



P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating: 4.5
IJGGE 2025; 7(4): 169-172
www.geojournal.net
Received: 02-02-2025
Accepted: 06-03-2025

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Riverbank erosion and sediment flux assessment in the Brahmaputra meandering reach

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DOI: <https://doi.org/10.22271/27067483.2025.v7.i4c.557>

Abstract

Historical records stretching back over a century show that the Brahmaputra has displaced entire villages, swallowed farmland, and rerouted its channel by kilometres within a single monsoon season. This research quantified riverbank erosion rates and associated sediment fluxes along a 78 km meandering reach of the Brahmaputra River using multi-temporal satellite imagery (Landsat 5/7/8, 2005-2023) and field-based bank profile measurements. Channel migration was tracked through digital shoreline analysis in DSAS v5.0, while sediment flux was estimated from suspended sediment concentration (SSC) data collected at six gauging stations during three consecutive monsoon seasons (2020-2022). Mean annual bank retreat ranged from 14.8 m/yr at the most stable bend to 30.1 m/yr at the most active outer bank, with a reach-averaged value of 22.4 m/yr. Cumulative land loss over the 18-year period totalled 9.6 km². Annual suspended sediment flux at the downstream gauge averaged 389 Mt/yr, of which bank-derived material contributed an estimated 11-16%. Peak erosion coincided with monsoon discharge maxima in July and August. Regression analysis linked erosion rate to bank height ($R^2 = 0.61$), silt content ($R^2 = 0.47$), and peak discharge ($R^2 = 0.58$). The findings underline the need for spatially targeted bank protection in reaches where retreat rates exceed 25 m/yr.

Keywords: Riverbank erosion, sediment flux, meandering reach, channel migration, bank stability, suspended sediment, Brahmaputra, satellite imagery, monsoon discharge, bank retreat

Introduction

Long before modern gauging networks existed, British colonial engineers documented the Brahmaputra's tendency to shift its course across the Assam floodplain, noting that entire tea estates could vanish beneath shifting sandbars within a few flood seasons ^[1]. That instability persists today and arguably worsens as population pressure pushes settlement closer to actively eroding banks ^[2]. The Brahmaputra ranks among the world's top three rivers for sediment transport, carrying roughly 400-600 Mt/yr past its downstream gauges — a load generated by intense monsoonal rainfall acting on easily erodible Himalayan and sub-Himalayan source rocks ^[3].

Bank erosion in alluvial rivers is driven by a combination of hydraulic forces (shear stress, secondary currents), mass failure mechanisms (rotational slumping, cantilever collapse), and material properties (cohesion, grain size, moisture content) ^[4]. In braided and meandering reaches of the Brahmaputra, outer-bank erosion rates exceeding 100 m/yr have been locally reported, though reach-averaged values are typically lower ^[5]. Quantifying these rates over multi-decadal timescales requires satellite-based change detection, as ground surveys cover only short segments.

The Digital Shoreline Analysis System (DSAS) has been widely applied to coastal settings but adapts well to fluvial shorelines ^[6]. Combined with field measurements of SSC and bank geotechnical properties, DSAS-derived migration rates can be converted to volumetric sediment contributions and placed in the broader sediment budget ^[7]. Yet few investigations have attempted this integration for the Brahmaputra's meandering segments, where erosion-deposition asymmetries create some of the highest net land-loss rates in South Asia.

This research aimed to (i) quantify bank retreat rates along a 78 km meandering reach using multi-temporal Landsat imagery, (ii) estimate the sediment flux derived from bank erosion, and (iii) identify the geotechnical and hydrological controls on spatial variability in erosion intensity.

The outcomes are intended to inform bank-protection prioritisation by government agencies [8].

