River Behavior and Morphological Analysis of a Meandering Channel in the Ganga River System, India

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ABSTRACT

The Rapti River and its tributaries exhibit a meandering morphology, characterized by a dynamic network of sinuous bends that undergo spatial and temporal variations in location and size annually. The most pronounced bankline modifications occur during the receding flow stages, as excess sediment accumulates in the form of point bars and side bars along the primary channel. This sediment deposition alters local flow dynamics and drives the migration of the thalweg. During flood events, river hydraulics undergo significant alterations, leading to variations in sediment transport dynamics and erosive forces, which in turn drive channel migration at multiple vulnerable reaches. A comprehensive understanding of river dynamics upstream and downstream of hydraulic structures is essential for their effective planning, design, and maintenance. Hydraulic analysis of river dynamics upstream and downstream of structures such as barrages and spurs are conducted to assess sediment deposition upstream and the effects of inadequate energy dissipation caused by skewed hydraulic jumps downstream. Morphological studies play a crucial role in sustainable river management, the design of restoration structures, and flood risk mitigation. To address these challenges, comprehensive analyses have been conducted, including assessments of river behavior and the impacts of barrages, embankments, and spurs on channel morphology. These areas are very much needed to pay attention. Effective stabilization of riverbanks in the study area requires the implementation of corrective measures, strategic planning, and governmental support to mitigate erosion and ensure long-term stability.

KEYWORDS
River behaviours, Rapti river, bank protection structures, remote sensing and GIS.

1. Introduction

Meandering rivers are among the most extensively analyzed fluvial systems globally [1]. Despite their ubiquity and significance, the intricate details of their dynamics remain partially understood [2, 3]. These systems are characterized by highly dynamic and fascinating processes, primarily driven by the interplay of bank erosion and sediment deposition [4]. Meandering rivers sculpt the floodplain through alternating patterns of erosion at the outer banks and deposition at the inner banks, creating their distinctive curvilinear structure as they flow downstream [5, 6]. Meander evolution is driven by the lateral migration of the river channel, which reshapes the floodplain and redistributes sediments through bank erosion and accretion processes [3, 7-9].

Meander classification provides critical insights into understanding these systems [3]. Meanders can be categorized based on planform geometry, flow characteristics, and sedimentary processes, reflecting the complex interaction between hydrodynamic forces and geological settings [10-12]. The formation of point bars—large sediment deposits at inner meander bends—further highlights the interplay between sediment transport and channel morphology [13-15]. Hydraulic structures, including barrages, embankments, and spur dikes, play a pivotal role in shaping the morphological evolution of natural river systems [16]. These structures influence the hydrodynamic and sedimentological processes that govern channel behavior, often resulting in both intended and unintended consequences [17]. The Rapti barrage, for instance, alters the natural flow regime by redistributing discharge patterns, which in turn affects sediment transport and deposition dynamics [18]. These changes can lead to notable modifications in channel morphology, including altered erosion and deposition zones, channel incision, or aggradation downstream of the barrage [19].

The phenomenon of why rivers meander in alluvial settings remains an intriguing and unresolved question in geomorphology [1]. A persistent challenge lies in understanding why confined riverine flows exhibit meandering behavior [20-22]. It is hypothesized that this behavior results from the system's response to self-induced transverse oscillations, influenced by various theoretical frameworks addressing the dynamics of water mass movement [23-25]. Numerous studies associate river meandering with sediment transport dynamics, stream load variations, and the systematic exchange of sediment between the riverbanks and the flowing water [26-28]. These processes are fundamental drivers of river meandering; however, none have entirely explained or accurately predicted meander scale. Meandering may develop as a response to deviations in river flow, leading to the formation of secondary flow patterns [29-33]. Numerous researchers interpret meandering as a stability-related phenomenon within river dynamics [20, 34-36]. Meandering is sometimes associated with the impact of the Coriolis force on river flow dynamic [37]. However, this may not be a crucial factor, as rivers in equatorial regions typically carry more water than those in higher latitudes. The hypothesis that meandering maximizes stream-energy losses has gained limited support [38-39], alternatively, the counter hypothesis suggests that meandering optimizes energy dissipation, making it the most probable river morphology, a perspective that remains compelling to some researchers [7, 40-42].

