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# Riverbank Erosion, Accretion, and LULC Dynamics in the Raidak-II River Basin: A Geospatial Analysis in Alipurduar, West Bengal

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**ABSTRACT: This study investigates the spatio-temporal dynamics of riverbank erosion, accretion, and land use/land cover (LULC) changes along the Raidak-II River in the flood-prone foothills of the eastern Himalayas in Alipurduar District, West Bengal, over 20 years (2003–2023). The river, shaped by intense monsoonal floods and geomorphic activity, was analyzed using multi-temporal Landsat imagery (2003, 2013, 2023) and processed through remote sensing (RS) and geographic information system (GIS) techniques. The primary objectives were to delineate zones of erosion and accretion, quantify their extent over time, and assess associated LULC transitions. The results indicate a total erosion of 6.79 km² and accretion of 28.94 km², with a net land gain of 22.15 km². Decadal analysis reveals an 80.34% reduction in erosion and a 144.09% increase in accretion between 2013 and 2023, suggesting evolving fluvial stability due to both natural and anthropogenic factors. LULC analysis revealed a sharp decline in cultivated land and a rise in settlements and riparian vegetation, highlighting land use transformation. Statistical analysis using the Friedman Test (p = 0.0054) and Dunn's Post-Hoc Test confirmed significant differences in LULC across the years, particularly between 2003 and 2023. The study highlights the need for policy interventions in erosion-prone zones, sustainable livelihood planning, and continuous geospatial monitoring. Future research should integrate hydrological modelling and community-based management for adaptive river basin governance.**

**Keywords**: Bank Erosion, Accretion, Remote Sensing, LULC Change, Statistical Analysis, Raidak-II River, Alipurduar.

## INTRODUCTION

Riverbank erosion and accretion are essential geomorphological processes that continuously reshape riverine landscapes, playing a pivotal role in maintaining ecological, hydrological, and morphological balance. These natural processes influence sediment transport, channel morphology, and floodplain dynamics while creating diverse habitats for both aquatic and terrestrial species (Leopold *et al*., 1964; Knighton, 1998). Erosion generates steep banks and undercuts that provide nesting sites for some species, whereas accretion forms sandbars and islands, enhancing habitat diversity. Moreover, sediments transported by rivers contribute nutrients to floodplains, maintaining soil fertility and floodplain ecosystems (Petts & Foster 1985; Nanson & Croke 1992).

However, uncontrolled or excessive riverbank erosion can cause severe socio-economic and environmental challenges. It leads to the loss of agricultural land, damage to infrastructure, displacement of populations, and degradation of natural ecosystems. Riverbank erosion typically occurs due to high flow velocities removing sediment from riverbanks, while accretion results from sediment deposition under lower flow conditions (Mukherjee *et al*., 2017). These processes are influenced by a complex interplay of natural factors such as hydrological conditions, terrain, soil characteristics, vegetation, and climatic variability, along with anthropogenic interventions such as deforestation, agricultural expansion, unplanned construction, and river engineering works (Suizu & Nanson 2018; Langat *et al.*, 2019; Alavez-Vargas *et al*., 2021).

The **Raidak-II River**, flowing through the Alipurduar district in the flood-prone foothills of the eastern Himalayas, is highly susceptible to these processes.

Characterized by seasonal monsoon floods, steep terrain gradients, and intense geomorphic activity, the river exhibits rapid bank erosion and accretion, leading to significant changes in land use and land cover (LULC) patterns (Hasanuzzaman *et al.,* 2021). However, despite these impacts, there remains a lack of systematic, long-term, geospatial studies addressing the dynamics of erosion, accretion, and LULC changes in this region. Most previous studies are either short-term or based on limited field surveys, lacking the spatial coverage and temporal depth required for comprehensive river management.

Recent advancements in **remote sensing (RS)** and **geographic information systems (GIS)** have revolutionized the monitoring of riverbank changes, enabling high-resolution, multi-temporal analysis of river systems (Wang & Mei 2016; Wang & Xu 2018). By integrating satellite imagery, spatial modeling, and LULC analysis, RS and GIS allow researchers to detect bankline migration, measure land loss and gain, and map high-risk areas with greater accuracy. Utilizing these modern geospatial tools, this study aims to generate critical insights into the river's morphological evolution, providing a scientific foundation for improved river management and mitigation strategies.

In this context, the present study aims to comprehensively assess the spatio-temporal dynamics of bank erosion, accretion, and land use and land cover (LULC) changes along the Raidak-II River over 20 years (2003–2023) using remote sensing (RS) and geographic information system (GIS) techniques. In recent years, statistical analysis has become an essential complement to geospatial techniques for interpreting and validating land use and fluvial geomorphic changes. Statistical tests are particularly useful in determining whether observed changes in land cover are significant over time or are due to random variation. Normality tests such as the Shapiro-Wilk test help assess the distribution characteristics of LULC datasets, ensuring the correct application of further parametric or non-parametric tests (Ghasemi & Zahediasl 2012). Levene's test is used to check the homogeneity of variances, which is critical for ensuring the reliability of comparative analyses (Gastwirth *et al.,* 2009). When assumptions of normality are violated, as often seen in geospatial temporal data, non-parametric tests such as the Friedman Test offer robust alternatives to repeated measures ANOVA for evaluating multi-year LULC trends (Conover, 1999). Furthermore, post-hoc tests like Dunn's Test with Bonferroni correction are applied to identify which specific years show statistically significant changes (Dinno, 2015). Integrating these statistical tools enables researchers to move beyond visual interpretation and quantify the magnitude and significance of landscape transformations, lending greater scientific rigour to geospatial environmental studies.

The key objectives of this study are to identify the spatial extent of areas experiencing bank erosion and accretion along the Raidak-II River in Alipurduar district, to quantify the magnitude of erosion and accretion within the study area over the two decades, and to identify and analyze the major driving factors responsible for these geomorphic changes, including hydrological, topographic, and anthropogenic influences.

The outcomes of this research can guide policymakers in prioritizing erosion-prone zones for disaster risk reduction, implementing livelihood diversification, improving infrastructure planning, and fostering community-based river management programs. Furthermore, the study highlights the need for integrating continuous geospatial monitoring into river basin management to ensure adaptive, sustainable strategies for the Raidak-II River and similar riverine environments.

## LITERATURE REVIEW

Many researchers have addressed riverbank dynamics and erosional and accretional processes by implementing geospatial methods. Yao *et al.* (2011) assessed the erosion and accretion over 50 years in the Yellow River, China, using topographical maps and satellite images; they observed major changes in the riverbank. Lovric and Tosic (2016) analyzed the lower stream (1958–2013) of the Bosna River and identified significant river morphology adjustments using remote sensing and GIS. Mukherjee *et al.* (2017) investigated spatial and temporal drift changes of the Ramganga River over a longer period (1923–2014) and classified erosion and accretion based on historical toposheets and Landsat images. Ophra *et al.* (2018), focusing on the Padma River, a tainted tributary of Bangladesh, studied the trend of bank erosion and associated the erosion pattern with land cover change. Hasanuzzaman *et al.* (2021) implemented DSAS and CA-Markov models to study the Kaljani River, proving their effectiveness in detecting past variations and forecasting channel changes, with possible accretion on the right bank and erosion on the left. Majumdar *et al.* (2021) examined riverbank erosion in the Manikchak Block, West Bengal, caused by the actively adjusting Ganga River. According to their findings, large tracts of fertile arable land are washed away annually, reducing agricultural yield and converting cultivable land into wasteland, thus impacting livelihoods, the economy, and food security. Ghosh *et al.* (2023) studied the confluence tendencies of the Raidak River and detected significant southward and southeastward migrations of the large confluences during 1955–2020. Ritu *et al.* (2023) anticipated bank line migration and LULC change scenario along the Padma River using NDWI, MNDWI, and DSAS tools in conjunction with GEE and ArcGIS.

