

Causes and Consequences of Channel Changes – A Spatio-Temporal Analysis Using Remote Sensing and Gis— Jaldhaka-Diana River System (Lower Course),

Jalpaiguri (Duars), West Bengal, India

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Abstract:

Channel changes with respect to time and space play a significant role in stream flow dynamics. The rambling and trailing of channels in the studied region has been studied through systematic analysis and interpretation of diverse channel configuration and multi-channel orientation using multi-temporal Topographical maps and Satellite images for a period spanning nearly 80 years (1930–2011). For this specific purpose **lower course of Diana River** in the **Jaldhaka-Diana river system** has been selected in the Duars region of the Jalpaiguri district, West Bengal which is virtually a zone of transition between the Himalayan Mountains and the North Bengal plain. **The prime objective of the study** is to reveal the spatio-temporal sequences of channel changes, consequent movement of confluence point and the factors and causes of such movement. **For this particular extraction,** Base map has been generated with the help of SOI Topographical maps and satellite images of the respective area. For this purpose updated version of ERDAS Imaging is employed as image processing tool for enhancing, merging and to update the spatial information of channel configuration and **Arc GIS for** final product generation. **Following the specific objective of the study** it has been deduced that during this span the confluence point has moved and re-oriented both upstream and downstream on a historical time scale and new confluence points have been created by repeated shifting and migration of channels. No definite trend is observed in the movement of the confluence points. However, but it is noticed that some distinct flow dynamics and channel maintaining processes are actively performing in this spatio-temporal analysis of channel changes.

Keywords: Morphogenetic complex, Multi-channel system, Confluence Dynamics, Channel avulsion, Channel shifting, Erosion-accretion process

1. Introduction:

This pain staking investigation and observation presenting an interactive as well as analytical interpretation on hydro-geomorphology and flow behaviour of the lower course of Diana river in the ***Jaldhaka-Diana confluence zone*** of Jalpaiguri, West Bengal, India based on multi-temporal analysis of remote sensing images and maps with a view to understand the landscape development and confluence dynamics. Channel confluences especially for the rivers with high to very high seasonal discharge (both water and sediment), marked variation in altitude and a sudden fall of slope from mountain to plain course form an important component of the river systems as they influence the morphology and hydrology of the reaches upstream and downstream of the confluence. The dynamics of the confluence points affects the availability of water in different reaches and the pattern of sediment dispersal around the confluence zone. A major engineering implication of such movements is in terms of scouring or aggradation which poses serious river management problems. River confluences are sites of fluvial systems with complex hydraulic interactions provided by the integration of two different flows and may be of purely different in character and flow pattern. They constitute an environment of competition, co-action and interaction of flow pattern.

1.1. Review of relevant literature:

River confluences have received very little attention from geomorphologists although some very interesting work have been carried out in terms of flow separation and hydraulic geometry (Best and Reid, 1984; Best, 1986, 1987, 1988) and facies models (Bristow et al., 1993). *In the local field* a very little attention has been given about this subject excepting one or two with a broad outlook. In national and international perspectives, especially in the Ganga plains, the dynamics of the individual channels has received a very wide attention, most notably the migration of the Kosi river ***(Geddes, 1960; Gole and Chitale, 1966; Arogyaswamy, 1971;Wells and Dorr, 1987; Agarwal and Bhoj, 1992),*** the decadal-scale 'hyperavulsive' Baghmati system *(Sinha, 1996; Jain and Sinha, 2003, 2004),* and a few other studies in the western Ganga plains *(Richards et al., 1993; Mitra et al., 2005).* However, the studies on river confluences even in the Ganga plains are surprisingly very limited *(Tangri, 1986; Roy and Sinha, 2005, 2007).* Our knowledge of the present-day environment of the margin of the Sikkimese and Bhutanese Himalaya and their piedmont zone in North Bengal between the Tista and Jainti rivers is mainly general and fragmentary. Some attention has been paid to floods and aggradations on alluvial fans in Duars, due to these damaging railway and road bridges and tea gardens. Among these works a very valuable item is the paper by Dutt (1966), presenting the first data on annual records of river discharges and sediment loads in the Lish, Gish and Neora rivers. *In the 1980s geomorphologists from North Bengal University* studied landslides and alluvial fans in the catchments of two left-bank tributaries of the Tista, called the Lish and Gish (Basu, Ghatowar 1986, 1988, 1990; Basu, Ghosh 1993). *Geologists from the Geological Survey of India* published a general sketch of the margin of the piedmont zone, and later surveyed the Quaternary sediments of the Himalayan foreland in West Bengal to distinguish several formations in the piedmont zone *(Chattopadhyay, Das 1992; Das, Chattopadhyay 1993).* At the end of the 20th century, more attention began to be paid to the interactive fluvial activity of various piedmont rivers east of the Tista. A preliminary concept was devised as regards the great role played by clusters of floods much higher than in Darjeeling Himalaya in the transformation of this part of the piedmont zone (Starkel, Sarkar 2002; Starkel 2004; Sarkar 2004, Soja, Starkel 2007; Sarkar 2008). In the meantime, Guha et al. (2007) studied the complex of high elevated terraces in the Jaldhaka river catchment. This part of the piedmont differs greatly from neighbouring in the absence of its Siwalik zone and the presence of incised river channels in the uplifted blocks of piedmont. The detailed study by Starkel et al (2008), has attempted to show the role of different factors in the present-day evolution of the Sikkimese-Bhutanese Himalayan piedmont.

