Channel confluence dynamics in the lower Chel river system, eastern sub-Himalayan West Bengal, India

In the present study channel confluence movements of two confluence points namely, Chel-Kumlai rivers' confluence and Chel-Neora rivers' confluence in the lower Chel-Neora river system has been analyzed using multi temporal Landsat images and topographical sheets. The study area is a part of region popularly known as 'Dooars' which falls in the zone of transition between the dissected outer Himalayan hill surface and the gently rolling Teesta-Brahmaputra plains, and is famous for notorious incidents of channel avulsion and river capture activities. This study tries to elucidate various fluvial processes responsible for confluence dynamics. The temporal scale of the study spans 62 years (1955-2017) and establishes the fact that the confluence points of the rivers have shifted both upstream and downstream in much variable rates during the assessment period. Avulsions, cut-offs, aggradations and river capture has been identified as controlling processes for such confluence dynamics.

Keywords: *Chel river, aggradation, confluence dynamics, junction angle.*

1. Introduction

Channel confluences form an important component of the river systems as they influence both morphology and hydrology of the reaches both upstream and downstream of the confluence (Roy and Sinha, 2007). From hydraulic perspectives, river confluences are active sites for occurrence of turbulence with convergent and divergent movements, resulting in upwelling and down welling of flows and formation of lateral vortex (Morisawa, 1968). Stevaux et al., 2009 describes channel confluences as sites of drainage systems with complex hydraulic interactions provided by the integration of two different flows which constitutes an environment of "competition and interaction" with gradual dynamism in flow velocity, river discharge and structure, physical and chemical properties of water and channel morphology. Thus it is not hard to imagine the implications of shifting of such complex sites. The implications can be far reaching and multi faceted i.e. hydrological, morphological, engineering, basin management, religious belief etc. The dynamics of confluence points affect the availability of water and pattern of sediment dispersal in different reaches and around the confluence points (Roy and Sinha, 2007). From engineering point of view, such movements trigger either scouring or aggradations and thus pose threats to riverine infrastructures. In India, confluence points bear aesthetic and mythological significance too, as confluence points of many great rivers are revered as holy place and many religious institutions are located at such confluences. Roy and Sinha, 2007 argue that study of river confluence dynamics also holds significance geologically as confluences generate peculiar sedimentary facies and the understanding of confluence dynamics can provide significant insight to alluvial architecture around the confluences. River confluences along the Ganga river also hold archeological significance as a number of human settlements have been reported around the Ganga-Yamuna confluence (Williams and Clarke, 1984, 1995).

In spite of so much significance, there is limited number of studies on confluence dynamics in Ganga plains (Tangri, 1986; Roy and Sinha, 2005, 2007). In the vicinity, channel confluence studies are almost non-existent. Recent works on lower Jaldhaka river system exhibit channel confluence dynamics in the Dooars region of sub-Himalayan West Bengal (Chakraborty and Datta, 2013 and Chakraborty and Mukhopadhyay, 2014).

2. Study area

The lower Chel river system under study is located between 26°41'N and 26°47'30''N latitudes and between 88°41'E and 88°46'30''E longitudes (Fig.1). It forms a part of an elongated area stream and North Bengal Gangetic plains. This part of the foothill region, east of Teesta river is popularly known as the Dooars spread over Darjeeling, Jalpaiguri and Alipurduar districts of West Bengal. The region is dissected heavily by parallel and sub-parallel rivers of Himalayan origin in almost north-south direction. Few foothill and plains' origin rivers serve as tributaries of major river of Himalayan origin.

The foothill situation makes the region ideal for aggradations. The rivers originating from different elevations of Himalaya, flowing southwards suddenly loose considerable gradient, velocity and thus transporting capacity

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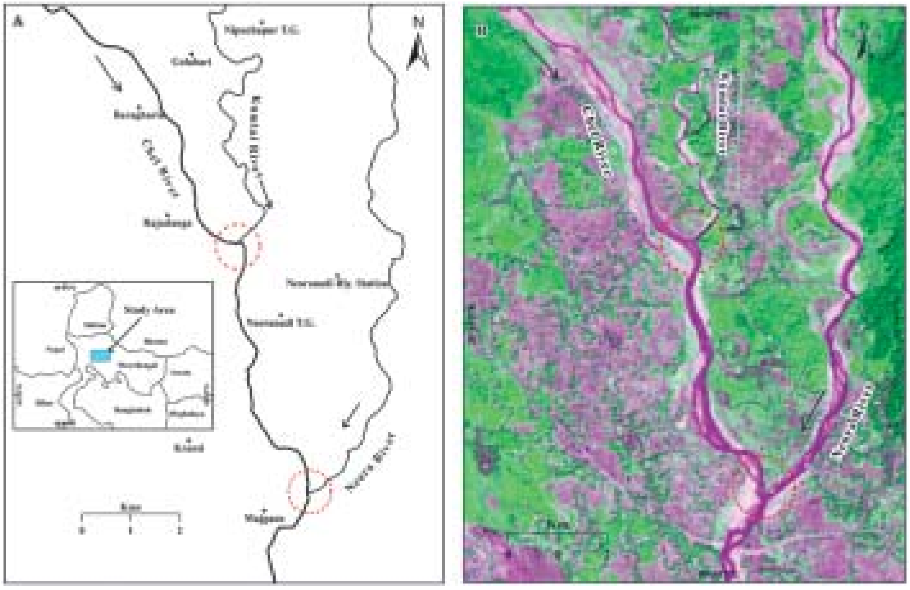

Fig.1 (A) Base map showing the study area in the Sub-Himalayan West Bengal. (B) Landsat 8 OLI/TIRS image of 1st December, 2017. Red dotted circles represent two confluence points, the Chel-Kumlai confluence and Chel-Neora confluence, under investigation.

reaching the plains. Therefore large amount of Himalayan detritus composed of large-medium and small sized boulders, cobbles, pebbles, sand, silt particles etc. gets deposited at or near the break of slope, transforming the region into a region of coalescing alluvial fans. These alluvial fans are being dissected into a bunch of interfluves by numerous southward flowing rivers which disperse and grades the sediments distance-wise to a great extent and thus we find presence of fine silt and clay beyond a distance of 25km (approximately) from the mountain front. The piedmont surface is inclined in the root part between 25% and 10%, before gradually declining to 5% and less, and at a distance of 30 km from the mountains to below 2% in areas not affected by uplift (Starkel et al. 2008). The continuous aggradations fills-in the channels resulting in rise of river beds and thereby cause river migration mostly through avulsions during floods.

