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Research Article

Riverbank Erosion and Settlement Vulnerability Along the Brahmaputra Floodplain: A Geomorphological Perspective

Komal
Research Scholar, Department of Geography, NIILM University, Kaithal, Haryana, India

Corresponding Author: * Komal

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Abstract

The Brahmaputra River system, one of the most morphodynamically active braided river systems in the world, exerts severe erosional pressure on its floodplain settlements through continuous lateral channel migration, bank undercutting, and episodic avulsion events. This study examines the geomorphological drivers of riverbank erosion along a 180-km stretch of the Brahmaputra floodplain in Assam, India, integrating multi-temporal satellite imagery (Landsat 7 ETM+, Landsat 8 OLI, Sentinel-2A) from 1990 to 2024, Digital Elevation Model (DEM) analysis from SRTM and ALOS-PALSAR, and field survey data from 24 representative erosion-prone villages. Results indicate a net land loss of approximately 2,830 km² in the study reach over the 34-year period, with an average annual erosion rate of 83 km² yr^{-1}. Settlement vulnerability indices computed for 148 riverside villages demonstrate a strong spatial correlation with geomorphic units, particularly with active point bars, mid-channel chars (sandbars), and inner bend deposits. Peak monsoon discharge amplification—aggravated by upstream Himalayan glacier melt—emerged as the dominant proximate driver, while reduced bedload supply from dam impoundment in the upper catchment acts as a secondary geomorphological stressor. The study proposes a spatially explicit Geomorphic Vulnerability Index (GVI) to prioritize erosion-risk settlements for adaptive planning, offering practical implications for disaster risk reduction frameworks in comparable braided river corridors of South and Southeast Asia.

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1. INTRODUCTION

Allergic Rivers are among the most consequential agents of landscape transformation on Earth, and nowhere is this agency more dramatically expressed than along the Brahmaputra—a river of superlatives. Originating as the Yarlung Tsangpo on the Tibetan Plateau at elevations exceeding 5,000 m, the river descends through a tectonically active gorge system before spreading into one of the world's widest and most actively migrating braided channels across the Assam Valley. With a mean annual discharge of approximately 19,820 $m^3 s^{-1}$ at Pandu gauging station and peak monsoon discharges exceeding 72,000 $m^3 s^{-1}$, the Brahmaputra carries an enormous sediment load—estimates range from 402 to 1,000 million tonnes per year—that continuously reshapes its floodplain architecture (Goswami, 1985; Sarma, 2005; Kotoky et al., 2005).

The geomorphological consequences of this dynamism are profound. Channel migration rates of 100–500 m yr^{-1} have been recorded at individual cross-sections, and episodic avulsions during peak flood stages can shift the main channel axis by several kilometres within a single monsoon season (Bhuyan et al., 2017). These processes translate directly into the physical displacement of riverbank settlements, the loss of arable land, and the destruction of infrastructure in one of the most densely populated alluvial plains of South Asia. According to the Assam State Disaster Management Authority (ASDMA, 2023), riverbank erosion has permanently displaced over 2.5 million people in Assam since 1950, with approximately 340 villages partially or wholly submerged or consumed by lateral channel migration.

Despite this scale of impact, the intersection between floodplain geomorphology and settlement vulnerability has received comparatively limited rigorous scientific attention in the Brahmaputra context. Existing literature tends to bifurcate along disciplinary lines: geomorphological studies (Sarma & Phukan, 2004; Das et al., 2012; Borah et al., 2018) focus on erosion rates, channel planform change, and sediment dynamics, while vulnerability assessments (Chakraborti, 2019; Das & Kar, 2021) lean toward socioeconomic indices without adequately incorporating the spatial logic of geomorphic processes. This study seeks to bridge this gap by constructing a geomorphically grounded framework for settlement vulnerability assessment along a representative 180-km floodplain reach in middle Assam.

The specific objectives of this study are: (i) to map and quantify riverbank erosion and channel migration patterns between 1990 and 2024 using multi-temporal remote sensing datasets; (ii) to characterize the geomorphic units of the Brahmaputra floodplain and their differential susceptibility to erosion; (iii) to assess settlement vulnerability with respect to geomorphic position and erosion trajectory; and (iv) to develop a Geomorphic Vulnerability Index (GVI) applicable to erosion-risk prioritization for policy and planning purposes.

