deactivation of one distributary which was acting as link channel between Manas and Aie (Fig. 3g) and separated Aie from Manas-Beki-Aie river system. The river Aie exhibited river straightening during the study period. The westward movement of the main stream to its paleo channel along with confluence migration in the initial decade, and other channel adjustments in the floods of 1988, 1990, 1991, 1996, 1998, 2000, 2007 and 2016 contributed to the river straightening (Fig. 3g). Aie undertook repetitive activation and deactivation of distributary between 1998 and 2003 on its right bank near Rowmari. Breaches and avulsive activities are also commonly found in Aie during the study period.

Sankosh and Torsa

The tributary Sankosh is found to relatively steady. The minor bankline adjustments in Sankosh includes shift in the position of the trunk channel in upstream of its confluence with Raidak-I (tributary of Sankosh) and repeated abandonment and reactivation of its distributaries near Dhamra Bil and Gaikhowa. Raidak-I also showed deactivation of its right distributary near Lalchandpur (Fig. 3i) which was acting as the connecting channel with Torsa. Torsa, on the other hand, undergone noticeable changes in the form of meander cut-offs, avulsions and bankline adjustments in the initial decade as well as in the floods of 1989, 1993, 1998, 2002 and 2005 (Fig. 3i).

Jaldhaka, Teesta and Atrai/Hurasagar

Jaldhaka, Teesta and Atrai/Hurasagar are western most tributaries of Brahmaputra. Except minor confluence and bankline adjustments, Jaldhaka did not show any significant morphological changes during the study period. Teesta is a braided river with relatively straighter course. Apart from minor bankline adjustments, the notable morphological changes in Teesta river include recurrence of breaches and widening of its braiding near Barakhata (Bangladesh) adjacent to Teesta barrage (Fig. 3j). In contrast to Jaldhaka and Teesta, the river Atrai/Hurasagar experienced meander cut-offs in its upper reach. Atrai/Hurasagar also showed several small breaches especially in the stretch between Manda and Atrai.

Left Bank Tributaries

The major left bank tributaries of Brahmaputra include Dibang, Lohit, Burhi Dihing, Disang, Dikhow, Dhansiri(L), Kolong, Kopili, and Jiniram.

Dibang and Lohit

Dibang is a braided river which originates in Indo-Tibetan boarder. Repeated abandonment and reactivation of Gango (distributary of Dibang) was noticed during the study period. The confluence of Dibang has also migrated westward and presently Dibang confluences with Lohit near west of Dibru-Saikhowa national park (Fig. 4a). However, a lean flow still maintains its connection with Lohit at earlier point of confluence. This confluence migration is manifested by sequential channel migration of Lohit. It took place in stages with diversion of greater flow and progressive shifting of trunk channel of Lohit through a small distributary that captured Dibru-Dangori river. In 2003, Lohit separated itself from Dibang, except for a lean flow, and made its present route through the southern margin of Dibru-Saikhowa national park (Fig. 4b$_{i-ii}$).