The region thus exhibits a geomorphic mosaic of high elevated terraces, channels, channel bars, flood plains. The signatures of spatio-temporal adjustments of rivers to the variation in controlling factors of tectonic, hydrologic, geomorphic and anthropogenic origin are strewn all over the region in the form of paleochannels, meander cutoffs, avulsion marks, misfit streams, Ox-bow formations, crevasses plays etc.

Kumlai origins from Sakam reserved forest at an elevation of 300m (approximaely) in the piedmont surface below Gorubathan and meets Chel to its left bank near Rajadanga at an elevation of 105m above msl. On the other hand Neora river originates in the Lesser Himalayan region at an elevation of 2200m of flowing southwards it joins the Chel also from the left near Majgaon downstream of Kranti at an elevation of 94 meters above msl.

3. Data used and methodology

This study uses topographical maps and multi temporal Landsat images to map the temporal variation in confluence points and channel positions during 62 years from 1955 to 2017. Therefore six Landsat scenes (1976, 1987, 1994, 2005, 2010, and 2017) with path/row: 139/41; 149/41 for 1976 image were collected from the USGS site (http:// earthexplorer.usgs.gov/). One 1: 250,000 scale U.S. Army corps of Engineers NG 45-8, Series - U502 topographical map (1955) was acquired from the University of Texas site (https://

TABLE 1: MAP SOURCES USED IN THE STUDY

Types of data	Publisher	Index/ map no.	Survey year	Scale	Spatial coverage		
Edition-2 Army Map Service (AMS) Series-U502	USArmy Corps of Engineers	NG45-8	compiled in 1955 from half-inch series,1: 126.720,SOI,1930-33	1:2,50,000	Jalpaiguri and Kochbehar District		
Topographical maps	Survey of India	78 B/9 and 78 B/10	1969-1971	1:50,000	Darjiling, Jalpaiguri and Dinajpur District		
Satellite images	Satellite/ sensor	Path/Row	Date of acquisition	Resolution (Meter)	Projection	WRS type	Bit depth
	Landsat 1-5 MSS	149/41	30.11.1976	60	UTM/WGS 1984	1	8
	Landsat 4-5 TM	139/41	31.12.1987	30	UTM/WGS 1984	2	8
	Landsat 4-5 TM	139/41	18.12.1994	30	UTM/WGS 1984	2	8
	Landsat 4-5 TM	139/41	13.10.2005	30	UTM/WGS 1984	2	8
	Landsat 4-5 TM	139/41	14.12.2010	30	UTM/WGS 1984	2	8
	Landsat 8 OLI/TIRS	139/41	01.12.2017	30 (15m for PAN)	UTM/WGS 1984	2	16

legacy.lib.utexas.edu/maps/india.html). All the Landsat scenes were downloaded from the USGS through their data visualization tool GloVis. (Table 1).

ArcGIS (version 10.1; ESRI, Redlands, CA) software package have been used for preparation of GIS database relating to temporal channel configuration maps. All the images were processed through ERDAS imagine (v.9.0) software and then were geo-referenced based on Universal Transverse Mercator (UTM) projection system (Northern hemisphere 45 zone and world geodetic system [WGS] 84) manually using GCPs collected during GPS survey. Junction angles between channel courses at the confluence points were measured as the angle between the tangents on the curved thalweg from the confluence point of the two channels (Roy and Sinha, 2007) (Figs.2A and 2B). The morphological implications of confluence dynamics were analysed through three parameters namely, sinuosity, braiding, and channel width (Table 2). Native knowledge about the area was also applied.

4. Description of confluence dynamics

The Chel and Kumlai rivers formed a confluence (A1) in 1955 (Fig.4A) near Rajadanga. While at the same time Chel-Neora confluence point (B1) was near Majgaon. Systematic reconstruction of channel configuration shows that the width of river Chel near the confluence has increased manifold from 189.3 m to 679 m during the period 1955-1976 which brought the left bank of Chel river nearer to river Kumlai. Consequently the earlier lower course of river Kumlai has been engulfed into river Chel thereby the Chel-Kumlai confluence point has shifted by 531m upstream to A2 (Fig.4B). The junction angle between the Chel-Kumlai has increased almost by double and sinuosity of Kumlai has decreased. During the same period, the river Chel has shifted westward along with increase in channel width downstream of Kranti. This has resulted in westward shift of confluence point between Chel and Neora by 154m to B2 (Fig.4B). During the period 1976-1987, the confluence area between the Chel and Kumlai experience huge aggradation most probably due to increased bank erosion in the upstream reaches. There has been a marked reduction in the width of Chel river from 679m in 1976 to mere 202.2 m in 1987 near the confluence and river Chel has shifted towards the right bank. This aggradation has pushed the Chel and Kumlai rivers southward resulting in downstream movement of the confluence point from A2 to A3 by 1192 m (4C). The Chel-Neora confluence too experience downstream movement by 150.46m during the period 1976-1987 due to accreation only. Within the next seven years a major flow separation develops around 900m upstream of Rajadanga in North-East direction, thus main channel (flow) avulsed through the earlier inter fluve and captures the lower Kumlai river by 1994 thereby moving the confluence

TABLE 2: COMPUTED VALUES OF JUNCTION ANGLE VARIATION FOR CHEL-KUMLAI AND CHEL-NEORA CONFLUENCE POINTS DURING 1955-2017

Year	Junction angle (Degree)	
	Chel-Kumlai	Chel-Neora
1955	66.5	115
1976	125	72.5
1987	71	57.5
1994	108	129
2005	117	38
2010	118	61
2017	113.5	66.5

