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CHANNEL MIGRATION AND INFLUENCING HYDROGEOMORPHIC ATTRIBUTES OF KULSI RIVER, NORTH EAST INDIA

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Abstract

Morphological change over time in a river system is a natural process. The channel shifting mainly occurred due to weak geology, unusual stream discharge, intense meandering river bed, soil properties, land use, and involvement of human activities. The Kulsi River is a south-bank tributary of the Brahmaputra River. The river is well recognised for high discharge, sediment supply, and channel diversion. Therefore, the paper aims to study the channel migration pattern and its influencing attributes. Satellite images are used to identify the spatio-temporal changes in the course of the channel. The digitisation of the river channel is done in the GIS platform (ArcGIS 10.6), and the channel morphology of different periods is overlayed to find out the rate of magnitude and shifting of the river course from 1972 to 2018 at the five-year interval. The secondary data are collected from authentic governmental sources and publications for the preparation of base layers. The data on channel hydraulics are collected from the field surveys at eight channel shifting locations. The study noted that about 11 km away from the Ukiam, the river was suddenly shifted to the west in 1995 for about 1 km from its earlier path in the easterly direction. The longitudinal profile and sinuosity index show that the upper course of the catchment area is incised with more soil erosion and sediment supply to foothills near the Ukiam, where the river drifts to the west from the eastern direction in early 1990. The results help devise plans to mitigate flood hazards in the Kulsi River.

Keywords: Channel avulsion, Morphodynamics, Hydro-geomorphology, Remote sensing, GIS

1. INTRODUCTION

River morphology is unpredictable and dynamic in varying environmental landscapes over both spatio-temporal scales. An avulsion is a process by which flow is diverted from the parent channel into a new course in the floodplain (Sonowal et al., 2022). A local avulsion forms a new channel that joins its parent channel downstream (Heller and Paola, 1996). The channel hydro-geomorphic factors such as natural bank geometry (e.g. meander wavelength, meander length, the radius of curvature, amplitude, channel width arc angle, and sinuosity), land use pattern, geologic structure, sedimentation, precipitation, bank erosion, discharges of various frequencies, vertical and horizontal heterogeneity of floodplain soils and distribution of riparian vegetation are some accountable factors for channel migration (Brice, 1982; Motta et al., 2012). Channel diversion mainly occurs within the floodplain region, and bank erosion is held because of lateral shifting of the course. Usually, it is a natural process, but with the age of time, it becomes semi-natural because of human intervention. Changing channel courses creates havoc on the physical and cultural landscapes. Sometimes, many people lose their household activities, agriculture fields, and substructures due to river migration and associated fluvial hazards. It is variable - some changes are gradual and unnoticeable, while others depend upon phenomena like extreme floods and droughts.

River abandonment to form a new channel at a lower elevation creates instability in the channel courses notably in the Mississippi in the United States (Fisk, 1947), the Kosi in India (Gole & Chitale, 1966), the Meander in Anatolia (Russell, 1954), the Saskatchewan in Canada (Smith & Perez-Arlucea, 1994), the Thomson in Australia (Brizga & Finlayson, 1990), and the Okavango in Africa (McCarthy at al., 1992). The experimental study of avulsion frequency and deposition rate (Bryant et al., 1995), along with the interpretation of geological records, shows that channel avulsion can result from high peak discharges, sediment accretion, tectonic upliftment, and channel jamming through the exogenous process (Jones & Schum, 1999). In India, the braided Koshi River stands out among the other rivers because of the high frequency of channel avulsion and other morphological changes, such as channel migration and channel width adjustment (Baniya et al., 2023). The Koshi River is one of the world's highest silt-yielding rivers, with an estimated annual sediment yield of 2.2 × 10 5 t/year (Baniya et al., 2023). Sinuous to meandering channel patterns are common in floodplains in the Koshi River course. A similar channel pattern is identified in the Kulsi River course because of the river's behaviour. The river experiences lateral shifting from the foothills of Meghalaya up to the floodplain region of the Brahmaputra. Every year, the Kulsi River causes a significant loss to the physical and cultural landscape near the bank of the river. Because of high discharge, the river raises its water level and submerges villages as well as hectares of productive land near the bank of the river annually. Besides, the region faces tremendous economic loss due to flood and lateral channel migrations. Another significant fluvial-geomorphic aspect of the Kulsi River is that it tends to form sand deposits due to high discharge. The river experienced a shifting at varied local scales after flowing into the foothills and the channels rejoining further downstream.

Geographical Information System (GIS) and multi-temporal satellite images are the most sophisticated tools to identify spatio-temporal river course changes (Hassan et al., 2017). The high-resolution images give accurate data for evaluating the trend of river shifting (Mohamad et al., 2018). This will be helpful for the assessment of the vulnerability of communities living on the floodplains. (Sonowal et al., 2022). The geospatial method has been applied in many world regimes and has proven effective in river course change analysis (Petropoulos et al., 2015). Therefore, the paper uses remote sensing and GIS techniques to identify channel migration, its intensity, and the influence of hydro-geomorphic channel migration indicators in the Kulsi River.