Human interventions do not directly alter the fundamental hydraulic and geomorphic processes, including sediment transport, erosion, and deposition. However, they influence the spatial distribution, intensity, and extent of these processes, resulting in substantial modifications to river morphology [43-44]. These changes can either accelerate or decelerate these processes, often with unintended consequences [45-46]. Human-induced modifications to river systems can be classified as direct or indirect. Direct interventions encompass water storage in reservoirs, flow diversion, channelization, the construction of levees and stop-banks, as well as bed and bank stabilization measures [47]. Poorly designed water development and river training structures, lacking comprehensive hydraulic assessments, can increase vulnerability by obstructing river flow and causing widespread inundation upstream and downstream [48]. Disruptions in water and sediment transfer have a direct impact on the structural and functional dynamics of the river, influencing both upstream and downstream regions of hydraulic infrastructure such as barrage [49-50].

Constructed by the Government of India between 1981 and 1985, the Rapti Barrage was designed to enhance irrigation in the adjacent agricultural regions. Functioning as

a point-source disturbance, the barrage exerts substantial off-site impacts, primarily by modifying the river's longitudinal connectivity and altering base-level conditions. The study area is subjected to multiple hydrological and geomorphological challenges, including recurrent flood inundation, bank erosion, elevated sediment loads, and dynamic river course shifts. A summary of extreme flood events occurring upstream and downstream of the Rapti Barrage is presented in Table 1.

Table 1. Chronological record of flood events occurring upstream and downstream of the Rapti Barrage from 1970 to 2024

Geographical extent of flood events	Flood event years*/#								
Nepal / Upper reach of the Rapti Barrage	-	-	1984	-	1989	1998	-	2007	2017
India / Lower reaches of the Rapti Barrage	1971	1974	-	1980	-	1998	2001	2007	2017

**Flood event years after 1970, # Source: National Institute of Disaster Management (NIDM)*

Embankments are commonly employed for flood management, riverbank stabilization, and enhancing navigational depth [51]. While these structures effectively mitigate risks associated with flooding and bank erosion, they also disrupt the natural flow processes of rivers [52]. By constraining lateral flow, embankments create localized hydraulic complexities, such as increased flow velocities near the structure and reduced velocities downstream [53]. These alterations can elevate flood levels and exacerbate sediment deposition within confined areas [54-55]. Furthermore, impermeable embankments, often designed to prevent water infiltration, can significantly disrupt sediment transport continuity [56-57]. This may result in sediment starvation downstream, causing riverbed degradation, or sediment accumulation upstream, which can reduce channel capacity and increase flood vulnerability [58]. By modifying flow and sediment dynamics, these hydraulic structures impact the natural equilibrium of rivers, highlighting the importance of their strategic design and placement to balance flood control, bank stabilization, and ecological integrity [59].

Spur dikes, widely employed for riverbank protection and channel alignment, exert a significant influence on river morphology by altering flow and sediment dynamics [60-61]. These hydraulic structures are strategically designed to redirect water flow away from erodible banks, reducing erosion risk and stabilizing the channel [62]. However, their presence introduces complex flow conditions, including turbulent eddies and localized flow acceleration, which often lead to the formation of scour holes immediately downstream of the structures [63-64]. This localized scouring is a direct consequence of the concentrated hydraulic forces generated by the deflection of flow, which increases shear stress on the riverbed in the vicinity of the spur dikes [65]. In addition to stabilizing banks, spur dikes can contribute to morphological changes along the river [66-67]. The spaces between adjacent spurs, referred to as embayments, often experience dynamic sedimentation processes [68-69]. These areas act as zones of reduced flow velocity, promoting sediment deposition and influencing the development of point bars or other depositional features [70]. Over time, this sediment accumulation can realign the main channel, affecting its curvature and overall planform geometry [71]. The interplay between sediment deposition in embayments and the scouring near spur tips creates a feedback mechanism that continuously modifies the riverbed and bank morphology [72].