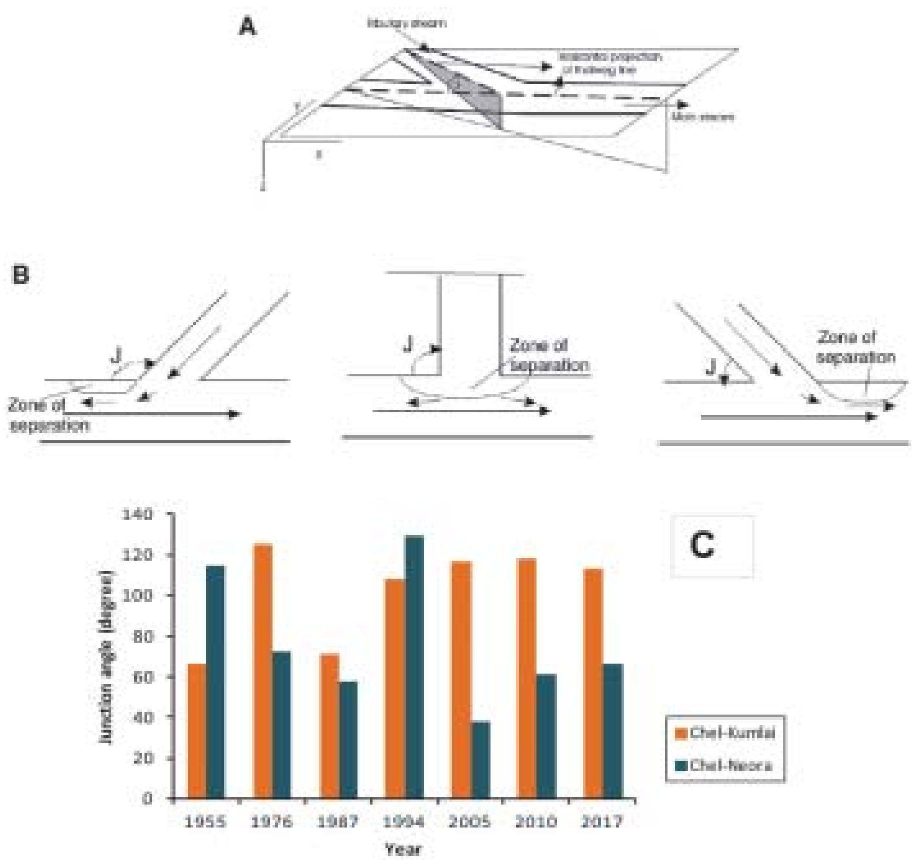

Fig.2 (A) Measurement of junction angle (adapted from Roy and Sinha, 2007). (B) Relation between junction angle and zone of separation; low junction angle favours mouth bar formation immediately downstream of the confluence point (adapted from Roy and Sinha, 2007). (C) Plot showing variation in junction angle for the Chel-Kumlai and Chel-Neora confluences for the period 1955-2017 (computed by the author).

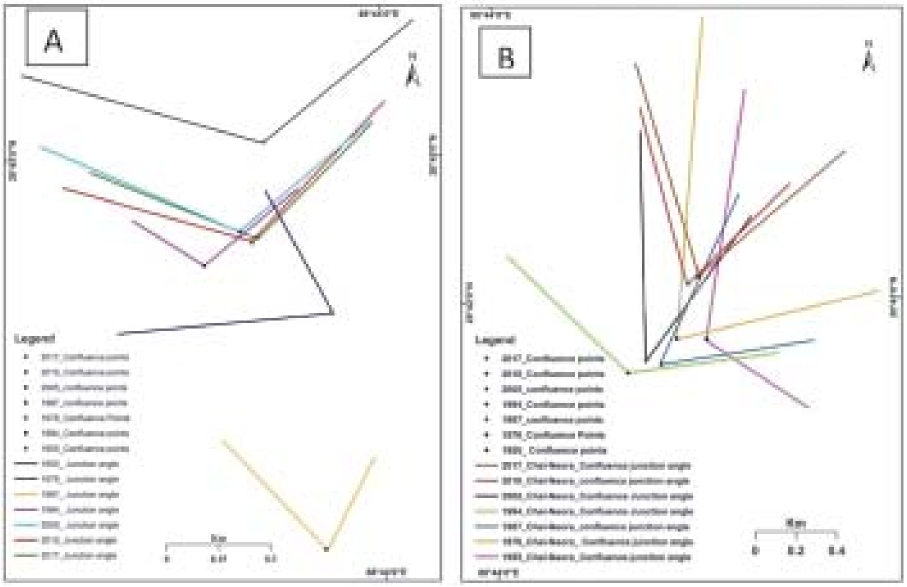

Fig.3 Channel confluence junction angle dynamics of (A) Chel-Kumlai and (B) Chel-Neora rivers during 1955-2017.

upstream by 885 m (A4) (Fig. 4D). It is notable that Kumlai river was almost completely stable during the period. It was due to flow separation of Chel river that a mid-channel bar of size 392 km-^{2} has come into existence. Further there has been a significant increase in the channel width of river Chel from 177.5 m in 1987 to 548.2m in 1994 just upstream of confluence point. Chel river is cutting short the Kumlai river and flow through its course but at the same time the secondary channels of the Chel river still flow through its earlier course. During the same period the Chel avulsed occupying pre-existing flow course seen during 1976 thereby shifting westward and restricting its flow towards the right bank downstream of Kranti and almost