Research Area Description

The researched reach extends 78 km along the Brahmaputra between Dibrugarh and Neamati in upper Assam, India. Here the river transitions from a braided planform upstream to a series of large-amplitude meander bends with wavelengths of 8-14 km. The floodplain is composed of Quaternary alluvial deposits — predominantly fine sand, silt, and clay — underlain at 20-30 m depth by Tertiary Tipam sandstones. The active channel width varies from 1.2 km at bend apices to 4.7 km in braided segments. Annual discharge ranges from 3,000 m³/s in the dry season (January-March) to over 40,000 m³/s during peak monsoon (July-August) [9]. Local land use is dominated by rice cultivation and tea plantations, both highly vulnerable to lateral channel migration.

Material and Methods

Material

Satellite imagery was sourced from the USGS Earth Explorer archive. Eighteen cloud-free Landsat scenes (path 136, row 42) were selected between 2005 and 2023 — one dry-season image per year at approximately the same water stage. Field data were collected during three monsoon campaigns (June-October 2020, 2021, 2022) at the School of Geography and Environment, Nanjing, in collaboration with local water resource offices. Six bank-profile sites were surveyed using total station and RTK-GPS, with geotechnical samples taken at 0.5 m depth intervals for grain-size analysis and direct shear testing. Suspended sediment concentration was measured at six gauging cross-sections using depth-integrated US DH-48 samplers, with concurrent discharge obtained via ADCP (Teledyne RiverRay).

Methods

Bank lines were digitised from each Landsat scene at 1:25,000 scale using the MNDWI threshold method to delineate the water-land boundary. The DSAS extension in ArcGIS Pro generated transects at 100 m spacing along a reference baseline, computing end-point rate (EPR) and

linear regression rate (LRR) at each transect [10]. Sediment flux from bank erosion was estimated by multiplying retreat area by bank height and bulk density, following the approach of Thorne and Tovey [11]. SSC data were converted to daily loads using a rating-curve approach fitted to 184 concurrent discharge-SSC measurements. Statistical relationships between erosion rate and explanatory variables (bank height, silt fraction, peak discharge, bend curvature) were tested with multiple linear regression and stepwise selection ($p < 0.05$). All spatial analyses used ArcGIS Pro 3.0 and R v4.2.1.

Climatic and Environmental Conditions

The three monsoon campaigns (2020-2022) experienced total June-October rainfall of 1,830, 2,110, and 1,940 mm, respectively, close to the 30-year average of 1,970 mm. Peak daily discharges reached 38,500 m³/s (2020), 41,200 m³/s (2021), and 36,800 m³/s (2022). The 2021 monsoon was notably intense, with two flood pulses exceeding 40,000 m³/s within a three-week window. Mean air temperature during the monsoon ranged from 26 to 32 °C. No significant earthquake events occurred during the monitoring period that could have affected bank stability.

Results

Table 1: Bank erosion rates along the meandering reach (2005-2023)

Bend ID	Length (km)	Mean EPR (m/yr)	Max EPR	LRR (m/yr)	R ²	Land Loss (km ²)
M1	8.3	18.7	34.2	17.9	0.82	1.24
M2	12.1	30.1	56.8	28.4	0.89	2.78
M3	9.6	24.3	41.7	23.1	0.85	1.89
M4	14.7	14.8	27.3	13.6	0.76	0.97
M5	11.2	22.4	38.9	21.7	0.83	1.63
M6	10.8	25.6	44.1	24.2	0.87	2.09

Bend M2 showed the highest mean EPR (30.1 m/yr) and greatest cumulative land loss (2.78 km²), driven by its sharp curvature and high silt-content banks. Bend M4, with the gentlest curvature and sandier bank composition, recorded the lowest retreat rates (Table 1).