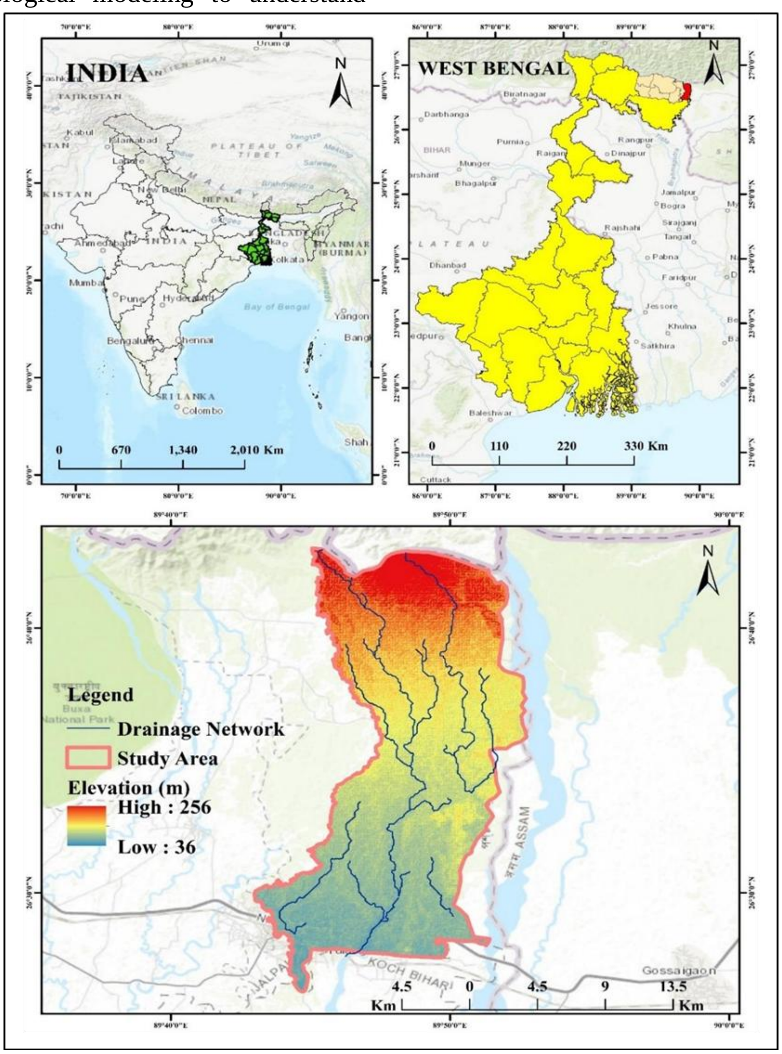
## RESEARCH GAP

Riverbank erosion/accretion is an important geomorphic process influencing the landscape of rivers, monsoon-influenced rivers such as the eastern Himalayas in particular. A number of global/regional studies have incorporated these processes in channel migration, land loss and socio-economic impacts Yao *et al.* (2011); Lovric and Tosic (2016); Mukherjee *et al.* (2017); Ophra *et al.* (2018); Hasanuzzaman *et al.* (2021); Majumdar *et al.* (2021); Ghosh *et al.* (2023); Ritu *et al.* (2023), etc. The use of Remote Sensing (RS) and Geographic Information Systems (GIS) to detect these changes has transformed fluvial research, allowing the analysis of its trends in space and time with increasingly accurate and detailed results (Wang & Xu 2018; Alavez-Vargas *et al.,* 2021). Despite notable advancements, several gaps persist in the literature, especially concerning Himalayan foreland rivers like Raidak-II, which display distinct seasonal morphodynamics and hydrological variability. These include poor integration of socio-economic vulnerability with geomorphological changes, limited application of hydrological modeling to understand flow–sediment–erosion interactions, minimal inclusion of community feedback in river management planning, and a lack of focus on the ecological impacts of accretion-dominated systems.

## MATERIALS AND METHODS

*A. Study Area*

The Raidak II River in Alipurduar district, West Bengal, India, is a transboundary river originating from Mount Akungphu in the Himalayas (6,400 m elevation). It enters India at Bhutan Ghat, splitting into Raidak I and Raidak II. The study focuses on the lower stretch of Raidak II (Bhutan Ghat to Chakchaka), with a catchment area of 349 sq km and a length of 58.89 km in India. Located in the Brahmaputra Plain beneath the Eastern Himalayas, the river forms a floodplain of quaternary sediments (sand, silt, clay, gravel, pebbles) in a tropical monsoon climate, with peak rainfall from June to September. The study area, at latitudes 26°20'–26°42'N and longitudes 89°45'–89°50'E, includes three villages—Dhantali, Lalchandpur and Jaydebpur (Kumargram Block)—vulnerable to riverbank erosion, threatening agricultural livelihoods.




**Map No. 1.** Location map of the study area.

*B. Data Sources*

The study utilized satellite imagery analysis to examine erosion, accretion, and riverbank changes along the Raidak II River in the Alipurduar district. Landsat TM (2003, 2013) and Landsat OLI/TIRS (2023) datasets (Table 1) were employed for consistent spatial resolution and spectral characteristics. All images were projected using UTM Zone 45N with the WGS84 datum. Riverbank lines were delineated from these images to analyze riverbank shifts over three periods: 2003–2023, 2003–2013, and 2013–2023. The analysis identified specific zones of erosion and accretion for each timeframe.

**Table 1: Different types of satellite data used in the study.**

| Data type | Satellite ID | Sensor ID | Path/row | Acquisition date | Spatial resolution(m) | Cloud Coverage (%) |
|---|---|---|---|---|---|---|
| Remote Sensing Images | Landsat 4-5 | TM | 138/ 42 | 12/20/2003 | 30 | 3 |
| | Landsat 8-9 | OLI & TIRS | 138/ 42 | 12/15/2013 | 30 | 0.05 |
| | Landsat 8-9 | OLI & TIRS | 138/ 42 | 12/19/2023 | 30 | 0.05 |
| | SRTM DEM | - | | 23/09/2014 | 1-ARC | - |

Source**:** http://earthexplorer.usgs.gov/

*C. Methodology*

**(i) Calculation of Eroding and Accreting Banks.** A systematic geospatial analysis was conducted to assess bank erosion and accretion along the Raidak-II River for three periods: 2003–2013, 2013–2023, and 2003–2023 (Table 1). The following steps were followed:

**(a) Identification of Unchanged Areas.** Shapefiles of riverbanks from 2003, 2013, and 2023 were analyzed using geoprocessing tools to identify unchanged areas. The overlapping regions across different years were extracted to create a new layer showing stable zones where no change occurred.