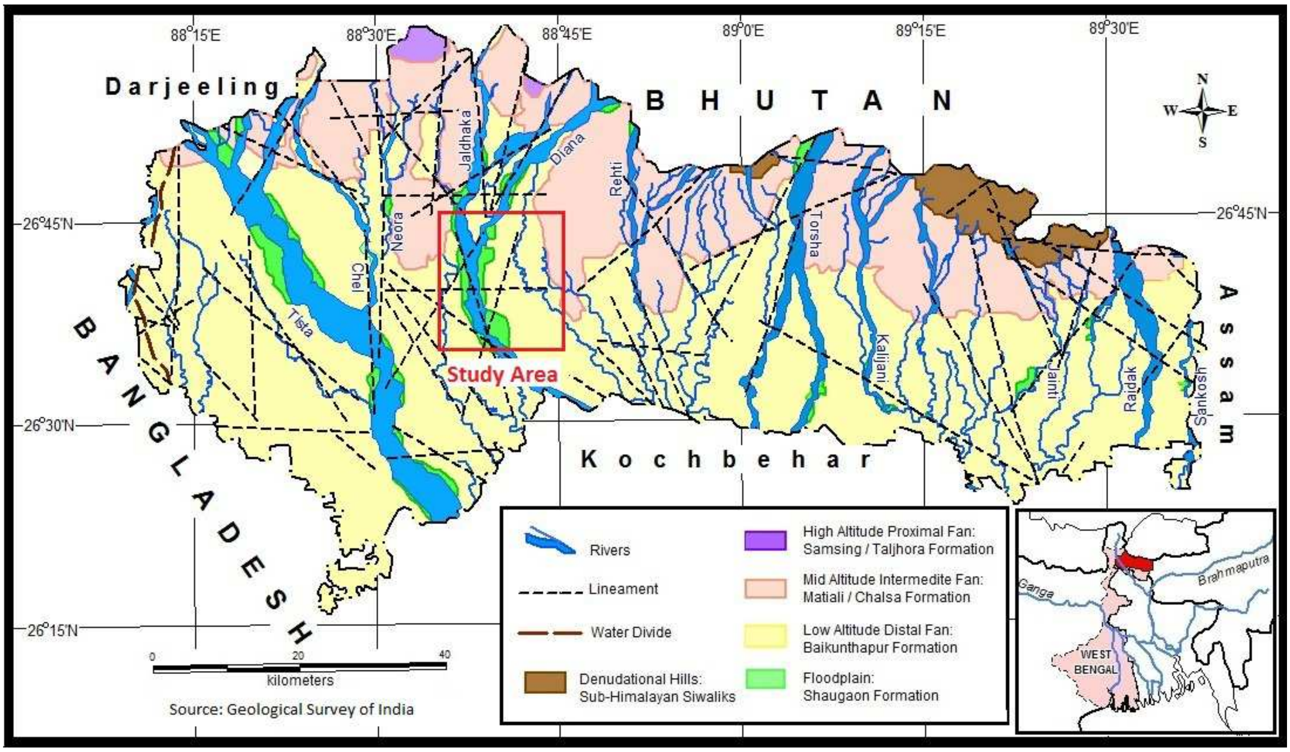
Several studies have shown that the floods often serve as the *triggering mechanism for avulsions* (Jones and Schumm, 1999; Jain and Sinha, 2003, 2004; Leier et al., 2005; Mitra et al., 2005). Moreover most of the classical, large-scale river capture events have been described from tectonically active mountain basins (Brookfield, 1998; Mather, 2000; Mather et al., 2000). In these areas, the capture is triggered by change in regional gradient associated with uplift. There are *very few examples of river capture* in the alluvial plains particularly from the Ganga-Brahmaputra plains. Richards et al. (1993) described the capture of the downstream reaches of the Bhakla by the Rapti River in the Ganga plains; Roy and Sinha (2005, 2007), studied the capture of a part of the Garra River by the Ganga between 1990 and 2000.

2. Study Area:

The area under study for present research presents a number of classical examples of channel changes involved with varied fluvial dynamics. Spatial nominations of cut off, shifting, avulsions, plugging and capturing of main and bifurcating channels are scattered randomly. The area is bounded by ***26°35'N*** to ***26°45'N*** Latitudes and ***88°50'E*** to ***89°0'E*** Longitudes in the district of Jalpaiguri, West Bengal ***(Fig. 1).*** This area represents a zone of transition between the Himalayan Mountains and the Gangetic plains, and displays the typical characteristics of the piedmont fans of the Himalayan foothills. This part of the foothill zone located in the east of Teesta River is known as the ***Duars*** in Darjeeling and Jalpaiguri districts of West Bengal.

The region may be classified into a number of interfluves of numerous rivers with active and abandoned channels which form a part of *the Brahmaputra drainage system*. Due to the foothills situation, as the streams coming from the hills suddenly reach the plain, there is a substantial decrease in velocity due to decrease in channel gradient and subsequent widening of the channel. The transporting capacity of the streams thus decrease enormously and they deposit their load consisting of boulders, pebbles, coarse sand, fine sand, silt and finer silt particles, at the point of the break in slope which finally transformed to *alluvial fans in the study region* . The mountain foreland is built up of alluvial fans and higher elevated terraces ***(Fig. 1).*** 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. The extent of the fans is roughly bounded by the 100 m contour. The alluvial plain with two steps of the floodplain extends to the south down to the Brahmaputra , these being modelled by the lower courses of meandering or braided rivers (in the case of large transient rivers), as well as by many meandering streams starting at the foot of the fans. Due to continuous channel fill deposition, height of the riverbeds increases, causing frequent shifting, anabranching and changing of river courses. In general, the major rivers including Teesta, Jaldhaka and Torsa are shifting from West to East. *The only exception is the shifting of the Diana River from East to West.*

The ***Jaldhaka*** is a trans-boundary river which originates from high mountain fronts in Sikkim and Bhutan Himalayas and flows southward across Bhutan into the Jalpaiguri district of West Bengal. River ***Diana***, the main right bank tributary of the Jaldhaka River, *originates in Samtse province of Bhutan* and flows south-westward into Jalpaiguri to join Jaldhaka near Nathua Hat ***(Fig 8b).*** The morphological expression of the rivers in the alluvial plains is related to their source area; some rivers are either braided (Jaldhaka) or meandering (Rangati, Jhumar) throughout their entire reach, while others show systematic variation from braided to meandering from upstream to downstream reaches. Distinct changes in the pattern of river channels from braided to meandering are noted with changes in river gradient and sediment load. Progressing downstream with changing rainfall regime, decreasing discharge, channel gradient and sediment load, these rivers gradually change their pattern from braided to meandering. The Jaldhaka, drains a large catchment, and is deeply incised in the Duars, where it drains active rising blocks and consequently its fan surface is developing farther downstream. River Diana, dissecting the southern part of the Lesser Himalaya is located in the belt of high precipitation and forms a chain of alluvial fans characterised by both large and small fan areas. Aggradations follow upstream into the hills, while farther downstream the braided channel tends to change into a meandering one. To the south, about 30 km from the Himalayan front, the meandering river channels are accompanied by floodplain, and reach an elevation of about 100 m above sea level. Rivers starting in the middle or lower parts of alluvial fans, like the Rangati ***(Fig 8f)*** and the Jhumar ***(Fig 8d)*** fed mainly by groundwater and supplemented by heavy rain during the monsoons, have a low gradient with successive braiding and meandering pattern, and are accompanied by channel, point



bars and narrow floodplain.