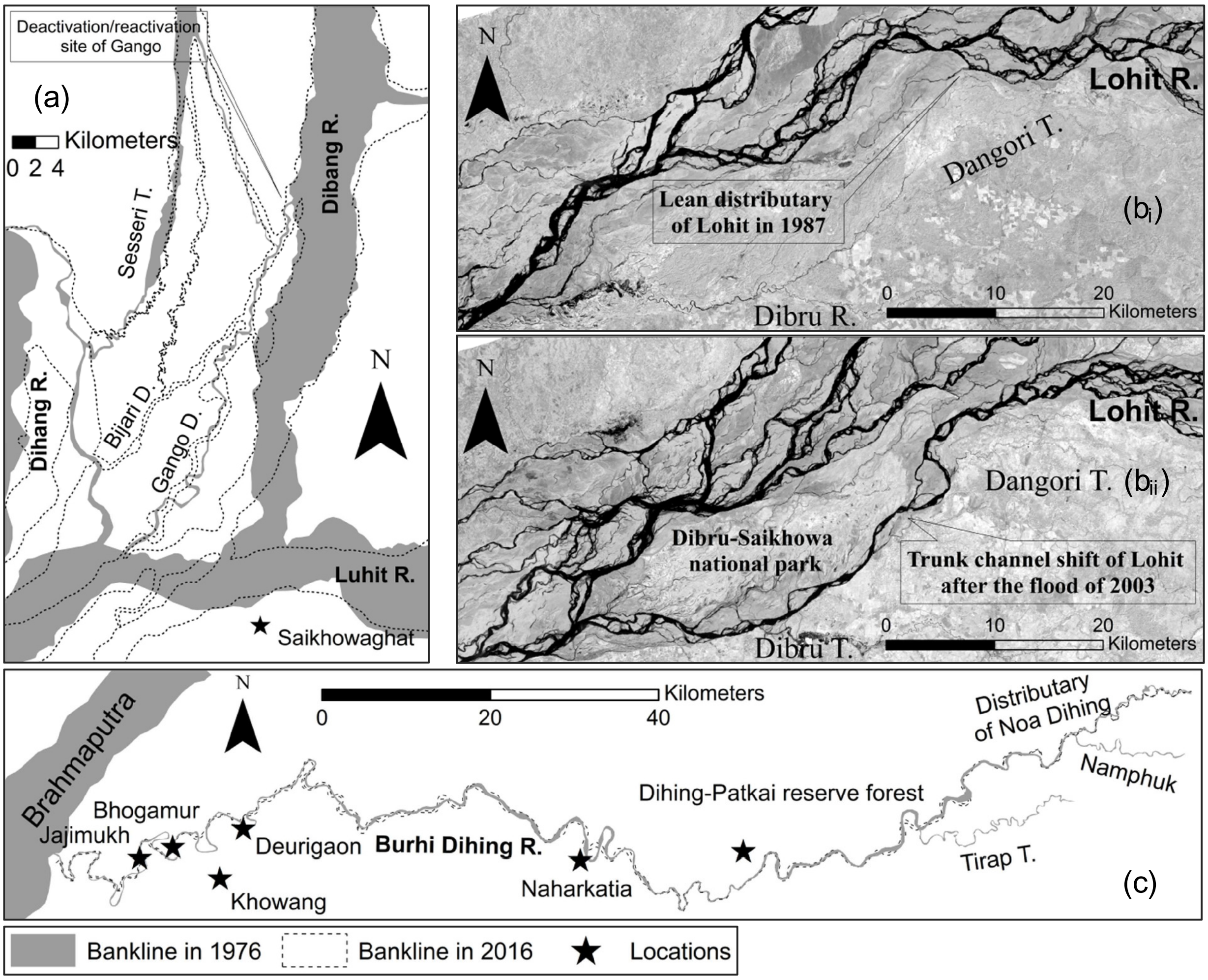

Fig.4. Distributary activity and confluence migration of Dibang (a), channel migration of Lohit (b$_{i-ii}$) and meander activities in Burhi Dihing (c).

Burhi Dihing, Disang and Dikhow

Burhi Dihing at upper stretch is formed by a distributary of Noa Dihing and its precursor river Namphuk. The river had shown minor meander in its upstream during the study period. However, the stretch of Burihi Dihing below Dihing Patkai reserve forest experienced four meander cut-offs in the initial decade near Jajimukh, Bhogamur, Khowang and Naharkatia. And, five more in the years of 1990, 1994, 1995, 1998 and 2009 near Tirap confluence, Deurigaon, Jajimukh, Naharkatia, Bhongamur respectively (Fig. 4c). Disang however found to be relatively steady in terms of morphological changes. It had only two meander cut-offs and other minor modifications in last four decades. Dikhow, on the other hand, underwent straightening in its channel through meander cut-offs at six places.

Dhansiri(L)

Dhansiri(L), one of the major tributaries of the Brahmaputra, is highly meandering in its planform. Numerous oxbow lakes all along the channel indicate meander cut-off in past which has continued in the study period as well (Fig. 5a). As many as five meanders cut-offs are noticed during the initial decade. Later, meander cut-offs along with transformations were witnessed in the year 1989, 1993, 1996, 1998, 1999, 2000, 2001 and 2003. In more recent years this trend receded though gradual expansions of several meanders are noticed. This can be a precursor to more meander cuts in near future.