2. STUDY AREA

The Kulsi River originates from the Meghalaya Plateau in Meghalaya, known as the Khri River, at an altitude of 1700 m above mean sea level. The tributaries like Um Krisinya, Um Siri, and Um Ngi confluence with the Khri River at Ukiam. After reaching the alluvial plain of Assam, it is known as Kulsi. Umkrisinya, Um Siri, and Um Ngi, Boko, Singra, Singua, Deosila are left bank tributary of Kulsi River. Batha and Umshru are the tributaries on the right bank (Thakuriah, 2023b). The Kulsi drains about 4,111.81 km^2 of geographical area on the southern bank of the Brahmaputra. Out of which about 1,956 km^2 area drains over Kamrup rural and Goalpara districts of Assam (India) within the geographical extension from 25˚31′ 58.8″ N to 26˚75′ 3.33″ N latitude and from 91˚E to 91˚48′ 30″ E longitude (Figure 1).

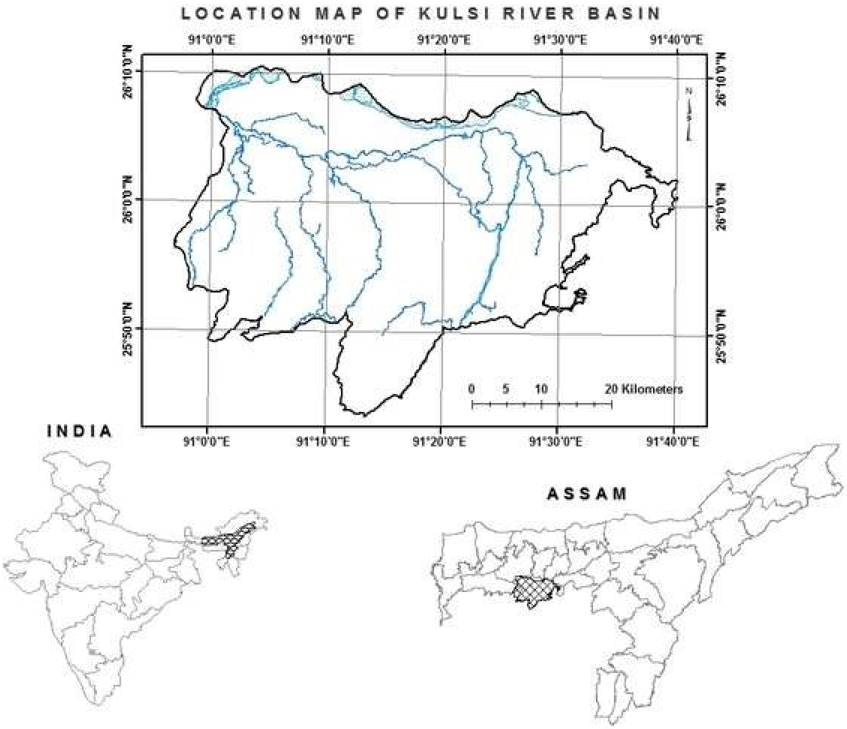

Figure 1: Location map of Kulsi River Basin

Structurally, the upper catchments area belongs to the age of Proterozoic with Assam-Meghalaya Gneissic complex with migmatite/banded Gneiss lithologic structure. The downstream belongs to the geological age of Meghalayan during the Barpeta-I formation with white to greyish sand, silt, pebble, and clay lithologic structure (Thakuriah, 2023a). In upper reach, the Kulsi flow over four microtectonic fault lines. From the river source to the confluence to the Brahmaputra, the river has a more expansive valley due to bed sedimentation and frequent channel diversion due to flood discharges (Thakuriah, 2023c). The channel morphology includes level to nearly level sloping (0^{o}-1^{o}) in plain and steeps (15º-30º) in the upper catchment. The Kulsi River flows over fine to fine-loamy soil in the catchment and coarse-silty soil texture near the confluence. The section of the downstream is covered mainly by young alluvium. Soil gets easily erodible during the high discharge or heavy precipitation in the Kulsi river basin. At the same time, the soil characteristics of the upper reach from Ukium to Chandubi outlet covered a fine texture and steep morphology with moderately steep sloping (15o-30o), and thus, extreme soil drain conditions existed. From Chandubi Lake outlet to Kulsi bifurcated point, it covers fine-loamy soil texture and undulating morphology with a moderately sloping surface (8o-15o) and has well soil drainage (Thakuriah, 2023c). The Kulsi River basin is characterised by a southwest monsoon with maximum rainfall from May to September and minimum rainfall during the winter. The average annual rainfall of Boko station in the Kulsi river basin was 1,796 mm from 1993 to 2018. The average gauge discharge of the Kulsi River at Kukurmara station was recorded at 61.80 cumecs during 1991-2018. During this period, the highest average annual discharge was recorded at 99.78 cumecs in 2014 (Thakuriah, 2023b).

3. DATABASE AND METHODOLOGY

3.1 Database

The Kulsi River basin is delineated from the Survey of India topographical sheets No: 78 N/4, 78 N/8, 78 O/1, 78 O/2, 78 O/5, 78 O/6, 78 O/9, 78 O/10, and 78 O/14 at 1: 50,000 scale. Multi-temporal Landsat satellite data and IRS LISS IV data for the years 1972, 1977, 1988, 1995, 2001, 2006, 2011, and 2018 were used to understand the dynamic nature of the Kulsi River. The details of the satellite image are mentioned below in Table 1.

