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The influence of urbanization on the morphology of the Barak River floodplain in Cachar District, Assam

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ABSTRACT

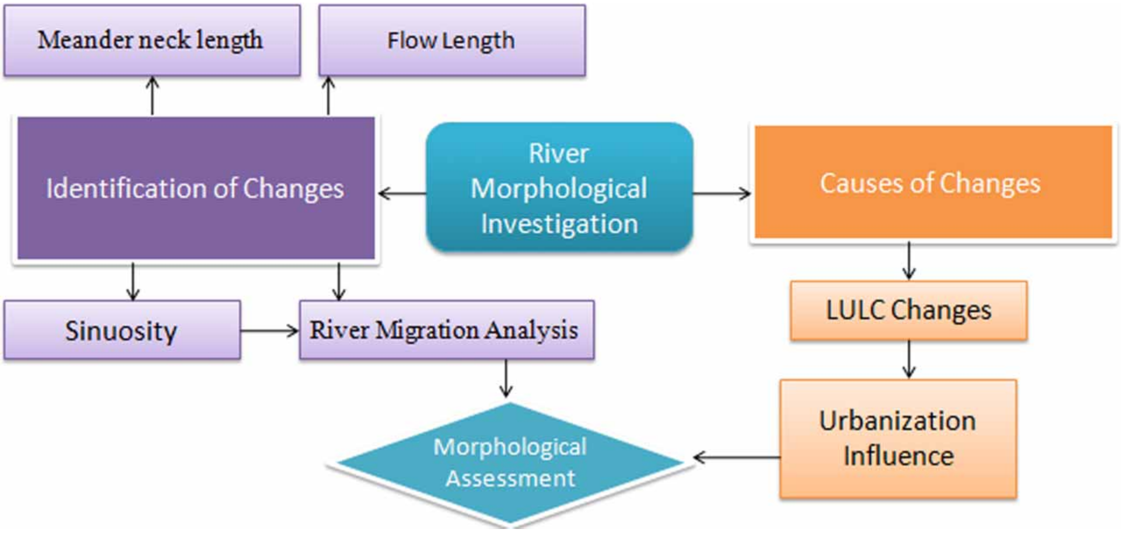
In the present study, the meandering behavior of the Barak River (Cachar), Assam was traced. Flow path length, meander neck length, sinuosity index, and river migration were determined segment-by-segment to demonstrate morphological changes. Decadal land-use land cover (LULC) maps were also prepared at the section scale using Landsat data (1990–2020) validated with the Kappa coefficient to characterize changes along alluvial floodplains. Urban growth and agricultural activities affect river morphology, especially where intensive agriculture was recorded, according to LULC studies. Due to urbanization, forestation constantly decreased, causing river variability. According to the results of the present study, river migration is very slow between Sec 1 and Sec 3. In terms of river stability, the parts are more stable, particularly Sec 1, which features less urbanization and agricultural activity than the other sections. The most vulnerable segments within the study area were considered to be Sec 2 and 4. There is a rather large amount of migration within sections, especially segments CC and GG. The river segments became more vulnerable as a new oxbow lake was formed and LULC changed over a decade. This stretch of Barak is characterized by a broad alluvial floodplain and is shifting since this study applies to various meandering types.

Key words: GIS, LULC, river meandering, river morphology, sinuosity, urbanization

HIGHLIGHTS

- Even slight changes to river meandering parameters (such as flow channel length, meander neck length, and sinuosity index) can affect river stability. Changes in meandering parameters and land-use practices across the floodplain could also affect river morphology.
- Urbanization and agriculture within floodplains cause river morphological changes over a decade.
- River morphology changes significantly due to oxbow formation.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The floodplain's alluvial nature is a significant asset to human society. Floodplains are one of the most vulnerable regions globally, as they are being degraded by river management and increased land-use pressure (Hazarika *et al.*, 2015). Interactions between inputs such as water (Frascati & Lanzoni, 2010; Chen & Tang, 2012; Jahani *et al.*, 2013), sediment and organic materials, and boundary characteristics such as geology (Blanckaert, 2003; Gordon & Meentemeyer, 2006; Cserkész-Nagy *et al.*, 2010), land use (Yousefi *et al.*, 2016), and anthropogenic elements (Dai *et al.*, 2008; Howard, 2009; Güneralp *et al.*, 2012) all affected river morphology. Alluvial river dynamics are important for human life because of spatial displacement in floodplains and changes in flood risk (Spitz *et al.*, 2001; Güneralp & Rhoads, 2009; Engel & Rhoads, 2012; Güneralp *et al.*, 2012; Yousefi *et al.*, 2016). Studies have discovered river systems as one of the most important variables in the morphological changes of floodplains. The modification of one of the morphological variables of a river can result in the alteration of other morphological and ecological characteristics of the river, including channel depth (Frothingham & Rhoads, 2003), sedimentation, and erosion process (Chu *et al.*, 2006; Engel & Rhoads, 2012; Yousefi *et al.*, 2019), restoration projects (Lorenz *et al.*, 2009; Lorenz & Feld, 2013), and urbanization development (Alayande & Ogunwamba, 2010; Lorenz & Feld, 2013). Therefore, changes in the fluvial system, such as morphological changes, are evident indicators of modified dynamics and characteristics of the system. The river is vulnerable to erosion and deposition to reach the equilibrium stage. The identification of erosion hazards and changes in land-use/land cover characteristics, as well as understanding the reasons for those changes, need the mapping of changing channel position.

River morphology refers to the cross-sectional form of a river channel and how the section of a river varies subject to sedimentation and erosion from banks and beds (Manjusree *et al.*, 2013). Riverbank erosion is a natural hazard that occurs frequently. Rivers get sluggish and produce meander bends when they reach maturity. Massive riverbank erosion is caused by these oscillations (Rahman, 2010). For detecting spatio-temporal changes in river erosion, much research has been carried out using remote sensing and GIS (Geographic Information System) techniques for some major rivers (Kotoky *et al.*, 2005; Sarkar *et al.*, 2012; Sinha & Ghosh, 2012; Gogoi &

Goswami, 2014; Verma *et al.*, 2021). Depending on the environment, bank erosion and channel migration can occur on different timelines (days, years, decades). Erosion can occur due to the undercutting of higher bank materials by channels during high floods, resulting in an overhanging cantilevered block that eventually fails, or due to overstepping of bank materials due to thalweg migration closest to the bank during the falling stages (Goswami, 2002). It has several negative socio-economic consequences, such as Serbian farmers losing fertile fields on the Danube's left bank due to flooding (Dragicevic *et al.*, 2012). Between 1970 and 2000, bank erosion in Bangladesh's Padma and Jamuna rivers displaced more than 2 million people from their homes (Islam & Rashid, 2011). The Ganga River near Allahabad, India, experienced a substantial morphological change (Pati *et al.*, 2008). Bihar and Assam were two of India's most extensively flooded and erosion-affected states, according to the National Disaster Management Authority of India (NDMA, 2014). The Brahmaputra Board, India, and the Space Application Centre (SAC), Ahmedabad, India (SAC and Brahmaputra Board, 1996), collaborated on a study in 1996 to determine the effects of river erosion on Majuli Island and to identify and demarcate the island portions that had changed along the bank line due to the river's dynamic behavior. From 1973 to 2003, remote sensing data were analyzed using the GIS tool to estimate bank erosion in the Brahmaputra River at Agyathuri, Assam, India (Bhakal *et al.*, 2005). The variations in the Brahmaputra river flow between 1970 and 2002 were studied using Landsat-MSS, TM, and ETM images (Das & Saraf, 2007).