Fig. - 1 - Study Area Complex

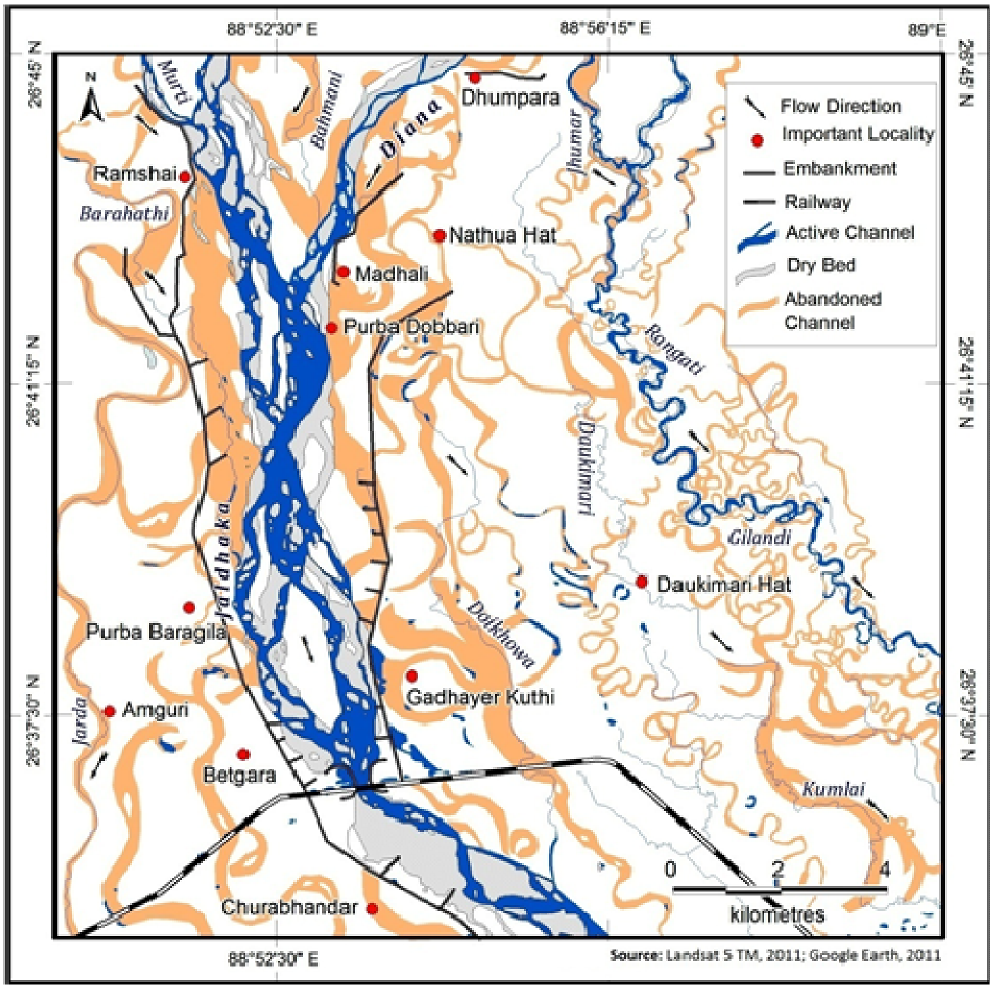


Fig. - 2 - Drainage Composition of the area

2.1 <u>Hydro-Geomorphic Components and Characteristics: aspects of channel changes</u>

Frequent floods in the lower reaches have forced many rivers to ***change their courses*** in the past. Following a disastrous flood in 1787, River Tista which used to flow into the Ganga deserted its channel and emptied itself into the Brahmaputra through a still more ancient channel (Hunter, 1876). Since the flood of 1954, river Jaldhaka was shifting towards East near Tandu Tea Garden in Nagrakata block. The river devastated 10 km (approx) of forest and almost 50% of the Tandu Tea Garden. To prevent the tendency of avulsion of Jaldhaka to river Bamni, an embankment had to be constructed.

From intensive observation, investigation and ground checking incorporated with previous reports it has been assigned that the entire area between *the left bank of Jaldhaka and the river Gilandi* is highly vulnerable to flooding. This assessment has been done on the basis of frequency and magnitude of past floods, nature of drainage conditions and terrain characteristics of the surrounding areas. *The right bank of Jaldhaka* adjacent to Betgara and Purba Baragila and the left bank of Diana near Nahthua Hat are also identified as vulnerable zones. The changing of river course is also due to presence of *structural weakness, instability and sudden change of hill side slope and steep channel gradient etc.* The piedmont zone of Duars has experienced not only the deposition of alluvium, but characterised by lithologic, structural and tectonic control along with *Neo-tectonic activity* where the important structural elements are – a) E-W trending faults and lineaments parallel to the mountain axis, b) Transverse faults trending N-S, NW-SE and NE-SW running across the mountain axis. Geological studies carried out in this region indicate the presence of these faults and lineaments and few amongst these faults and lineaments are proved to be active in geologically recent times while a few others are presumed to be active ***(Fig 1).*** Thus the neo-tectonic network of transverse and parallel faults and lineaments parallel to the Himalayan axis are considered to be major contributing factors to the instability of this region. Any movement or adjustment along these structural elements will have an effect on river morphology and channel changes of the area. Eroded materials from uplifted parts are deposited in the down faulted depressions leading to aggradations and shifting of rivers. Thus a very high mean annual rainfall in this region along with the above factors is also one of the primary causes of flood in this region over the ages. Tectonic activity is still expressed in the network of river channels where junctions of streams follow latitudinal fault lines as with the lower courses of rivers Jaldhaka and Diana. This is very well manifested in the southward flowing Jaldhaka bending sharply towards south-east near Betgara. The almost right angular bends of Rangati and Gilandi near Daukimari Hat are also revealing marked tectonic control ***(Fig.1, Fig.2).*** Streams are often incised up to 3–5 meters as in the case of Jarda and Barahathi nadi which indicates their association with uprising blocks.

Reasons for high frequency of floods in the lower piedmont plains of the region are ***excessive and continuous rainfall*** of several days in the catchment areas of the rivers and simultaneous melting of snow accumulated on high mountain peaks. The Duars is among the rainiest parts at the Himalayan margin and It has a normal seasonal distribution of rainfall, with 80–90% concentrated in the rainy season and a slight to meagre rain during the winter (0–50 mm). Mean annual rainfall fluctuates between 3000 and 6000 mm and the highest totals occurring close to the steep front of the Lesser Himalaya. Clustering of heavy and continuous rain, noted either in every year or at 1–3 year intervals, is a very important factor from the geomorphologic point of view. Sudden ***bursting of artificial embankments*** on the rivers may also cause floods in the region, so, s***oil erosion*** is also remarkable in the catchment area of the rivers due to high deforestation and unscientific cultivation on the hill slopes. The silts and debris's thus, collected, are carried by the rivers from the hills and simultaneously are deposited on their riverbeds. Thus, gradual rise of riverbeds results a severe bank erosion, channel degradation, and diversion with marked changes of channel pattern. Numerous paleo-channels, valley fills and aggradational channels have thus been formed in the study areas which are now occasionally used as spilled channels and usually marked as abandoned channels (***Fig.-2, Fig 8g).*** The marked water level fluctuation of Jaldhaka and Diana clearly reveals the flow characteristics and subsequent fluvial dynamics in relation to flood level situation in the study region.

3. Materials and Methods:

For systematic study, analysis and interpretation of the present problem varied specification of spatio-temporal data are used involving maps, images and flow behaviour data of the respective river are used. Temporal variation of channel position along with channel bed and banks as well as confluence points were analyzed for the last eighty years using three different periods of *SOI Topographical Maps* and several repetitive Satellite Images with specific enhancement and merging of the same.

Three sets of Topographical Maps for the studied area were collected from The Survey of India for the years *1929–30(1:63 360), 1964–65 and 1969-70(1:50 000).* These maps have shown relief by reference to contours either of 50 or 100 feet (in 1930) or 20 meters (in 1964–65), and delineating the river channels with meandering, braiding and bank relief.

Table-1: Nature of data with respective date and resolution

Nature and types of Data	***Acquired date***	***Resolution***
SOI-Topographical Maps	*1929-30, 1964-65, 1969-70*	*1:63,360,1:50,000*
Landsat TM	*1990*	*30m*
Landsat ETM	*2001*	*30m*
Landsat TM	*2011*	*30m*
Google Earth (Geo Eye)	*2011*	*With Zoom, 10m*

***Table shows the nature of data used for the specific study*

The satellite images in digital format for the whole area between 1991 and 2011 from *Landsat 5 TM* (spatial resolution 30 m) and *Landsat 7 ETM$^+$ (spatial resolution 15 m)* have been analysed to compare changes after the several great floods occurring during the recent times. *Landsat 7 ETM$^+$* has been used after merging the panchromatic image with 15m resolution and further enhanced and compared with Topographical maps of previous periods. This enhanced image of fine resolution gave the better view of channel changes and subsequent geomorphic implication. There has been further supplementation in the form of satellite imagery from *Google Earth (Geo Eye,* 2011***)***.