**(b) Calculation of Bank Erosion.** Bank erosion was calculated by subtracting the unchanged area (Ua) from the recent year's river boundary (Cry) using the equation:

Bank Erosion = $Cry - Ua$ (1)

Geoprocessing tools were used to subtract overlapping areas between the river boundaries of the two periods, isolating the zones of erosion. This method accurately quantified erosion for each period.

**(c) Calculation of Bank Accretion.** Bank accretion was computed by subtracting the unchanged area from the previous year's river boundary (Cpy) using the equation:

Bank Accretion = $Cpy - Ua$ (2)

Through similar geoprocessing steps, areas of accretion were identified by removing stable zones from earlier river boundaries, highlighting the newly accreted regions for each period.

This GIS-based approach allowed precise quantification of erosion and accretion zones over time, facilitating effective assessment of riverbank dynamics.

**(ii) Land Use and Land Cover (LULC) Change Detection.** Land cover and land use changes within the Raidak-II River were analyzed through satellite imagery for the years 2003, 2013, and 2023. Following required pre-processing, these were classified into nine classes: Cultivated Land, Settlement, Plantation, Vegetation, Non-perennial River, Perennial River, Side/Mid Bar, Road, and Railway. Post-classification comparison was applied to identify temporal changes within three time intervals: 2003–2013, 2013–2023, and 2003–2023. Accuracy validation was implemented through reference data to validate the reliability of classification.

**(iii) Use of Statistical Test.** Statistical tests were implemented to determine the significance of changes. Shapiro-Wilk and Levene's tests were applied to check data normality and homogeneity of variances, whereas the Friedman Test and Dunn's Post-Hoc Test identified significant differences among the years.

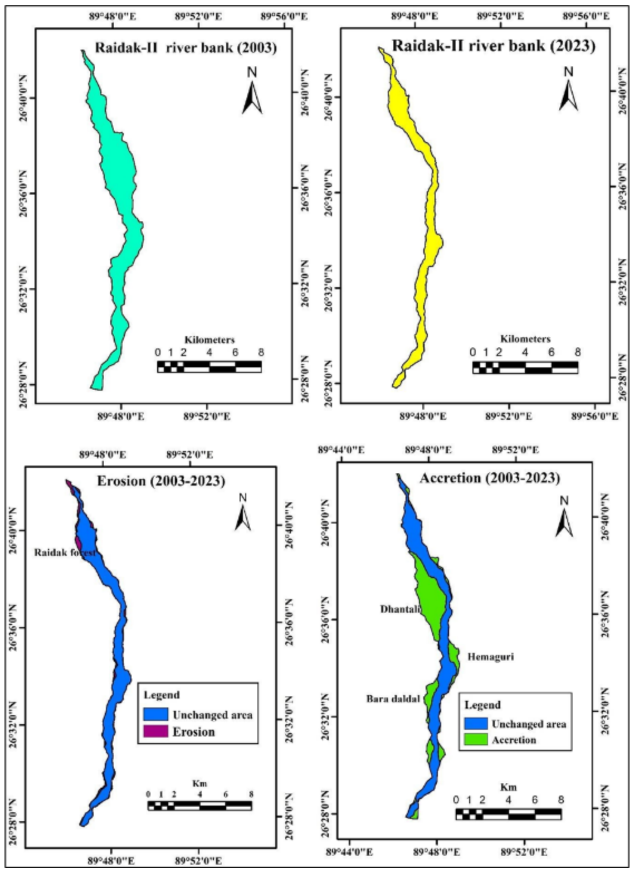
## RESULTS

*A. Raidak-II River Bank Erosion and Accretion Analysis* (*2003–2023*)

The Raidak-II River, a significant waterway in its region, has experienced dynamic geomorphological changes over the past two decades (2003–2023). Bank erosion and accretion are critical processes shaping the river's ecosystem, impacting land use, settlements, agriculture, and biodiversity. Using ArcGIS-based analysis, this report quantifies the extent of bank erosion and accretion over the 20 years, with decadal breakdowns (2003–2013 and 2013–2023). The study also examines changes in land use and land cover (LULC) classes, providing insights into the environmental and socio-economic implications of these processes.

**(i) Bank Erosion (2003–2023).** Bank erosion, the process of material loss from riverbanks and riverbeds due to turbulent flow and high precipitation, has significantly impacted the Raidak-II River's surrounding areas. Over the 20 years from 2003 to 2023, a total of 6.79 km² of land was eroded. This erosion has led to substantial losses of fertile agricultural land, settlements, riverbeds, and forested areas, posing environmental and socio-economic challenges. Key affected areas include Amarpur, Jaydebpur, Bolguri, Paglarhat, Chengmari, Boro Daldali, Purba Chakchaka, Pashchim Chengmari, Purba Narathali, New Land Tea Garden, Hemaguri, Barobisha, Pashchim Chakchaka, Kumargram (severely impacted), and Guchaimari. The intense flooding and high precipitation over the past two decades have exacerbated these losses, undermining riverbanks, shifting riverbeds, and encroaching into vital forest ecosystems.

**(ii) Bank Accretion (2003–2023).** Bank accretion, the deposition of sediments along riverbanks due to reduced flow velocity and gentler slopes, has been a dominant process in the Raidak-II River. Over the past 20 years, the total area of accretion reached 28.94 km², significantly surpassing the eroded area of 6.79 km². This net gain in land has contributed to the formation of new river islands, bars, and alluvial lands, fostering ecological benefits such as enhanced biodiversity and habitat creation. Key areas of accretion include Jaydebpur, Dhumpara Forest, Amarpur, Dhantali (notably high accumulation), Lalchandpur, Chengmari, Dakshin Chengmari, Hemaguri, Uttar Narathali, Boro Daldali, Guchaimari, Radhanagar, Borobisha, Purba Chakchaka, Pashchim Chakchaka, and Kamakhyaguri. These areas have benefited from sediment deposition, which supports the growth of riparian vegetation and stabilizes riverbanks.