Table 1: Details of satellite images used in the study

Sensor	Date of acquisition	Bands used	Resolution
MSS	22 Nov 1972	MTL	60 m
MSS	24 Dec 1977	MTL	60 m
MSS	19 Feb 1988	4,3,2	60 m
MSS	26 Mar 1995	4,3,2	30 m
ETM+	15 Dec 2001	4,3,2	30 m
LISS IV	20 Mar2006	2,3,4	5 m
OLI and TIRS	06 Mar 2011	5,4,3	30 m
LISS IV	19 Feb 2018	2,3,4	5 m

To understand the flow characteristics of the river, the fluvial and geomorphic databases are collected from the field from the point of Ukium to Nagarbera, where it joins the Brahmaputra River. We have also used secondary databases, especially the soil map, the geological map at the scale of 1:50,000 from the Geological Survey of India, rainfall data from the Indian Meteorological Department, Guwahati (Borjhor) and Regional Sericulture Research Station (RSRS), Boko, and discharge data from Central Water Commission, Shillong in order to know their role in lateral channel migration.

3.2 Channel Migration Assessment

To identify the spatio-temporal migration of the Kulsi River, the satellite images were projected with the coordinate system of WGS 1984 UTM Zone 46N. The dynamic nature of the Kulsi River courses over different years was digitised and analysed in ArcGIS 10.6 software. The morphometric parameters like longitudinal profile, sinuosity index, channel gradient and channel slopes are computed using the SOI toposheets at a scale of 1:50,000 and contour interval of 20 m.

Longitudinal Profile: The longitudinal profile is the natural law of the river and depends on the length and gradient of the channel from the source to the outlet point. The river carries the materials from the source and starts depositing the materials where the river finds the equilibrium point (Mackin, 1948). The longitudinal profile helps to identify the equilibrium state of the river. The profile waning takes place gradually depending on the nature of the topography, tectonic activity, geologic structure, sediment transport, flow resistance, discharge, depth and width. The longitudinal profile helps to measure channel slope, channel gradient, and stream length gradient index (SL). In this study, these parameters were calculated with the help of digitised contours from the SOI toposheets at 20 m contour intervals.

Channel gradient, $G = \frac{VD}{HD}$

Where, VD is the vertical drop of the slope and HD is the horizontal space of the slope.

Stream length gradient index, $SL = \Delta H \times \frac{L}{\Delta L}$

Where, ΔH is the change in elevation of the reach, L is the total stream length from the source to the reach of interest, ΔL is the length of the reach (Hack, 1973).

Sinuosity Index: The sinuosity index defines the channel pattern of a drainage basin. It is a major morphometric factor that affects the topography characteristics of the river course. According to Brice (1982), the sinuosity index is the ratio of the length of the channel to the length of the meander belt axis. The sinuosity pattern of the channel is analysed in the ArcGIS platform by applying the following formula Brice (1982).

S.I = $\frac{CL}{MB}$

Where, CL is the length of the channel and MB is the length of the meander belt axis

Hydraulic Attributes: Cross-sectional channel characteristics and flow characteristics of river channels were analysed through cross-sectional channel geometry, especially the channel width, depth, velocity, and discharge. From the point of Ukium to Nagarbera, eight cross-sectional hydraulic attributes were collected during the pre-monsoon season of 2019-2020 using wooden boats on the river course. The width, depth, and velocity are measured for each cross-section. A cup meter is used to measure the depth water velocity of each cross-section, and the surface velocity of water is read through the floating method. Spatial information of each cross-section, especially location and height, was collected from the field using handheld GPS. Figure 2 shows the location of the sample cross-sections at different channel diversion sites from the Ukium to Nagarbera.

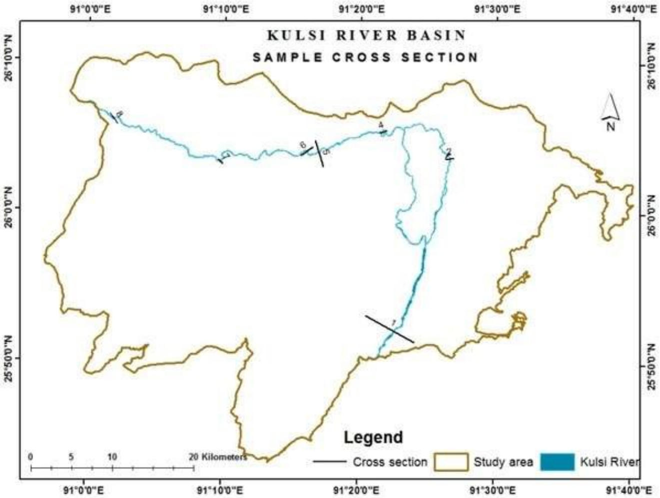

Figure 2: Location of the cross-sections at different channel migration sites from Ukium to Nagarbera

4 RESULTS

4.1 Morphological Changes in Kulsi River

To analyse the dynamic nature of the river, we have used the different years of a satellite image at the intervals of 5 years, i.e. 1972, 1977, 1988, 1995, 2001, 2006, 2011, and 2018. Kulsi River is more sinuous at the river's former course, creating channel bars. The multi-temporal satellite images show that the river's course underwent drastic changes after the 1990's. The 1972, 1977, and 1988 images show the river meandering through Langkher, Baregaon No.2, and Bherveri village. However, from 1990 to 1995, the river completely abandoned its old course and started flowing through the new course through the Pantan village. The detailed measurement of Lower Kulsi River channel diversion at some selected cross-sections is shown in Table 2. The year 1972 is taken as the base year, and at the interval of 5 years, the changes are shown up to 2018.

