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Contours In Motion: Spatio-Temporal Analysis Of The Brahmaputra River Morphodynamics

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Abstract

The River Brahmaputra, a major and highly dynamic transboundary river in Southeast Asia, causes significant riverbank erosion and deposition in Assam, posing substantial natural hazards to land, infrastructure, livelihoods, and the regional economy. This research analyses spatio-temporal changes in the riverbank line between 1997 and 2023 using Landsat satellite imagery and Geographic Information System (GIS), methods like Normalized Difference Water Index (NDWI) and overlay analysis, validated with historical imagery from Google Earth software and field visits. Over the past 26 years, the river has undergone significant morphological shifts. Approximately 1077 sq.km. were lost due to erosion, but 1482 sq. km were gained via deposition, indicating a net deposition overall. Erosion impacts were most severe in upper Assam, particularly Dibrugarh district (173.66 sq.km.), while deposition was greatest in lower Assam, led by Barpeta district (174.21 sq.km.). Districts experienced varied net changes, with Dhemaji facing a significant loss and Barpeta gaining the most land. River gradients, monsoons, sediment loads, and human activities influence these dynamics. Given the profound environmental, ecological, and socio-economic consequences, the study stresses the need for integrated, region-specific river management approaches, including sustainable land use, continuous monitoring, community participation, and engineering solutions to mitigate hazards and improve resilience.

Keywords: *Brahmaputra river, NDWI, riverbank erosion, Sedimentation, GIS.*

INTRODUCTION

The study of riverbank erosion and deposition plays a crucial role in understanding river morphology (Yin et al. 2021, Angelaksi et al. 2023, Zhang et al. 2024). Riverbank erosion represents a natural hazard, causing both land loss and socioeconomic challenges. As the river descends from higher regions into the plains, deposition of sediments begins in the riverbeds, leading to the river flowing through a meandering channel (Alekseevskiy et al. 2008, Bizzi and Lenner 2015). This causes a significant oscillation and widespread riverbank erosion (Das and Bhowmik 2013, Rahman 2010). One of the other important phenomena is that the composition of the riverbanks is predominantly fine silt and sand; this kind of composition leads to significant instability due to their hydraulic properties and characteristics. Consequently, bank failure is one of the most frequently observed phenomena (Thorne and Lewin 1982).

Several studies have explored the spatio-temporal changes in river erosion and deposition using Remote Sensing and GIS techniques (Sarma and Acharjee 2012, Chakraborty and Datta 2013, Gogoi and Goswami 2013). In this paper, an attempt has been made to analyze changes in the Brahmaputra riverbank line from 1997 to 2023. As one of the largest river basins in Southeast Asia and globally, it affects the lives of approximately 66 million people directly or indirectly every year (Oki and Kanae 2006, Piao et al. 2010, Schuol et al. 2008). Therefore, any kind of change in the river basin directly affects many people's lives. Every year, devastating floods occur on the river. Assam is a state that is most affected by the Brahmaputra River's dynamic process, including devastating floods, erosion, and deposition of sediments (Coleman 1969). These phenomena significantly affect the state's economy, infrastructure, and the livelihoods of the communities living along the river bed. Therefore, to understand the dynamic nature of the river, the paper attempts to focus exclusively on the state of Assam. To get deeper insights, district-wise measurements of erosion and deposition have been taken.

The river Brahmaputra, sometimes referred to as the 'moving ocean', is a trans-Himalayan River which originates from southern Tibet (China), flows through countries like China, Bhutan, India, and Bangladesh. The river crosses approximately 2880 km from its origin to its confluence in the Bay of Bengal. The drainage system is known as one of the most crucial drainage systems for Northeast India and Bangladesh. The river catchment is bordered by the Kailash and Neyn-Chen-Tanglha Mountain ranges in the north, the Salween River basin and Patkai range in the east, the Nepal Himalayas, Naga and Barail ranges, and Meghalaya plateau in the south, and the Gangess river basin in the west. The catchment area is interspersed with numerous tributaries and distributaries. Some major tributaries of the river are Manas, Gadadhar, Kopili, Lohit, etc. In several regions, the river is known by several names, like in Tibet, the river is known as Tsangpo, flowing 1100 km parallel to the Himalayas before entering India. From the state of Arunachal Pradesh, the river enters India, where the name of the river is Dihang. After covering 226 km, the river reaches Pasighat, from here, only the river enters the plain. Approximately 52 km downstream, the Dihang river meets with two trans Himalayan rivers, Lohit and Dibang, from this area the river is known as the Brahmaputra River. The river then traverses 640 km in the Assam valley in an east-west direction. In this region, the river faces dynamic channel shifts, erosion, deposition, etc., and the river meets with its several tributaries. After crossing the Meghalaya plateau, the river turns southward and enters Bangladesh. In Bangladesh, the river is called the Yamuna River. Flowing 337 km, it eventually merges with the river Ganges at Goalundo (Sarma 2004).