Several researchers investigated the impact of urbanization on the hydrological, geomorphological, and biological processes in the fluvial system (Clark & Wilcock, 2000; Kondolf *et al.*, 2007; CJ McCann, 2013; Das *et al.*, 2014). Human interaction changes river courses by focusing on man-made barriers that control flow rates (Gregory, 2006). Many developing nations with high population growth experience particularly significant changes (UN-Habitat, 2014). Urban expansion is not restricted to large metropolitan areas; it also occurs in medium and small cities (Riad *et al.*, 2020). Riad *et al.* (2020) found that the high rate of increase in the urban area significantly affects water resources in the peri-urban portion which is responsible for environmental strain. Significant land-use changes occur over short enough time scales that aerial photographs can be utilized to compare and assess channel geometry changes, specifically channel width and urbanization effect over the land (Galster *et al.*, 2008). The degree of channel change due to urbanization depended on transport and connection of affected areas and receiving channel characteristics (Bledsoe & Watson, 2001). The intricate link between urbanization and channel morphology comprises various aspects. For instance, Leopold (1970) discovered that residential expansion in the United States narrowed the channel width of a river for 20 years. An increase in channel widths and homogeneity is one of the effects of urbanization (Doll *et al.*, 2002). This rise reduced flow length and drainage intensity (O'Driscoll *et al.*, 2009, 2010). Urbanization also led to an increase in the amount of runoff. Water, sediment, nutrients, and other materials have all been affected by changes in land use. Urbanization near rivers and streams reduces the time for certain natural events. Urbanization influences stream flow, sediment transport and deposition, channel bank stability, and channel widening (CJ McCann, 2013). Urbanization can significantly impact the water cycle within a drainage basin. During urban development, trees and other vegetation are typically removed and replaced with impermeable surfaces. These land-use changes reduce precipitation infiltration, forest cover interception, and drainage efficiency. These effects reduce lag time, increase the hydro-graph peak, and increase total runoff for specific rainfall amounts (Anderson, 1970). The risk of slope erosion rises due to deforestation exposing the soil (Johnson & Beschta, 1980). The degree of riffle embedding and the size of the particles were variables that provided a useful indicator of how the stream might react to impacts from humans (Price & Leigh, 2006). Due to the urbanization of some areas of the basin, stream flow and storm runoff have increased in Baltimore, Maryland (Nelson *et al.*, 2006). The minor land-use changes significantly impacted regional soil erosion rates and sediment transport to China's Lushi river basin (Wang *et al.*, 2012). The upper Brahmaputra plains' river dynamics impacted land usage and directly impacted floodplain people's livelihoods (Hazarika *et al.*, 2015). Flooding and river meandering are impacted by deforestation (Barasa & Pereram, 2018; Adnan *et al.*, 2019). The LULC of the bank adjacent valley region is changed by stream erosion-accretion, exposing locals to hazards (Thakur *et al.*, 2012). Therefore, it is indicated from the literature that urbanization was one of the prime influencing factors regarding river morphological changes.

Most human populations have grown up near rivers, particularly in floodplains. As a result, research on the effects of urban sprawl on alluvial rivers' geomorphology is necessary to advise landscape managers. Especially in the context of LULC changes in terms of channel modifications, the current work attempts to link the status of such changes utilizing modern methodologies. The future behavior of fluvial systems can be anticipated by understanding pattern changes in fluvial parameters throughout urban growth. This can assist watershed managers in better understanding the consequences of land cover changes, particularly urban development, on fluvial system characteristics, allowing them to make better management decisions and reduce the damage caused by river alteration.

1.1. Present study

The Barak River flows parallel to the Brahmaputra in the southeast part of the Himalayan range in northeastern India, covering roughly 1.38% of the country's total geographical area (Nath & Ghosh, 2022). The landscape comprises hills and plain land terrain; the plain region is surrounded on three sides by hills, except in the west (Singh & Ghosh, 2022). The floodplain areas are made up of different LULCs, including agricultural fields, tea garden complexes, rural and urban populations, and abandoned and uncultivated areas (Das & Das, 2014). Rivers, streams, ponds, oxbow lakes, floodplains, seasonal wetlands, marshes, and waterlogged areas make up a large part of the terrain (Reang *et al.*, 2018). The Barak River's discharge and sediment carrying capacity have increased (Annayat & Sil, 2020a). The channel behavior of the Barak River was studied using satellite imagery and field data to identify river sections that remained stable between 1910 and 1988 (Bardhan, 1993). Between 1918 and 2003, a quantitative investigation of the Barak River found an increasing trend in erosion and deposition (Laskar & Phukon, 2012). The study's goal was to evaluate how much flow management was needed in upstream catchments to provide safe flow at downstream damage locations in the Barak River (Choudhury *et al.*, 2014), which was used to detect changes in the river's planform features. Furthermore, massive bank shifting in the Barak River was investigated, with the study predicting that it will soon have severe consequences for the economy and people's livelihood (Annayat & Sil, 2020b).

The valley is influenced by the river's high meandering and shifting behavior in various places (Nath & Ghosh, 2022). Increased urbanization has also been a concern for the valley in recent decades. Land usage, land cover, and river morphology are all linked, according to past research. LULC investigations, on the other hand, are critical for land and water resource management, particularly in flood-prone, highly meandering regions such as Barak. Despite the importance of this issue, there are no clear studies in this region that have addressed the dynamic relationship between river morphological changes and urbanization effects on river morphology. The main goals of this study are to (i) investigate morphological changes in the meandering river Barak, which is one of the most important and largest rivers in North-East India, from 1990 to 2020; and (ii) to assess the effects of urban development on floodplains and their impact on river morphology.

1.2. Study area

River Barak flows into Assam at 24° N latitude and 93° E longitude from the Naga Hills' Barail Range at roughly 2,995 m. Surma and Kushiyara separated the river Barak on its way to Bangladesh. Several abandoned meandering loops and decadal shifts can be found in the river Barak, which flows through India's tropical region. The Barak River is approximately 900 km long, 532 km in India and the remaining kilometers in Bangladesh. The

Barak valley in Assam was followed for 129 km out of 532 km in India. The Barak valley is located in the southwest monsoon zone and has a width of around 25–30 km (Choudhury *et al.*, 2014). Katakhal, Jiri, Chiri, Modhura, Longan, Sonai, Rukni, and Singla are the main tributaries of the river Barak. The Barak River channel position has varied significantly throughout the Barak valley, with a considerable northward trend to the west of Silchar (Das, 2012). Since the river flow followed a severe meandering pattern, many erosion events resulted in river migration during most of the study period. Meanders flow through floodplains when alluvial rivers erode and deposit silt along their banks, resulting in course shifts. Cut-off development is always conceivable in the research area due to considerable sinuosity and erosion. As a result, long-term planning is essential to mitigate flood and erosion damage. Silchar, in Assam's Barak Valley, is one of the busiest towns in northeast India. It connects Tripura, Manipur, Mizoram, and Southern Assam as a significant commercial hub. As a result, flood and erosion damage mitigation planning is essential, particularly for this major town and its surroundings.