Merging with high resolution Image is carried on for better mapping and presentation. All temporal data were registered carefully in *Remote Sensing environment involving ERDAS Imagine software and further processing has been carried on for product generation to the GIS Environment involving Arc GIS software*. Finally, after careful processing of *rectification, enhancement and edge matching technology,* spatio-temporal shifts of confluence points were extracted and mapped in the GIS environment.

4. Results and Discussions:

Based on the extraction and analysis from different maps and images various aspects of fluvial dynamics in the lower course especially regarding the confluence zone movement have been processed. A systematic description of Confluence Dynamics for the time period from 1930-2011is presented in the following section followed by the processes involved in the shifting of the Jaldhaka-Diana confluence point.

4.1 Fluvial Dynamics of Confluence Shift:

A detailed analysis has been undertaken on the fluvial dynamics of confluence shift at the confluence zone of Jaldhaka-Diana which is markedly noted as ***'belt of confluence shift'*** (Fig.- 6) and resultant mapping clearly reflects that the area has undergone significant channel shifting, bifurcating and avulsion, i.e., especially confluence point is randomly scattering and channel pattern shows highly intricating. There have been significant departures in channel plan form regarding channel geometry, position of channels and the exact location of the Jaldhaka-Diana confluence over the considerable period of time (Fig. 4). The shifting belt of confluence point and present-day channel belt of the Jaldhaka and Diana are distinctly braided, but the older courses of Diana (Rangati, Jhumur etc.) reveal significant sinuous pattern particularly in lower-middle reaches **(Fig.3; 1930,'65).** Apart from the active channels the area is characterized by threads of abandoned channels, ox-bow lakes, channels with stagnant water, swamps, meander scars etc. which are easily recognizable on satellite images with their *characteristic form and spectral signatures*.

The drainage map of **1930** (Fig.3) represents a very complicated drainage network where at the junction with the Diana, the braided Jaldhaka displayed 200–500 m wide, with a 1‰ gradient and manifesting a tendency towards meandering. Further downstream near Betgara, it forms a complicated channel pattern of meandering and braiding with maximum width of almost 1 km. A flood protecting embankment along right bank of Jaldhaka has been constructed to protect the villages like Betgara and Churabhandar which is also a yard-stick for channel changes in this area. The confluence of Diana and Jaldhaka is indicated by the *point C1*. Jarda, Barahathi nadi, Bahmani, Singrimari and Doikhowa are some noted left and right bank channels along with several threads of old abandoned channels are either underfit or overfit and might be the remnants of pre-existing courses**.**

By **1965** *(Fig. 3), the Diana-Jaldhaka confluence* has shifted by about 1.5 km in a downstream direction from *C1 to C2*. The apparent cause of this shift is the westward avulsion of the Jaldhaka through the reactivation of a pre-existing channel. There is significant widening of the Jaldhaka especially in the stretch between Ramshai and Purba Baragila, where the width reaches about 1.5 km. with distinctly bifurcation. The much narrower left bank channel roughly follows the 1930s path and joins Diana. To protect the villages along the right bank, the embankment has been extended up to Purba Baragila and such embankments have also been constructed to protect the town of Ramshai against encroachment by the river and to prevent avulsion of Jaldhaka into the Barahathi nala. Along the Left bank of Jaldhaka, another embankment is under construction near Gadhayer Kuthi to check the left-lateral shifting. Another notable change has been identified due to the construction of a Railway bridge across the area. The narrow railway bridge spanning the river as well as the supporting pillars considered to be barriers to the natural flow of water, interrupting the natural load movement behaviour. This has caused extreme drainage congestion, heavy siltation on the upstream side of the structure, followed by bank erosion and widening of the river bed. The Diana River during this time has maintained its meandering channel except for a sudden widening near Nathua Hat where the channel is 900 m wide. The Dhumpara embankment was also constructed during this period and the resultant flow diversion caused by this embankment has probably led to the cut-off of the meander north of Dhumpara. During 1956, Diana avulsed through the rivulets Jhumar and Rangati just south of Kalabari Tea Garden, devastating about a 100 sq. km (approx) area. Due to this the original course of river Jhumur was abandoned and it now became a tributary of river Rangati. By constructing an embankment at Kalabari, the course of Diana was thrown back to its own. But this river has a tendency to avulse to river Rangati.

*In **1970**, the resultant extraction (Fig.4)* represents the scenario after the major flood which affected Jalpaiguri in 1968. The Diana-Jaldhaka confluence has shifted further downstream by about 3 km from *C2 to C3*. This has been caused due to aggradations in the confluence area resulting from increased sediment load during the flood. North of Ramshai, the Barahathi nadi has been diverted into Jaldhaka, in the process of channel derangement which seems to be controlled by the embankment. The left bank embankment along Jaldhaka has been extended further north almost up to Nathua Hat which led to the marked disintegration of the Sigrimari and the Doikhowa channel systems by cutting off their water courses.

*The drainage network of **1990** (Fig.4) shows* a remarkable shift in the Diana-Jaldhaka confluence point by about 11 km upstream from C3 to C4. This is a result of an eastward avulsion of the Jaldhaka main channel, thus capturing the lowermost stretch of Diana, causing the confluence to move upstream. The avulsion occurred through reactivation of the channels between Jaldhaka and Diana, including the lowermost stretches of Bahmani. An interesting outcome of this major avulsion was that the villages of Madhali and Purba Dobbari, which used to be situated along the right bank of Diana, now came to be situated on the left bank of Jaldhaka. The *likely cause of this eastward shift* is the construction of deflecting spurs along the right bank of Jaldhaka. The abandoned bed of Jaldhaka along Ramshai is now occupied by the river Murti, whose confluence point with Jaldhaka has moved several km. downstream. Murti has now captured the upper reaches of the Barahathi nadi completely, leaving trails of water bodies in its beheaded part ***(Fig 8c).***

The channel of Diana has been shortened considerably, and is distinctly braided in some places with an average width of over 400 m. The Sigrimari is even more disintegrated and can now only be traced by strings of elongated water bodies. Rangati and Jhumar have developed more prominent flood plain and point bars.

*By **2001** (Fig.5)*, the Diana-Jaldhaka confluence has again shifted downstream by about 1.5 km from C4 to C5. This has been apparently caused by a local avulsion where the main channel of Jaldhaka shifted by 1 km towards west. The earlier course is now occupied by the lowermost stretch of Bahmani, which has changed its direction of flow and is now seen as a tributary of Diana. The westward shift of Jaldhaka has also resulted in the upstream shift of the Murti-Jaldhaka confluence by more than 5 km. Murti now meets Jaldhaka in the vicinity of Ramshai *(Fig 8a).* The Jaldhaka channel width varies from an average of 1.5 km to more than 2 km just upstream of the Railway Bridge. In 1997, a single major flood caused the channel to extend further. In 1998, major shifting took place. Jaldhaka, by breaching the left bank embankment avulsed into river Doikhowa and engulfed a huge area of north-western part of Dhupguri block. The main channel of Jaldhaka carrying almost the entire discharge is still seen flowing against the left bank embankment near Gadhayer Kuthi. In addition, the series of floods in 1998 as well in 2000 when the discharge several times exceeded 2000 m^3/s (and once even 5000 m^3/s), changed the branches of the Jaldhaka (as well as the lowest-course parts of the Diana) completely.