Table 2: Extent of cross-sectional channel changes at selected points across river Kulsi

Cross Section	1972-1977		1977-1988		1988-1995		1995-2001		2001-2006		2006-2011		2011-2018	
	R (Km)	L (Km)	R (Km)	L (Km)	R (Km)	L (Km)	R (Km)	L (Km)	R (Km)	L (Km)	R (Km)	L (Km)	R (Km)	L (Km)
A-A1				0.04w		**1.031w**		0.08w	0.018e	0.005w			0.011w	0.010w
B-B2			- 0.05w	-0.02e 0.79w	- 0.03w	-0.01e **0.792w**	0 0.03w	0		0.03w			- 0.008w	-0.008e
C-C3	0.09w	0.11w	0.26w	0.35w	02w	0.23w	0.28w	0.2w	0.01e	0.01e	0.03w	0.03w	0.004e	0.002e
D-D4		0.06n	0.07n	0.10n	0.09n	0.11n	0.06n	0.06n	0.06n	0.012n		0.04n	0.029n	0.03n
E-E5			0.15s	0.10s	0.09s	0.09s	0.03s	0.02s	0.05s	0.08s			0.07s	0.05s
		-0.08n	0.07n	0.06n	0.03n	0.05n			0.61s	0.62s	0.02s	0.02s	0.003s	0.006n

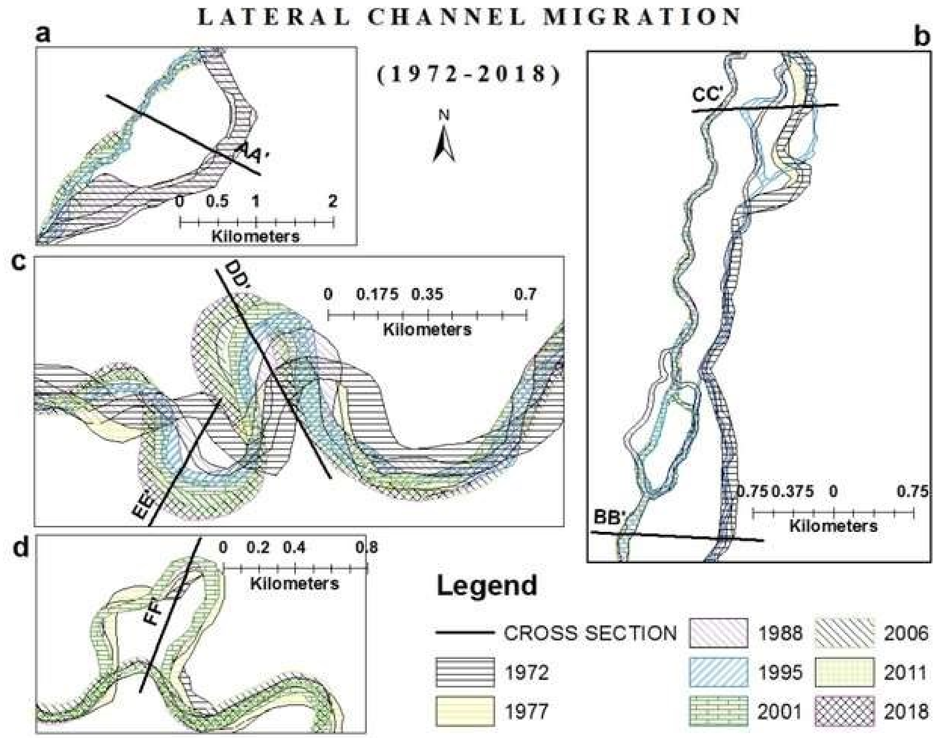

Figure 3: Spatio-temporal changes in river morphology. a) and b) shows new branching and cutting off the old through aggradations, c) shows lateral channel migration through the erosion of the meander bend, and d) shows channel avulsion through cutting off the meander neck.

In the years 1972, 1977, and 1988, the channel was in the right direction along cross-section AA' (Figure 3a), and in the early 1990s, the channel was shifted towards the left direction with an extent of about 1 km and till now the river flow in the same direction. The river discharge and rainfall data of the study area augments the channel avulsion. The higher rainfall (>2000 mm) at Boko rain gauge station was recorded in 1993, 1995, and 1996 (Figure 5), with recorded higher discharges in 1993 and 1995, above the yearly average discharge of 80m^3/sec. In cross-sections BB' and CC', there is a quick diversion off the new channel along interconnecting wetlands because of high seasonal discharge and sedimentation of the main channel (Figure 3b). In 1972 and 1977, the channel was in the right direction, and the early 1980s, the channel shifted to the left with an extent of 0.8 km, and after that, the river flowed in the same direction. During 1972-2001, the channel was rapidly progressive in meander formation because of high discharge in the channel and/or continued flow of water currents that helped erode the sediment and lead to lateral erosion. Afterwards, the meander cut-off and oxbow lake formations were observed within the cross-sections DD' EE' and FF' (Figure 3c and 3d).

