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Spatio-Temporal Dynamics Of Bank Erosion And Accretion Along The River Ganga In The Prayagraj City

Manjeev Vishvkarma[1] Prof. Azizur Rahman Siddiqui Siddiqui[2]

[1]Research Scholar, Department of geography, University of Allahabad, Prayagraj
[2]Professor and Former Head, Department of geography, University of Allahabad, Prayagraj

Abstract

River bank erosion and accretion are fundamental fluvial processes that control channel migration, floodplain development, and landscape evolution in large alluvial rivers. The River Ganga in the Prayagraj city exhibits pronounced lateral instability due to its meandering to braided planform, variable discharge, sediment load, and increasing anthropogenic interventions. This study examines the spatio-temporal dynamics of bank erosion, accretion, and stable banks along the River Ganga between 2002 and 2022 using multi-temporal satellite imagery and GIS-based overlay analysis. River channel boundaries were delineated for the years 2002, 2012, and 2022, and polygon overlay techniques were applied to quantify changes for the periods 2002–2012, 2012–2022, and the cumulative period 2002–2022. Results reveal that bank erosion remained the dominant process throughout the study period, accounting for 54.79% of the total bank area over two decades. However, a noticeable shift from erosion-dominated conditions (2002–2012) to enhanced accretion (2012–2022) was observed, indicating partial channel adjustment in recent years. The spatial patterns highlight intense erosion along outer meander bends and downstream reaches, while accretion is concentrated along inner bends, point bars, and abandoned channels. The findings emphasize sustained lateral channel migration and long-term bank instability in the Prayagraj city, with important implications for floodplain management, infrastructure planning, and riverbank protection strategies.

Keywords: Bank erosion, Accretion, Channel migration, River Ganga, Prayagraj, GIS, Remote sensing

1. Introduction

River systems are inherently dynamic geomorphic entities that continuously adjust their morphology in response to variations in discharge, sediment supply, channel slope, and boundary conditions (Thorne, 1982). Among the various fluvial processes governing river behavior, bank erosion and accretion play a critical role in controlling channel migration, floodplain development, and long-term landscape evolution. Bank erosion refers to the lateral removal of bank material by flowing water, while accretion involves the deposition of sediments along channel margins, resulting in bank advancement. The spatial balance between these two opposing processes determines the degree of channel stability or instability in alluvial river systems (Knighton, 1998).

In large alluvial rivers, bank erosion and accretion are influenced by complex interactions between channel planform, flow hydraulics, sediment transport, and floodplain characteristics (Nanson & Hickin, 1986). Outer meander bends are commonly subjected to high flow velocity and shear stress, leading to enhanced bank erosion, whereas inner bends and point bars promote sediment deposition and accretion (Bridge, 2003). Over time, these processes drive lateral channel migration, cutoff formation, and floodplain accretion, shaping the geomorphic framework of river corridors. Persistent bank erosion not only alters river morphology but also poses significant socio-economic challenges by threatening agricultural land, infrastructure, settlements, and flood protection structures.

During the past few decades, increasing human interventions have significantly modified natural fluvial processes in major rivers worldwide. Construction of embankments, barrages, dams, bank protection works, sand mining, and rapid urban expansion have altered flow regimes and sediment budgets, often intensifying bank erosion in downstream and adjacent reaches (Best, 2019). In densely populated river basins such as the Ganga basin, these anthropogenic pressures compound natural hydrological variability, resulting in frequent channel adjustments and bankline instability.

The River Ganga, one of the largest and most important alluvial rivers of South Asia, exhibits pronounced spatial and temporal variability in channel morphology along its course (Bandyopadhyay et al., 2014). Flowing through the Indo-Gangetic Plain, the river is characterized by a wide floodplain, low gradient, high sediment load, and seasonally variable discharge. Numerous studies have documented extensive channel migration, bank erosion, and floodplain reworking along different reaches of the Ganga, particularly in its middle and lower courses (; Saha & Bandyopadhyay, 2015; Ghosh et al., 2016). These studies highlight that erosion–accretion dynamics in the Ganga are governed by both natural processes and human-induced modifications.