The Brahmaputra River is unique in that it traverses diverse climatic and physiographic zones, from the cold, dry plateau of Tibet to the steep, rain-drenched Himalayas, the alluvial Assam valley, and finally the fluvial plains of Bangladesh (Sarma 2004). The river valley lies in a high seismic zone, and several earthquake activities cause course alteration of tributaries, massive landslides, ground fissures, and excessive sedimentation (Poddar 1952, Evans 1964). In the years 1897 and 1950, such a historical earthquake happened in this area, which created a massive disaster. Respect of being situated in the high seismic zone, the climate, soil composition, braided channel bed, etc., also accelerated the erosion rate of the river (Geological Survey of India 2010). The region experiences a monsoonal climate, with an annual rainfall averaging 500 cm. The lower ranges experience more precipitation than the Himalayan region. Flooding in the Brahmaputra River Basin is an annual phenomenon (Kale 2003), with Assam experiencing widespread devastation each year. Tropical evergreen and mixed deciduous forests predominantly cover the valley. At higher elevations, some alpine meadows and steppe vegetation are found. The river banks mainly consist of fine silt and sand, making it highly unstable under hydrodynamic forces. Consequently, bank failures are also very common in this area (Thorne and Lewin 1982).

The Brahmaputra River carries one of the highest sediments loads globally. In Assam, the river follows a highly braided channel system with numerous islands and mid-channel bars. According to Goswami (1985), these channel bars are submerged during high summer flows and undergo frequent changes in geometry and location. Erosion and deposition of these bars are common in this area. The river ranks as the fourth

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largest in the world in terms of average discharge, with a flow of 19,830 m^3/s. Significant seasonal and daily variations in discharge increase the rate of erosion and deposition. Therefore, it is very important to understand the present condition of the river and how it has changed through the ages.

STUDY AREA

Geographically, the state of Assam is located between 24° 8′ N and 28° 2′ N latitude and 89° 42′ E and 96°E longitude (Fig. 1), covering an area of 78,438 sq. km. The present study focuses on the River Brahmaputra, which flows through the 21 districts of the state. The river, characterized by its highly dynamic and braided nature, is prone to bankline changes, erosion, deposition, and other fluvial processes, significantly impacting the surrounding landscape and settlements. Given the river's dynamic nature, studying its bankline shifts and the fluvial process is essential for understanding its long-term morphological changes and their implications for river management and disaster mitigation in Assam.