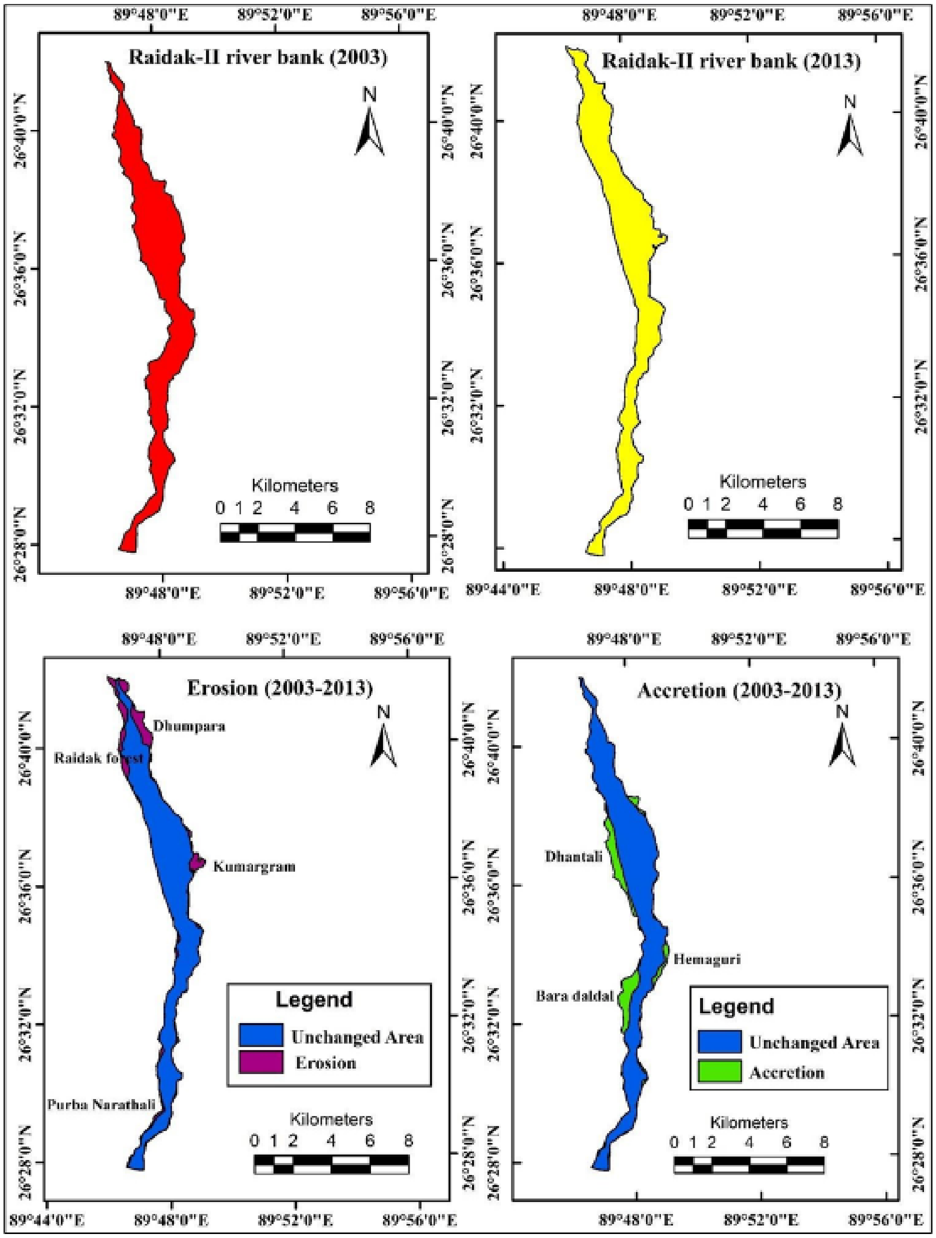



**Map No. 2.** Bank erosion and accretion (2003-2023).

*B. Decadal Bank Erosion and Accretion*

**(i) Decadal Bank Erosion (2003–2013).** From 2003 to 2013, the Raidak-II River experienced significant erosion, with a total of 4.12 km² of land affected. This erosion impacted various land uses, including agricultural fields, settlements, and forested areas, causing damage to infrastructure such as hydraulic structures and transport networks. The magnitude of erosion during this decade reflects the river's high-energy flow conditions, which removed substantial sediment from riverbanks.

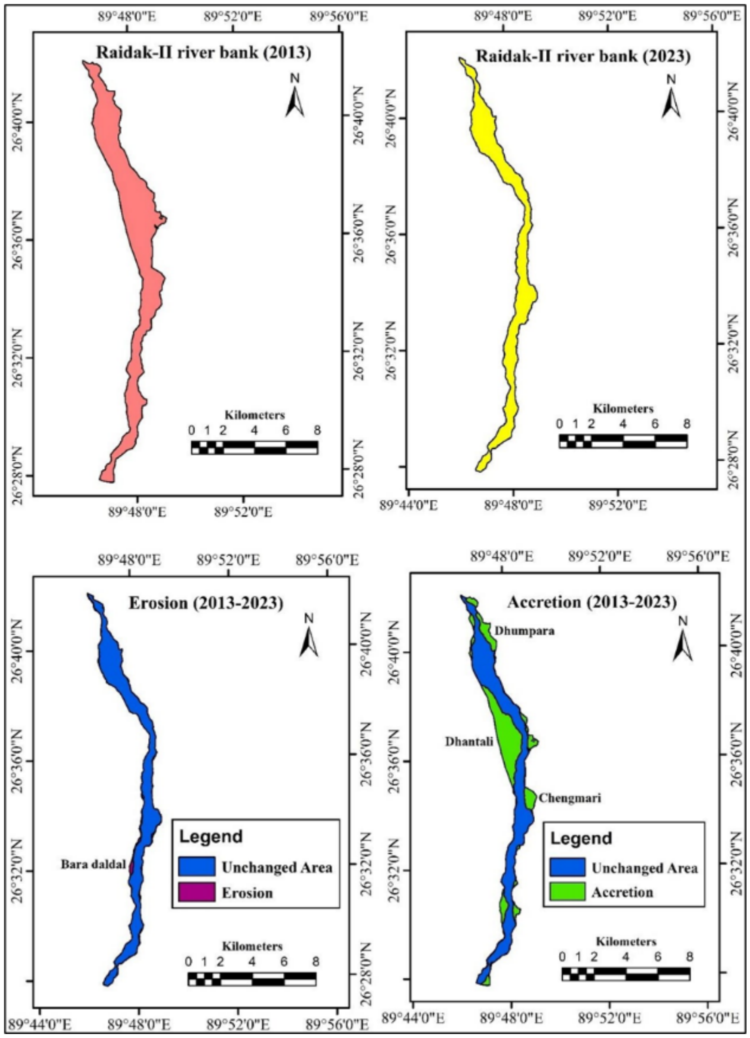
**(ii) Decadal Bank Accretion (2003–2013).** Between 2003 and 2013, the Raidak-II River recorded a total accretion area of 4.65 km², slightly exceeding the erosion area of 4.12 km² for the same period. This net land gain facilitated the development of new alluvial lands, which have been utilized for agriculture and pasture. Significant accretion occurred in Amarpur, Dhantali, Lalchandpur, Dakshin Chengmari, Hemaguri, Uttar Narathali, Boro Daldali, Radhanagar, Guchaimari, Barobisha, Purba Chakchaka, Pashchim Chakchaka, and Kamakhyaguri. The deposition of sediment has promoted riparian vegetation, contributing to bank stability and ecological health.




**Map No. 3.** Decadal Bank erosion and accretion (2003-2013).

**(iii) Decadal Bank Erosion (2013–2023).** In the subsequent decade (2013–2023), the extent of erosion decreased significantly, with a total eroded area of 0.81 km². While this represents a reduction compared to the previous decade, the erosion still affected multiple land uses, including agricultural lands and settlements, highlighting the ongoing challenge of managing riverbank stability in the Raidak-II River basin.

**(iv) Decadal Bank Accretion (2013–2023).** From 2013 to 2023, accretion increased substantially, with a total area of 11.35 km², far exceeding the 0.81 km² of erosion during the same period. Notable accretion occurred in Alipurduar, Dhumpara Forest (including Raidak Forest), Dhantali (highest accumulation), Amarpur, Kumargram, Lalchandpur, Chengmari, Radhanagar, Guchaimari, Purba Narathali, Purba Chakchaka, Pashchim Chakchaka, and Kamakhyaguri. These deposits have created new landforms, supported agricultural development, and enhanced riparian vegetation, contributing to the ecological balance of the river system.