2. MATERIALS AND TECHNIQUES

2.1. Data collection

The multi-spectral remote sensing and Landsat data used in this study were contributed by the United States Geological Survey (USGS). Between 1990 and 2020, Landsat images were taken every 10 years (Table 1).

2.2. Techniques

This study included two types of analysis. The study's first aim was to investigate morphological changes concerning changes in the sinuosity index, which were linked to bank erosion. The second goal was to identify land-use changes and their impact on river morphological changes. The methods for analyzing bend characteristics and quantities of LULC change over the channel length in the chosen study reach using remotely sensed data are represented in Figure 2.

The morphological analysis was carried out using the sinuosity of the segments (as shown in Figure 1) associated with their river migration. Sinuosity was calculated using decadal layer stacking of Landsat data (S). Using ArcMap software, the flow path distance (C) and meander neck length (L) of each decade were calculated. Flow path distance (C) was divided by meander neck length to calculate sinuosity (L). River migration analysis was carried out by digitizing the river's center line from each Landsat image. Then, to detect river morphological behavior, a correlation between river migration and sinuosity was performed.

$$S = \frac{C}{L} \tag{1}$$

where S refers to the sinuosity, C refers to the flow path distance, L refers to the meander neck length.

Table 1 | Satellite data used in the study.

ID	**Landsat 5**	**Landsat 7**	**Landsat 7**	**Landsat 8**
Year	1990	2000	2010	2020
ID	TM	ETM +	ETM +	ETM +
Path	146	146	146	146
Row	43	43	43	43
Resolution (m)	30 × 30	30 × 30	30 × 30	30 × 30

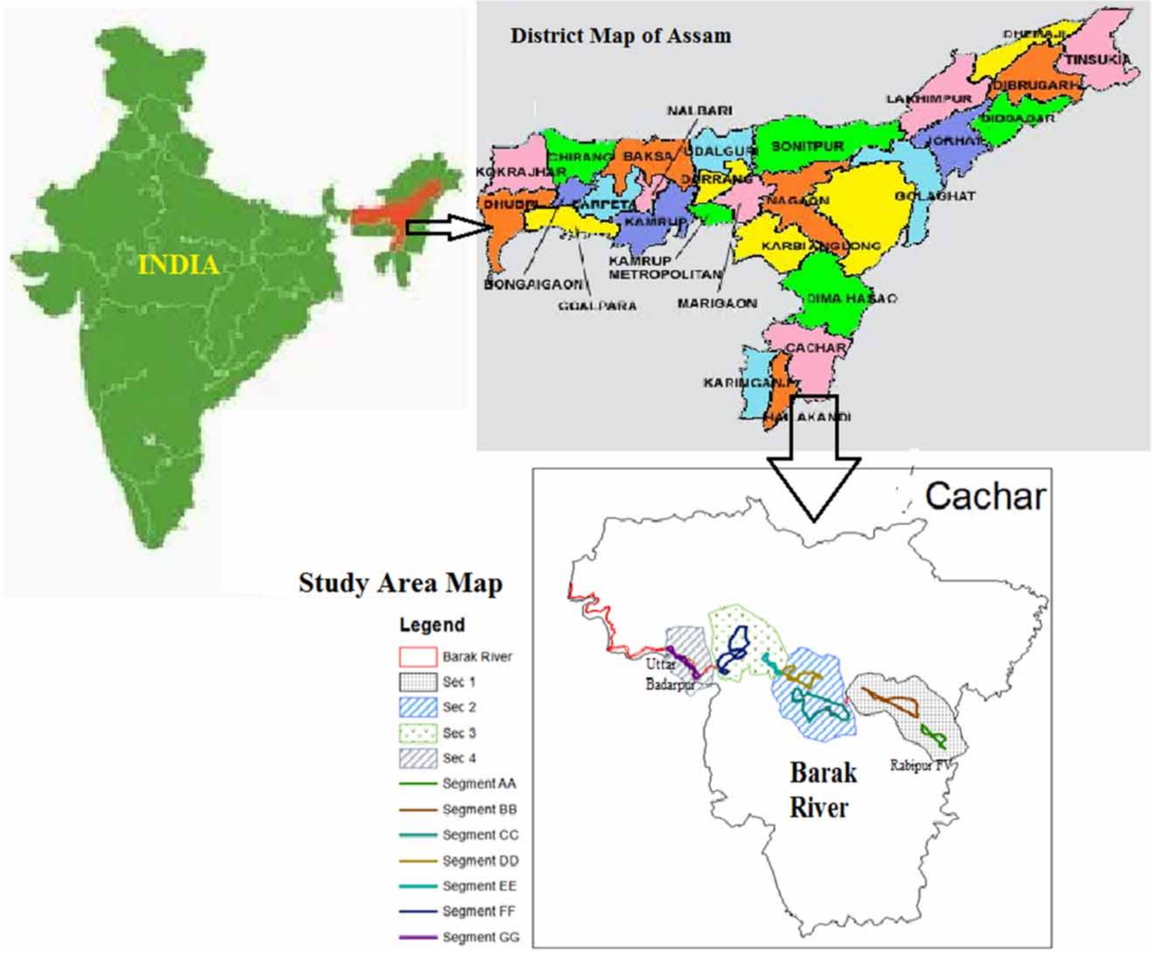


Fig. 1 | Study area map.

The methodology to calculate the sinuosity index was shown in the flow chart (Figure 2). The spatial variation of the sinuosity index was calculated segment-wise by dividing the study area into seven segments (AA, BB, CC, DD, EE, FF, and GG).