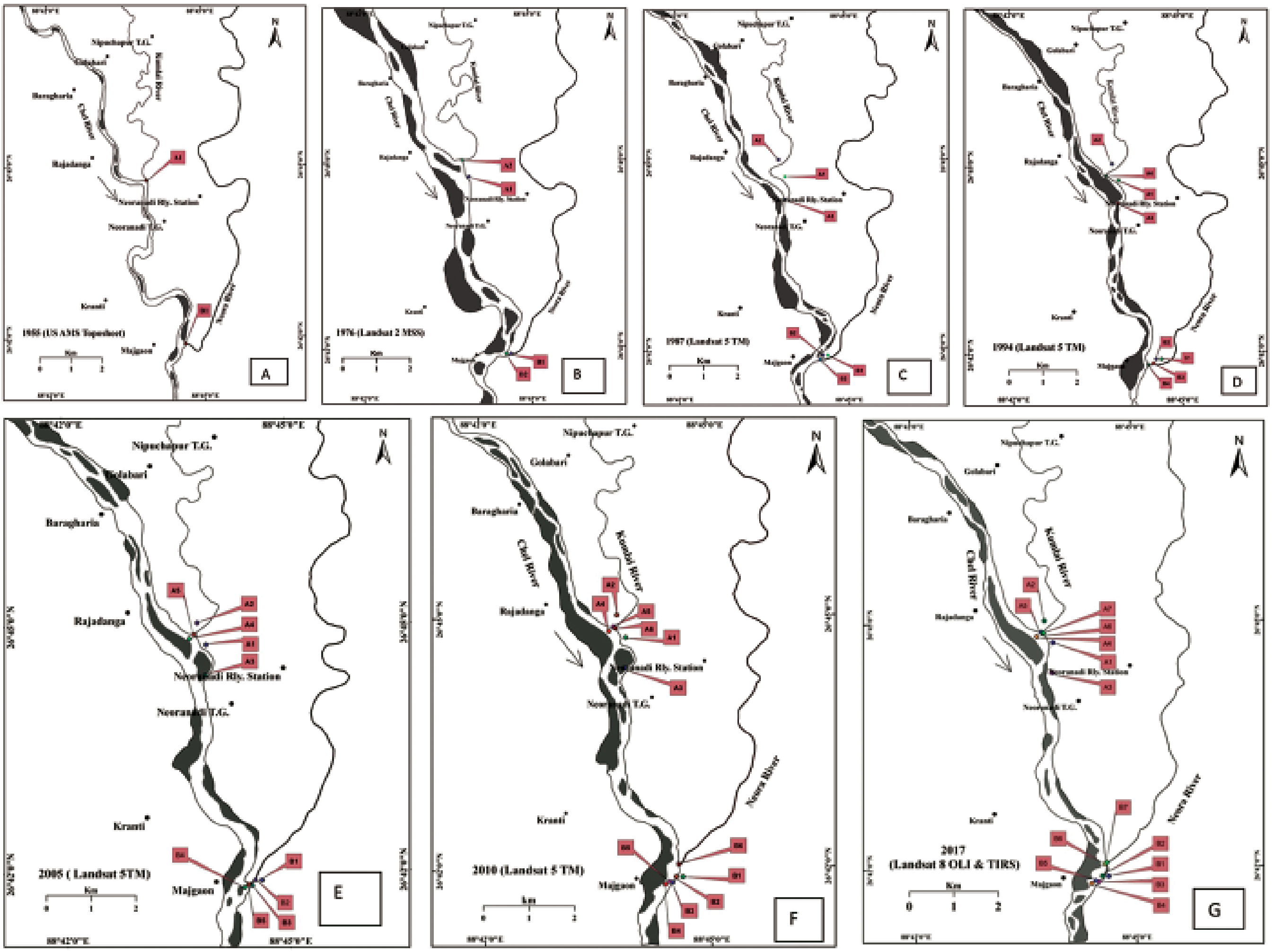

Fig.4. Temporal Channel configuration maps showing location of confluence points of Chel-Kumlai and Chel-Neora. Note: Chel-Kumlai confluence points are represented by A1-A7 and Chel-Neora confluence points are represented by B1-B7.

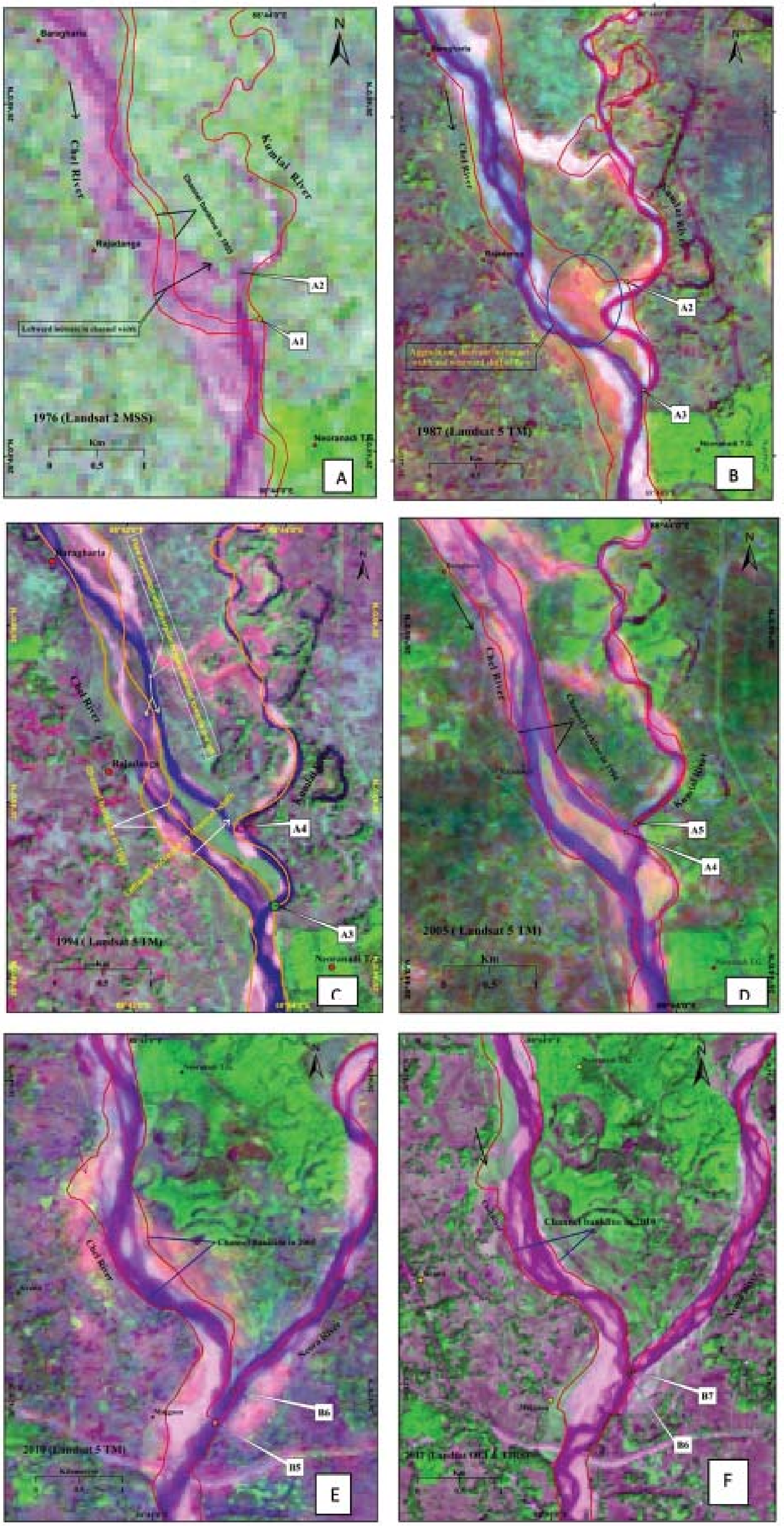

Fig.5 Enlarged representation of channel confluence points dynamics between the Chel-Neora rivers during the period 1955-2017 and probable reasons.