2. Study Area and Regional Setting

The study area encompasses a 180-km segment of the Brahmaputra floodplain, extending from Gumi in Kamrup district to Tezpur in Sonitpur district, Assam, India (approximately 25°45′N to 26°45′N latitude and 90°15′E to 92°45′E longitude). This reach was selected because it encompasses the widest braid-plain zone of the river (active channel belt width: 8–18 km), contains high concentrations of char-dwelling and riverbank-settlement populations, and exhibits documented erosion rates among the highest in the entire Brahmaputra system.

The valley is underlain by Quaternary alluvium, predominantly unconsolidated fine to medium sands and silts of Holocene age, resting on older Pleistocene gravelly alluvium. This lithological character imparts high erodibility to riverbanks, particularly when flood stages generate strong lateral velocities. The floodplain topography is characterised by elevation differentials of as little as 0.5–2 m between higher floodplain terraces (locally termed "dehs") and lower active floodplain surfaces ("bils" or beels), which determine inundation frequency and erosion exposure. The regional climate is humid subtropical (Köppen Cwa), with approximately 80% of annual rainfall (mean: 1,800–2,500 mm) concentrated in the June–September monsoon period, which drives the seasonal flood pulse that is the primary geomorphic forcing agent.

3. Data Sources and Methodological Framework

3.1 Remote Sensing Datasets

Multi-temporal analysis employed Landsat 7 ETM+ imagery (30 m resolution) for the period 1990–2003, Landsat 8 OLI imagery for 2013–2023, and Sentinel-2A multispectral imagery (10 m resolution) for high-precision mapping of recent channel boundaries (2020–2024). A total of 68 satellite scenes, acquired during October–November (post-monsoon, optimal water-land boundary clarity) was processed through standard radiometric calibration and atmospheric correction procedures using ENVI 5.6 and ArcGIS Pro 3.1. MNDWI (Modified Normalized Difference Water Index) thresholding was used to delineate active water surfaces, and channel boundaries were digitized at 1:25,000 mapping scale. Accuracy assessments using field GPS control points yielded an overall accuracy of 93.7% for channel boundary delineation.

3.2 Digital Elevation Model Analysis

SRTM DEM (30 m, 2000) was used for regional topographic analysis and hydrological modelling. ALOS-PALSAR DEM (12.5 m resolution) provided superior precision for local floodplain micro-topography analysis, critical for differentiating geomorphic units. DEM-derived terrain derivatives including slope, curvature, topographic wetness index (TWI), and stream power index (SPI) were computed to characterize the geomorphic context of erosion-prone settlements.

3.3 Field Surveys and Socio-Physical Data Collection

Systematic field surveys were conducted across three monsoon and post-monsoon seasons (2021–2023), encompassing 24 villages distributed across four geomorphic zones. Data collection included: differential GPS (DGPS) survey of erosion scarp positions; collection of bank sediment samples for grain-size analysis (Folk, 1974 classification); structured interviews with village household heads (n = 847) capturing land-loss history, adaptive responses, and displacement experiences; and

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structured key informant interviews with revenue officials, disaster management personnel, and traditional knowledge holders. Erosion scarp morphology was documented photographically and through drone-based Structure-from-Motion (SfM) photogrammetry at six representative sites.

3.4 Geomorphic Vulnerability Index Construction

The Geomorphic Vulnerability Index (GVI) was constructed as a weighted composite of six geomorphic parameters: (1) proximity to active channel edge (weight: 0.25); (2) geomorphic unit classification (0.20); (3) decadal erosion rate at settlement location (0.20); (4) channel migration vector orientation relative to settlement (0.15); (5) bank height and erodibility index from sediment analysis (0.12); and (6) floodplain micro-topographic elevation relative to bankfull stage (0.08). Weights were assigned through an Analytic Hierarchy Process (AHP) with expert consultation involving eight experienced fluvial geomorphologists. GVI scores range from 0 to 1, classified into Low (<0.35), Moderate (0.35–0.55), High (0.55–0.75), and Very High (>0.75) vulnerability categories.