The drainage network of **2011** (Fig.5), shows no major change as compared to 2001. There has been a nominal downstream shift in the Diana-Jaldhaka confluence point by 0.05 km from C5 to C6. This can be attributed to aggradations. Near Ramshai, the main channel of Jaldhaka has shifted slightly eastwards, resulting in the downstream shift of the Murti-Jaldhaka confluence by about 1 km ***(Fig 8a)***. There is a visible reduction in the area occupied by sand and gravel bars as well as stable vegetated islands within the Jaldhaka channel. The Diana channel has been considerably straightened. An embankment has been constructed near Madhali in order to prevent re-occupation of the abandoned course towards Nathua Hat ***(Fig 8e).***

Several facts emerge from this study of shifting and changes of confluence point i.e. ***'belt of confluence shift' (Fig- 6)***. ***Firstly,*** although there is a ***net upstream movement*** of the confluence point by nearly 5.7 km during the period of study, there is ***no definite trend*** of movement in either direction (Table 3). Both upstream and downstream movements have occurred during the period of study which is probably due to changing discharge and velocity in the Jaldhaka-Diana confluence zone.

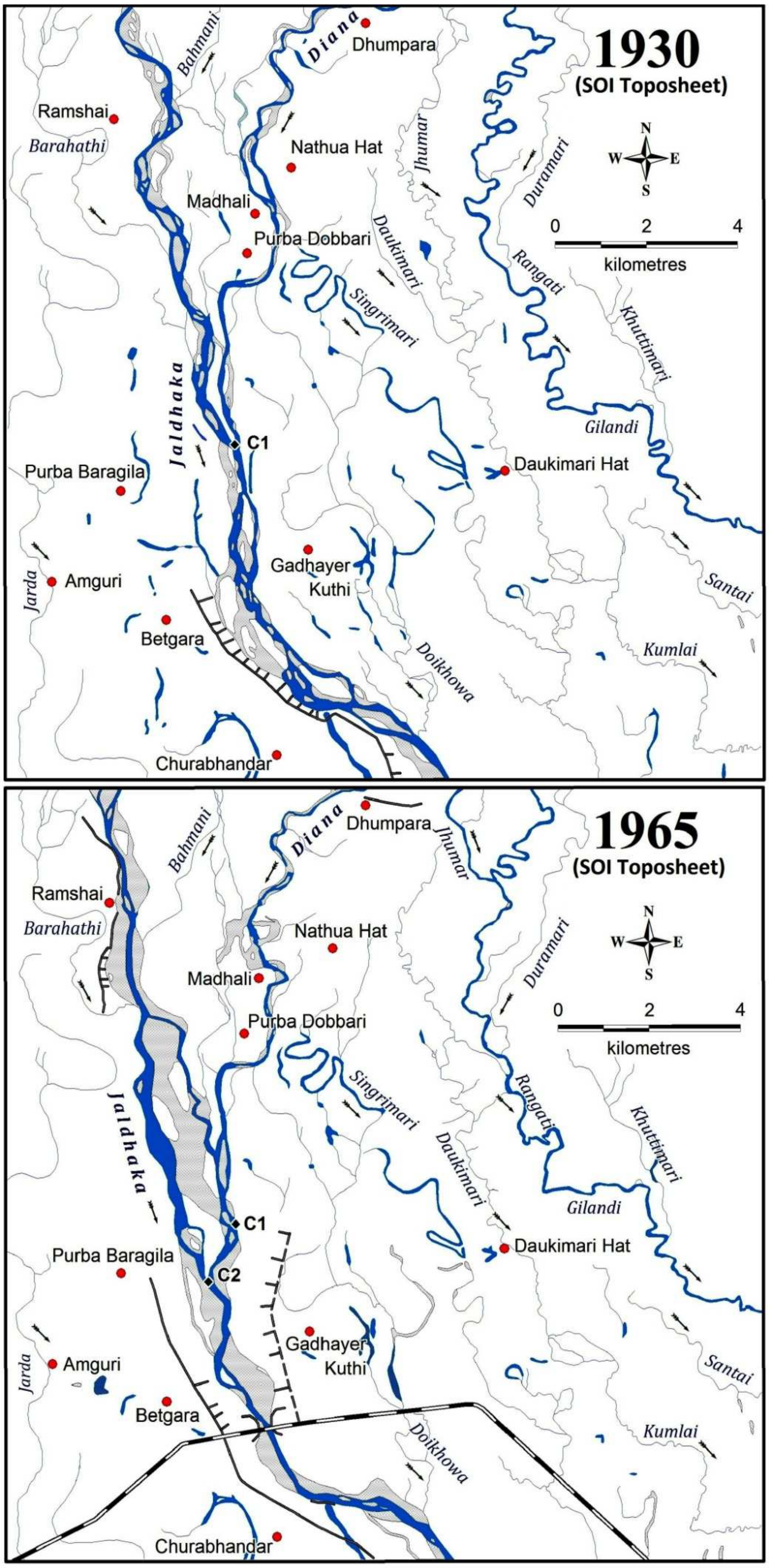


Fig. - 3 - Shifting of Confluence from 1930-'65

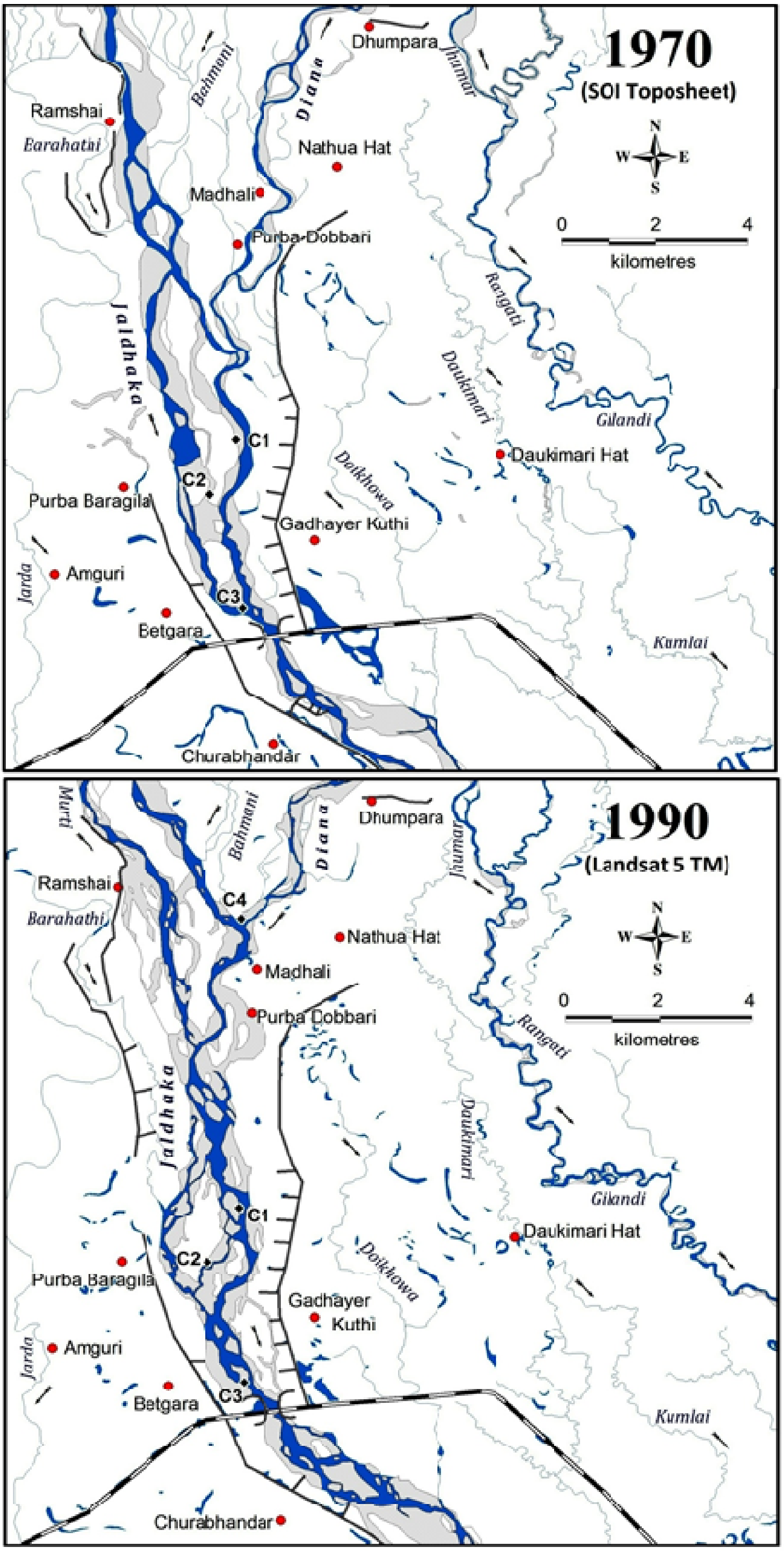


Fig. - 4 - Shifting of Confluence from 1970-'90

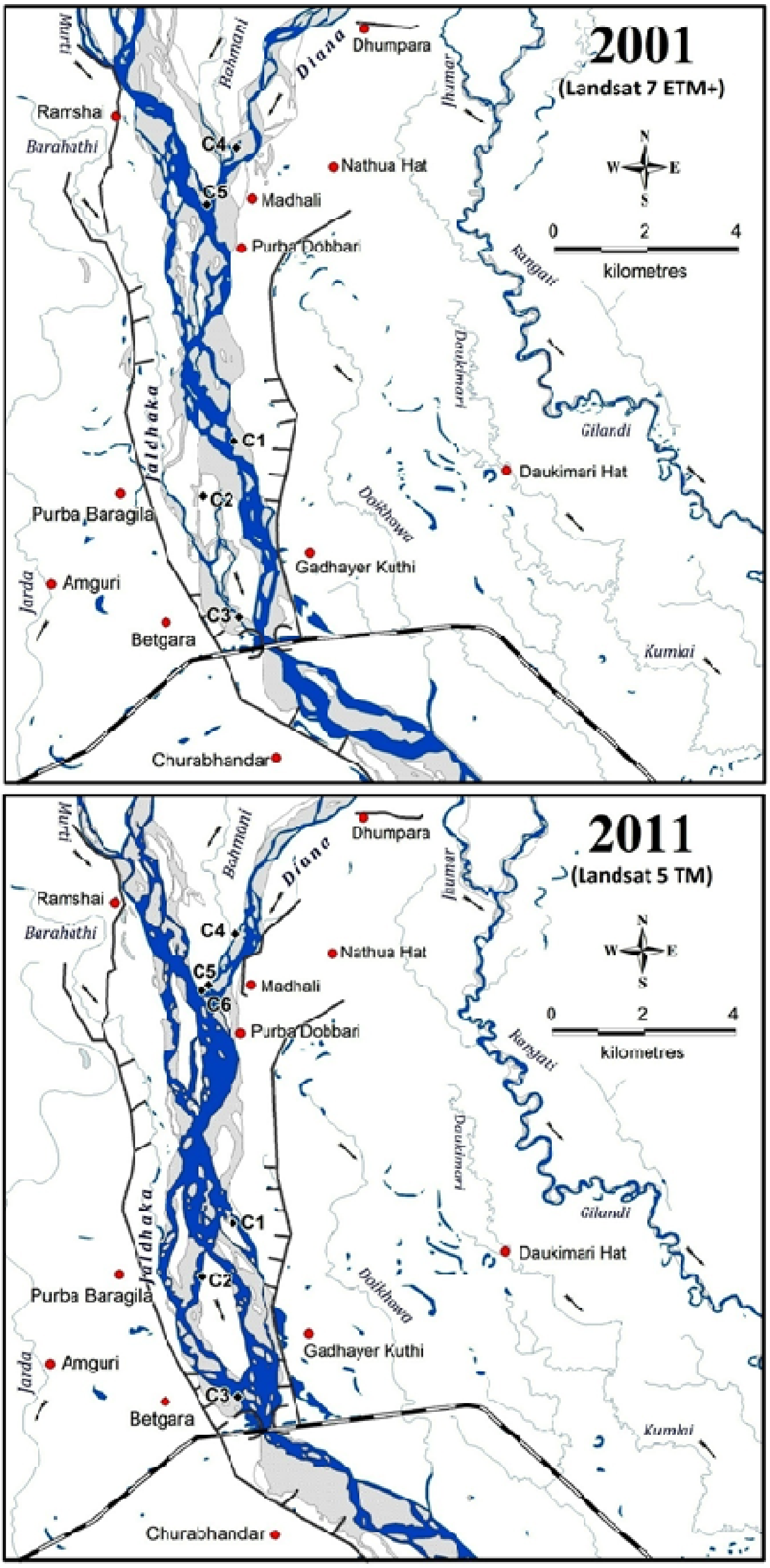


Fig. - 5 - Shifting of Confluence from 2001-'11