reach up to village Majgaon. Whereas Neora river is stable during this whole time period. This local avulsion of Chel seems responsible for the downward shift of confluence point from B3 to B4 by 168.13 m (A4). By the year 2005 the Chel-Kumlai confluence point experience further upstream movement from A4 to A5 by 158m. This upstream movement of confluence point can be attributed to the increase in the size of mid-channel bar developed during 1987-1994 and further leftward movement of main flow of Chel. Downstream, the Chel-Neora confluence point also exhibits an upstream movement from B4 to B5 by 110m (4E). The straightening and westward movement of Neora river decreasing the junction angle is responsible for the same. The flow separation that was observed since 1994 at a distance of around 900m upstream of Rajadanga and was present during 2005 window has been transformed into a single flow and significantly the flow is restricted to the left bank of the Chel river in 2010 window. The confluence point has shifted downstream from A5 to A6 by 55.27m (4F). The Chel-Neora confluence point moves 431.82 m upstream from B5 to B6 during 2005-2010 due to eastward movement of river Chel forced by the increment in the size of point bar east of Majgaon. The period during 2010-2017, exhibits upstream movement of Chel-Kumlai confluence by 22 m due to little eastward movement of river Chel. During the same period Chel-Neora confluence moved upstream from B6 to B7 by 66m (Fig.4G).

5. Discussion

Table 3 and Figs.5 and 6 summarize the confluence dynamics of the lower Chel river system and probable fluvial mechanisms behind such movements. Note worthily, there are a few points that emerge from the study. Firstly, there has been a net upstream shifting of both the confluence points (~310.62m for Chel-Kumlai confluence and ~318.81m for Chel-Neora confluence), there is no definite trend of movement. The movement of confluence points was variable in different direction and movement rate was also variable. Secondly, various fluvial processes have caused such

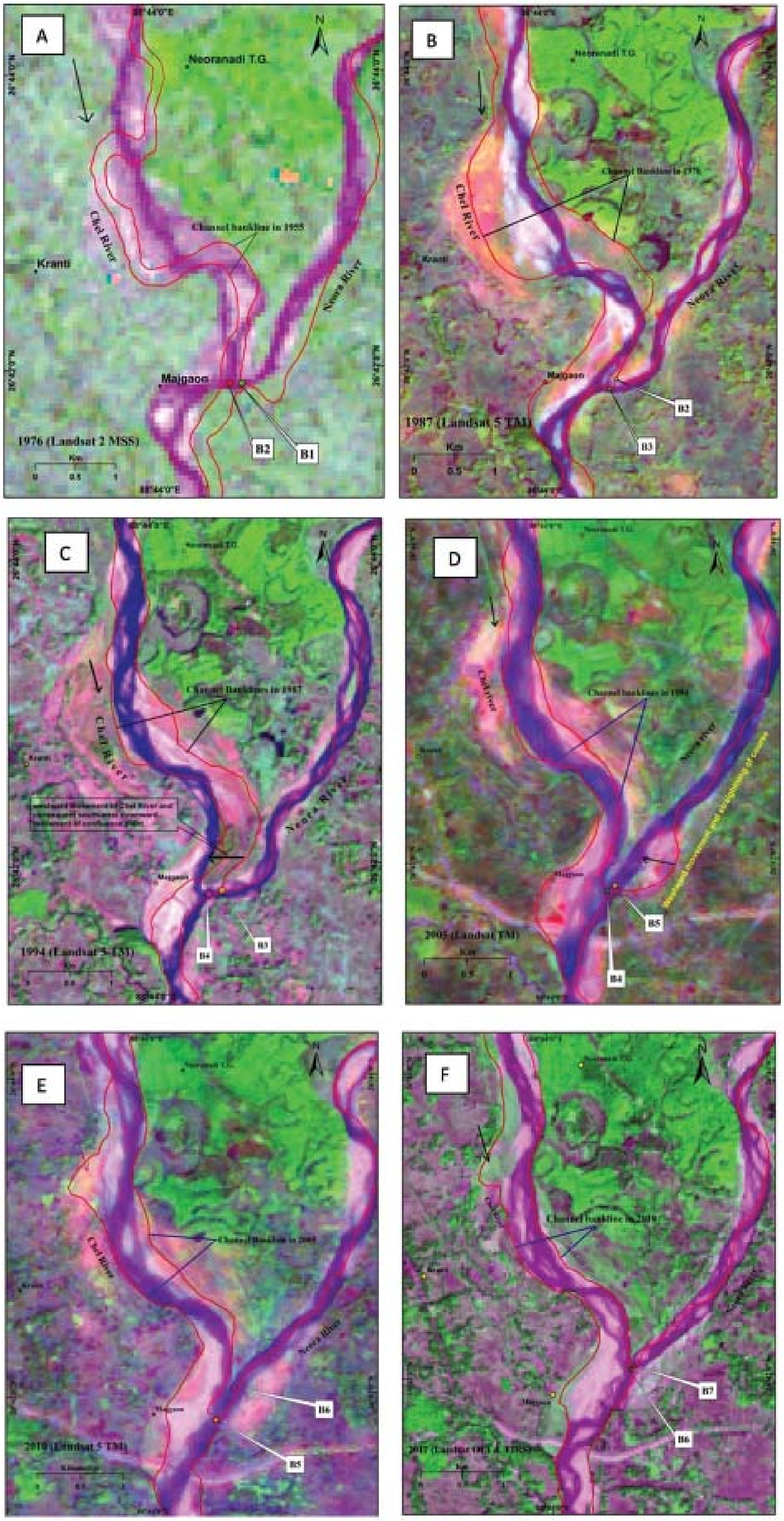

Fig.6. Enlarged representations of channel confluence point dynamics between the Chel-Neora rivers during the period 1955-2017 and probable reasons.

confluence movements, viz. avulsion, river capture, aggradations, variable junction angle. Lastly, there are significant morphological alterations in the lower Chel system during the assessment period which seems to correspond with the confluence dynamics.