**Map No. 4.** Decadal Bank erosion and accretion (2013-2023).

### *C. Quantification of Bank Erosion and Accretion of the Raidak-II River* (*2003–2023*)

The Raidak-II River has undergone significant changes in erosion and accretion over the past two decades (2003–2023). Between 2003 and 2013, the river experienced 4.12 sq. km of erosion and 4.65 sq. km of accretion, resulting in a slight net gain of 0.53 sq. km of land. In the subsequent decade (2013–2023), erosion drastically decreased to 0.81 sq. km—an 80.34% reduction compared to the previous decade. Conversely, accretion dramatically increased to 11.35 sq. km, a 144.09% increase from the earlier decade. This resulted in a significant net gain of 10.54 sq. km of land during this period. Over the entire 20-year period (2003–2023), the river lost a total of 1.86 sq. km due to erosion but gained 12.94 sq. km through accretion, resulting in a net gain of 11.08 sq. km in land area. This trend clearly demonstrates that accretion dominated over erosion throughout the study period, with particularly strong gains in the most recent decade. The formation of new landforms such as islands, bars, and levees indicates dynamic sediment deposition processes and potentially human interventions that promoted land-building.

**Table 2: Erosion and Accretion Area Changes of Raidak-II River (2003–2023).**

| Period | Erosion Area (sq. km) | % Change in Erosion (compared to the previous period) | Accretion Area (sq. km) | % Change in Accretion (compared to the previous period) |
|---|---|---|---|---|
| **2003–2013** | 4.12 | – | 4.65 | – |
| **2013–2023** | 0.81 | -80.34 | 11.35 | +144.09 |
| **2003–2023** | 1.86 | +129.63 | 12.94 | +14.02 |

Source: Calculated by the author

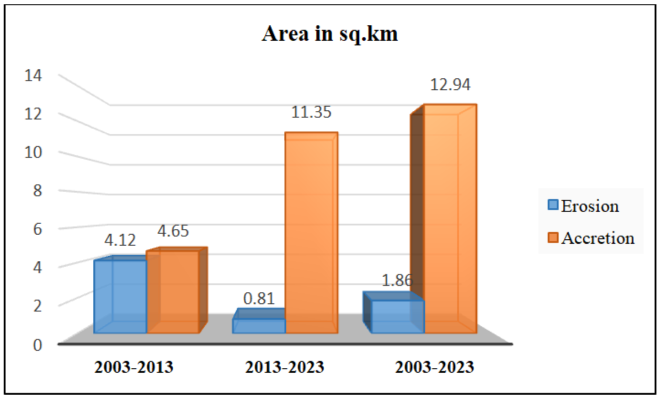



**Fig. 1.** Erosion and accretion areas of the Raidak-II River, 2003-2023.

*D. Affected Areas of Bank Erosion* (*2003–2023*)
Bank erosion along the Raidak-II River between 2003 and 2023 has caused widespread damage to agricultural lands, settlements, riverbeds, and forest areas. The erosion not only reduced productive farmland but also destabilized river channels, damaged settlements, and threatened critical forest ecosystems. Over the two decades, several key locations have been repeatedly affected, highlighting the serious environmental, socio-economic, and ecological consequences of continuous riverbank erosion in the region. Understanding these affected areas is essential for planning effective erosion management and mitigation strategies.

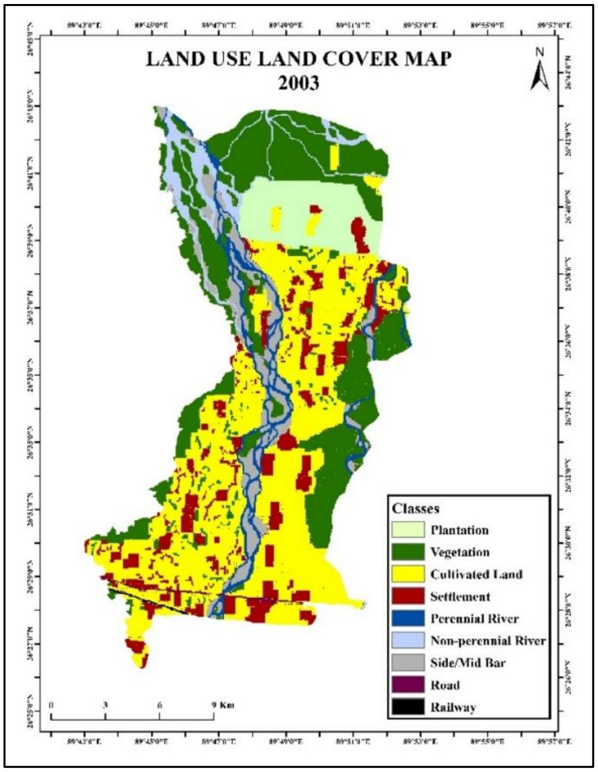
**Table 3: Identification of the affected areas of bank erosion (2003–2023) in the area.**

| Periods | Erosion (in sq. km) | Affected Area | | | |
|---|---|---|---|---|---|
| | | Agricultural land | River bed | Settlement | Forest |
| **2003–2013** | 4.12 | Amarpur, Jaydebpur, Bolguri, Paglarhat, Chengmari, Boro Daldali, Purba Chakchaka, Pashchim Chengmari, Purba Narathali | Bhutanghat, Turturi khanda, Maynabari, Bolguri, Paglarhat, Hemaguri, Boro Daldali, Guchaimari, Barobisha, Purba Chakchaka, Pashchim Chengmari, Purba Narathali, Pashchim Chengmari. | Amarpur, Jaydebpur Bolguri, Paglarhat, Chengmari, Hemaguri, Boro daldali, Pashchim Chengmari. | Dhumpara, Raidak forest |
| **2013–2023** | 0.81 | New land tea garden, Amarpur, Boro daldali, Hemaguri, Barobisha, Purba Chakchaka, Pashchim Chakchaka, Purba Narathali | Bhutanghat, Turturi khanda, Maynabari, Dhumpara, Amarpur, Bolguri, Pashchim Chengmari, Chengmari, Hemaguri, Barobisha, Alipurduar, Purba Chakchaka. | Bolguri, Hemaguri, Boro Daldali, Purba Chakchaka, Pashchim Chakchaka | Dhumpara |
| **2003–2023** | 1.86 | Amarpur, Jaydebpur, Kumargram （mostly eroded）, Boro daldali, Guchaimari, Purba Chakchaka, Pashchim Chakchaka, Purba Narathali | Dhumpara, Pashchim Chengmari, Chengmari, Guchaimari, Purba Chakchaka, Pashchim Chakchaka, Purba Narathali | Amarpur, Jaydebpur, Kumargram （mostly eroded）, Boro daldali, Guchaimari, Purba Chakchaka, Pashchim Chakchaka, Purba Narathali | Dhumpara, Raidak forest, |