Secondly, there are ***multiple processes*** along with complex fluvial dynamics which have caused these movements viz. avulsion, local cut-offs, river merging and aggradations.
Thirdly, there are significant ***morphological and hydrological changes*** in the river systems during the period of study which seem to correspond to the confluence movements and resultant status of the present orientation. **(Fig. - 7)**

Table: - 2- Spatio-Temporal sequence of shifting of confluence point of River Jaldhaka and Diana

Period	Direction of Movement	Total Shift (km)	Process Involved	Remarks
1930-1965	Downstream	(C1-C2) ~ 1.5 km	Westward Avulsion of Jaldhaka	**Net Shift from 1930-2011:** (C1-C6) ~ 6 km Upstream
1965-1970	Downstream	(C2-C3) ~ 3 km	Aggradations and accretion	
1970-1990	Upstream	(C3-C4) ~ 11 km	Eastward Avulsion of Jaldhaka leading to Capture of lower course of Diana	
1990-2001	Downstream	(C4-C5) ~ 1.5 km	Local Avulsion and Erosion-accretion processes	
2001-2011	Downstream	(C5-C6) ~ 0.05 km	Aggradations	

Source - Compiled by the Authors

4.2 Avulsions and Cut-offs:

Major and minor avulsions of river channels have caused significant movement of the confluence point both upstream and downstream. It has been observed that the Jaldhaka-Diana confluence moved upstream by ~11 km during 1970–1990 while the same confluence moved downstream by ~1.5 km during 1930–1965 and again by ~1km during 1990-2001 (Fig.4). The precise timings of these avulsions are not known at this stage. Another example is the avulsion of Diana through Jhumar in 1956, which caused Jhumar to abandon its original course and become a tributary of Rangati.