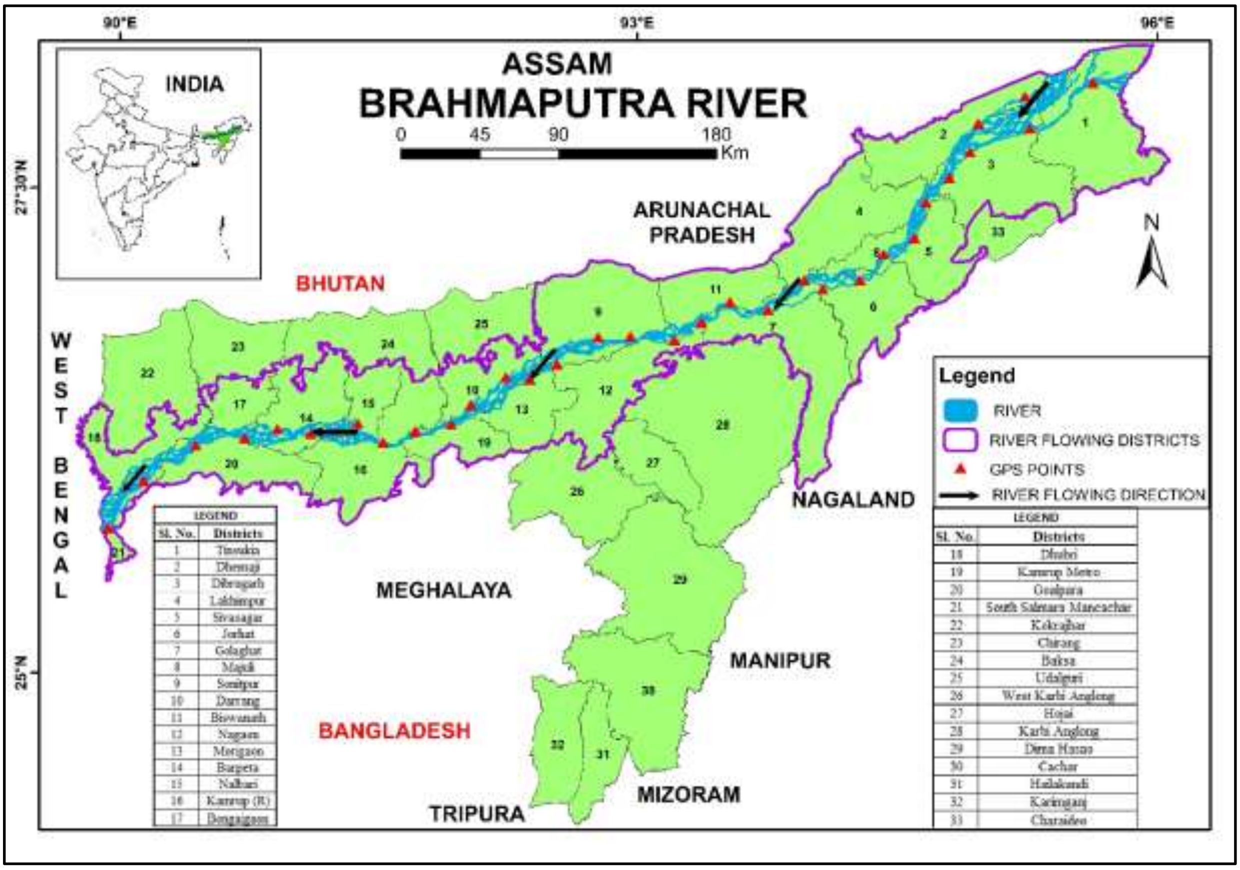

Figure 1: Location Map of the Study Area

METHODOLOGY

The research work is supported by both primary and secondary data, ensuring a comprehensive and well-rounded analysis. Multispectral satellite data from the Landsat series (Landsat 5, 8, and 9) for 1997 and 2023 (Table 1) were obtained from the United States Geological Survey (USGS) portal[1]. These datasets were integrated into GIS software, specifically ArcGIS 10.3, and for cross-verification, historical images of Google Earth Pro software were used. The NDWI algorithm (Equation 1) is applied using the raster calculator tool in GIS software to delineate the channel of the River Brahmaputra and enhance its presence in the satellite imagery.

[1] United States Geological Survey (USGS) portal: https://earthexplorer.usgs.gov/

The formula of NDWI is $\mathrm{NDWI} = \frac{(\mathrm{Green} - \mathrm{NIR})}{(\mathrm{Green} + \mathrm{NIR})}$. (1)

Since the NDWI raster calculation effectively identifies water bodies (McFeeters 1996, Qiao et al. 2012), this method was chosen to detect the River Brahmaputra channel within the state of Assam. The NDWI generates pixel values ranging from -1 to 1, where higher values indicate the presence of water bodies, with values decreasing as the presence of water diminishes (Zheng 2021, Laonamsai et al. 2023). The water bodies of the River Brahmaputra identified from the NDWI classification for 1997 and 2023 were reclassified and converted into polygons for overlay analysis. The intersect and erase tools were used to delineate areas of erosion, deposition, and unchanged regions of the river, which were then clipped according to the district boundaries of Assam for further analysis. For validation, the bankline of 1997 was overlayed in the historical images of Google Earth Pro software, and for 2023, field visits were done, and GPS points were taken in 32 locations. Vector files for state and district boundaries were sourced from the Survey of India (SOI) portal[2]. All maps were transformed into the Projected Coordinate System (PCS) under Universal Transverse Mercator (UTM) zone 46N with datum WGS-84. Data arrangement, processing, and analysis were conducted using MS Excel 2019. The methodological flowchart is shown in Figure 2.

Table 1: Details of satellite data used

YEAR	PLATFORM	SENSOR	DATE OF ACQUISITION	PATH / ROW	RESOLUTION	BAND NUMBER USED
1997	LANDSAT 5	TM	05-01-1997	134/041	30m	B2, B4
			01-03-1997	135/041		
			03-01-1997	136/041		
			19-01-1997	136/042		
			18-05-1997	137/042		
			01-01-1997	138/042		
2023	LANDSAT 8, 9	OLI	05-01-2023	134/041	30m	B3, B5
			04-01-2023	135/041		
			03-01-2023	136/041		
			03-01-2023	136/042		
			01-01-2023	137/042		
			09-01-2023	138/042		