Kolong and Kopili

Kolong actually was an anabranch of Brahmaputra, called Kolong Suti which lost its connection at the point of bifurcation due to blocking the same by construction of an embankment. The present day Kolong receives Diju and Haria rivers on its left bank and outfalls to Brahmaputra near Kachusila. In the past Kolong had only one outfall, i.e., into Kopili. But during early 1990's, the river started carrying its main flow to Brahmaputra through Pakaria (Sonai) (Fig. 5b) via two tributaries one each of Kolong and Pakaria (Fig. 5b). In terms of bankline change, Kolong is found to be steady, however had meander cut-offs and transformations in upper most portion. River Kopili is larger than Kolong which originates in the high hills of Dima Hasao (Barail range). In terms of morphological dynamics, the river Kopili is found to be relatively steady. Kopili had only three meanders cut-offs during the entire study period; two in the initial decade and one in 2004 (Fig. 5b).

Jinjiram

River Jinjiram flows almost parallel to Brahmaputra and outfalls (to Brahmaputra) near Phulbari. Jinjiram had its outlets near Rowmari (Bangladesh) in past. After multiple rearrangements, Jijiram finally shifted its outlet to Brahmaputra near Phulbari in the year of 2000 (Fig. 5c). This shift separated the downstream tributaries of Jinjiram viz., Gumai Jhora, Galwang and Kalo. It also caused abandonment of the distributary Jinjiram had in 1976 that flowed past Mankachar which had outlets to Old Brahmaputra as well as to Jamuna, though the distributary is kept alive by Kalo river. Jinjiram lost several meanders in its downstream but it is not a case of cut-off rather abrupt channel adjustments forced by encroached flow from Brahmaputra in a series of breaches during 1995-2000.

DISCUSSION

Evidently, frequent distributary activities, meandering activities, avulsions and confluence migration are the dominant agents of morphological dynamics in the rivers of Brahmaputra.

Range of activities viz., formation, growth, abandonment and reactivation associated with distributaries are readily noticed in Brahmaputra plain especially in northern tributaries during the study period (e.g., Subansiri, Pagladia, Manas-Beki-Aie, Kopili, etc.). In the riverine system of Brahmaputra plain which is densely dissected with numerous rivers and rivulets, the distributaries often serve as connecting channel between contiguous river systems. Thus their activities lead to reorganization in channel network, which is evident in in several rivers endowed with distributaries in the Brahmaputra system.

Considering the frequency of occurrence and preserved imprints of abandoned channels in the plain, majority of the rivers of Brahmaputra can be categorized as free meanders (Ikeda, 1989). Meandering activities between the rivers of both the banks shows a variation in pattern that reflects their difference in fluvio-geomophic setups (Table 1 and 2). Meander dynamics is found common more amongst the smaller right bank rivers e.g., Panchnoi, Puthimari, Pagladia, etc. The larger rivers tend to form braiding. Though less common, meandering activities are also noticed in some larger tributaries e.g., the river Subansiri. In Subansiri, these activities are mainly triggered by change in its flow regime. It may be recalled that Subansiri captured Ghagar and the combined flow led to modification in meanders along the stretch downstream. It is evident as most of the meander cut-offs are confined to this stretch. Two more relatively larger rivers viz., Aie and Torsa also showed large turn around in their lower reaches that led to abandonment of meanders. In left bank, meander cut-offs are appeared to be more in relatively larger rivers e.g., Dhansiri(L) and Burhi Dihing.