The morphological assessment over the study area varies very frequently. Therefore, The LULC investigation of the study area was divided into four sections (Sec 1, Sec 2, Sec 3, and Sec 4) to identify morphological behavior closely. The section includes various segments of the study area that were notified in Figure 1. The maximum likelihood (ML) classifier (supervised classification) has been commonly used because of its availability and lack of a long training process. The ML classifier uses the likelihood that a pixel belongs to a specific class. ML was used to classify Landsat images. The ERDAS software generated an area of interest polygons using the reference data samples. Sub-setting, layer stacking, and complete composition are all required for Landsat image per-processing for land-use mapping. The flowchart depicts the progressive procedures of land-use mapping (Figure 2). User-developed spectral signatures of known categories were used in supervised classification. The goal of the study area's LULC mapping is to determine changes in land-use patterns between 1990 and 2020. The study area

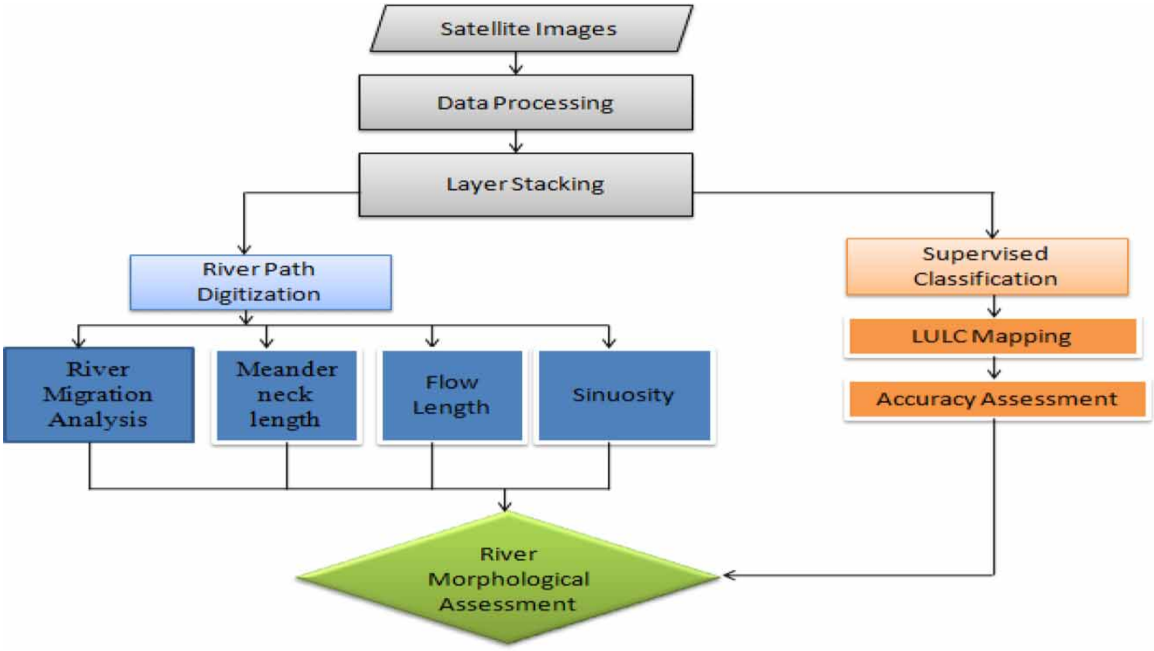


Fig. 2 | Flow chart of investigation.

was divided into five classes: bare soil, settlements, agricultural land, forests, and water bodies. To assess the accuracy of the categorized maps, a post-classification accuracy assessment was conducted. Various studies have investigated the accuracy of LULC maps using methods such as the Kappa coefficient, error matrix, and indices (Manandhar *et al.*, 2009; Rahman *et al.*, 2019; Kumari *et al.*, 2019). The kappa coefficient was calculated using the formula below.

$$\text{Kappa coefficient} = \frac{\sum_{i=1}^{\mathrm{m}} \mathrm{O}_{ii} - \sum^{m} n_{ii}(\mathrm{T}_1\mathrm{A}_1)i = 1}{n^2 - \sum_{i=1}^{m} n_{ii}(\mathrm{T}_1\mathrm{A}_1)} \tag{2}$$

where m is the number of rows in the matrix, O_{ii} denotes the number of observations in row i and column i, T_i denotes the total number of categorized pixels in class i, and A_i denotes the total number of actual data pixels in class i.

A morphological assessment based on river position and LULC changes was analyzed simultaneously, which will aid land and river management in the study region.

3. RESULTS

3.1. Morphological assessment

The morphological investigation was investigated along with river segments from 1990 to 2020 using ArcMap and corresponding changes in river morphology. The present study chose 134 km of river reach to investigate river Barak migratory characteristics critically. The river reach was separated into seven segments (AA, BB, CC, DD, EE, FF, and GG) within the study area (Figure 3). Sinuosity was calculated by determining the flow path length of the river divided by meander neck length for that period. The output of sinuosity analysis over each segment was summarized in Table 2.

The most stable sections are Segment AA, which started from Robipur F.V. to Alni Grand (Figure 3). The average sinuosity of the segment varies from 1.47 to 1.51. The average river migration was lower than other segments (28.93 m) as shown in Table 2. The variation of sinuosity was also lower than comparing other portions of the study area. For the next Segment BB, the sinuosity varies from 1.11 to 1.22. The variation of sinuosity was higher than upstream Segment AA, indicating higher vulnerability. The average variation over the segment between the study periods was 67.3 m. The next Segment CC, which runs from Shibpur Pt I to Dadripar Pt V, was one of the vulnerable sections from the upstream study area. The average migration over the section between 1990 and 2020 was 232.79 m. This was very much higher comparing other segments except Segment GG. This is