Source: USGS website

[2] SOI portal: https://surveyofindia.gov.in/

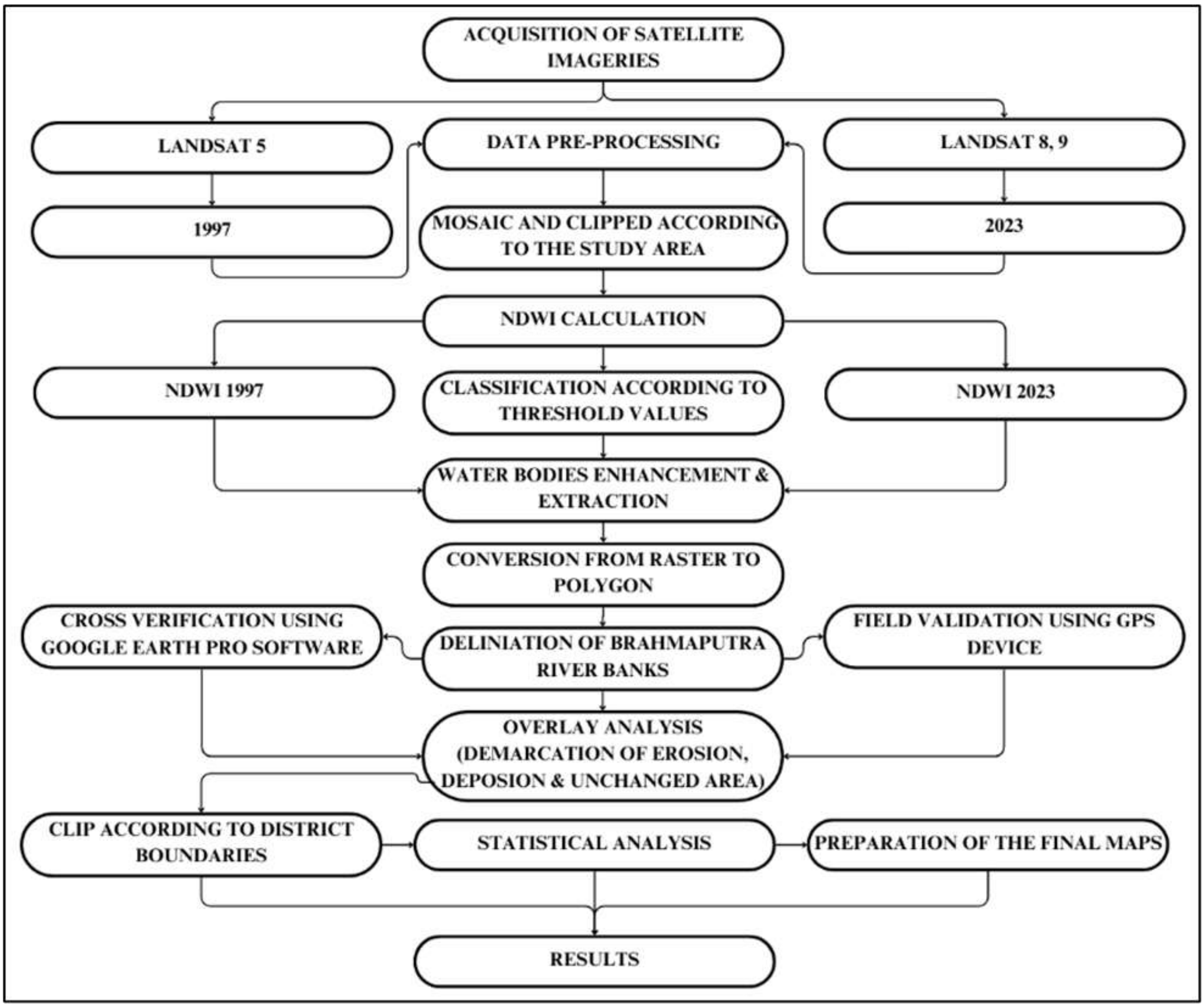

Figure 2: Methodological Flow Chart

RESULTS

A. Analysis of Brahmaputra River Bankline Changes (1997 – 2023)

The Brahmaputra River's dynamic nature necessitates detailed monitoring of its bankline changes. This study covers the period from 1997 to 2023, focusing on bankline alterations across three administrative divisions of Assam: upper Assam, middle (North and Central Assam), and lower Assam. Utilizing ArcGIS 10.3 software, banklines from the given years have been mapped (Figure 3a), and overlay analysis has been conducted to quantify the areas of erosion, deposition, and unchanged area (Figure 3b).

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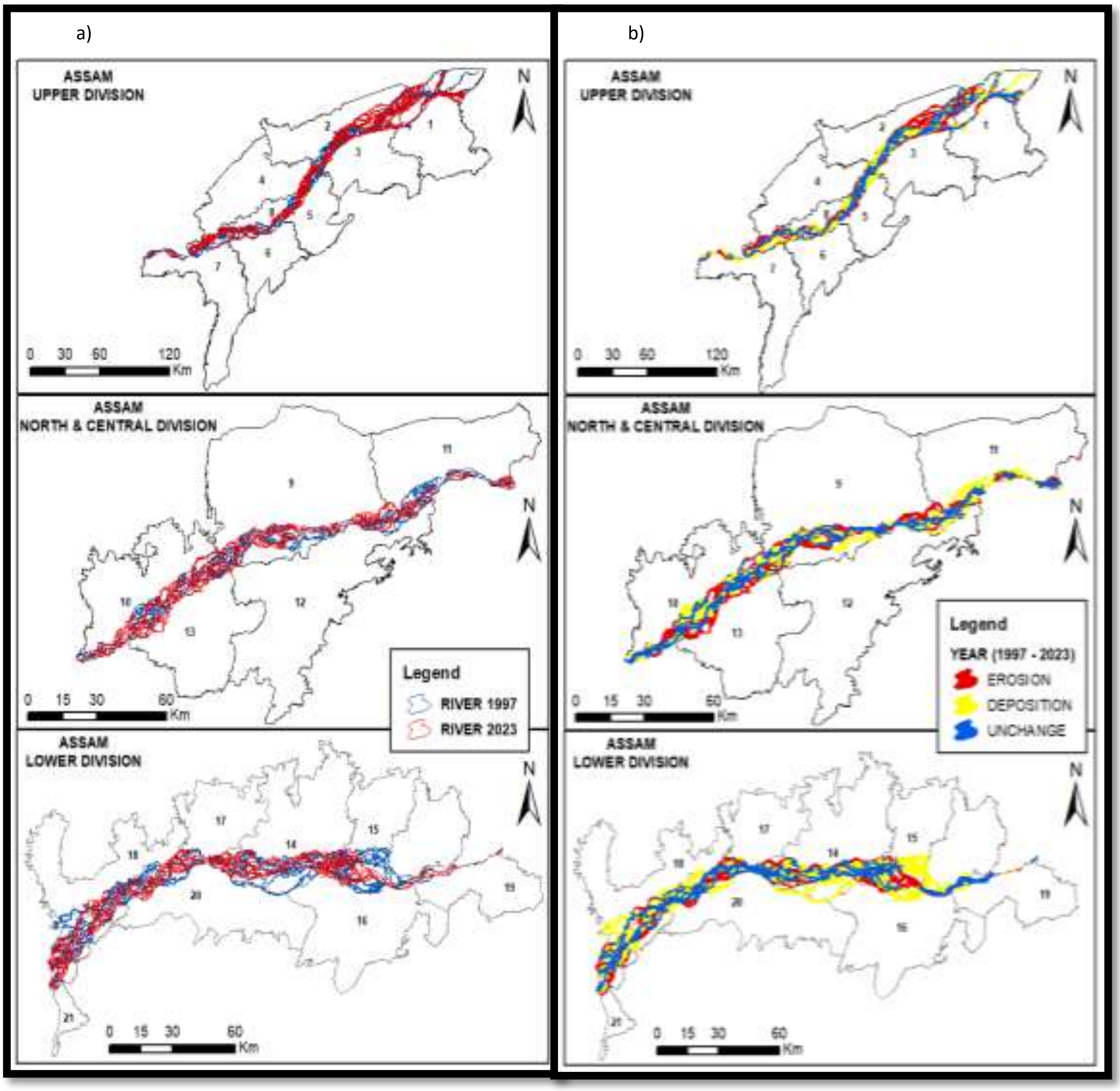