The rate of movement of the lateral migration of the channel is observed from 1972 to 2001 due to the river clip process. The rate of movement was 0.08 km (1972-1977), 0.06 km (1977-1988), and 0.054 km (1988-1995) on the right bank towards the north direction. However, the scenario changed in the early 2000s when the channel left its original course and drifted its direction towards the left. This is due to the river clip and slip-off slope process. The river drifts towards the left, about 0.61 km from 2001 to 2006. The river course formed a meander cut-off neck in 2002. The cross-section DD' is continually shifting towards the right (north) with the help of river clip process and moving at the rate 0.06 km from 1972 to 1977, it again shifts at same direction about 0.10 km (1977-1988), 0.11 km (1988-1995), 0.06 km (1995-2001), 0.012 km (2001-2006), 0.0497km (2006-2011), and 0.034 km (2011-2018). The cross-section EE' is also continually shifting towards left (south) at the rate of 0.15 km from 1977 to 1988; it continues to move towards south 0.092 km (1988-1995), 0.03 km (1995-2001), 0.05 km (2001-2006), and 0.069 km (2011-2018). However, from 2006 to 2011, there was no clear channel lateral movements.

4.2. Hydrogeomorphic Attributes

Longitudinal Profile and Channel Gradient

In the state of Meghalaya, the river originates at an altitude of 1700 m near Nonglyer (known as Khri River) and runs down for about 200 km. After reaching the alluvial plain of Assam, the river is known as the Kulsi River. The river has knick points due to the presence of the resistance rock, changes in slopes, high channel gradient, and high SL value in the upper courses. The knick points at 16 km and 54 km downstream from Nonglyer are presumed due to the Guwahati fault passing along the Kulsi River course (Yin et al., 2010), whereas the third knick point at about 10 km upstream of Ukium corresponds with the Banded Gneissic Complex of the Shillong Plateau. The alluvial plain associated with high stream length gradient indices in the upstream indicates tectonic activity (Imsong et al., 2018). The slope gradient and SL value of Kulsi River from Ukium (80m) to Nagerbera (35 m) abruptly fall by about 41 cm/km and 0.02, respectively, shown in Table 3. The Kukurmara site, about 34 km downstream from Ukium reach, has a slope gradient of about 0.98 m/km, indicating that the upstream's highly eroded materials are deposited downstream in the lower river courses (Figure 4).

Sinuosity Index (SI)

The Sinuosity index of the Kulsi River from the point Balijori to the confluence of the Brahmaputra near Nagarbera was found at 1.20 and 1.24 in the years 1972 and 2018, respectively. A river having a sinuosity index of 1.05 to 1.5 is called sinuous. It shows that

the downstream Kulsi River is highly sinuous. From the point of Ukium to Balijora, the sinuosity index was found to be 1.10 in 1972 and 1.05 in 2018; the low Sinuosity index in this stretch specifies solid structural control and flows over the Kulsi fault line.

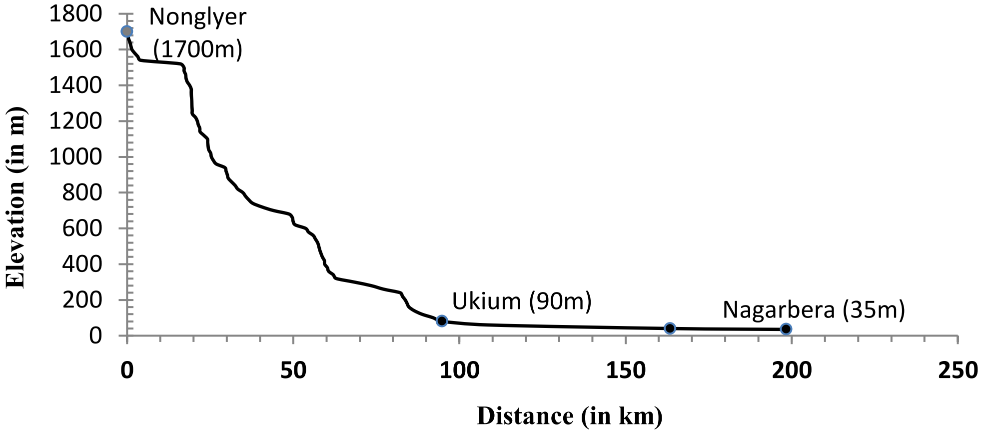

Figure 4: Longitudinal profile of the Kulsi River shows major knick points and high stream gradient in the upper course

Table 3: Relief characteristics of Kulsi River computed from the longitudinal profile

Name	Elevation (in m)	Stream length (in km)	Channel gradient, G (m/km)	Stream length Gradient index, SL
Nonglyer	1700	0	-	-
Ukium	80	101	16.02	3.185
Kukurmara	47	34	0.98	0.019
Chamaria	42	39	0.12	0.002
Nagarbera	35	25	1.38	0.005

Cross-Sectional Channel Characteristics

The cross-sectional channel characteristics play a significant role in lateral channel migration. Channel migration areas were surveyed from the Ukium to Nagarbera. Eight sample cross-sections were taken along the downstream direction of the Kulsi River for cross-sectional morphological measurements. Table 4 lists the characteristics of each cross-section: width, average and maximum depth, surface water, depth water velocity, and discharge. It is observed that the maximum channel width (90 meters) of the Kulsi River is in the vicinity of the foothill. However, along with the downstream, it varies from 32 to 84 meters due to the bifurcation of the main channel after crossing Kulsi Point. The average depth of the channel varies from 0.32 meters at cross-section 1 to 1.83 m at cross-section 4. High sediment deposits in the Kulsi River are observed in the foothills bed, which lowers the channel depth. The velocity of the water depends on its depth - the surface velocity is increased with increasing depth. Therefore, maximum water discharge is found at cross-section 8 with a discharge rate of 613.41 cumecs.