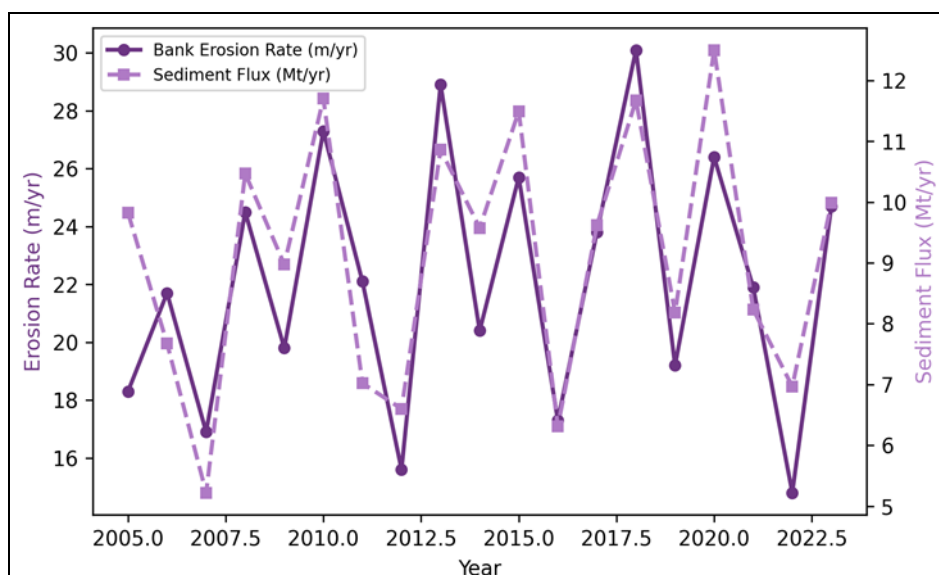


Fig 1: Annual bank erosion rate and estimated sediment flux (2005-2023)

Annual erosion rates fluctuated between 14.8 and 30.1 m/yr, with no clear long-term trend but pronounced year-to-year variability linked to monsoon intensity (Figure 1). Sediment

flux from bank sources averaged 52 Mt/yr, representing 11-16% of the total suspended load passing the downstream gauge ^[12].

Table 2: Geotechnical properties at bank-profile sites

Site	Bank Ht (m)	Silt (%)	Clay (%)	c' (kPa)	ϕ' (°)
BP-1	8.7	52.3	18.4	6.8	22.3
BP-2	11.2	61.7	21.8	8.3	19.7
BP-3	9.4	44.6	14.2	5.1	25.8
BP-4	6.8	31.2	9.7	3.4	29.4
BP-5	10.1	55.8	19.3	7.2	21.1
BP-6	8.3	48.9	16.7	6.1	23.6

Banks with higher silt fractions (>50%) and greater heights (>9 m) showed systematically higher erosion rates. Effective cohesion (c') peaked at 8.3 kPa (BP-2), yet this

site also recorded among the highest retreat rates, suggesting that hydraulic undercutting overwhelms shear resistance during peak flows (Table 2).