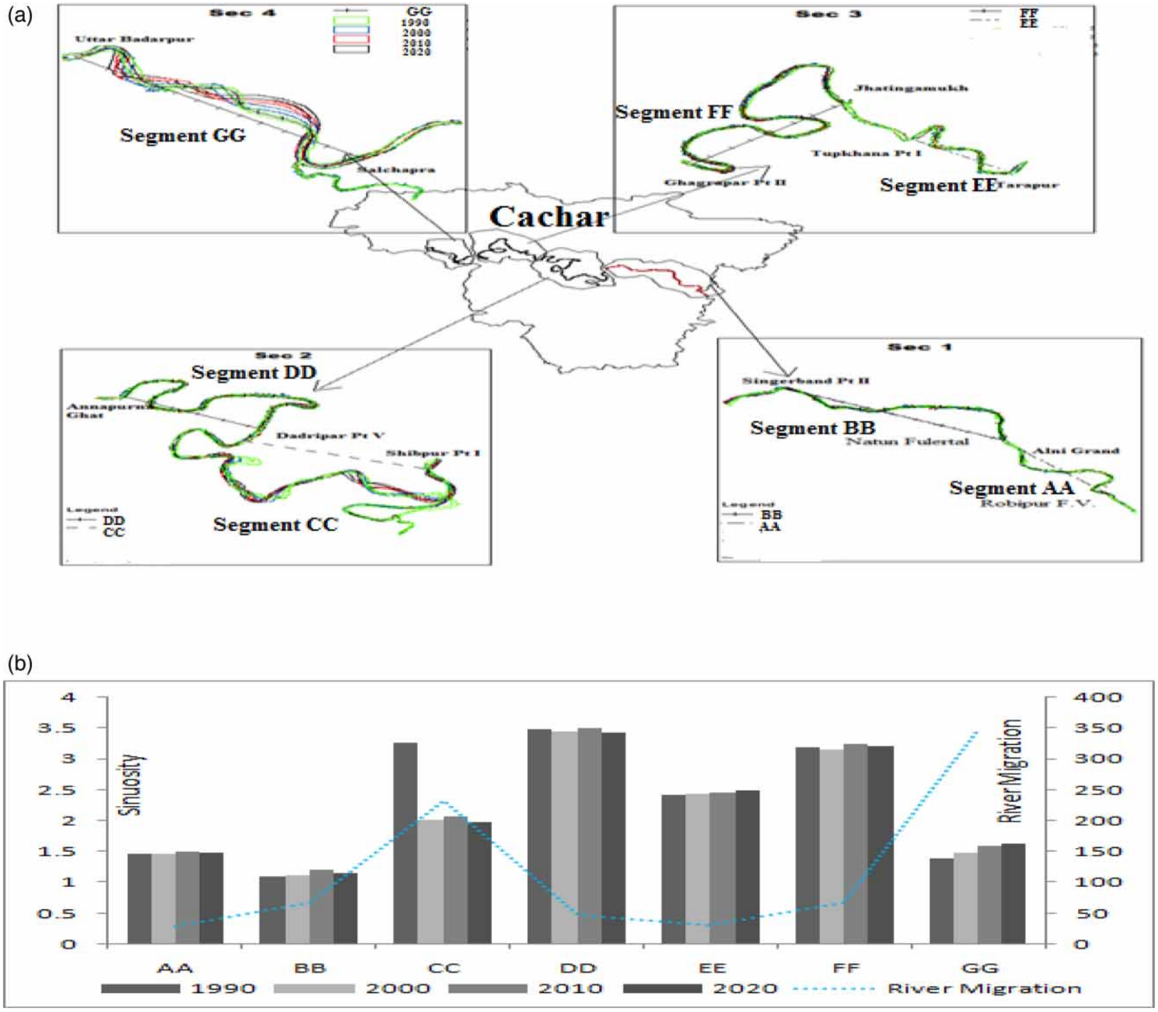


Fig. 3 | (a) River sections within the study area and (b) segment-wise sinuosity changes and river migration over the study period.

Table 2 | Segment-wise river morphological analysis.

AA	Flow path length (*C*)	Meander neck length (*L*)	Avg. Migration 1990–2020	C	BB	Flow path length (*C*)	Meander neck length (*L*)	Avg. Migration 1990–2020	C
1990	11,334	7,702	28.93	1.47	1990	8,443	7,599	67.3	1.11
2000	11,634	7,945		1.46	2000	8,500	7,541		1.12
2010	11,712	7,725		1.51	2010	9,186	7,530		1.22
2020	10,973	7,361		1.49	2020	8,559	7,413		1.15
CC	**Flow path length (*C*)**	**Meander neck length (*L*)**	**Avg. Migration 1990–2020**	**C**	**DD**	**Flow path length (*C*)**	**Meander neck length (*L*)**	**Avg. Migration 1990–2020**	**C**
1990	27,100	8,288		3.26	1990	14,589	4,189		3.48
2000	16,277	8,079		2.01	2000	14,634	4,239		3.45
2010	16,436	7,870		2.08	2010	14,340	4,097		3.50
2020	16,310	8,254	232.79	1.98	2020	14,532	4,221	46.59	3.44
EE	**Flow path length (*C*)**	**Meander neck length (*L*)**	**Avg. Migration 1990–2020**	**C**	**FF**	**Flow path length (*C*)**	**Meander neck length (*L*)**	**Avg. Migration 1990–2020**	**C**
1990	6,661	2,741		2.43	1990	23,991	7,480		3.20
2000	6,915	2,833		2.44	2000	23,171	7,324		3.16
2010	7,045	2,866		2.45	2010	24,472	7,507		3.25
2020	6,992	2,793	30.06	2.50	2020	24,414	7,604	66.6	3.21
GG	**Flow path length (*C*)**	**Meander neck length (*L*)**	**Avg. migration 1990–2020**	**C**					
1990	9,785	6,766		1.40					
2000	10,316	6,967		1.48					
2010	10,994	6,897		1.59					
2020	11,392	6,984	345.65	1.63					

because an oxbow formed near Sonaimukh (Kaptanpur) between 1990 and 2000, cutting off a large section of the river course from the main Barak. As a result, the center line distance in this part of the river decreased significantly (10.26 km) between study periods. Therefore the sinuosity of the section varies between 3.26 and 1.98. A sharp reduction of sinuosity affects the portion of land and makes the land more vulnerable, as migration analysis indicates. For the Segment DD, which runs from Dadripar Pt V to Annapurna Ghat was stable parts primarily Silchar township areas. Where maximum of the sharp curved bend of river protected by protection structure. Therefore, the variation of sinuosity was also less (3.44–3.50) and river migration was much less than upstream Segment CC. The next Segment EE was considered upstream Tarapur to Tupkhana Pt I. Subsequently, and the Segment FF starts from Jhatingamukh to Ghagrapar Pt II. For Segment EE, the sinuosity varied from 2.43 to 2.50 with a river migration of an average of 30.06 m within the study period. Also, for Segment FF, the average sinuosity was between 3.16 and 3.25 with a river migration of 66.6 m on average. The Segment GG was considered from Salchapra to Uttar Badarpur. From 1990 to 2020, this land area exhibited the highest migration activity, as per morphological investigation indicated. The sinuosity of this segment varies between 1.40 and 1.63. High shifting characteristics of rivers were observed within this portion of the study area. Almost 345.65 m on the average River shifting was observed between the study periods. Since 2005, some protection control policies have been taken especially in this part of the river. Therefore, a significant reduction in migration activities with incremental sinuosity was observed in this segment. The overall river migration and changes in sinuosity were summarized in Figure 3.

After morphological investigation over the study period, it was concluded that river migration activities vary from segment to segment. The highest affected areas due to river migration were segments GG and CC. A considerable sinuosity fluctuation was also detected in this section of the river.

3.2. Land-use land-cover analysis

The segment-wise river characteristic was the difference. Therefore, the study area was further divided into four sections (Sec 1, Sec 2, Sec 3, and Sec 4) to identify land-use change parameters correctly for each section (Figure 4) and notify the changes (Figure 5).