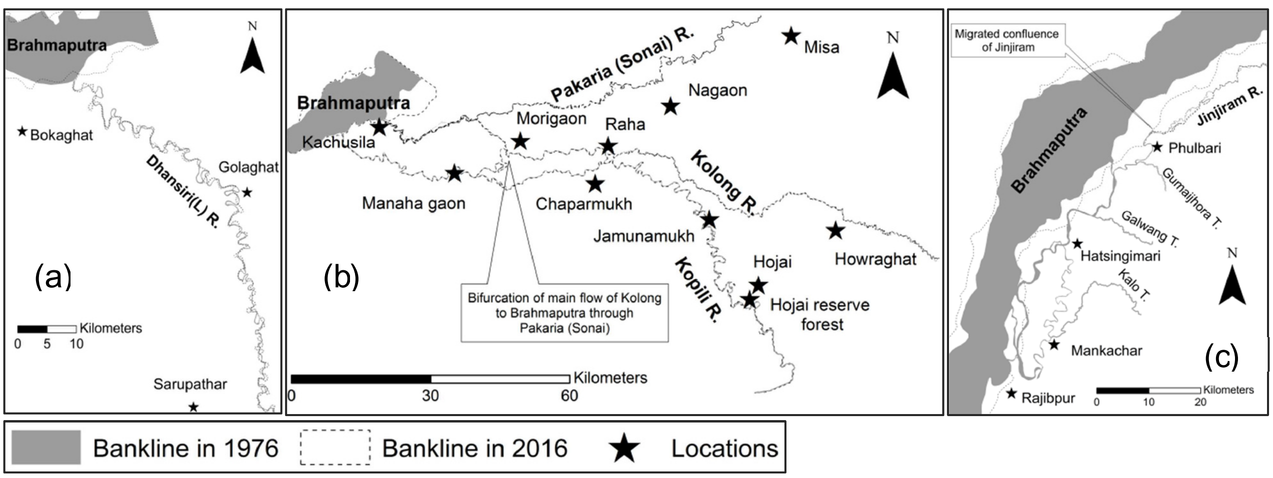

Fig.5. Meander activities in Dhansiri(L) (a), bifurcation of main flow of Kolong to Brahmaputra through Pakaria (Sonai) and meandering activities in Kolong and Kopili (b) and confluence migration and bankline activities in Jinjiram (c).

Table 1. Major morphological activities of the right bank rivers of Brahmaputra during 1987-2016

Rivers	Morphological activities			Highlights
	Meander cut-offs	Avulsions	Confluence migrations	
Dihang	Rare	Rare	Rare	Widening of the river
Simen	Occasional	Common	Common	Frequent confluence migration
Gai[a]	Occasional	Frequent	Rare	Very frequent avulsion activities
Jiadhal	—-[b]	Frequent	—-[b]	
Subansiri	Frequent	Occasional	Rare	Overall westward shift
Ranganadi	Occasional	Occasional	Rare	Devastating breaches have occurred
Dikrong	Occasional	Occasional	Occasional	Straightened significantly
Jia Bhareli	Rare	Rare	Rare	Lower portion is shifting westward
Panchnoi	Frequent	Occasional	Rare	High meandering activities
Dhansiri(R)	Common	Rare	Rare	South-easterly directed flow in foot hills
Puthimari	Common	Rare	Rare	Among most active right bank rivers of middle Brahmaputra
Pagladia	Common	Occasional	Occasional	
Manas/Beki	Rare	Rare	Rare	Back and forth channel shift
Aie	Common	Occasional	Rare	Split from Manas river system
Sankosh	Rare	Rare	Rare	Relatively stable river
Torsa	Common	Occasional	Occasional	Channel adjustment in lower reach
Jaldhaka	Rare	Rare	Occasional	Relatively stable river
Teesta	Rare	Rare	Rare	
Atrai/Hurasagar	Frequent	Rare	Rare	Frequent small sized meander cut offs in upper reach

Note: <2 event = Rare; 2-5 events = Occasional; 6-10 events = Common; >10 events = Frequent. [a] Counts are for the stretch up to the confluence with Batua-Laipulia channel; [b] Could not be calculated because of swinging channel pattern

Table 2. Major morphological activities of the left bank rivers of Brahmaputra during 1987-2016