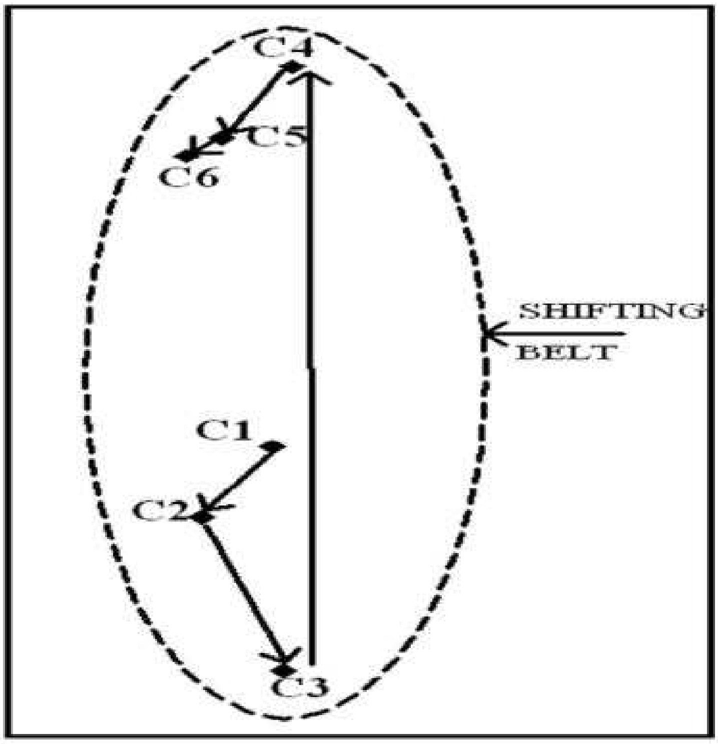


Fig. - 6 - Spatio-Temporal trend of confluence shifting

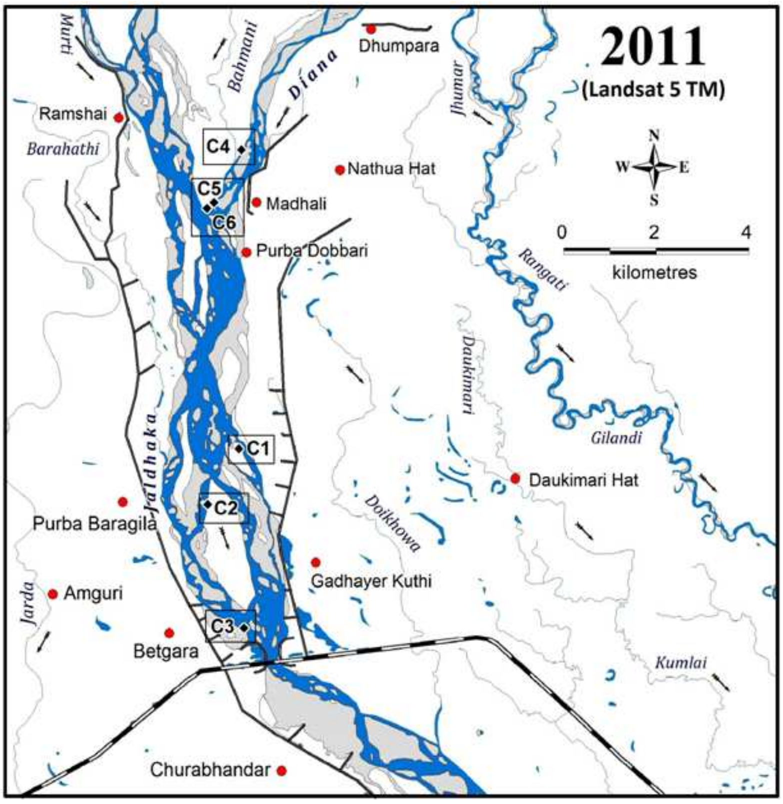


Fig. - 7 - "Zone Of Complex" of Confluence shifting

Hydrological readjustments seem to be the main factors controlling these movements. Both the Jaldhaka and the Diana rivers show large variability in flood magnitude, which would promote channel instability and cause avulsion. Reoccupation of pre-existing channel during floods seems to be the plausible mechanism of avulsion in the study area. In response to hydrological variability (mainly flood magnitude), lateral erosion and local aggradations, the channel avulses into a nearby channel. After avulsion, the pre-avulsed channel carries significant flow for some time but eventually aggrades and becomes a misfit channel. Low stream power, high sediment yield and proximity of the mountain front have triggered decadal-scale avulsions, some of which may have been tectonically controlled. However, bank instability and hydrological variations are more likely to have caused these avulsions here. Apart from that, local readjustment of channels through cut-offs and channel capture has also influenced the movement of the confluence points.

4.3 River Capture by Lateral Shifting:

River capture is essentially caused by local base level difference between two river 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 and one of the basic mechanisms by which the river enlarges its drainage network and it affects the landscape development in a very significant way. In this area, the capture is triggered by change in regional gradient associated with uplift. The capturing of the lower reaches of river by another predatory stream would result in upstream movement of the confluence point. Here the capture of a part of the Diana by the Jaldhaka River between 1970 and 1990 resulting in upstream movement of the Diana-Jaldhaka confluence is also associated with avulsion (Fig.4). Due to repetitive avulsions, the smaller channel (Diana) became very close to the large river (Jaldhaka) and both flowed nearly parallel to each other for a while. The progressive lateral erosion by the Jaldhaka river caused the planation of the water divide between the two rivers and the Jaldhaka river captured the lower reaches of the Diana thereby moving the confluence point upstream by about 11 km. Due to this major shift, the villages of Madhali and Purba Dobbari, which used to lie on the right bank of Diana were now situated along the left bank of Jaldhaka. Another significant capture can be seen in the diversion of the upper reaches of the Barahathi nadi by the Murti River between 1965 and 1970 and as a result, the Murti-Jaldhaka confluence, which used to be located several kilometres upstream, now shifted to near Ramshai village (Fig.- 3,4). Such local readjustment has significant implications for redistribution of sediment and water discharges within and among the river basins.

4.4. Aggradations:

The Diana-Jaldhaka confluence point moved downstream by almost 3 km between 1965 and 1970 and this movement may be interpreted to be a direct manifestation of aggradations in the confluence area and local avulsions of the primary channel in a multi-channel system (Fig.3). These changes may be explained by increased water and sediment discharges during major floods which affected the region in 1968. In the Diana-Jaldhaka confluence area, the growth of large bars seems to have pushed the primary channel of the Diana and the Jaldhaka rivers away from each other in a multichannel system thereby moving the confluence point downstream. A trend towards aggradations was also observable from the satellite images of the area between 2001 and 2011 (Fig.5). It is likely that such degradation and aggradational regimes in a selected reach have alternated over time in a large river system in response to fluctuations in monsoonal strength. Such fluctuations would therefore move the confluence point upstream and downstream in a major way on a longer time scale.