The Prayagraj city stretch of the River Ganga represents a geomorphically sensitive segment where the river transitions from a predominantly meandering to a more braided or multi-channel planform. The confluence of major tributaries, seasonal monsoonal floods, large sediment influx, and expanding urban footprint make this reach especially prone to bank erosion and channel shifting. Despite its geomorphic and socio-economic significance, systematic long-term assessments of bank erosion and accretion dynamics in the Prayagraj stretch remain relatively limited compared to extensively studied reaches such as Malda or the lower Ganga plains. Existing studies often focus on short-term channel changes or qualitative descriptions, leaving a gap in understanding long-term spatio-temporal patterns of bank processes in this reach.

Advancements in remote sensing and geographic information system (GIS) techniques have enabled quantitative analysis of river channel dynamics over extended temporal scales. Multi-temporal satellite imagery, combined with GIS-based overlay analysis, has proven effective in detecting bankline shifts, channel migration, and erosion–accretion patterns in large river systems (Rinaldi & Darby, 2007; Bhuiyan & Dutta, 2012). These techniques allow for objective, repeatable measurements of spatial changes in river morphology and provide valuable insights into long-term channel behavior, particularly in data-scarce regions.

Several studies have successfully employed satellite-derived river channel polygons and overlay analysis to quantify erosion and accretion processes along major alluvial rivers. For example, Mandal and Mandal (2018) analyzed channel migration of the River Ganga using multi-temporal satellite data and reported dominant erosion along outer meander bends and enhanced accretion along inner bends and abandoned channels. Similar approaches have been applied to other large rivers such as the Brahmaputra and the Yellow River, demonstrating the robustness of GIS-based techniques in capturing spatio-temporal river dynamics (Islam & Ahmed, 2011; Xu, 2002).

However, there remains a need for reach-specific studies that integrate quantitative assessment with spatial interpretation of bank erosion and accretion over longer timeframes. In the context of the Prayagraj city reach, understanding how bank processes have evolved over the last two decades is particularly important for assessing channel stability, floodplain vulnerability, and future river management strategies. Long-term analysis can reveal whether the system is becoming more stable or increasingly unstable and can help identify zones of persistent erosion that require targeted intervention.

In this context, the present study aims to analyze the spatio-temporal dynamics of bank erosion, accretion, and stable banks along the River Ganga in the Prayagraj city over a 20-year period (2002–2022). Using multi-temporal satellite imagery and GIS-based polygon overlay analysis, the study quantifies the areal extent and percentage contribution of different bank processes for three-time intervals: 2002–2012, 2012–2022, and the cumulative period 2002–2022. By integrating quantitative results with spatial mapping, this study seeks to enhance understanding of long-term channel behavior and provide scientific support for sustainable river management and bank protection planning in the Prayagraj city region.

2. Study Area Profile

The study focuses on the Prayagraj city stretch of the River Ganga, located between approximately 81°40′E–81°55′E longitude and 25°20′N–25°30′N latitude. This reach is characterized by a wide alluvial floodplain, multiple channel threads, migrating meanders, and active sediment redistribution. Seasonal monsoonal floods, variable discharge regimes, and increasing anthropogenic pressures contribute to frequent bankline adjustments and channel instability.

3. Database and Methodology

3.1 Satellite Data and Channel Extraction

Multi-temporal satellite imagery corresponding to the years 2002, 2012, and 2022, downloaded from USGS Earth Explorer, was used to delineate river channel boundaries. Water indices and visual interpretation techniques were employed to extract river channel polygons for each time period.

3.2 Bank Erosion and Accretion Analysis

River banks for each year were digitized from the extracted channel polygons. A polygon overlay (Union) analysis was applied in a GIS environment to identify spatial changes in bank positions for 2002–2012, 2012–2022, and 2002–2022 (cumulative)

Based on spatial overlap and non-overlap of channel polygons, bank processes were classified into:

1) **Erosion:** River areas present in the earlier year but absent in the later year
2) **Accretion:** New river areas appearing in the later year
3) **Stable banks:** Areas where river boundaries remained unchanged

Areal extent and percentage contribution of each bank process were computed for all three-time intervals.

4. Results

4.1 Quantitative Assessment of Bank Processes

The quantitative analysis reveals pronounced spatio-temporal variability in bank erosion, accretion, and stability along the River Ganga in Prayagraj city (Table 1).