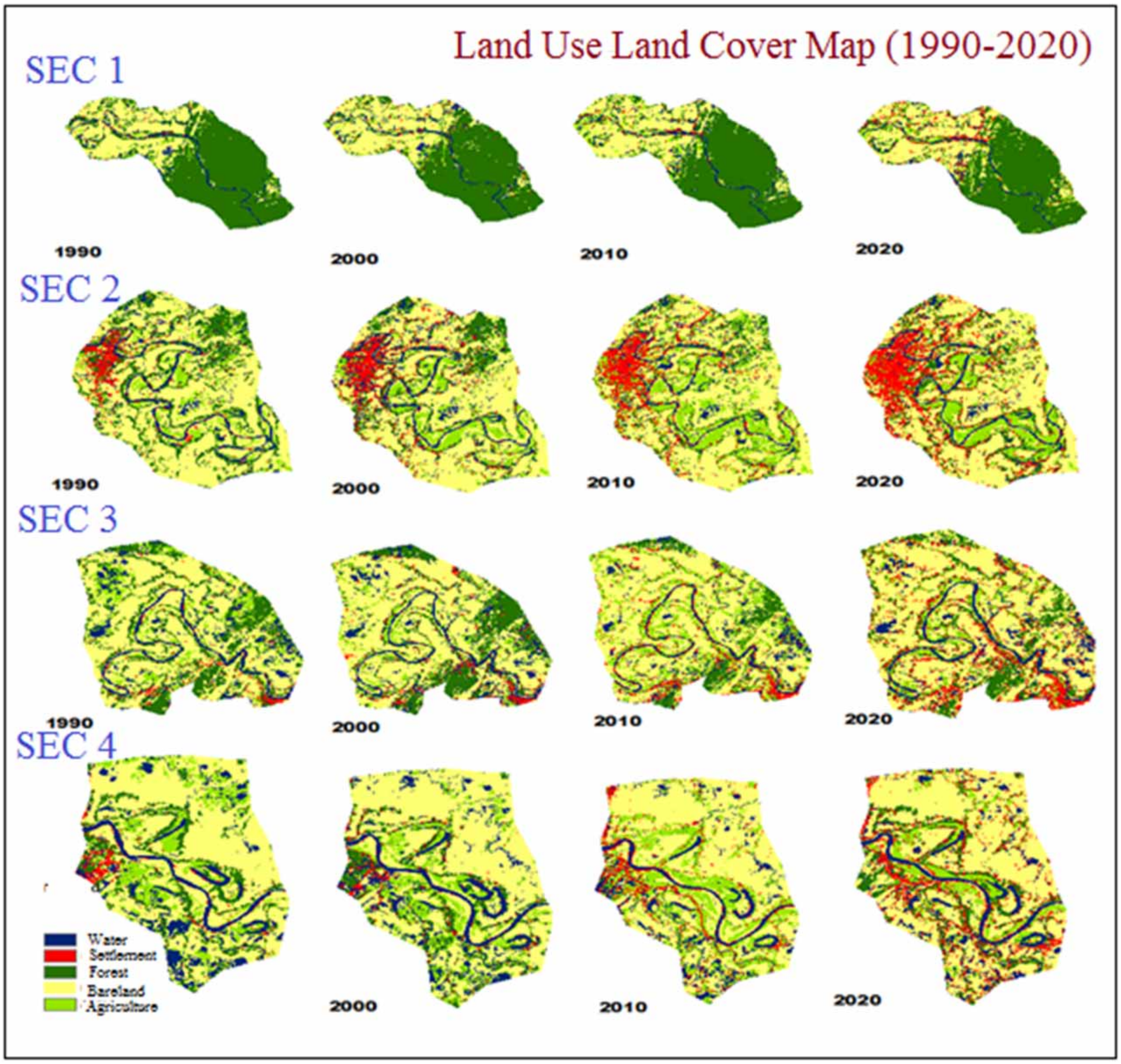


Fig. 4 | LULC mapping over Sec 1 to Sec 4 (1990–2020).

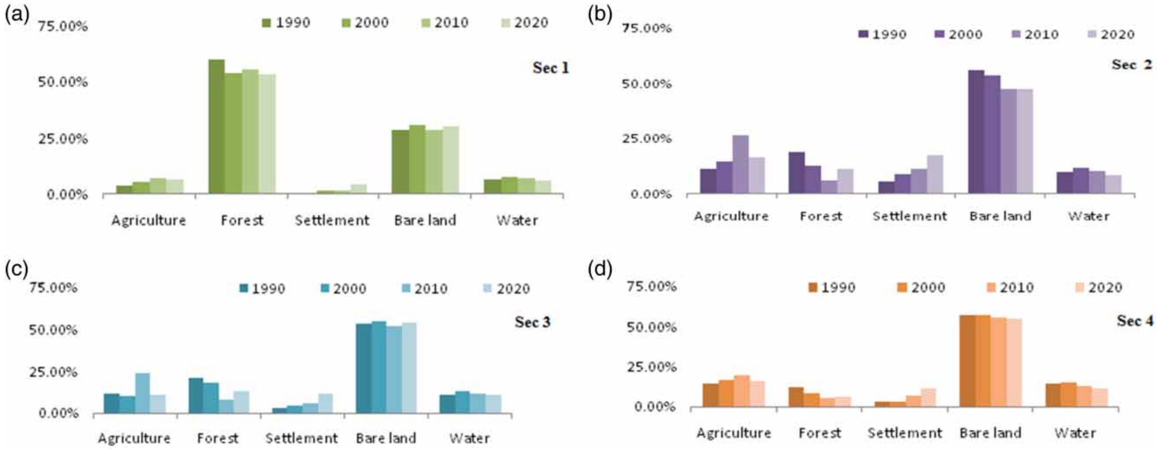


Fig. 5 | (a) LULC variation over Sec 1; (b) LULC variation over Sec 2; (c) LULC variation over Sec 3; and (d) LULC variation over Sec 4.

According to sinuosity and river migration studies, both segments AA and BB are mostly stable in terms of river stability (Figure 3(b)). In the study area, section AA was the most stable segment. As a result, for LULC mapping, both segments were concatenated in Sec 1 (Figure 3(a)). Figure 4(a) shows the results of decadal LULC mapping at Sec 1. During the study period, deforestation had a significant impact on the land. According to LULC mapping from 1990, over 60.3% of the entire area in this section was covered in deep hilly forests. According to LULC mapping, forest land was reduced to 53.3% in 2020. The increase in agricultural practice from 3.7 to 6.4% throughout the study period was also influenced by urbanization. In places where more than 50% of the land is still under forestry, agricultural land is still less influenced than other parts of the study area; less than 5% of the land area was used for settlement. However, within the last decade (2010), this part of the river has seen a significant increase in Settlement (from 1.9 to 4.4%). For LULC analysis, segments (CC and DD) were treated as Sec 2 (Figure 3(a)). A section-by-section LULC analysis shows considerable variations in LULC practice over time (Figure 4(b)). Between 1990 and 2010, the percentage of forest land declined from 18.5 to 5.6%. During the LULC study, settlement increased from 5.20 to 11%, while agriculture increased from 10.91 to 26.91%. All those parameters, such as urbanization, agriculture, and forestry, were heavily influenced by river migration in this zone. For the following two segments (EE and FF), for identification of land-use patterns of those segments, these portions are grouped as Sec 3 for LULC analysis (Figure 4). Figure 4(c) shows the LULC mapping for these sections. In the last decade, the zone has become more urbanized due to reduced forestation and increased settlement and agricultural activities. Within the last decade, the rate has risen dramatically from 6.1 to 11.6% for settlement. For the final Segment GG, it was taken into a single section, which was denoted as Sec 4. The LULC analysis of the section is shown in Figure 4(d). Compared to other parts where urbanization was a big concern at the time, the LULC outcome was similar. A sharp development in urbanization relates to increased agricultural activity and settlement land. Within the study period, a sharp increase in settlement from 2.8 to 11.1% and a constant loss of forest land (from 11.8 to 5.2%) significantly impacted river migration.

Except for Sec 1, all vulnerable sections were severely impacted by urbanization. In the present study, it was discovered that land-use parameters, such as the rate of settlement and the rate of agriculture practiced, fluctuated significantly over a decade, with a consistent loss of forest land seen throughout the study. From the LULC study, the LULC influencing parameters and their characteristics on river morphology needed to be identified to understand their characteristic toward river migration further. Therefore, the percentage of increment of those unstable LULC parameters within the study period was studied (Figure 6(a)–6(c)).