Table 4: Cross-sectional channel characteristics at channel shifting points

Cross-section	Depth (in m)		Width (m)	Area (m^2)	Velocity (m/sec)		Discharge (m^3/sec)
	Maximum	Average			Depth water	Surface water	
1	0.75	0.32	90.1	28.83	0.007	2.51	72.36
2	1.10	0.56	36.5	20.69	0.346	12.2	252.42
3	2.00	1.50	32	48.19	0.220	5.6	269.86
4	3.26	1.83	35.2	64.41	0.350	6.81	438.63
5	2.14	1.17	51.6	60.37	0.325	4.97	300.03
6	2.88	1.75	54.8	95.90	0.339	4.05	388.39
7	2.80	1.13	84	95.42	0.366	5.6	534.35
8	2.70	1.31	67	87.63	0.410	7	613.41

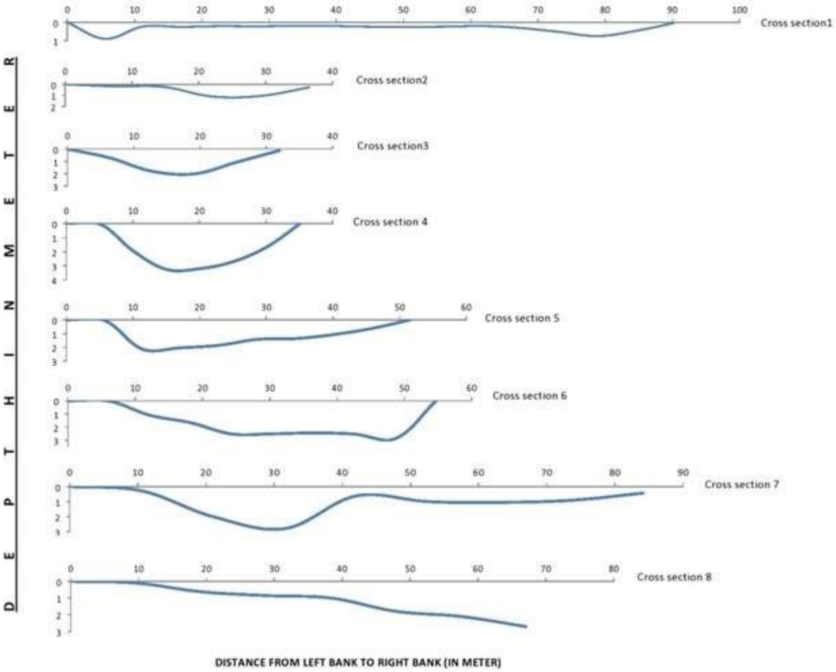

Figure 5: Cross-sectional morphology of the channel at selected sites. Cross-section 1 exhibits a wide valley with sediment deposits on the channel bed. A narrow V-shaped profile was developed in cross-sections 3 and 4; Cross-sections 2, 5, 6, and 7 developed a meander channel cross profile.

The cross-sectional morphology of the Kulsi River at selected sites is shown in Figure 5. It is observed that the width of the channel is found to be maximum with sedimentation along a river bed in cross-section 1, where the new channel was created after the 1988 flood. A narrow V-shaped profile was developed in cross-sections 3 and 4. Cross-sections 2, 5, 6, and 7 developed a meandering channel in the cross profile due to the erosion and deposition works of the river. The helical flow of the meander bend plays a vital role in sediment transport and deposition (Azpiroz-Zabala et al., 2017). On the inner bank, a slip-off slope is created due to the deposition of sediments. The river cliff slope is created due to the undercut by erosion on the outer bank. So, the maximum depth of the channel cross-sectional profile at the meander bend is formed along the concave bank due to the action of helical flow in the meander bend.

Flow Characteristics

The Kulsi River's flow regime mainly depends on the monsoon's seasonal rhythm. Northeast India experiences a southwest monsoon with high precipitation in the pre-monsoon period, and sometimes it is unpredictable. For instance, in the William Nagar rain gauge station of Meghalaya, located southwest of the Kulsi basin, rainfall intensity rose to 32.4 cm in an hour on 22 Sept 2014. Total and average hourly rainfalls for the same day are 191.2 cm and 7.96 cm, respectively. Similarly, the daily rainfall in the Guwahati Airport rain gauge station was recorded at 15.53 cm on 23 Sept 2014. This is the highest daily rainfall recorded during the present decade in Assam. The maximum annual rainfall of more than 2100 mm is recorded in 1977, 1988, and 1993.