Table 1: **Areal extent and percentage distribution of bank erosion, accretion, and stable banks (2002–2022)**

Bank Process	Area (Km2)			Percentage (%)		
	2002-2012	2012-2022	2002-2022	2002-2012	2012-2022	2002-2022
Erosion	16.29	9.82	18.64	50.4	38.97	54.79
Accretion	7.08	9.17	8.79	21.91	36.39	25.84
Stable	8.95	6.21	6.59	27.69	24.64	19.37
	32.32	25.2	34.02	100	100	100

Source: Calculated by Research

The above table reveals that during 2002–2012, bank erosion was the dominant process, affecting 16.29 km² (50.4%), indicating intense lateral channel instability. Accretion covered 7.08 km² (21.91%), while 27.69% of the banks remained stable. In 2012–2022, erosion declined to 9.82 km² (38.97%), whereas accretion increased significantly to 9.17 km² (36.39%), suggesting enhanced depositional activity. Stable banks accounted for 24.64%. Over the entire period (2002–2022), erosion remained dominant, covering 18.64 km² (54.79%), followed by accretion (25.84%) and stable banks (19.37%).

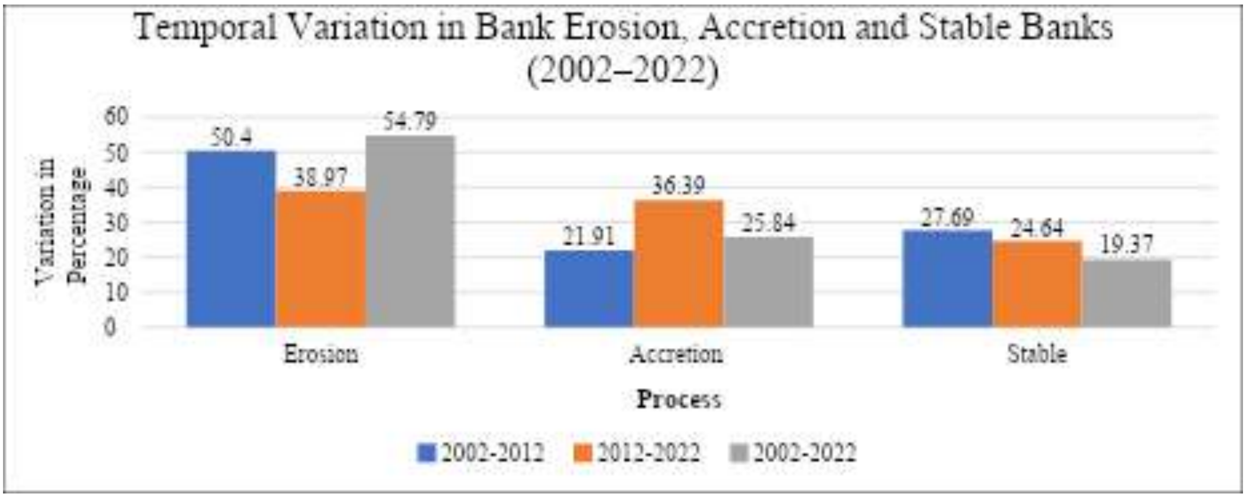

Figure 1: Temporal variation in bank erosion, accretion, and stable banks along the River Ganga in Prayagraj city for the periods 2002–2012, 2012–2022, and 2002–2022

4.2 Temporal Trends

The graphical representation shows a clear temporal shift in bank dynamics. Erosion peaked during 2002–2012 and declined in the subsequent decade, while accretion increased markedly between 2012 and 2022. The continuous decline in stable banks indicates persistent channel adjustment rather than long-term stabilization.

5. Spatial Patterns of Bank Erosion and Accretion

5.1 Bank Dynamics (2002–2012)

The spatial distribution map for 2002–2012 highlights extensive bank erosion zones along outer meander bends and actively migrating reaches. These erosional zones dominate the river corridor, consistent with the quantitative dominance of erosion (50.4%). Accretion zones are primarily confined to inner bends, abandoned channels, and low-energy reaches, while stable banks occur sporadically along relatively straight or constrained sections.