Figure 3: a) Brahmaputra River Bankline (1997 & 2023)
b) Brahmaputra River Fluvial Process (1997-2023)

Table 2: District and Division-wise change detection of fluvial dynamics (Brahmaputra River)

Sl. No.	DISTRICTS	YEAR 1997 - 2023				DIVISIONS	TOTAL (Sq. Km.)	AVERAGE in Sq. Km (FLUVIAL PROCESS/DISTRICTS)
		UNCHANGED (Sq. Km.)	EROSION (Sq. Km.)	DEPOSITION (Sq. Km.)	Difference in Sq. Km. (Deposition-Erosion)			
1	TINSUKIA	30.25	72.43	85.21	12.78			

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2	DHEMAJI	22.45	85.7	57.19	-28.51	UPPER ASSAM	UNCHANGED = 188.01 EROSION = 519.12 DEPOSITION = 533.09	UNCHANGED = 23.5 EROSION = 64.89 DEPOSITION = 66.64
3	DIBRUGARH	61.25	173.66	162.7	-10.96			
4	LAKHIMPUR	4.78	19.52	7.07	-12.45			
5	SIVASAGAR	2.17	6.42	14.47	8.05			
6	JORHAT	15.17	24.5	39.16	14.66			
7	GOLAGHAT	21.67	75.12	92.2	17.08			
8	MAJULI	30.27	61.77	75.09	13.32			
9	SONITPUR	62.68	99.63	109.63	10	MIDDLE ASSAM	UNCHANGED = 166.6 EROSION = 258.69 DEPOSITION = 327.96	UNCHANGED = 33.32 EROSION = 51.74 DEPOSITION = 65.59
10	DARRANG	55.91	62.1	107.5	45.4			
11	BISWANATH	24.95	42.6	61.18	18.58			
12	NAGAON	1.57	5.81	13.46	7.65			
13	MORIGAON	21.52	48.55	36.19	-12.36			
14	BARPETA	72.84	84.38	174.21	89.83	LOWER ASSAM	UNCHANGED = 265.56 EROSION = 298.92 DEPOSITION = 620.59	UNCHANGED = 33.19 EROSION = 37.36 DEPOSITION = 77.57
15	NALBARI	10.1	32.57	64.07	31.5			
16	KAMRUP RURAL	29.4	20.11	95.85	75.74			
17	BONGAIGAON	22.94	21.33	31.79	10.46			
18	DHUBRI	18.92	24.71	53.89	29.18			
19	KAMRUP METRO	13.95	1.45	6.77	5.32			
20	GOALPARA	54.11	41.53	105.72	64.19			
21	SOUTH SALMARA-MANKACHAR	43.3	72.84	88.29	15.45			
TOTAL		620.2	1076.73	1481.64	404.91			