The Kulsi River exhibits unique flow characteristics marked by significant seasonal variations in rainfall. Peak flow occurs during the monsoon, with more variable runoff patterns after each storm event. Current flows to a base flow characterise the inter-monsoon period reached just before the onset of the subsequent monsoon. The yearly average discharge of the Kulsi River varies from 38.541 cumecs in 1998 to 99.789 cumecs in 2014. From 1993 to 2018, the average annual discharge was 62.304 cumecs. Figure 6 represents the deviation of the annual discharge from the mean annual discharge from 1993 to 2018. The time cycle of these annual accumulations seems to be irregular in its period and amplitude. It is also observed that there has been a wide variation in annual flow characteristics since 1993, with sustained high discharges during 1993, 1995, and 2014. Figure 5 shows annual discharge data from 1993 to 2018, indicating a cyclic fluctuation with peaks in almost every alternative year. The pattern of variation of the annual peak flow of the river is also represented in the figure. It is observed from the annual hydrograph of the Kulsi River that the trend of peak flow decreased from 1996 to 2013.

5. DISCUSSION

The literature shows that the hydromorphological dynamics in low-lying alluvial channels may emerge due to floods. The peak discharge in the channel typically creates new branches, cutting off the meanders and oxbow lakes (Struzynski et al., 2015). The floodplain characteristics include quick drains, those with high gradients, absence of vegetation cover or low vegetation, minor reliefs, and water table below the floodplain surface support channel avulsion by incision. The avulsions in the Kulsi channel after crossing the Ukium foothills (Figure 3a) fulfil all these conditions. Here, the interconnecting river wetland, locally known as Kendil Bill, along the Chikadonga tributary of the Kulsi River, plays a significant role in channel diversion.

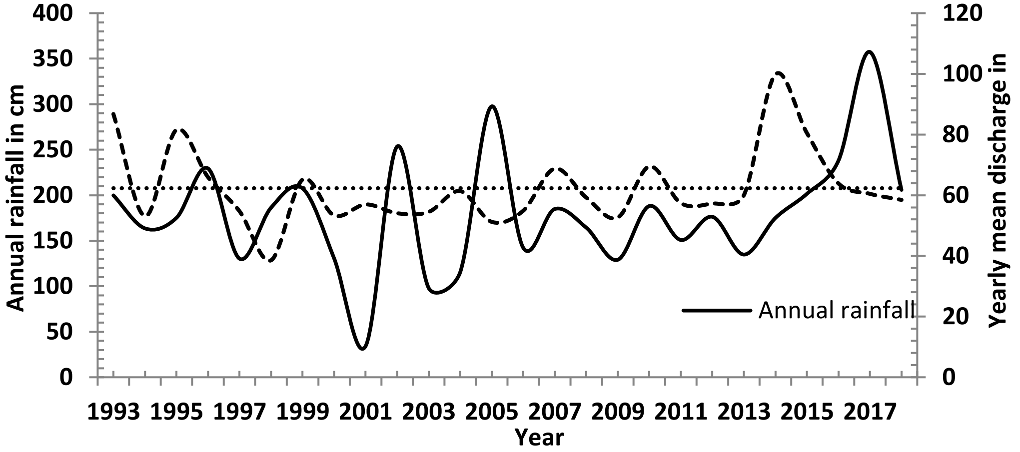

Figure 6 : Annual average discharge of Kulsi River at the point of Kukurmara and annual rainfall of Boko rain gauge station for the year 1993-2018.

Figure 8 illustrates the aerial view of channel change from 1972 to 2018 at the Chikadonga tributary. Here, the tributary flow is 2.80 km parallel to the main channel, and the spacing between them is about 80 meters near Lankhar village in 1967. The mainstream Kulsi diverted at this point by cutting the meander bend and joining with the Chikadonga River during bank-full discharge and floods after 1988. The rise of the channel bed through the sedimentation process cuts off the main channel after 1995 and creates a new pathway along the interconnecting wetlands, especially in the foothills of Kulsi (Figures 3a and 3b). Further downstream, the bank line is migrated through the cutting off of the meander neck (Figure 3d) and meander bend (Figure 3c). The tectonically active upstream of Kulsi River, as evidenced by the morphometric factors such as longitudinal profile, gradient, and stream length gradient index, proves faster erosion and excess sediment flux upstream leads to enormous sedimentation downstream, which is unable to carry through the meander bend and hence the channel form a new pathway for its flow. This variability of water discharge highly impacts bank erosion, especially during the bank-full stage (Dragicevic et al., 2017). Interestingly, the Lower Kulsi basin received 1800 mm to 2200 mm yearly mean rainfall during the last ten years (2009-2018), as shown in Figure 7. The extreme rainfalls in the upper catchment area cause massive flood situations in the low-lying areas that result in channel shifts and land loss on the bank of the Kulsi River.

For instance, a maximum annual rainfall of above 3500 mm was recorded in 2017 at the Boko rain gauge station, which is located within the study area. Due to this abnormal rainfall, the river experiences high discharges in the downstream plain regions with a high stream flow velocity in a short time span. The diversion of the river can be attributed to this increased sediment flux associated with the extreme rainfall event. It is identified that the river experienced an abandonment of a meandering loop due to this event by cut-offs. The high channel gradient of 16 m/km from the source to the foothills at Ukiam and the stream length gradient index of 3.185 indicate that the channel tends to have faster erosion and sediment flux downstream.