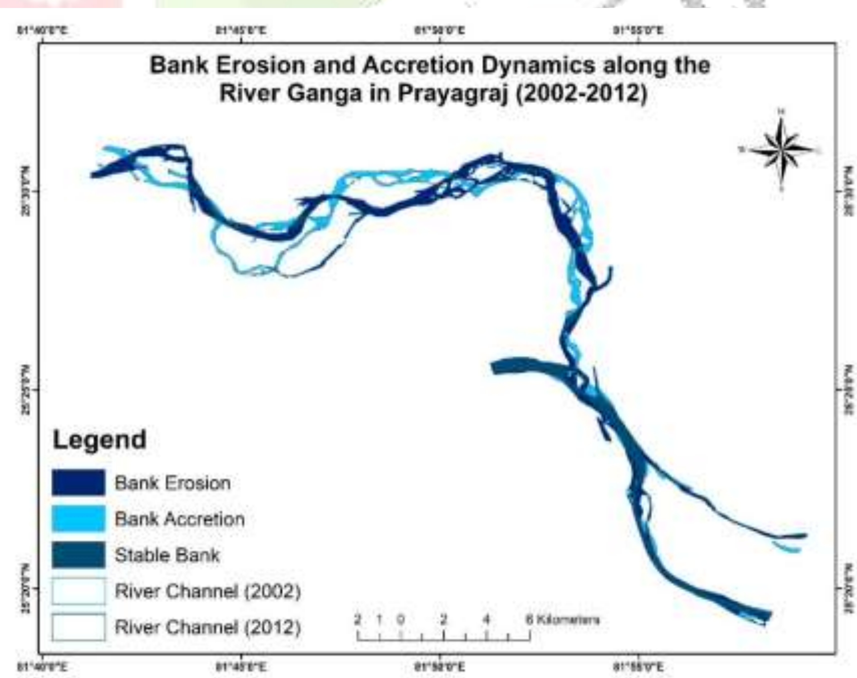

Figure 2: Spatial distribution of bank erosion, accretion, and stable banks along the River Ganga in Prayagraj city during the period 2002–2012

5.2 Bank Dynamics (2012–2022)

Between 2012 and 2022, erosion zones persist along several outer bends but with reduced spatial extent. Accretion zones expand significantly along point bars, inner bends, and previously eroded margins, reflecting increased sediment deposition and partial channel stabilization. Stable banks remain limited but indicate gradual channel adjustment.

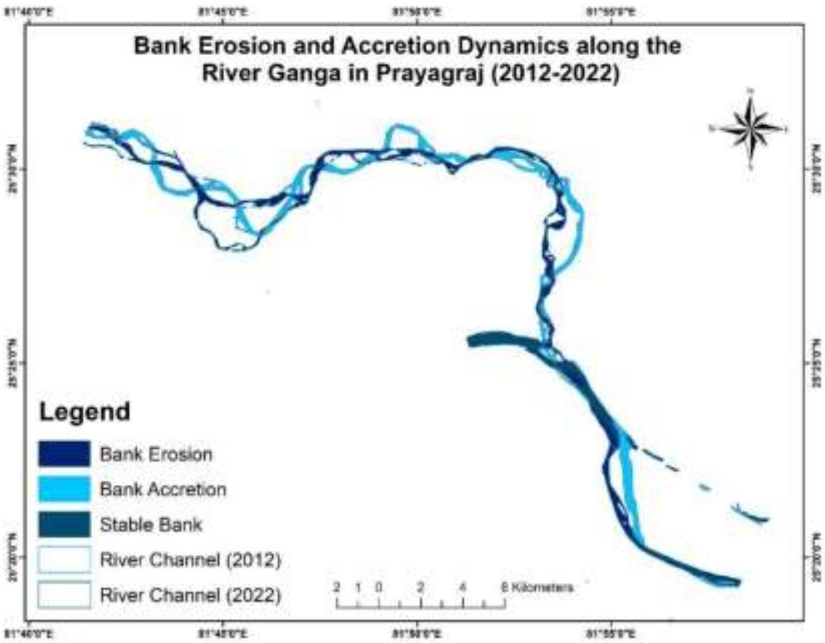

Figure 2: Spatial distribution of bank erosion, accretion, and stable banks along the River Ganga in Prayagraj city during the period 2002–2012

5.3 Cumulative Bank Dynamics (2002–2022)

The cumulative erosion–accretion map illustrates long-term channel evolution over two decades. Bank erosion dominates large sections of the river, particularly along downstream reaches and outer meander bends, confirming sustained lateral instability. Accretion zones are concentrated along depositional features but do not fully compensate for erosional losses. The relatively small proportion of stable banks highlights the geomorphically active nature of the Prayagraj city stretch.