5.1 Avulsions

Avulsion is defined as the sudden and abrupt change in a river course. Floods during the rainy season is often related to the triggering of avulsions (Jones and Schumm, 1999; Jain and Sinha, 2003, 2004; Leir et al., 2005; Mitra et al., 2005). Hydrological variability (mainly flood magnitude), lateral erosion and local aggradations also serve as the triggering factors for avulsion of a channel into nearby channel (Roy and Sinha, 2007). In the study area, the Chel-Neora confluence point move downstream from B3 to B4 by168.13m during 1987-1994 (Table 3). Chel avulsed occupying pre-existing flow course seen during 1976 thereby shifting westward and restricting its flow towards the right bank downstream of Kranti and almost reach up to village Majgaon. Neora river is stable during this time period (Fig.6C). Rivers of sub-Himalayan North Bengal shows large variability in flood magnitude, thereby triggering channel instability and causing channel avulsion. So hydrological readjustment can be attributed to the main factor behind the movement. The Chel basin exhibits a classic example of a basin straddle in the zone of transition between the dissected upper hill surface and the lower gently rolling plains (Lama and Maiti, 2019), which favours large scale aggradations, rise in valley floor and consequent channel migration mostly through avulsion during floods. Low stream power, gentle gradient, high sediment yield and proximal positions of rivers are likely to cause avulsions and hence the movement of confluence points. Further entire basin southward falls within a distance of 50km from the mountain front, so role of tectonics in triggering such avulsions cannot be ruled out. Results on avulsion mechanism in the study area is consistent with the studies on eastern Ganga plains (Jain and Sinha,2003, 2004; Sinha et al.,2005) and lower Jaldhaka-Diana

Table 3: Summary of spatio-temporal channel confluence dyanamics, probable reasons and morphological implications

Period	Direction of confluence movement	Total shift	Causative process	Morphological changes	Remarks
	Chel-Kumlai confluence				
1955-1976	Upstream in Northern direction	A1-A2 (~531m)	Width increment of river Chel and capuring of lower course of Kumlai	P decreased from 1.37 to 1.2 and B incresed from 1 to 1.66 for Chel. P increased from 1.59 to 1.77 and B remained unchanged at 1 for Kumlai; J increases.	Net movemet of Chel-Kumlai cofluence (A1-A7) is 310.62m in N-W direction.
1976-1987	Downstream in Southerly direction	A2-A3(~ 1192 m)	Aggradation, width reduction and westward movement of Chel	P decreases from 1.2to 1.19 and B decreases from 1.66 to 1.36 for Chel. P decreases from 1.77 to 1.44 and B remained unchanged at 1 for Kumlai; J decreases.	
1987-1994	Upstream in N-W direction	A3-A4(~904.34 m)	Flow separation ,diversion of main flow of Chel towards the left bank and river capture	P decreases from 1.19to 1.18 and B increases from 1.36 to 1.53 for Chel. P increases from 1.44 to 1.53 and B remained unchanged at 1 for Kumlai; J increases.	
1994-2005	Upstream in N-E direction	A4-A5(~158 m)	Little increment in channel width of river Chel	P decreases from 1.18to 1.11 and B increases from 1.53 to 1.57 for Chel. P remains stable at 1.53 and B remained unchanged at 1 for Kumlai; J increases.	There is no definite trend of the confluence dynamics.
2005-2010	Downstream in S-E direction	A5-A6 (~55.27 m)	Little Westward movement of river Chel	P increases from 1.11to 1.18 and B decreases from 1.57 to 1.53 for Chel. P increases from 1.53 to 1.58 and B remained unchanged at 1 for Kumlai; J remains unchanged.	
2010-2017	Upstream in N- E direction	A6- A7(~22 m)	Little eastward movement of river Chel	Both P and B remains unchanged at 1.18 and 1.53 respectively for Chel. Both P and B remains unchanged at 1.58 and 1 respectively for Kumlai; J decreases.	
	Chel-Neora confluence				
1955-1976	Westward direction	B1-B2 (~154m)	Westward shift of river Chel	P decreased from 1.5 to 1.31 and B remains unchanged at 1 for Neora; J decreases.	Net movemet of Chel-Kumlai cofluence (B1-B7) is 318.81m in northly direction.
1976-1987	Downstream in S-W direction	B2-B3(~150.46 m)	Aggradation	P increased from 1.31 to 1.43 and B too increases from1 to 1.21 for Neora; J further decreases.	
1987-1994	Downstream in S-W direction	B3-B4(~168.13m)	Local avulsion	P decreased from 1.43 to 1.41 and B too increases from1.21 to 1.4 for Neora; J increases.	
1994-2005	Upstream in N-E direction	B4-B5 (~110m)	Westward movement and straighning of course of Neora before confluence	P decreased from 1.41 to 1.32 and B too decreases from 1.4 to 1.29 for Neora; J decreases.	There is no definite trend of the confluence dynamics.
2005-2010	Upstream in N-E direction	B5-B6(~431.82m)	Little eastward movement of river Chel before confluence and river capture	P decreased from 1.32 to 1.23 and B too decreases from 1.29 to 1.27 for Neora; J increases.	
2010-2017	Upstream in N-E direction	B6-B7(~66m)	Eastward movement of river Chel	P decreased from 1.23 to 1.19 and B too decreases from 1.27 to 1.25 for Neora; J increases.	

river system, Jalpaiguri (Dooars), West Bengal (Chakraborty and Datta, 2013).