Source: Calculated by the author

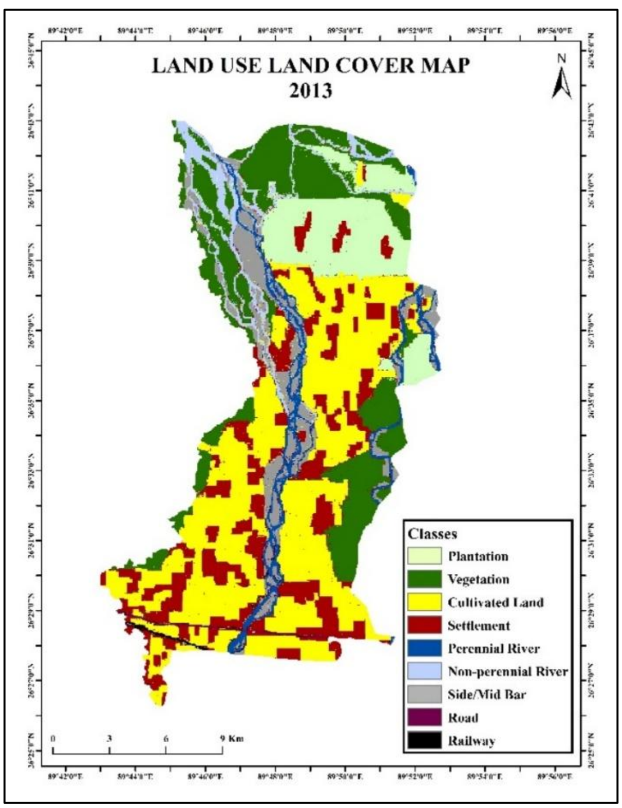
*E. Changes in Land Use/Land Cover* (*LULC*) (*2003–2023*)
Analysis of the LULC maps for 2003, 2013, and 2023 reveals significant shifts in the land cover patterns along the Raidak-II River corridor, driven by fluvial processes, human interventions, and regional development activities over the past two decades.

**(i) LULC in 2003.** In 2003, the study area was predominantly agricultural, with Cultivated Land covering 100.86 sq. km (38.62%). Riverine classes, including Non-perennial River and Perennial River, jointly occupied over 22 sq. km, indicating a moderate river system. Plantation, Settlement, and Infrastructure (Roads, Railway) occupied smaller portions of the land.



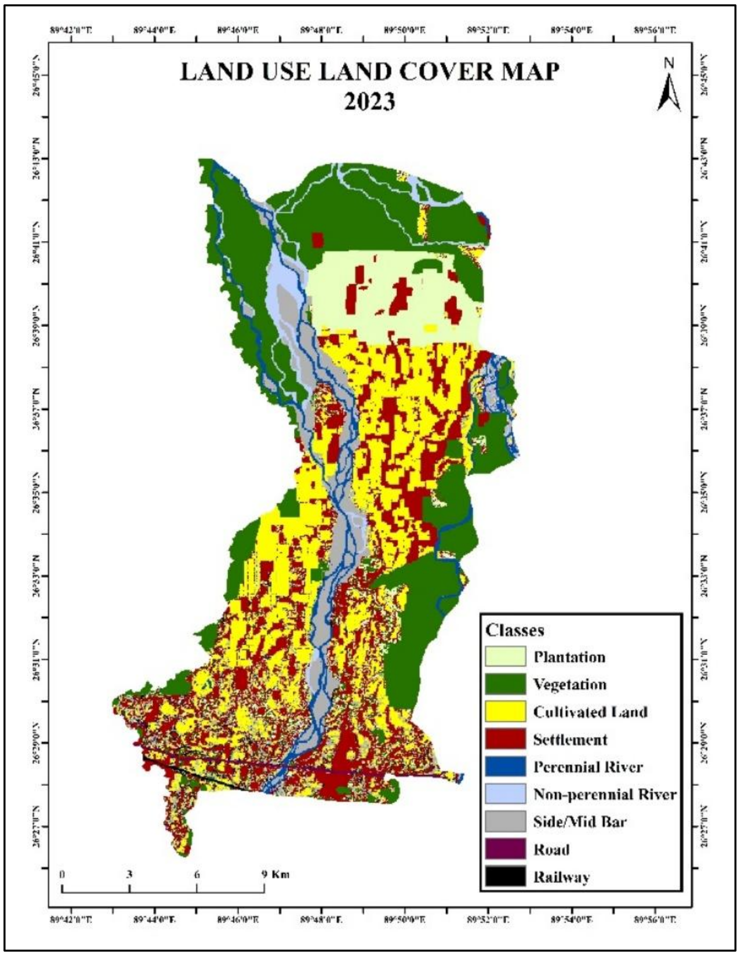

**Map No. 5.** Land use land cover map of the study area in 2003.

**(ii) LULC in 2013.** By 2013, noticeable changes emerged. Cultivated Land declined to 91.44 sq. km (35.02%), while Plantation increased to 30.24 sq. km (11.58%), possibly indicating agricultural land conversion or reforestation efforts. Settlement expanded to 41.78 sq. km (16.00%), reflecting early urban growth. Additionally, infrastructure like roads, covering 1.55 sq. km.




**Map No. 6.** Land use land cover map of the study area in 2013.

**(iii) LULC in 2023.** In 2023, the landscape changed considerably. Cultivated Land sharply reduced to 56.35 sq. km (21.58%), signifying rapid farmland loss. Settlement grew further to 50.61 sq. km (19.38%), alongside continued infrastructure expansion (Road: 2.40 sq. km, Railway: 3.26 sq. km). Vegetation significantly increased to 74.01 sq. km (28.34%), indicating potential reforestation or natural regrowth, while Plantation slightly decreased to 26.99 sq. km (10.33%).




**Map No. 7.** Land use land cover map of the study area in 2023.

From 2003 to 2023, farmland sharply declined by over 44.51 sq. km, mainly due to urbanization and agricultural abandonment. Settlement areas almost doubled, reflecting rapid urban growth. Vegetation cover increased, indicating some ecological restoration. Infrastructure such as bridges, roads, and railways expanded, improving connectivity. River areas and mid-bars showed dynamic changes, highlighting ongoing erosion and sedimentation processes. The table below presents the area and percentage distribution of LULC classes for the three years.

**Table 4: The area under different LULC classes in the study area (2003, 2013 and 2023).**

| **Classes** | **2003 Area (sq km)** | **2003 (%)** | **2013 Area (sq km)** | **2013 (%)** | **2023 Area (sq km)** | **2023 (%)** |
|---|---|---|---|---|---|---|
| Cultivated Land | 100.86 | 38.62 | 91.44 | 35.02 | 56.35 | 21.58 |
| Non-perennial River | 10.67 | 4.09 | 12.39 | 4.74 | 8.61 | 3.30 |
| Perennial River | 12.03 | 4.61 | 10.72 | 4.11 | 10.91 | 4.18 |
| Plantation | 20.26 | 7.76 | 30.24 | 11.58 | 26.99 | 10.33 |
| Railway | 0.70 | 0.27 | 1.55 | 0.60 | 3.26 | 1.25 |
| Road | 1.46 | 0.56 | 2.04 | 0.78 | 2.40 | 0.92 |
| Settlement | 26.89 | 10.30 | 41.78 | 16.00 | 50.61 | 19.38 |
| Side/Mid Bar | 17.67 | 6.77 | 20.02 | 7.67 | 28.00 | 10.72 |
| Vegetation | 70.60 | 27.04 | 50.91 | 19.50 | 74.01 | 28.34 |
| Total | 261.13 | 100.00 | 261.10 | 100.00 | 261.14 | 100.00 |

Source: Calculated by the author

The changes in LULC classes reflect the interplay between natural fluvial processes and anthropogenic activities. The table below highlights the percentage changes in LULC classes across the two decades.