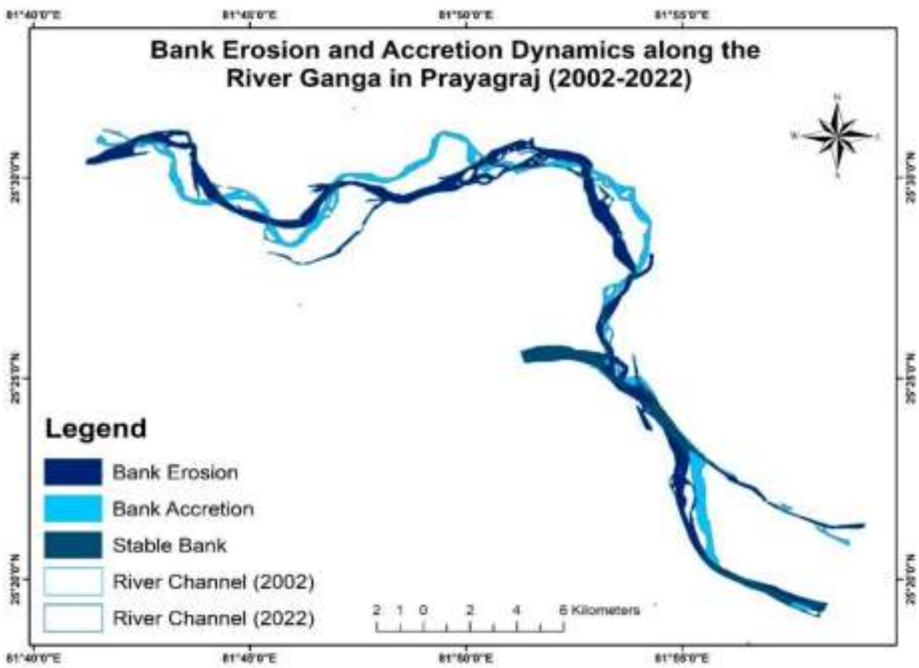

Figure 4: Cumulative bank erosion, accretion, and stable bank dynamics along the River Ganga in Prayagraj city for the period 2002–2022

6. Discussion

The spatio-temporal analysis of bank erosion, accretion, and stability along the Prayagraj city stretch of the River Ganga reflects sustained lateral channel migration driven by both natural fluvial processes and anthropogenic influences. The dominance of bank erosion over the entire study period (2002–2022) indicates long-term channel instability typical of large alluvial rivers flowing through unconsolidated floodplain sediments (Thorne, 1982; Knighton, 1998).

The high proportion of erosion during 2002–2012 (50.4%) suggests a phase of pronounced channel instability, likely associated with concentrated flow along outer meander bends and frequent monsoonal floods. Similar erosion-dominated phases have been reported from other reaches of the River Ganga and comparable alluvial rivers, where episodic high flows accelerate bank retreat and channel migration (Bandyopadhyay et al., 2014; Saha & Bandyopadhyay, 2015). The spatial concentration of erosion zones along outer bends in the study area further confirms the strong control of channel planform geometry on bank erosion processes.

A noticeable shift in bank dynamics is observed during 2012–2022, with reduced erosion (38.97%) and enhanced accretion (36.39%). This change indicates partial channel adjustment characterized by increased sediment deposition along inner bends, point bars, and previously eroded margins. Such alternating phases of erosion and accretion are typical of rivers adjusting toward a dynamic equilibrium rather than achieving long-term stability (Nanson & Hickin, 1986; Bridge, 2003). The continuous decline in stable bank areas suggests that channel reorganization remains active across much of the river corridor.

Anthropogenic interventions, including urban expansion, embankments, and localized bank protection works, may have influenced the observed spatial patterns by modifying flow concentration and sediment redistribution. While these measures can locally reduce erosion, they often shift erosional stress to adjacent or downstream reaches, explaining the persistence of erosion zones in several parts of the study area (Best, 2019).

The cumulative assessment for 2002–2022 highlights the long-term dominance of erosion (54.79%), indicating that accretion has not fully compensated for erosional losses at the reach scale. This persistent erosion underscores the vulnerability of floodplain land and infrastructure along the Prayagraj city stretch. Overall, the results demonstrate that despite recent increases in accretion, bank erosion remains the principal driver of channel evolution, emphasizing the need for river management strategies that accommodate natural channel dynamics rather than relying solely on localized structural controls.

7. Conclusion

This study demonstrates that bank erosion has been the primary driver of channel evolution along the Prayagraj city stretch of the River Ganga between 2002 and 2022. Although accretion increased significantly during 2012–2022, erosion continues to dominate long-term bank dynamics. The observed spatio-temporal patterns highlight the need for continuous monitoring of bank processes to support sustainable river management, floodplain planning, and bank protection measures in the region.

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