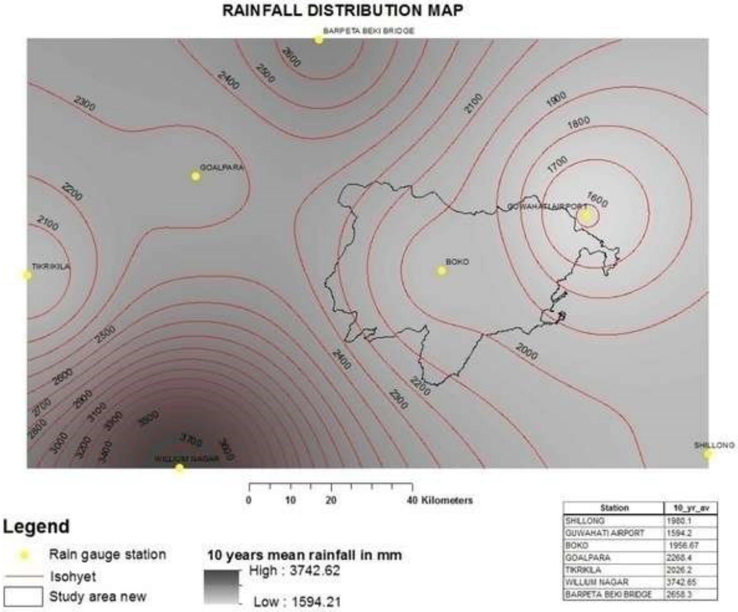

Figure 7 : Mean annual rainfall distribution in the study area

6. CONCLUSION

The paper is focused primarily on the spatio-temporal changes in Kulsi River using multi-temporal satellite data, topographic sheets with 20 m contour interval, structural and geological, hydrological attributes such as gauge rainfall, and water discharge, and cross-sectional channel geometry through field survey methods for the first time. Integrating multi-temporal satellite images and other hydrodynamic settings of the basin in GIS helps us detect lateral channel migration, the nature of their shifting, and its consequences on the landscapes. The morphotectonic character, extreme rainfall, and high discharge influence the channel migrations of the Kulsi River from the Ukium point to the confluence point near Nagerbera. There are five channel reaches that are identified as the most dynamic in their lateral direction. They mainly belong to the young alluvial soil where progressive meandering, meander cut-off, and oxbow lake formation occur. Most of the bank line is migrated by cutting off the meander neck and meander bend. The river clip, slip-off slope, channel width, meander belt, and sediment supply are also responsible for channel diversion. The river's upper course stretch from Ukiam to Dumukh belongs to the active tectonic zone, and here, interconnecting riverine wetlands play a significant role in lateral channel migration during and after flood events. The highly erodible sediment of active tectonic catchments is deposited in the mainstream due to a sudden velocity drop in the foothills. Consequently, it changes its course along the riverine wetland during massive floods after 1988. The study offers in-depth information on channel avulsion in the Kulsi River, which helps to plan for constructing structural measures to mitigate the risks of flood hazards in future.

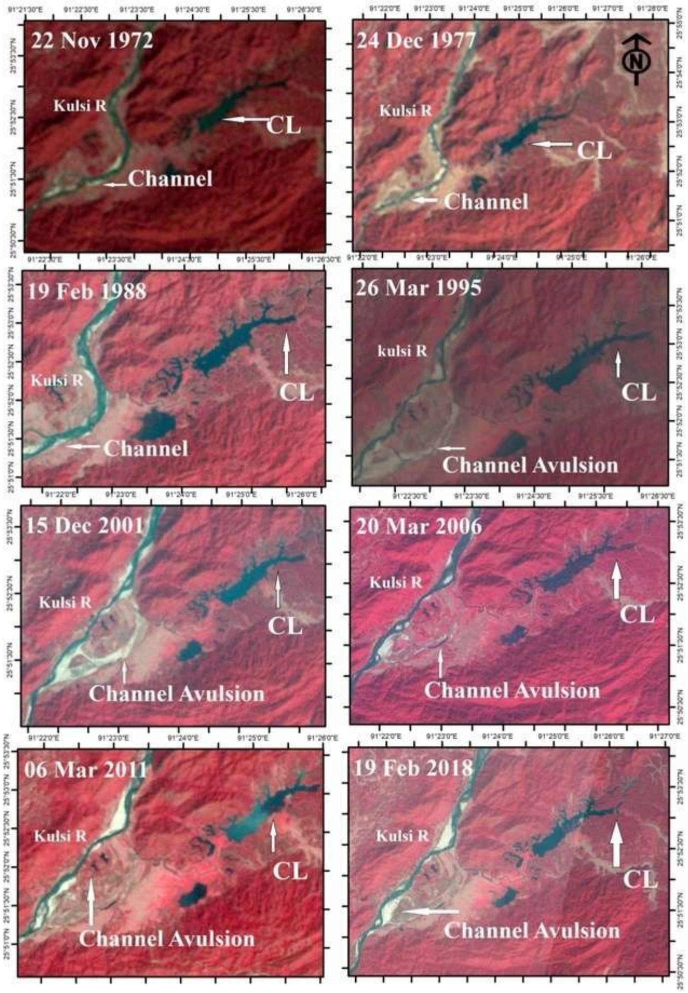

Figure 8: Satellites imagery showing channel avulsion (1972-2018) in Kulsi River

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Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author upon reasonable request. The authors declare no conflict of interest in the completion of the work.

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