**Table 5: LULC Changing Patterns (2003–2023).**

| Land Class | 2003 (%) | 2013 (%) | Change (2003–2013) | 2013 (%) | 2023 (%) | Change (2013–2023) | Change (2013–2023) |
|---|---|---|---|---|---|---|---|
| Cultivated Land | 38.62 | 35.02 | -3.60 | 35.02 | 21.58 | -13.40 | -17.04 |
| Non-perennial River | 4.09 | 4.74 | 0.65 | 4.74 | 3.30 | -1.44 | -0.79 |
| Perennial River | 4.61 | 4.11 | -0.50 | 4.11 | 4.18 | 0.07 | -0.43 |
| Plantation | 7.76 | 11.58 | 3.82 | 11.58 | 10.33 | -1.25 | 2.57 |
| Railway | 0.27 | 0.60 | 0.33 | 0.60 | 1.25 | 0.65 | 0.98 |
| Road | 0.56 | 0.78 | 0.22 | 0.78 | 0.92 | 0.14 | 0.36 |
| Settlement | 10.30 | 16.00 | 5.70 | 16.00 | 19.38 | 3.38 | 9.08 |
| Side/Mid Bar | 6.77 | 7.67 | 0.90 | 7.67 | 10.72 | 3.05 | 3.95 |
| Vegetation | 27.04 | 19.50 | -7.54 | 19.50 | 28.34 | 8.84 | 1.30 |

Source: Calculated by the author

**(iv) Accuracy Assessment of LULC Classification.** The accuracy of LULC classification was assessed for 2003, 2013, and 2023, with overall accuracy and Kappa coefficients indicating reliable results. The table below summarizes the accuracy assessment. ($p > 0.05$)

**Table 6: Accuracy Assessment of LULC classification.**

| Year | Overall Accuracy (%) | Kappa Coefficient |
|---|---|---|
| 2003 | 78 | 0.72 |
| 2013 | 88 | 0.85 |
| 2023 | 86 | 0.83 |

Source: Calculated by the author

*F. Statistical Analysis of LULC Changes* (*2003–2023*)

To assess whether the LULC data followed a normal distribution, the Shapiro-Wilk Normality Test was performed for the datasets from 2003, 2013, and 2023.

**Table 7: Shapiro-Wilk Normality Test Results.**

| Year | Test Statistic | p-value | Interpretation |
|---|---|---|---|
| 2003 | 0.7850 | 0.0137 | NOT Normal ($p < 0.05$; reject normality) |
| 2013 | 0.8741 | 0.1359 | Normal ($p > 0.05$; normal distribution) |
| 2023 | 0.8966 | 0.2330 | Normal ($p > 0.05$; normal distribution) |

Source: Calculated by the author

The results showed that the 2003 data had a test statistic of 0.7850 with a p-value of 0.0137, which is less than the significance level of 0.05. This indicates that the data for 2003 does not follow a normal distribution. However, the datasets for 2013 and 2023 were found to be normally distributed with p-values of 0.1359 and 0.2330, respectively, both exceeding the 0.05 threshold. This suggests that while the more recent datasets exhibit normality, the older data from 2003 deviate from it. Following this, Levene's Test was applied to assess homogeneity of variances among the years. The results are shown in Table 8.

**Table 8: Levene's Test for Homogeneity of Variance.**

| Test Statistic | p-value | Interpretation |
|---|---|---|
| 0.0059 | 0.9941 | Variances are homogeneous ($p > 0.05$) |

Source: Calculated by the author

The test resulted in a statistic of 0.0059 and a p-value of 0.9941, which is well above the 0.05 significance level. This result confirms that there is no significant difference in the variances among the three groups, meaning the variances can be considered equal. However, since the 2003 data is non-normal, it was necessary to apply a non-parametric test. Hence, the Friedman Test is a good alternative to Repeated Measures ANOVA was conducted, and the results are shown below:

**Table 9: Friedman Test Result.**

| Test Statistic | p-value | Interpretation |
|---|---|---|
| 10.444 | 0.0054 | Significant difference among years ($p < 0.05$) |

Source: Calculated by the author

Given the violation of normality in 2003, a non-parametric Friedman Test was conducted to examine the overall differences in LULC across the years. The results of the Friedman Test reveal a statistically significant difference in land use and land cover (LULC) distributions across the years 2003, 2013, and 2023. With a test statistic of approximately 10.44 and a p-value of 0.0054 (less than the common significance threshold of 0.05), this finding suggests that notable changes have occurred in the LULC patterns over these years. The significant result highlights that, when considering all three years collectively, there has been substantial variation in the areas occupied by different land cover classes, indicating shifting land use trends and environmental changes within the study region. To identify which specific pairs of years differ, Dunn's Post-Hoc Test (with Bonferroni correction) was performed. The pairwise comparison results are presented in Table 10.

**Table 10: Dunn's Test Pairwise Comparison (Bonferroni adjusted p-values).**

| Comparison | Adjusted p-value | Interpretation |
|---|---|---|
| 2003 vs 2013 | 0.038481 | Significant ($p < 0.05$) |
| 2003 vs 2023 | 0.004456 | Significant ($p < 0.05$) |
| 2013 vs 2023 | 0.134812 | Not Significant |

Source: Calculated by the author

The results indicate statistically significant changes between 2003 and 2013 ($p = 0.0385$) and between 2003 and 2023 ($p = 0.0045$), both of which are below the 0.05 significance threshold. This means substantial LULC changes occurred in these intervals. However, no statistically significant difference was observed between 2013 and 2023 ($p = 0.1348$), suggesting that land use changes were more prominent in the earlier decade (2003–2013) and stabilized somewhat in the following decade (2013–2023). These results suggest that the major shifts in land cover likely occurred during the earlier part of the study period.

## DISCUSSIONS

The Raidak-II River's morphodynamic evolution over 2003–2023 reveals a clear dominance of accretion over erosion, reflecting both natural sediment dynamics and anthropogenic influences. Over the 20 years, accretion (12.94 km²) substantially exceeded erosion (1.86 km²), yielding a net gain of 11.08 km². Such net accretion is characteristic of many Himalayan-foreland rivers, where reduced channel gradients and sediment trapping by upstream structures promote deposition on lower-energy reaches (Hasanuzzaman *et al.*, 2021; Mondal *et al.*, 2017; Phukan *et al*., 2012). These systems are inherently dynamic, often characterized by braided patterns and the formation of numerous river islands and bars due to high sediment loads and fluctuating discharge (Sarkar, 2017). Detailed analyses on adjacent systems like the Sankosh and Raidak-I rivers similarly link morphological indicators—bar formation and floodplain widening—to decadal shifts in monsoonal flow intensity, corroborating our finding of accelerated accretion in the latter decade (Singha, 2017). The substantial net gain in land through accretion, as observed in the Raidak-II, contributes to significant ecological benefits such as enhanced biodiversity and habitat creation, as newly formed alluvial lands provide fertile ground for pioneer vegetation and diverse aquatic and terrestrial species (Phukan *et al*., 2012).