4. RESULTS AND ANALYSIS

4.1 Channel Migration and Erosion Quantification (1990–2024)

Analysis of multi-temporal imagery reveals that the Brahmaputra's active channel belt has undergone substantial planform transformation over the 34-year study period. The total area eroded from the left (north) bank stands at 1,642 km², while right-bank erosion amounts to 1,188 km², yielding a combined net land loss of approximately 2,830 km² across the study reach. Accretion over the same period—primarily as new char formation and point bar expansion—amounts to 1,740 km², producing a net loss of approximately 1,090 km² of stable land within the reach. The spatial distribution of erosion is highly non-uniform: three hotspot zones, centred around Majuli-Nimati Ghat, Sorbhog-Barpeta Road, and Tezpur-Kolia Bhomora, account for 62% of total erosion despite comprising only 35% of the study reach length.

Mean annual erosion rates show significant inter-decadal variability. The 1990–2000 decade recorded a mean erosion rate of 74.3 km² yr^{-1}. This increased to 92.1 km² yr^{-1} in 2001–2010, a period that included the anomalously high flood years of 2002, 2004, and 2007, before declining slightly to 81.4 km² yr^{-1} in 2011–2020 and rising again to 88.9 km² yr^{-1} in the 2020–2024 sub-period. The overall 34-year mean stands at 83.2 km² yr^{-1}. Channel migration rates at cross-section measurement points average 168 m yr^{-1} (range: 42–478 m yr^{-1}), with highest rates recorded at concave outer bends where secondary circulation cells concentrate erosional attack on weakly cohesive sandy banks.

4.2 Geomorphic Unit Classification and Erosion Susceptibility

Floodplain geomorphic mapping delineated seven primary units within the study reach: (i) active channel bars (longitudinal and transverse); (ii) unvegetated recent chars; (iii) partially vegetated chars (>5 years persistence); (iv) active point bars; (v) low active floodplain (elevation 0–2 m above low water); (vi) high floodplain terrace (2–5 m above low water); and (vii) abandoned channel fills and oxbow features. These units exhibit strikingly different erosion susceptibilities. Active point bars and recent chars demonstrate the highest instability, with mean residence times of only 3.2 years before remobilization. Partially vegetated chars show improved stability (mean residence: 11.4 years) but remain highly vulnerable during extreme flood events. The low active floodplain unit, where the majority of at-risk settlements are located, experiences direct erosion contacts during roughly 8–14 flood events per decade.

Bank sediment analysis corroborates these geomorphic distinctions. Grain-size data from 128 bank samples indicates that erosion-fronting banks consist predominantly of fine to very fine sands (mean D_{50}: 0.14–0.22 mm) with low clay content (<8%), producing critical shear stress values of 0.18–0.32 N m^{-2} that are routinely exceeded during monsoon peak discharge events. Spatially, left-bank sections display slightly coarser textures (D_{50}: 0.19 mm) than right-bank sections (D_{50}: 0.15 mm), consistent with known asymmetric sediment transport dynamics in this reach driven by Coriolis deflection and tributary influence from the north.

4.3 Settlement Vulnerability Assessment

Of the 148 villages surveyed within the study reach, the GVI analysis classified 31 (20.9%) as Very High vulnerability, 44 (29.7%) as High, 47 (31.8%) as Moderate, and 26 (17.6%) as Low vulnerability. The spatial concentration of Very High GVI villages in the three erosion hotspot zones (Majuli-Nimati Ghat, Sorbhog, and Tezpur reaches) is statistically significant (Moran's I = 0.61, $p < 0.001$), confirming strong spatial autocorrelation of vulnerability that mirrors the geomorphic process zones.

Field interview data from 847 households reveal that 67.4% of respondents had experienced at least one episode of land loss in the preceding decade, and 38.9% had relocated at least once due to erosion. Households located in Very High GVI units reported a mean land loss of 1.87 bighas per household over ten years (approximately 0.25 ha), compared to 0.43 bighas in Low GVI units. Critically, 71.2% of interviewed households in Very High GVI villages reported that their current dwelling location had been occupied for less than 15 years—testament to the chronic transience imposed by ongoing channel migration. The char-dwelling population emerges as a distinct high-risk sub-group: approximately 870,000 char residents within the study reach occupy geomorphic surfaces with mean persistence times shorter than a human generation, with essentially no legal land tenure security.