Rivers	Morphological activities			Highlights
	Meander cut-offs	Avulsions	Confluence migrations	
Dibang	Rare	Rare	Rare	Large confluence alteration
Lohit	Rare	Rare	Rare	
Burhi Dihing	Occasional	Rare	Rare	Limited meander activities noticed
Disang	Occasional	Rare	Rare	
Dikhow	Occasional	Rare	Rare	
Dhansiri(L)	Frequent	Rare	Occasional	One of the most active left bank river of Brahmaputra
Kolong	Common	Rare	Occasional	Split from Kopili river system
Kopili	Rare	Rare	Rare	Relatively steady river

Note: <2 event = Rare; 2-5 events = Occasional; 6-10 events = Common; >10 events = Frequent

Recurrence of avulsions in the right bank rivers of Brahmaputra have been a feature in the study period (Table 1). The breaches in Simen, Gai and Jiadhal commonly lead to avulsive activities which are found to be as high as 15 times in case of Jiadhal in last three decades. Jones and Schumm (1999) attributed avulsion to reduction in capacity of channel to transport all of the water and sediment delivered to it. The upper catchments of the above rivers are characterized with high rainfall (Dhar and Nadargi, 2004; Datta and Singh, 2004) and thus have high monsoonal discharge and sediment flux. During receding stages of flow the rivers deposit sediments all along their channels reducing channel capacity. At times this leads to absence of distinct river courses at some stretches. High seasonal flow and large sedimentation along the river bed leads to frequent avulsion in rivers in this stretch.

Avulsion near confluence and river capture and aggradation due to Brahmaputra bankline migration are found to be the dominant processes of confluence migration in the rivers of Brahmaputra. The river Simen is found to be the most active in this regard. Minor alterations of confluence points are noticed in almost all north bank tributaries of Brahmaputra. In contrast, south bank tributaries are found stable except for Jinjiram which experienced confluence alteration caused by widening of Brahmaputra along the reach.

CONCLUSIONS

The spectrum of activities that have been shaping and reshaping morphology of the rivers of Brahmaputra in the plain has been presented in this paper. Occurrence of river capture, rerouting of flow, formation and abandonment of distributaries, change in outlet observed during the last 40 years indicate the continuation of river reorganization in Brahmaputra. Episodic breaches and avulsions are common and has been an agent of morphological changes especially in right bank tributaries. The role of fluvio-geomorphic contrast in the nature and frequency of morphological activities in right and left bank tributaries is discernable. This comprehensive study strengthens the spatio-temporal understanding of the dimensions of the morphological changes in rivers of Brahmaputra. This understanding can be vital input to water resource development and management planners in the uncertain riverine environment of Brahmaputra.

Acknowledgement: The authors acknowledge the U.S. Geological Survey as the source for Landsat images.

References

Bora, A.K. (2004) Fluvial geomorphology. *In:* Singh, V.P., Sharma, N. and Ojha, C.S.P. (Eds.), The Brahmaputra Basin Water Resources. Kluwer Academic Publishers, Dordrecht, pp.88–112.

Coleman, J.M. (1969) Brahmaputra River: channel processes and sedimentation. Sediment. Geol., v.3, pp.129-239.

Das, A.K., Sah, R.K. and Hazarika, N. (2012) Bankline change and the facets of riverine hazards in the floodplain of Subansiri–Ranganadi Doab, Brahmaputra Valley, India. Nat. Hazards, v.64, pp.1015-1028.

Datta, B. and Singh, V.P. (2004) Hydrology. *In:* Singh, V.P., Sharma, N. and Ojha, C.S.P. (Eds.), The Brahmaputra Basin Water Resources. Kluwer Academic Publishers, Dordrecht, pp.139–195.

Dhar, O.N. and Nandargi, S. (2004) Rainfall distribution over the Arunachal Pradesh Himalayas. Weather, v.59, pp.155-157.

Dixon, S., Smith, G.S., Nicholas, A., Best, J., Bull, J., Vardy, M., Goodbred, S. and Sarker, M.H. (2015) Megascours: the morphodynamics of large river confluences. Geophys. Res. Abstr., v.17, EGU2015-5394.