A decadal breakdown highlights a pronounced shift in river behaviour: 2003–2013 saw nearly balanced erosion (4.12 km²) and accretion (4.65 km²), whereas 2013–2023 experienced an 80 % reduction in erosion alongside a 144 % surge in accretion. This transition likely reflects a combination of natural hydro-climatic variability and increasing land-use interventions. Afforestation efforts in the catchment can lead to increased bank stability by enhancing root cohesion, thereby reducing erosion potential and promoting sediment deposition (Langat *et al.*, 2019). Embankment construction, while aimed at flood protection, can confine flow, increase velocity within the channel, and prevent natural overbank spilling, potentially leading to increased sediment deposition within the embanked sections and a rise in bed levels over time (Akter & Baten 2021). Irrigation withdrawals, by reducing overall river discharge, especially peak flows, can further contribute to decreased erosive power and enhanced sediment deposition in downstream reaches (Richter *et al.*, 1997). Field observations of enhanced riparian vegetation along Jaydebpur and Amarpur suggest that bank stabilization by plants, a common riparian restoration technique, further reduced channel incision and favoured mid-channel bar and floodplain sediment deposition.

Concurrent LULC changes mirror these geomorphic processes and rising anthropogenic pressures. Cultivated land declined sharply (−44.51 km² from 2003 to 2023), while vegetation cover rebounded (+8.84 %), indicating both farmland abandonment on newly accreted zones and targeted reforestation. Settlement areas nearly doubled, reflecting rapid settlement expansion in floodplain zones—a trend observed across developing regions where population growth drives conversion of agricultural land to build environments (Mondal *et al.*, 2013; Rahman *et al.*, 2017). Infrastructure growth (bridges, roads, railways) has further fragmented natural landscapes, altered hydrological regimes by creating barriers or diverting flow, and can exacerbate runoff and flood risks in certain areas (Forman *et al.*, 2003).

Statistical analysis confirms these transformations: The Friedman test detected a significant overall change in LULC distributions ($\chi2=10.44$, $p=0.0054$), and Dunn's post-hoc comparisons identified significant shifts between 2003–2013 ($p=0.0385$) and 2003–2023 ($p=0.0045$) but not between 2013–2023 ($p=0.1348$), suggesting that the most dramatic land-cover transitions occurred in the earlier decade. The non-normality of the 2003 dataset warranted the use of non-parametric tests (Shapiro-Wilk $p=0.0137$) and homogeneity of variances across years (Levene's $p=0.9941$) (Friedman, 1937; Laerd Statistics, 2023).

Thus, as a whole, the interplay between fluvial dynamics and land-use transformations in the Raidak-II basin underscores the need for integrated watershed management. While accretion has created new lands for agriculture and habitat, offering opportunities for livelihood and ecological enhancement (Sarkar, 2017), persistent erosion threatens riparian communities and vital infrastructure, leading to displacement and economic hardship (Rakib *et al.*, 2024). Sustainable strategies must therefore balance sediment management, riparian restoration, and land-use planning to enhance both ecological resilience and socio-economic well-being in this dynamic riverine landscape (Brierley & Fryirs 2005). This involves careful consideration of upstream sediment supply, maintaining healthy riparian corridors through native vegetation planting and bioengineering techniques, and implementing land-use policies that guide development away from high-risk erosion zones while promoting sustainable agricultural practices and reforestation in accreted areas (Poff *et al.,* 2010).

## CONCLUSION AND POLICY RECOMMENDATIONS

To sustainably manage the Raidak-II River basin, an integrated river-catchment approach must be adopted that balances sediment dynamics, ecological integrity, and local livelihoods. First, sediment management plans should be developed upstream—through controlled-release structures and check-dams—to moderate peak flows and reduce excessive bank erosion downstream (Langat *et al.,* 2019). Second, riparian buffer zones planted with native vegetation (e.g., Vetiver grass, bamboo) should be legally protected and expanded along vulnerable stretches (Jaydebpur, Amarpur) to stabilize banks and enhance habitat continuity. Third, land-use zoning regulations must discourage settlement and high-intensity agriculture on newly accreted bars, instead designating these areas for controlled agroforestry or community forestry schemes that both generate livelihoods and maintain riparian cover. Fourth, embankment and levee construction should be paired with floodplain reconnection designs—such as gated spillways—that allow periodic inundation of accreted lands, reducing flood risk while replenishing soil fertility. Fifth, participatory monitoring and early-warning systems, leveraging community observations and simple gauge stations, can help anticipate bank-failure events and coordinate timely responses (Langhorst & Pavelsky 2023). Policymakers should forge cross-sectoral collaboration between irrigation, forestry, urban development, and disaster-management agencies to ensure that interventions in one sector (e.g., irrigation withdrawals or bridge construction) do not inadvertently exacerbate downstream erosion or sedimentation.

Over the past two decades, the Raidak-II River has exhibited a net accretion of 11.08 km²—driven by decadal increases in sediment deposition and moderated erosion—resulting in the formation of new alluvial landforms and significant LULC transformations. Statistical analyses (Friedman and Dunn's tests) confirm that the most dramatic land-cover changes occurred between 2003 and 2013, with stabilization thereafter. While accretion has created opportunities for agriculture, habitat regeneration, and floodplain expansion, persistent bank erosion continues to threaten riparian communities and infrastructure. The intertwined geomorphological and anthropogenic processes underscore the need for holistic, adaptive river-basin management that integrates sediment control, riparian restoration, land-use planning, and community engagement. Only through coordinated policy action and community collaboration can the Raidak-II basin's dynamic landscape be guided toward resilience, ensuring both ecological health and socio-economic well-being for its dependent populations.

## FUTURE SCOPE

The present study provides an essential understanding of riverbank erosion, accretion and LULC dynamics in the Raidak-II River basin; however, some aspects remain open for further studies. Further works should couple hydrological and sediment transport models for better representing the sophisticated processes of channel form, flow routing and sediment transport. Such models offer a finer analysis of the sources of fluvial instability and may be used to forecast potential eroding or aggrading reaches in response to various climatic conditions and flow regimes. Moreover, the use of additional higher-resolution satellite imagery (*i.e.,* Sentinel-2, PlanetScope, or UAV) can enhance the spatial and temporal resolution of change detection maps and allow for more precision in the delineation of riverbank and land use changes. Significant promise also exists to apply machine learning tightly coupled with AI/analogue experiments to model and predict future land use and floodplain changes (e.g., riverbank migration), particularly when trained on historical geospatial and environmental data. In addition, broadening the scope to community-based participatory GIS and local knowledge systems could lead to adaptive and inclusive river management schemes. Longitudinal socio-economic surveys combined with spatial information on geomorphic changes could also give important information on how human livelihoods are adapted or influenced by river dynamics. Finally, comparison with other rivers in the Himalayan foreland region could reveal supra-basin scale patterns of river response and feed into broader sustainable management frameworks for like fluvial causes of the same class.

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