These morphological changes are further amplified by the interactions between spur dikes and the river's hydraulic forces [73-75]. The resulting sediment dynamics can have both localized and system-wide impacts, altering flow paths, modifying floodplain connectivity, and influencing

habitat distribution [53]. A comprehensive understanding of these processes is critical for optimizing the design and placement of spur dikes to ensure effective riverbank protection while minimizing unintended consequences on river morphology and ecology [76]. Understanding the intricate relationships between meandering processes, hydraulic structures, and morphological changes is crucial for effective river management and conservation [5, 77-78]. This study utilizes remote sensing and GIS techniques to examine meander classification and assess the impacts of the Rapti barrage, embankments, and spur structures on channel morphology and sediment dynamics.

The primary objective of this study is threefold. Firstly, it aims to examine the behavior and classification of meanders within the Rapti River system, focusing on understanding its dynamic processes and geomorphological features. This includes categorizing the meanders based on their planform geometry, sediment transport mechanisms, and the interactions between flow dynamics and riverbank stability. These analyses have been carried out using remote sensing and GIS techniques, which facilitated the extraction and classification of meander patterns and morphological features from multi-temporal satellite imagery and spatial data. Secondly, the study investigates the impact of the Rapti barrage on the river system, particularly its influence on flow regulation, sediment deposition, erosion patterns, and overall channel morphology. The analysis conducted using temporal satellite data and geospatial overlays in GIS, assesses how the barrage alters the natural processes of sediment transport and its role in shaping the downstream river environment. Thirdly, the study evaluates the impact of various bank protection structures, such as embankments and spur dikes, on the morphological evolution of the channel. These structures, designed to mitigate erosion and stabilize riverbanks, are examined for their role in modifying flow patterns, sediment dynamics, and channel configuration. Remote sensing and GIS were employed to analyze spatial changes in channel geometry and to detect the influence zones of these hydraulic structures over time. The interactions between these hydraulic structures and the natural processes of alluvial rivers are studied to provide a comprehensive understanding of their effectiveness and potential unintended consequences. This paper consolidates the findings of the river morphology analysis, emphasizing their broader applicability to other alluvial river systems, such as the Ganga, Gandak, Sarda, Kamala, Bagmati, Ghaghara, Kosi, and Brahmaputra rivers. The insights gained from this study contribute to a deeper understanding of river dynamics and can inform the design and management of hydraulic structures and conservation strategies in similar fluvial environments worldwide.

2. About the study area

The Rapti River Basin of Ganga River System, located in the northern part of India, spans from 26°18'03" to 28°33'13" North and 81°33'13" to 83°45'03" East, encompassing a total drainage area of approximately 15,153 km². The Rapti River Basin elevation ranges from approximately 73 meters (minimum) to 1,877 meters (maximum) above mean sea level, with a mean elevation of around 325 meters. The river meanders, characterized by their unique geomorphological features and dynamic nature, have long been a subject of extensive study in the field of fluvial geomorphology [79-82]. This is due to their widespread occurrence, distinct morphological forms, and their significant role in shaping landscapes, as well as the practical implications of their movement for flood management, sediment transport, and channel stability [83].

In this study, several segments or reaches within the Rapti River system have been selected for detailed analysis, focusing on various aspects of river behavior, sediment dynamics, and morphological

changes. These segments were chosen based on their representative features, which provide insight into the river's hydrodynamics, erosion, deposition processes, and interactions with hydraulic structures. The specific study locations, including the respective reach characteristics, are summarized in Table 2. A location map illustrating the spatial extent of the study area and its key features is provided in Figure 1.