5.2 Aggradations

The Chel-Kumlai confluence and Chel-Neora have shifted downstream between 1976-1987 from A2-A3 and B2-B3 respectively (Table 3). These downward movements can be asserted to the mechanism of aggradations in the confluence area. The transition of degradational to aggradational regime around 1980s is well evident in the Landsat images of 1987 in the form of large bars in the confluence area (Fig.5B). An increased sediment budget due to bank erosion in the upstream reaches would encourage aggradations in the confluence area downstream due to reduced velocity and gradient (Roy and Sinha, 2007). The development and increment in the size of bars have pushed the primary channels of Chel, Kumlai and Neora farther from each other in the confluence area and thus the confluence points have moved downstream (Figs.5B and 6B).

Alterations in the degradational and aggradational regimes in a selected reach over time in a large river system such as Ganga is much likely the response to fluctuations in monsoonal strength (Gibling et al., 2005). Such fluctuations would therefore move the confluence point upstream and downstream in a major way on a longer time scale (Roy and Sinha, 2007). Few studies have documented the systematic upstream migration of major confluence points in the Ganga plain due to increased accretion of rivers in response to increased erosion in the Himalayan catchments and base level changes due to sea-level fluctuations during late Pleistocene-Holocene (Tangri, 1986; Singh, 1987). Few workers have attributed role of tectonic tilting in channel shifts in the Ganga plain, probably during early Holocene (Mitra et al., 2005). The principal cause of aggradations around the confluence area in the study area is hydrological changes induced by the fluctuations in amount of monsoonal rains and large scale erosion in the catchment area due to clearing of natural forests for making way for tea and beetle nut plantations seems most likely among all possible causes.

5.3 River capture

River capture is essentially caused by local base level difference between two channels which in turn controls the erosion potential. The captured river has a higher base level and lower erosion potential whereas the predatory stream has a lower base level and higher erosion potential (Roy and Sinha, 2007). The predatory river captures the lower reaches of another river and results in the upstream movement of the confluence point. River capturing is an important fluvial mechanism by which river enlarges its drainage network and thereby significantly alters the landscape evolution. It also impacts the distribution of discharge and sediment within and among the drainage basin in a very significant way. Mather, 2000 have documented the transfer of ~15% of water and sediment budget due to river capture in Sorbas basin of SE Spain during Plio-Pliestocene period. While most of the river capture has been reported from the tectonically active mountain river basins (Brookfiled, 1998; Mather, 2000; Mather et al., 2000), a few reported examples from Ganga plains can be cited here. The capturing of lower reaches of Bhakla river by Rapti river during avulsion which left upper reach of Bhakla river left as misfit channel (Richards et al., 1993). The capturing of lower part of Garra river by Ganga river during 1990 and 2000 and consequent upstream movement of confluence point by ~7.5km has been well described (Roy and Sinha, 2007). Documented events of river capture in the alluvial plains of Dooars region of sub-Himalayan West Bengal is almost non-existent. The only instance is the capturing of lower reach of Diana river by Jaldhaka river during 1970-1990 thereby shifting the confluence point upstream by 11 km (Chakraborty and Datta, 2013; Chakraborty and Mukhopadhyay, 2014). For the present study of Chel basin, the instance of river capture of very local nature is observed twice for Chel and Kumlai rivers. During the period 1955-1976, the channel width of Chel increases manifold eastwards coupled with eastward shifting of main flow. This led to the complete plantation of earlier interfluves area and thereby Chel captured the lower reach of Kumlai river which led to upstream movement of confluence point by ~531m (Fig.5A and Table 3). Period 1976-1987 witnessed major accretion near the confluence point which pushed the two rivers farther and consequently the confluence points moved downstream. But during 1987-1994, a flow separation develops above Rajadanga and the eastern flow avulse through the accretion area developed during 1976-1987 and captures the lower Kumlai, thereby shifting the confluence point upstream by 4 904.34m (Fig.5C and Table 3).

5.4 Stream junction angle

The junction angle between the main stream (M) and tributary stream (T) depends on their relative gradient (S_M/S_T) (Horton, 1970; Howard, 1971). A wide junction angle indicates a higher slope of the tributary stream relative to the main stream and a low angle indicates nearly equal slopes (Roy and Sinha, 2007). Therefore the confluences with wider junction angles are more dynamic and are likely to erode, migrate, avulse and create flooding. In contrary to this the confluences with lower junction angles would be more stable. Any change in the junction angle would therefore is much likely to manifest itself through channel stability and or channel dynamism (Roy and Sinha, 2007). Measurements of junction angles for both Chel-Kumlai and Chel-Neora show that the angles have been significantly variable during the assessment period. Computed junction angle values for Chel-Kumlai were much variable compared to the Chel-Neora junction angle (Table 2). This is manifested in terms of the fact that the amount of confluence points shifts for Chel-Neora has been recorded much larger than the Chel-Neora confluence.

At the Chel-Kumlai confluence, the junction angle shows a very sharp increase during 1955-1976, then a steep decrease during 1976-1987 and then again followed by a period of sharp increase during 1987-1994. After 1994 the junction angles remained almost stable between 100 to 120 degrees. This indicates that the slope ratio (S_M/S_T) must have increased manifold during 1955-1976 and 1987-1994 which facilitated to erode its banks and capturing of the lower reaches of the Kumlai river thereby moving the confluence points upstream (Fig.5A and 5C). The decrease in slope ratio (S_M/S_T) during 1976-1987 as evident from the low junction angle indicates that the relative slope of Kumlai (tributary) has decreased with respect to that of the Chel (main stream) and this encouraged deposition of sediments in the confluence area resulting in bar formation thereby downward shifting of confluence points.

For the Chel-Neora confluence, a moderate level increase in junction angle is witnessed during 2005-2010 (Table2). It seems, this mild increase in junction angle have increased the slope ratio (S_M/S_T) during the period which allowed the Chel to widen its width by eastward erosion thereby capturing the lower reach and shortening the Neora river. Consequently the confluence point has migrated upstream by ~431.82m during this period (Table 3 and 6E).