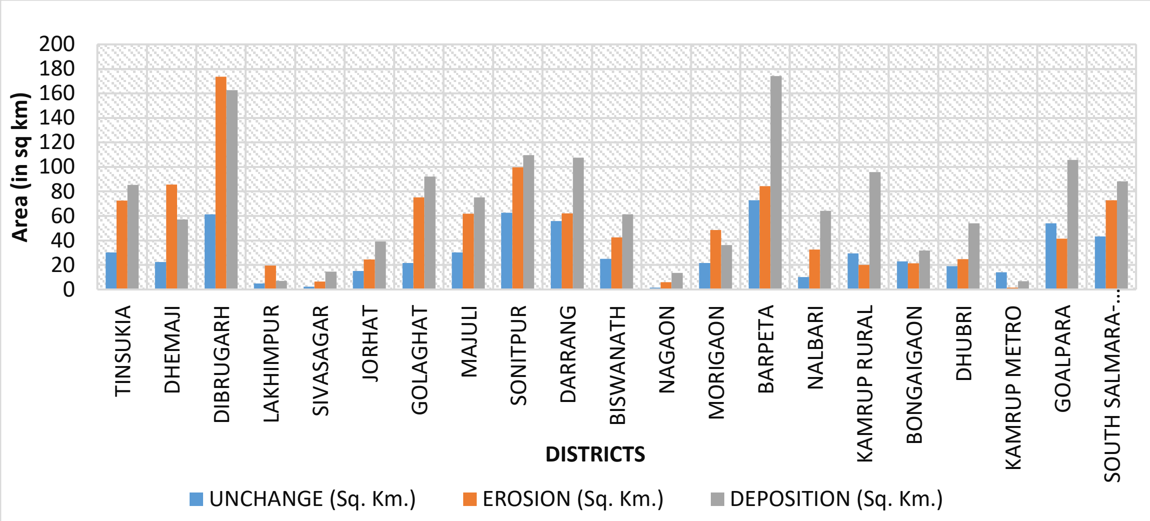

Figure 4: District-wise fluvial dynamics of the Brahmaputra River

From Table 2 and Figure 4, it is clear that the Dibrugarh district experiences the highest rate of river erosion (173.66 sq. km) among all districts, followed by Sonitpur (99.63 sq. km), Dhemaji (85.7 sq. km), Barpeta (84.83 sq. km), Golaghat (75.12 sq. km), and others. The intense erosion can be attributed to several factors, including the river's strong current, meandering nature, and seasonal monsoon floods, which weaken the riverbanks. In addition, high agricultural activities further destabilize the banks, while other human interventions, such as sand mining, stone quarrying, deforestation, unregulated constructions, etc., contribute to soil instability, making these areas more susceptible to erosion and substantial land loss.

In contrast, depositional activities are most pronounced in Barpeta (174.21 sq. km), followed by Dibrugarh (162.7 sq. km), Sonitpur (109.63 sq. km), Darrang (107.5 sq. km), Goalpara (105.72 sq. km), and others. The landscape in these districts is heavily influenced by the accumulation of sediments transported by rivers, particularly during the monsoon season, when sediment transport is at its peak. The river's natural tendency to spread out and lose energy in certain sections results in siltation and the formation of new land features, such as sandbars and alluvial plains. Over time, these higher rates of deposition contribute to changes in river courses, making the channels braided.

Considering the net difference between erosion and deposition rates over the past 26 years (1997-2023), the river has eroded approximately 1,076.73 sq. km of land while depositing 1,481.64 sq. km. Dhemaji district has recorded the highest land loss (-28.51 sq. km), followed by Lakhimpur (-12.45 sq. km), Morigaon (-12.36 sq. km), and Dibrugarh (-10.96 sq. km). The prevalence of severe erosion in these districts highlights the urgent need for riverbank protection measures, such as afforestation, riverbank reinforcement, and sustainable land management practices, to mitigate erosion rates. On the other hand, Barpeta district has recorded the highest land gain (89.83 sq. km), followed by Kamrup Rural (75.74 sq. km), Goalpara (64.19 sq. km), Darrang (45.4 sq. km), and others. The coexistence of both erosion and deposition in these districts signifies a highly dynamic fluvial process where sediment is constantly transported and redeposited. This continuous interaction between erosion and deposition plays a significant role in shaping the physiography of these regions, influencing land use patterns and settlement dynamics over time.

The unchanged areas represent regions where the land remains stable, experiencing neither significant erosion nor deposition. Districts such as Barpeta (72.84 sq. km), followed by Sonitpur (62.68 sq. km), Dibrugarh (61.25 sq. km), Darrang (55.91 sq. km), Goalpara (54.11 sq. km), and others exhibit relatively stable landscapes. This stability can be attributed to natural or artificial control measures such as soil structure, vegetation cover, well-managed riverbanks, and effective flood control measures that mitigate bank erosion. The presence of large, unchanged areas suggests that river dynamics do not affect all districts equally, as some regions maintain their landscape integrity due to either natural resistance to erosion or proactive human interventions.