Settlement increased significantly throughout the section. Significant deforestation occurred in all sections between 2000 and 2010, as well as an increase in agricultural activities (Figure 6(a)–6(c)). Between 1990 and 2010, a 60% increase in agricultural methods was observed in Sec 2. During the previous decade, the settlement increase was nearly 60%. From 1990 to 2010, 45% of forest land was lost due to urbanization. For Sec 3, a sharp rise in agriculture practice was observed from 2000 to 2010. Within this section of the study area, about 80% forest land increment was observed during the last decade. For Section 4, a significant increase (95%) of the settlement area was impacted by the loss of 35% of the forest land within this section of the study area between the years 2000 and 2010. Still, 30% of the land was lost during the last decade, making the land more urbanized.

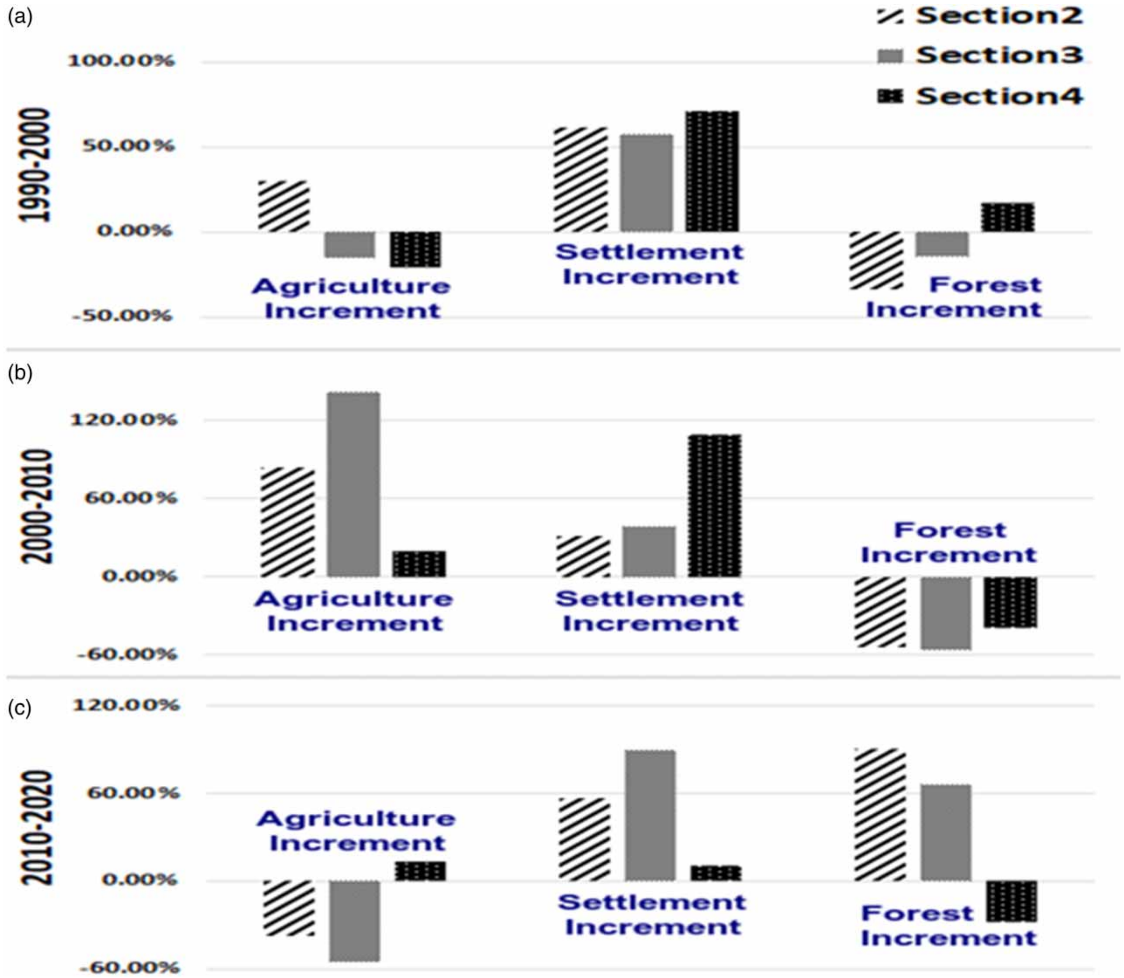


Fig. 6 | (a) 1990–2000 increment of influencing parameter of river migration for unstable sections; (b) 2000–2010 increment of influencing parameter of river migration for unstable sections; and (c) 2010–2020 increment of influencing parameter of river migration for unstable sections.

Although there has been significant improvement in LULC characteristics over the last decade, particularly in sections 2 and 3, the rate of settlement increment over the decade is still relatively high (Figure 6(a) and 6(b)).

3.2.1. Accuracy assessments

The accuracy of LULC maps utilizing randomly picked points was evaluated using the Kappa coefficient technique in this study. The points were chosen to approximately evenly represent each of the LULC classes and came from throughout the study region. Because field data were not accessible between 1990 and 2010, the ground observations were gathered from the Google Earth Pro-domain. Furthermore, for the year 2020, ground observations were derived in part from field visits and the Google Earth pro-domain. The assessment results show an overall accuracy level of 85.57, 82.60, 80.57, and 79.69% for 1990, 2000, 2010, and 2020, respectively, with Kappa statistics of 0.837, 0.818, 0.787, and 0.774.

4. DISCUSSION

The most vulnerable segments within the study area were Segments CC and GG. This was covered under Sec 2 and Sec 4, respectively. The highest percentage of settlement land was covered under Sec 2. Almost 17.2% of the total area of the section was covered under the settlement by 2020 LULC. Also, a high percentage of land was covered under agriculture practices in the section. Also, for Sec 4, almost 20% of the total land of the section covers under agricultural practice by 2010 LULC. A sharp rise in settlement and agricultural practices greatly influenced river stability.

Each section's most influenced LULC parameter can be identified. Except for Sec 1, all susceptible areas have been severely impacted by urbanization. In the current study, area usage parameters such as the rate of settlement and the rate of agriculture changed considerably over a decade, with a continuous loss of forest and bare land observable throughout. Therefore, Figure 7(a) shows the black highlighted region of the most affected area (especially Sec 2) due to settlement from 1990 to 2020, primarily due to the growth of Silchar township areas. In Figure 7(b), the red highlighted areas reflect the areas that have been most affected due to agricultural activities. The most agriculturally affected areas are mostly those at the river's bank side, particularly those (Sec 2 and Sec 4) where the river migration rate is substantially higher than the rest of the area. The agricultural activity observed increases nearby floodplain region where comparatively high settlement occurred (Figure 7(a) and 7(b)). According to a literature review, settlement and agricultural practices both impacted river morphology simultaneously (Anderson, 1970; Wohl, 2000; Bledsoe & Watson, 2001; Nelson *et al*., 2006; Price & Leigh, 2006; Galster *et al*., 2008; Yousefi *et al*., 2019). Human involvement and riparian land-use changes can sometimes increase riverbank erosion (Gordon & Meentemeyer, 2006; Rutherfurd & Price, 2007; Yanan *et al*., 2011). Urbanization simultaneously increases agriculture activities in the present study area. Due to intensive agriculture, pesticides and herbicides become more useful for more growing up of agriculture. Heavy intensive farming methods destroy soils by interfering with natural soil processes and make more vulnerable toward river stability (Burnette & Agouridis, 2014; Sial *et al*., 2021). Hence from the present analysis, it is also identified that urbanization lead to increase agriculture practices as well as human interference and both affect toward river morphology.