Goswami, U., Sarma, J.N. and Patgiri, A.D. (1999). River channel changes of the Subansiri in Assam, India. Geomorphology, v.30, pp.227-244.

Hajek, E.A. and Edmonds, D.A. (2014) Is river avulsion style controlled by floodplain morphodynamics? Geology, v.42, pp.199-202.

Hazarika, N., Das, A.K. and Borah, S.B. (2015) Assessing land-use changes driven by river dynamics in chronically flood affected Upper Brahmaputra plains, India, using RS-GIS techniques. Egypt. Jour. Remote Sens. Space Sci., v.18, pp.107–118.

Hermas, E.A., Abou El-Magd, I.H. and Saleh, A.S. (2010) Monitoring the lateral channel movements on the alluvial fan of Wadi Feiran drainage basin, South Sinai, Egypt using multi-temporal satellite imagery. Jour. African Earth Sci., v.58, pp.89-96.

Hosu, M. and Sabo, H. (2012) The Morphodynamics of the Somes River Channel, Northwestern Romania, as Response to Natural Influences. APCBEE Procedia, v.1, pp.210-215.

Ikeda, H. (1989) Sedimentary Controls on Channel Migration and Origin of Point Bars in Sand-Bedded Meandering Rivers. *In:* Ikeda, S. and Parker, G. (Eds.), River Meandering. American Geophysical Union (Water Resources Monograph 12), pp.51-68.

Jones, L.S. and Schumm, S.A. (1999) Causes of avulsion: an overview. *In:* Smith, N.D. and Rogers, J. (Eds.), Fluvial Sedimentology VI. International Association of Sedimentologists (Special Publication) 28, pp.171-178.

Lahiri, S.K. and Sinha, R. (2012) Tectonic controls on the morphodynamics of the Brahmaputra River system in the upper Assam valley, India. Geomorphology, v.169-170, pp.74-85.

Lahiri, S.K. and Sinha, R. (2014) Morphotectonic evolution of the Majuli Island in the Brahmaputra valley of Assam, India inferred from geomorphic and geophysical analysis. Geomorphology, v.227, pp.101-111.

Purkait. B. (2004) Ground water development. *In:* Singh, V.P., Sharma, N. and Ojha, C.S.P. (Eds.), The Brahmaputra Basin Water Resources. Kluwer Academic Publishers, Dordrecht, pp.411–418.

Sarker, M.H., Thorne, C.R. and Aktar, N. (2013) Morpho-dynamics of the Brahmaputra–Jamuna River, Bangladesh. Geomorphology, v.215, pp.45-59.

Sarma, J.N. (2005) Fluvial process and morphology of the Brahmaputra River in Assam, India. Geomorphology, v.70, pp.226-256.

Sarma, J.N., Borah, D. and Goswami, U. (2007) Change of river channel and bank erosion of the Burhi Dihing river (Assam), assessed using remote sensing data and GIS. Jour. Indian Soc. Remote Sens., v.35, pp.93–100.

Sarma, J.N. and Phukan, M.K. (2004) Origin and some geomorphological changes of Majuli Island of the Brahmaputra River in Assam, India. Geomorphology, v.60, pp.1-19.

Sarma, J.N. and Phukan, M.K. (2006) Bank erosion and bankline migration of Brahmaputra river in Assam during the twentieth century. Jour. Geol. Soc. India, v.68, pp.1023-1036.

Slingerland, R. and Smith, N.D. (2004) River avulsions and their deposits. Annu. Rev. Earth Planet. Sci., v.32, pp.257-285.

Thorne, C.R., Russell, P.G. and Alam, M.K. (1993) Planform Pattern and Channel Evolution of the Brahmaputra River, Bangladesh. *In:* Best, J.L. and Bristow, C.S. (Eds.), Braided rivers. Geol. Soc. London Spec. Publ., no.75, pp.257-276.

Willett, S.D., McCoy, S.W., Perron, T., Goren, L. and Chen, C. (2014) Dynamic Reorganization of River Basins. Science, v.343, pp.1248765.

(Received: 14 July 2017; Revised form accepted: 6 February 2018)