5. Conclusions and Suggestions:

Detailed analysis of channel patterns, as surveyed from 1930 and especially since 1990, shows very distinct changes. In large river channels like Jaldhaka, there has been continuous change in the braided pattern. Since 1990, the area occupied by fans is expanding, not only by way of vertical aggradations but also through horizontal progression in both upstream and downstream directions. The mountain margin and neighbouring part of the piedmont receive the high rainfall, which causes flash floods and frequent avulsions, as well as expansion and up-building of the alluvial fans. The clustering of heavy rain events since the 1990s is in particular reflected in a widening of braided channels, their avulsion and the shifting of braided sections by even 10–15 km downstream (as compared with maps from the 1960s). The stable meandering channel as recorded in old SOI maps (1930) is replaced by braided channels, as in the case of the river Diana. Frequent avulsions were recorded in the studied section. Reactivation of periodic streams and debris flows also caused a downstream shift by some 5–15 km in the beginnings of stable meandering channel reaches. This is especially visible along the lower course of the Diana channel. The phenomenon is connected with the high frequency with which flooding was recorded after 1993, as well as probably – in the case of the Diana – with the exploitation of dolomite at the mountain front on the Bhutanese side (Starkel et. al., 2008).

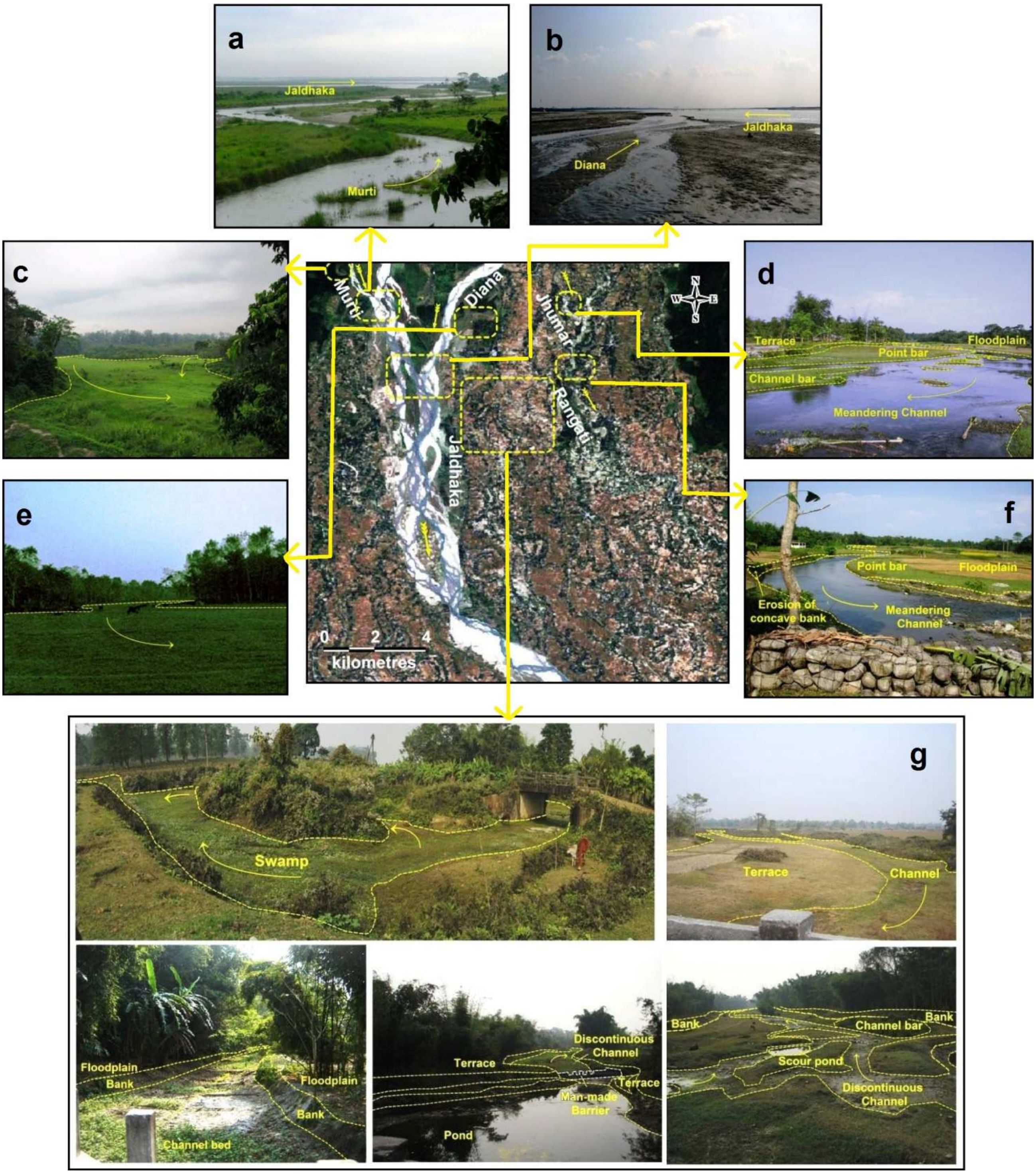


Fig 8: Geomorphic Panorama of Jaldhaka-Diana System (Lower Course)

(a) Jaldhaka-Murti Confluence near Ramshai; (b) Jaldhaka-Diana Confluence near Madhali; (c) Abandoned upper reach of Barahathi Nala at Ramshai; (d) Jhumar; (e) Abandoned bed of Diana south of Dhumpara; (f) Rangati; (g) Palaeochannels and spillways between Diana and Rangati.

(The photographs were taken during field surveys from 2010-2012. The precise location of each photo has been pointed out on the image of the study area.)

Similar observations were made by Starkel et al (2008) in the Jaldhaka-Diana confluence area. However, their study was more generalised covering the entire Sikkimese-Bhutanese piedmont, and did not go into the details of the mechanisms of the shifts. The nature and processes of shifting are found to be very similar to those observed by Roy and Sinha (2005, 2007) in the Ganga-Garra confluence area in Uttar Pradesh. The factors leading to channel shift are however different from those of North Bengal. The North Bengal rivers are significantly influenced by structural and tectonic controls, which is absent in the case of the Ganga-Garra region. Also, catchment area mining in the Bhutan hills is an important factor contributing to channel dynamics in the North Bengal foothills. In the Ganga-Garra confluence zone, the shifts are manifestations of local fluctuations in water and sediment budget.

Changing of river course and shifting of river is not a new feature for this region, but with increasing habitation and changing land use pattern, ***the situation has become more vulnerable.*** Also, deforestation that has heavily occurred in the area due to ***natural and man induced hazards*** like illegal cutting of trees, replacement of the natural forest lands and tea gardens with settlements and cultivation, unscientific dolomite mining in Bhutan and surrounding hills leading to siltation of river beds, etc. has aggravated the problem. The problem of channel shifting is more acute in the plains, where there is inundation and erosion of valuable agricultural lands, tea gardens, villages, etc. apart from the immediate loss of life and property and disruption of the communication systems, inundation by flood waters leaves behind large deposits of coarse sand on the agricultural lands, rendering them unfit for cultivation for a long time. Short term protective measures in and around the areas prone to submergence can only minimise the extent of devastation but they cannot eradicate the root causes. Soil conservation in the catchment areas is probably the only effective long term measure to check the ravages caused by shifting rivers.

Confluence dynamics in major river systems is a critical component as well as a significant issue of river processes and additional work, particularly on major confluences, on a longer time scale may provide further insight on the causative factors and its impact on the hydrological regime of the river systems. In addition to natural factors, large projects such as river interlinking may significantly alter the hydrologic regime of the river systems and may trigger such movements at a shorter time scale (Roy and Sinha, 2007).

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