On the other hand, an oxbow was produced when a major portion of the river channel between Govindapur and Satrakandi (Segment CC) was cut off from the main Barak. One of the main reasons for the high migration rate over the decade in Segment CC was the oxbow formation. Large river areas have been cut off from the main Barak due to oxbow formation, exposing the land to hazards. The most seriously damaged downstream after the oxbow are Govindapur, Sonabarighat II, Sonabarighat I, and Satrakandi. A sharp rise in urbanization and

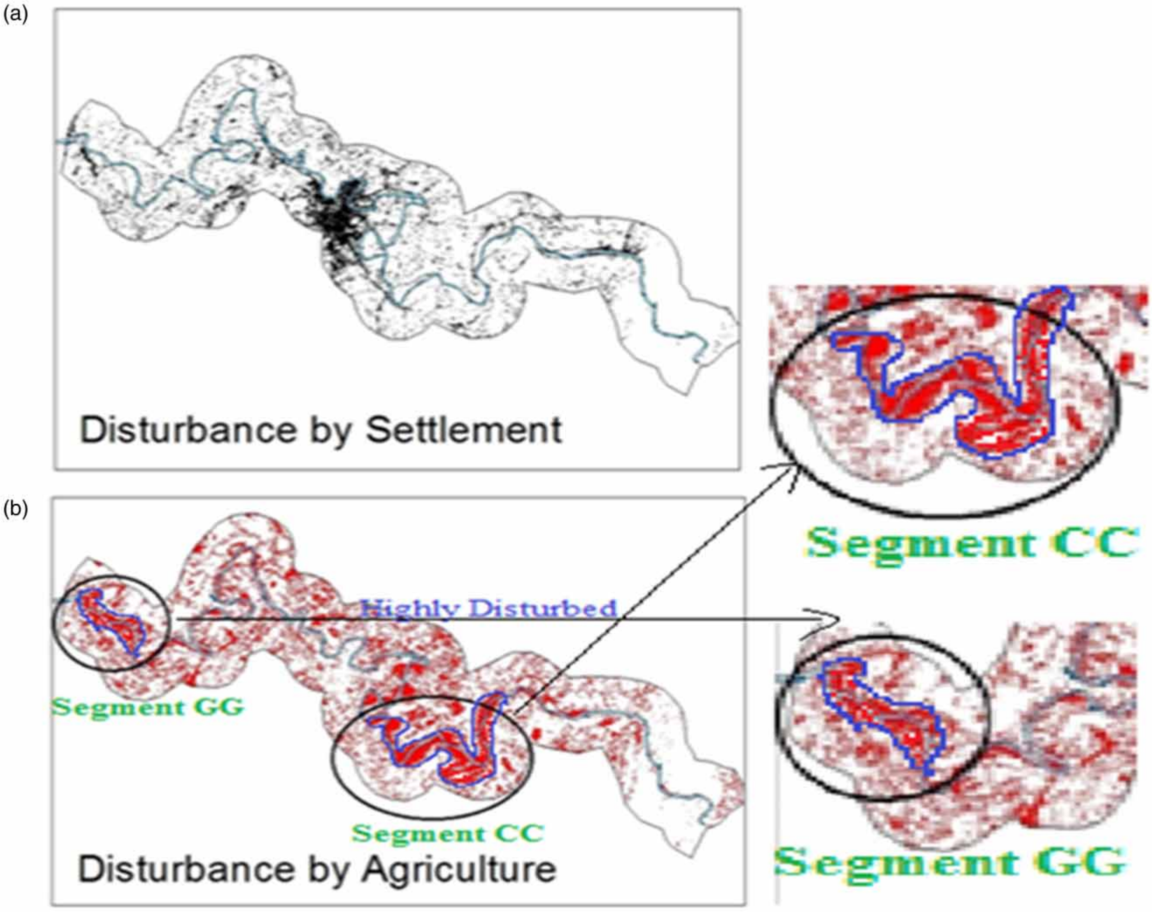


Fig. 7 | (a) Changes in the settlement and (b) changes in agriculture practices. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wp.2022.133.

morphological changes due to oxbow both affect the stability of the river, particularly in this segment of the study area.

However, for Sec 4, because NH 38 is so close to the vulnerable zone at Polarpar (Segment GG), this land has a greater priority for future morphological assessment. This highway is the only way to get from Silchar to the rest of the country. According to data from the water resource department and river migration analysis, the highway has already seen significant erosion during the recent floods. However, following the erection of suitable protective structures within this zone in 2017, the erosion effect has decreased, even during high peak discharge periods. As a result, good land and river management may help to mitigate the effect soon.

5. CONCLUSION

The present work indicates that multi-temporal satellite data (Landsat) can be used to monitor river morphological activity with LULC changes using RS and GIS. The present analysis shows that rivers migrate very slowly between Sec 1 and Sec 3. Especially in Sec 1, where there were less urbanization and agricultural operations, the sections are more stable in terms of river stability. Sec 2 was considered one of the most vulnerable segments within the study area. Where high migration is observed within sections, especially Segment CC. The difference in sinuosity was due to a large cut-off near Sonaimukh, Dhamalia and Baghadhar are key areas for future oxbow development. Erosion is rapidly increasing there. Although identifying critical urbanization and agricultural activity from coarse resolution images was difficult. However, the LULC analysis of Sec 4 found that, like the other three sections, urbanization and agricultural increment were significant with the loss of forest land. This was one of the prime influencing factors toward the river instability aspect. But since from last decade, there were some river protection policies have been imposed within the study area, especially for Sec 2 and Sec 4. As per field visits and local interviews, a huge reduction in erosion activities from that vulnerable section was observed in the last decade. As erosion becomes more complex, localized bank protection cannot provide a long-term answer to the problem of executing and maintaining protection activities. As a result, this research will aid in determining the long-term impact of LULC on river migration and meandering river morphology. It shows why it is critical to create and implement sustainable watershed development policies to keep the urbanization effect on the vulnerable catchment area in balance. With the right conservation measures and land-use management, this sort of highly migratory river might be protected. As a result, this study will assist in assessing the long-term influence of LULC on river migration and the morphology of meandering rivers. It explains the importance of developing and implementing sustainable watershed development policies to maintain the urbanization effect on the vulnerable catchment area.

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AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by A.N. and S.G. The first draft of the manuscript was written by A.N. and final manuscript checked by S.G. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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