B. Comparative Analysis Across Divisions

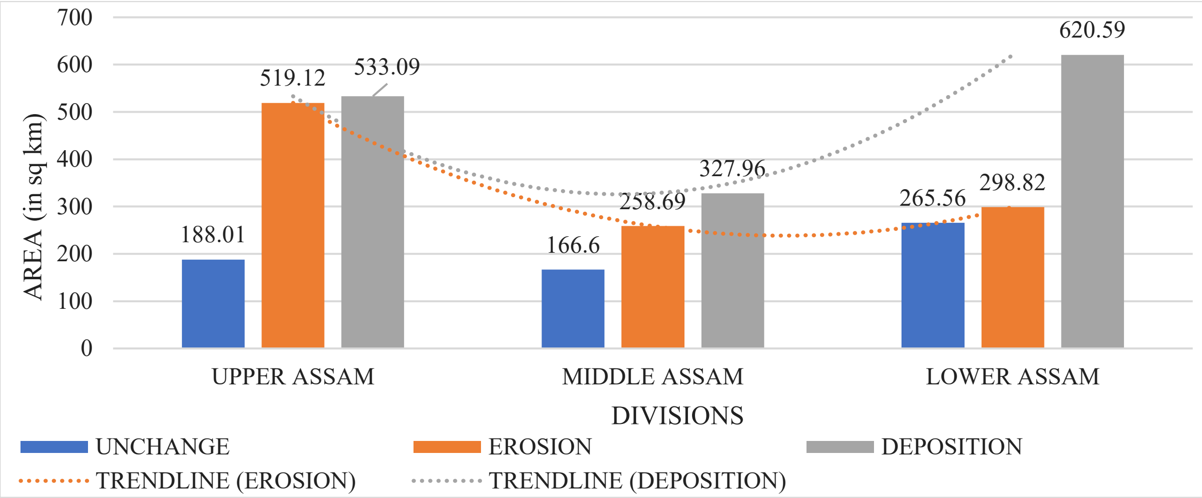

Figure 5: Division-wise fluvial dynamics of the Brahmaputra River

The graph (Figure 5) shows a comprehensive overview of the spatial variability in river erosion, deposition, and stable land areas across different divisions, highlighting the complex interplay between these processes. The fluvial process decreased from upper Assam to middle Assam before peaking again in the lower Assam area. The ratio of erosional to depositional activities is nearly equal in upper Assam, whereas the middle Assam and lower Assam areas are more prone to depositional activities. However, erosion is most active in upper Assam, totalling 519.12 sq. km with an average of 64.89 sq. km, while deposition is most prominent in lower Assam, totalling 620.59 sq. km with an average of 77.57 sq. km as the river reaches the later part of its mature stage. This spatial variability suggests that each division faces unique challenges and opportunities in terms of land management and riverine ecosystem maintenance. Areas experiencing high erosion require targeted interventions to protect infrastructures and agricultural land, whereas regions with high deposition need sediment management to prevent flooding and maintain navigable waterways. Notably, lower Assam has a greater extent of stable land areas (unchanged area 265.56 sq. km), but on average, middle Assam has the most stable land of 33.32 sq. km compared to other divisions. The existence of these stable regions indicates that with proper management and favourable natural conditions, the adverse impacts of river dynamics can be effectively mitigated.

This study highlights that the highest deposition is observed in lower Assam. As the river progresses towards its late mature stage, the decreasing river-bed gradient results in a significant loss of transportation power, leading to sedimentation. This natural process contributes to the formation of Char (sand bar) lands, which support agriculture and local livelihoods, also poses challenges in terms of land stability and ownership disputes. The influence of numerous tributaries further complicates the hydrodynamics of the Brahmaputra, affecting water discharge and velocity at different points along its course.

Overall, this analysis highlights the need for region-specific river management strategies that balance environmental conservation, economic development, and disaster risk reduction to ensure sustainable land use and resilience against fluvial changes.

CRITICAL INSIGHTS AND IMPLICATIONS

The bankline changes along the River Brahmaputra have far-reaching environmental, ecological, and socio-economic implications:

- **Environmental Impacts:** High erosion rates lead to the loss of fertile land, negatively impacting agriculture and leading to displacement. Deposition, while creating new landforms, also changes the river navigation patterns and affects the aquatic ecosystem by altering habitats.
- **Ecological Impact:** Habitat loss for riverine species, both flora and fauna, is a direct consequence of these changes. The alteration of natural habitats has led to a decrease in biodiversity, affecting the river's ecological balance.
- **Socio-economic Impact:** Communities residing along the Brahmaputra River have been facing displacement due to erosion, leading to loss of livelihoods, particularly in agriculture and fishing practices. Deposition, while creating new lands, may lead to disputes over land ownership and usage rights. The economic burden of rebuilding and relocation due to erosion-induced damage is substantial.

DISCUSSION

The morphodynamics of the River Brahmaputra play a significant role in shaping the landscape of Assam, particularly through the processes of erosion, deposition, and stable landforms. The river, known for its dynamic nature, undergoes constant changes due to both natural and anthropogenic factors. The study revealed that erosion is more pronounced in upper Assam, primarily due to the sudden decrease in gradient as the river enters Assam from Arunachal Pradesh. The high-velocity water coming down from the steep terrains of Arunachal Pradesh starts depositing sediments upon entering the relatively flatter Assam plain. During the monsoon season, the water currents strike the riverbanks and causing severe erosion, mostly in the loose newer alluvium. Additionally, deforestation in the upstream areas further exacerbates erosion by reducing vegetation cover and increasing sediment load in the river.

The role of the government authorities in managing and mitigating the impacts of erosion and deposition is crucial. Over the years, the Governments of India and Assam have invested in various flood and erosion control measures. The construction of embankments, revetments, and the arrangement of river training works have been the priority under multiple schemes such as the Flood Management Programme (FMP) and the Brahmaputra Board's River stabilization initiatives (Flood and River Erosion Management Agency of Assam 2025). However, despite these interventions, the long-term effectiveness of these measures remains debatable due to the dynamic nature of the river and the increasing pressure from anthropogenic activities and climate change. Sustainable river management policies, including afforestation with selected plant species, dredging, and proper land-use planning, are essential to mitigate erosion and deposition-related challenges.

Local communities play a vital role in shaping and responding to the river's morphological changes. Many residents living along the banks of the Brahmaputra have adapted to seasonal changes by employing indigenous techniques such as bamboo reinforcement for bank stabilization. However, large-scale bank erosion often displaces thousands of people annually, leading to socio-economic challenges (Dekaraja and Mahanta 2021). Increased community participation in river management programs, early warning systems, and sustainable agricultural practices can help mitigate the impacts of erosion and deposition.