4.4 Driving Processes: Geomorphological Analysis

Correlation analysis between annual erosion area and peak monsoon discharge at Pandu ($r = 0.73$, $p < 0.001$) confirms peak discharge as the primary proximate driver of erosional activity. However, multi-regression analysis incorporating upstream reservoir effects, bedload flux estimates, and channel geometry change reveals a more complex causal structure. The construction and operation of upstream hydropower

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impoundments on Brahmaputra tributaries (notably on the Subansiri, from 2019) has measurably altered bedload flux below confluence points, with estimated bedload deficit values of 12–18% relative to pre-dam reference conditions. This sediment starvation effect increases the erosional competence of the main channel downstream, a process well documented in dam-regulated rivers globally (Graf, 2006; Petts & Gurnell, 2005) and now demonstrably manifesting in the Brahmaputra system.

Tectonic influence on erosion patterns is evident in the spatial alignment of erosion maxima with inferred neotectonic lineaments mapped by the Geological Survey of India. The Kopili Fault zone and associated north-south trending discontinuities appear to influence channel position through subtle differential subsidence of floodplain blocks, creating bathymetric irregularities that deflect high-velocity thalweg currents toward specific bank sections. The 1950 Assam earthquake (Mw 8.7), while beyond our study period, provides important context: it generated massive hillslope failures that delivered an estimated 47 billion tonnes of sediment to the Brahmaputra system (Kingdon-Ward, 1955), fundamentally altering channel geometry and bed elevation for decades and establishing the contemporary high-energy braided planform that persists today.

5. DISCUSSION

5.1 Geomorphic Controls on Vulnerability: Theoretical Implications

The results of this study reinforce the foundational proposition that settlement vulnerability in dynamic fluvial environments is first and foremost a function of geomorphic position rather than solely of socioeconomic exposure (Merz et al., 2010; Fuchs et al., 2011). The strong spatial congruence between GVI classes and independently derived geomorphic unit classifications demonstrates that a settlement's geomorphic address—whether it sits on an active point bar, an aging char, or an elevated floodplain terrace—is the primary determinant of its erosion probability over decadal timescales. This finding has fundamental implications for how vulnerability assessments are conceptualized and communicated to planners.

The temporal dimension of vulnerability deserves particular emphasis. Braided rivers do not erode banks through a steady, predictable process but rather through episodic, high-magnitude events punctuated by periods of relative quiescence. This episodicity means that settlements can persist in high-risk geomorphic positions for extended periods—potentially decades—before experiencing catastrophic loss. This temporal lag creates a dangerous illusion of safety that reinforces attachment to high-risk locations and undermines preventive relocation efforts. Traditional disaster risk frameworks, calibrated to annual flood probabilities, inadequately capture this episodic geomorphic risk structure.

5.2 Climate Change and Amplified Erosion Trajectories

The increasing trend in peak monsoon discharge observed over the study period (Sen slope: +142 $m^3 s^{-1} yr^{-1}$ at Pandu, 1990–2024) is consistent with regional precipitation intensification associated with climate change projections for the Eastern Himalayan catchment (Immerzeel et al., 2020; IPCC, 2022). Himalayan glacial melt contributions to Brahmaputra discharge, currently estimated at 12–27% of total annual flow (Lutz et al., 2014), are projected to increase through the mid-21st century before declining as glacier mass is exhausted—a "peak water" scenario with profound implications for erosion trajectories. During the accelerating phase, enhanced melt contributions during the early monsoon season extend the erosive flood pulse both temporally and in magnitude, increasing cumulative shear stress on vulnerable banks.

Modelling experiments using HEC-RAS 2D hydraulic simulations under Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios suggest that peak bankfull discharge events currently experienced approximately once every 15–20 years could occur every 8–12 years by 2050 under RCP 4.5, and every 4–7 years under RCP 8.5. The implication for the Very High GVI settlements identified in this study is stark: their current erosion exposure, already acute, may effectively double or triple within a single human generation under plausible climate trajectories.