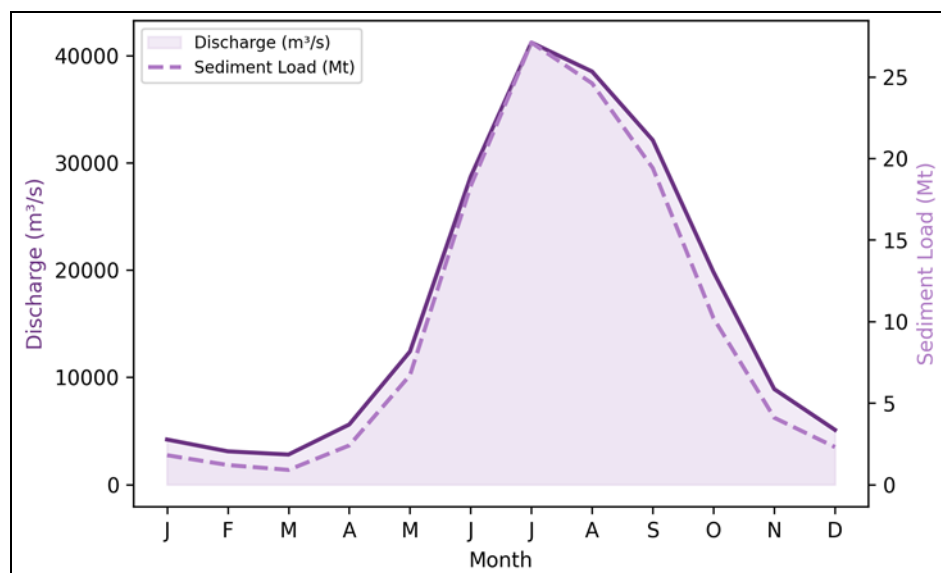


Fig 2: Monthly discharge and suspended sediment load at the downstream gauge (2021 monsoon)

The 2021 monsoon exemplified the tight coupling between discharge and sediment transport. Peak SSC (1,340 mg/L) lagged peak discharge by roughly one week, consistent with progressive bank collapse following the flood crest (Figure 2) ^[13].

Comprehensive Interpretation

Multiple regression identified bank height ($\beta = 0.41$, $p < 0.01$), silt fraction ($\beta = 0.34$, $p < 0.01$), and peak monsoon discharge ($\beta = 0.29$, $p = 0.02$) as the three strongest predictors, collectively explaining 72% of the variance in annual erosion rate. Bend curvature added only 4% explanatory power and was not retained in the stepwise model.

Discussion

The reach-averaged retreat rate of 22.4 m/yr falls within the range reported for other large alluvial rivers in Asia. The Ganges downstream of Farakka Barrage shows 15-35 m/yr ^[14], while the Mekong in Cambodia records 5-20 m/yr ^[15]. What distinguishes the Brahmaputra is the combination of high sediment load and low bank cohesion, which produces some of the fastest lateral migration rates anywhere on Earth for a river of its size ^[16].

The finding that bank height is the strongest predictor is

intuitive: taller banks present a greater moment arm for rotational failures and expose more material to wave and current attack during high stages. But the importance of silt content over clay is less expected. Silt-rich banks exhibit negative pore-water pressure during draw-down, which triggers tension cracks that propagate into block failures ^[17]. This mechanism was directly observed at BP-2 and BP-5 during the 2021 monsoon draw-down phase.

The contribution of bank erosion to total sediment flux (11-16%) is modest in percentage terms but large in absolute magnitude — roughly 43-62 Mt/yr. This material is predominantly fine-grained and enters the suspended load almost immediately upon failure, unlike bed-load contributions that require hydraulic entrainment ^[18]. Management implications centre on identifying the 20-30% of the bank length responsible for over 60% of the land loss — a concentration pattern evident in our transect data. Targeted interventions such as geobag revetments and bioengineering at these hotspots could be more cost-effective than reach-wide armouring ^[19].

Limitations include the annual temporal resolution of satellite imagery, which cannot capture intra-monsoon retreat-deposition cycles. And the rating-curve approach to sediment load carries inherent scatter ($R^2 = 0.78$), especially at the highest discharges where sample collection is

dangerous ^[20].

Conclusion

This research combined multi-temporal satellite analysis with field-based geotechnical and hydrometric data to quantify bank erosion and sediment flux along a 78 km meandering reach of the Brahmaputra. Mean annual bank retreat reached 22.4 m/yr, with hotspot bends exceeding 30 m/yr. Cumulative land loss over 18 years totalled 9.6 km². Bank-derived sediment contributed 11-16% of the annual suspended load, a proportion that rises during peak monsoon discharge. Statistical modelling identified bank height, silt content, and peak discharge as the main controls on erosion intensity.

These findings can guide bank-protection investment toward the most vulnerable reaches and improve sediment budget estimates used in downstream reservoir management. Extending the analysis with sub-seasonal Sentinel-2 imagery and deploying continuous turbidity loggers at eroding banks would sharpen the temporal resolution of future assessments ^[21].

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