Non-Governmental Organizations (NGOs) and other social organizations have been instrumental in addressing the issues arising from the Brahmaputra's dynamic behaviour. Various NGOs work alongside governmental agencies to implement afforestation programs, conduct awareness campaigns, and provide relief to displaced populations. Organizations such as Aaranyak and the North East Development Foundation have contributed significantly to research, advocacy, and policy recommendations for sustainable river management (Aranyak 2019). Their role in fostering community participation, promoting sustainable practices, and conducting impact assessments has been valuable in complementing governmental efforts.

RECOMMENDATIONS

- Riverbank Stabilization Projects: Implementing bioengineering solutions, such as planting native and exotic plant species along riverbanks, to stabilize soil and reduce erosion.
- Sustainable Land Use Practices: Encouraging land use practices that minimize soil disturbance and reduce the impact of human activities on river dynamics.
- Regular Monitoring and Early Warning Systems: Utilizing geospatial technology for continuous monitoring of riverbank changes to predict and manage potential risks.
- Community Involvement: Engaging local communities in conservation and management efforts to ensure sustainable coexistence with the river.
- Policies and Regulations: Strengthening regulations on activities like sand mining and construction along riverbanks to prevent exacerbating erosion and sedimentation.

Implementing these measures makes it possible to mitigate the negative impacts of the Brahmaputra's dynamic nature and ensure sustainable development for the region.

Photos

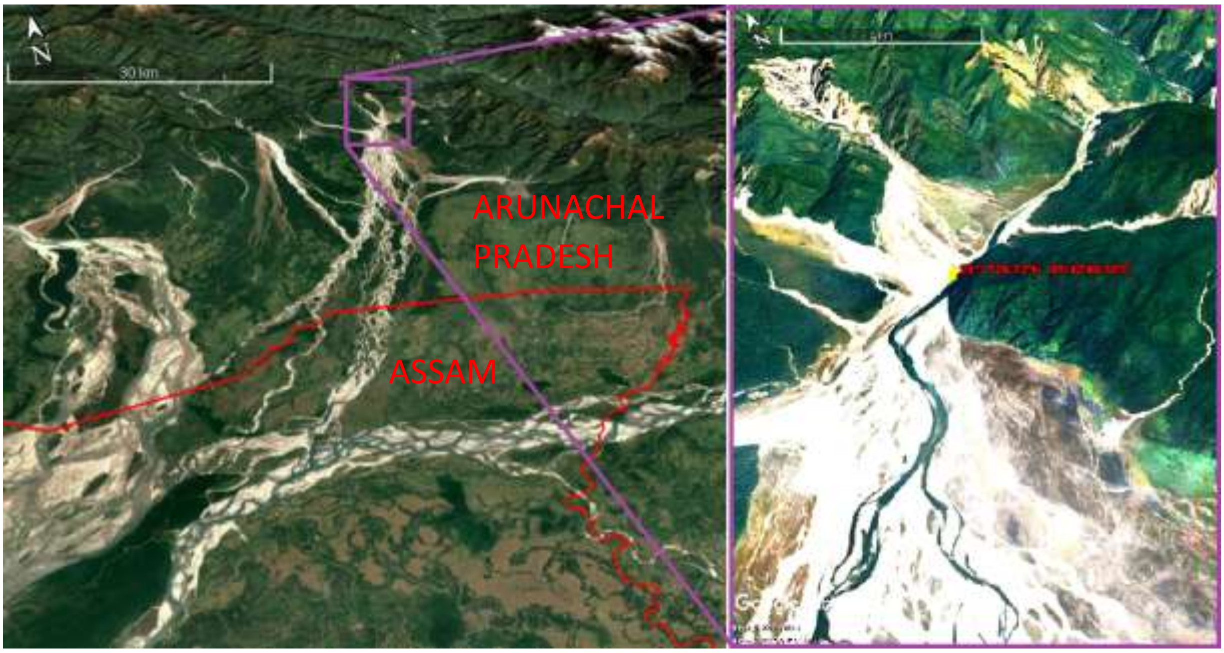

Photo: High erosional activities at the upper reach of the Brahmaputra River

CONCLUSION

In conclusion, this study reveals the profound and dynamic influence of the Brahmaputra River on Assam's geomorphology, ecosystems, and human settlements, emphasizing the urgent need for integrated, adaptive, and sustainable river management. The extensive analysis of erosion and deposition patterns over the 26 years from 1997 to 2023 underscores the river's highly volatile morphodynamics and its far-reaching socio-economic and environmental impacts. The uneven distribution of land loss and gain across districts, where some areas like Dhemaji and Lakhimpur face acute erosion, while others like Barpeta experience substantial deposition, calls for region-specific strategies rather than a one-size-fits-all approach. These spatial variations are shaped by a complex interplay of natural forces, such as monsoonal flows, sediment loads, and geological conditions, compounded by human interventions like deforestation, unplanned development, and encroachments. The consequences include widespread displacement, habitat fragmentation, agricultural loss, and infrastructure vulnerability, all of which pose threats to the region's long-term resilience. Addressing these challenges demands a multifaceted approach that combines continuous monitoring through geospatial technologies, the application of eco-friendly and engineering-based erosion control, proactive land-use planning, and meaningful community engagement in both risk assessment and mitigation. Moreover, the integration of hydrological modeling with remote sensing and GIS offers promising avenues for predicting future river behavior and crafting forward-looking, evidence-based policies. This research thus serves as a critical foundation for fostering informed decision-making and long-term sustainability in managing one of the world's most dynamic river systems.

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