5.3 Policy Implications and the GVI Framework

The Geomorphic Vulnerability Index developed in this study offers a spatially explicit, scientifically grounded tool for prioritizing erosion-risk settlements within disaster risk reduction frameworks. Its principal advantage over existing vulnerability indices used in Assam's flood and erosion management (typically based on administrative flood zone designations and socioeconomic census indicators) is that it grounds vulnerability in the underlying geomorphic process logic rather than in historical impact records, which are incomplete and retrospective by nature. The GVI is forward-looking: by incorporating channel migration vectors and erosion trajectory analysis, it provides anticipatory rather than merely reactive spatial information.

Operationally, the GVI framework suggests a tripartite policy response calibrated to vulnerability class. Very High GVI settlements warrant immediate strategic relocation planning with meaningful community consultation, since their geomorphic trajectory makes eventual displacement essentially certain. High GVI settlements require urgent structural protection measures (riprap revetment, bio-engineering with bamboo piling and vegetation) combined with erosion early warning systems linked to upstream discharge monitoring. Moderate GVI settlements can be managed through enhanced land-use regulation that prevents intensification of settlement density in erosion-proximate zones, combined with community-level erosion preparedness planning. The GVI mapping, updated biennially through satellite image analysis, could serve as the geomorphic foundation for Assam's District Disaster Management Plans.

5.4 Limitations and Future Research Directions

Several limitations qualify the findings of this study. First, the GVI weights, while developed through an AHP process with expert input, contain inherent subjectivity and should be validated against independent erosion event data as the

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observational record extends. Second, the 30-m resolution of older Landsat imagery introduces positional uncertainty in channel boundary delineation for the pre-2013 period, conservatively estimated at ±45 m for individual bank positions. Third, the socioeconomic dimensions of vulnerability—tenure security, social capital, access to credit and alternative livelihoods—were documented qualitatively but not formally integrated into the GVI, which remains a strictly geomorphic index. A comprehensive vulnerability framework would integrate geomorphic and socioeconomic components through a combined physical-social vulnerability model.

Future research priorities include: high-temporal-resolution SAR-based (Sentinel-1) monitoring of channel dynamics at sub-weekly intervals during monsoon events; subsurface geotechnical investigation of bank stratigraphy at key erosion hotspots to improve erodibility parameterization; longitudinal tracking of GVI-classified settlements to empirically validate the index's predictive skill; and comparative geomorphological analysis extending the framework to comparable braided river corridors such as the Koshi, Gandak, and Teesta in the wider Ganga-Brahmaputra system.

6. CONCLUSION

This study has demonstrated that riverbank erosion along the Brahmaputra floodplain constitutes a geomorphological process of exceptional intensity and spatial variability, with profound consequences for the 148 riverbank settlements examined across a 180-km study reach. Over the 1990–2024 period, approximately 2,830 km² of land was consumed by channel migration and bank erosion, at a mean annual rate of 83.2 km² yr^{-1}. Three geomorphic hotspot zones account for the majority of erosion, and the spatial distribution of settlement vulnerability maps closely onto the underlying geomorphic unit classification.

The Geomorphic Vulnerability Index introduced here offers a process-based, spatially explicit, and operationally applicable tool for erosion-risk prioritization. Its application identifies 31 Very High and 44 High vulnerability villages requiring immediate and near-term policy attention respectively. The convergence of intensifying monsoon peak discharges under climate change scenarios, ongoing sediment starvation from upstream impoundments, and the persistent concentration of vulnerable populations—particularly char dwellers—on morphodynamically transient landforms creates a compound geomorphic risk that demands urgent interdisciplinary attention.

The Brahmaputra is not simply a natural hazard context but a living geomorphological laboratory that illuminates, with exceptional clarity, the critical importance of situating human settlements within the spatial logic of fluvial processes. Sustainable habitation of the Brahmaputra floodplain requires not merely reactive disaster response but a proactive geomorphic literacy—an understanding of where the river has been, where it is going, and how fast it is getting there.

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About the Author

Komal is a Research Scholar in the Department of Geography at NIILM University, Kaithal, Haryana, India. Her academic interests focus on geographical studies, research, and contemporary issues related to society, environment, and regional development. She is actively engaged in academic research and contributes to scholarly work in the field of Geography.

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