6. Major findings

The present study exhibits well that the two major confluence points of lower Chel system namely, Chel-Kumlai and Chel-Neora were dynamic and moved both upstream and downstream during the assessment period spanning 62 years. Some of the movements were massive but some years confluences also recorded almost nil movements. Both confluence points have registered net upstream movement by 310.62m and ~318.81m for Chel-Kumlai and Chel-Neora respectively.

Inspite of being in close vicinity, the two confluence points recorded variable amount of movement. Chel-Kumlai confluence point was more dynamic than the Chel-Neora confluence during the six inter-phases of assessment period. There seems no particular trend in the confluence dynamics for both confluence points.

There are several processes responsible of these confluence movements viz. avulsion, cut-offs, river capture

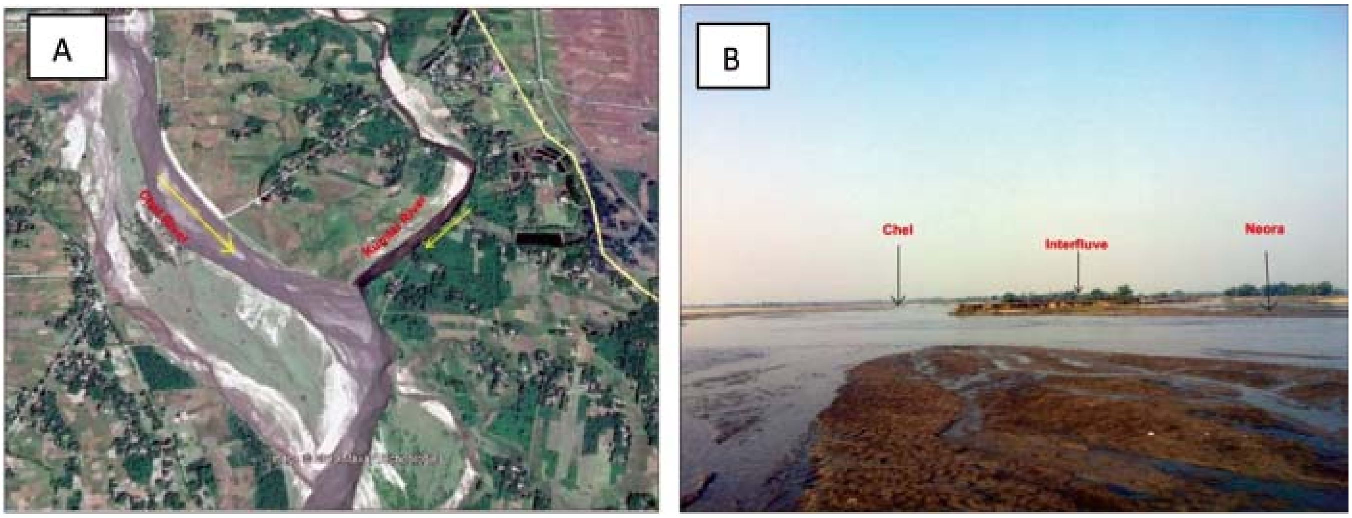

Fig.7 (A) Google Earth Image (12.05.2017) showing confluence of Chel and Kumlai Rivers near Rajadanga.. (B) Confluence of Chel-Neora, near Majgaon during January, 2014.

and aggradations. We observed that river capture has moved the confluence point upstream whereas aggradations resulted in downstream shifting of confluence point. The avulsion mechanism is responsible for both upstream and downstream movement.

Hydrological variability in terms of flood magnitude seems to be the important factor triggering avulsions. The fluctuation in the monsoonal strength can likely be seen as reason for hydrological variability which alters degradation and aggradations regimes in the study area as described by Gibling et al., 2005 for Ganga river system.

North Bengal rivers are significantly influenced by structural and tectonic controls too. So the role of tectonics in confluence dynamics of study area cannot be ruled out.

Junction angle also play an important role in confluence dynamics. Measurements of confluence junction angles shows that sharp decrease in junction angle encouraged aggradations near the confluence resulting in bar development thereby moving the confluence downstream. Whereas the sharp increase in junction angle increased instability and moved the confluence point upstream mostly through river capture and avulsion.

There are significant morphological changes in terms of sinuosity, braiding intensity and channel width in the rivers during the assessment period which correspond to the confluence movements.

The study suffers from limitations in assessing the overall channel confluence dynamics scenario of the region due to lack and limitation of relevant data which is common across the Dooars region. Being a border region, Survey of India topographical maps covering the area also are restricted in use and not available in public domain. The SOI toposheet covering Neora river 78 B/13 could not be assessed for the same reason. The two CWC gauging stations, located along NH-31C road bridge on Chel river at Odlabari and Diana river at Red Bank tea garden records only the gauge height and therefore quality long historical data relating to daily precipitation, discharge, sediment load and flood history could not be procured relating to selected rivers for this study. Nonetheless the present study has attempted to provide insight into the channel confluence scenario of the region along with its probable causes and morphological implications. The study leaves a scope for further in-depth studies on the subject incorporating hydrological and tectonic factors in the future which will certainly give much deeper insight to disentangle the cause and effect relations of channel confluence dynamics in a tectonically active piedmont region.

Conclusions

Channel confluence dynamics is the manifestation of dynamism of main channel along with its tributaries induced by multiple factors. Thus an attempt was made to reconstruct the historical channel confluence dynamics in the lower Chel-Neora river system to understand the trend of confluence dynamics and probable factors driving such movements. The study found that there was large variability in the amount of confluence dynamics in the region during the entire study period. The confluence point movements have been erratic without displaying any specific trend. Aggradations, avulsions and river capture processes were found to be the major factors behind the confluence dynamics. Further study coupled with tectonics and long term hydrological data can give deeper insight into the mechanism and causative factors of confluence dynamics of the region.

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CONTINGENCY ANALYSIS OF A 10-BUS POWER SYSTEM USING POWER WORLD SIMULATOR

(Continued from page 85)

The standard load flow methods like Newton-Raphson model, DC model etc, are the important tools to evaluate the contingency analysis and helps the operators, in advance, to locate the defensive operating state to combat the line overloads and/or voltage violations. Contingency ranking helps the severity of the outages and this is done by the sensitivity factors. The sensitivity factor, LODF, have been addressed here. The authors have used Power World simulator in their study. Power World simulator is designed to evaluate all these analyses on a power system network.

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