Table 2. Analyzed characteristics and specific locations within the Rapti River system in India

S. No.	Studied aspects	Locations within the Rapti river system
1.	Meander classification	Nine distinct meander patterns (A to G_2) have been identified in proximity to specific locations, including Bolua and others. A - Bolua; B_1 - Sukrooliya; B_2 - Kakra Kalan C - Andhra Purwa; D - Gosainpur; E - Shawagunj F - Sahiapur; G_1 - Gadrahia; G_2 - Bangarha Bugurg
2.	Impact of Rapti barrage on the river system	The Rapti Barrage (Laxmanpur Barrage) is located on the Rapti River at Laxmanpur Kothi in Shravasti District, Uttar Pradesh, at coordinates 27°51'53" N, 81°48'48" E.
3.	Impact of embankment structures on channel morphology	This study focuses on four morphologically active areas categorized based on the presence of bank protection structures: (A) absence of bank protection structures (near Karmohni), (B) partial bank protection structures (near Hanharpur), (C) single-sided bank protection structures (near Kakra Kalan), and (D) double-sided bank protection structures (near Bangarha Bugurg).
4.	Impact of spurs structures on channel morphology	A series of five repelling spurs is located in Duhiya (Harijan Basti) village, near the Maloni embankment, at coordinates 26°41'31" N,
5.	Development of embayment between spurs	83°23'26" E. This spur system is near Gorakhpur town, Uttar Pradesh.

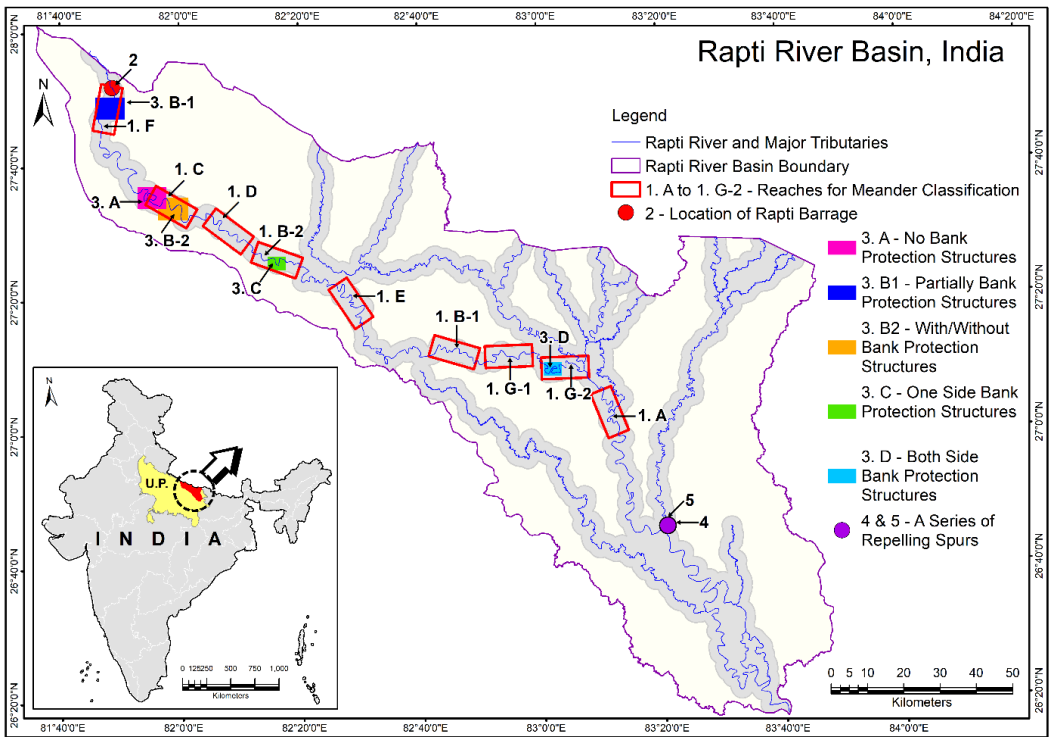


Figure 1. Location map of Rapti River Basin, India

3. Materials and Methods

3.1. Data used and sources

This study utilizes a range of spatial and temporal data sources to construct various thematic layers for the Rapti River system, which were integrated from satellite imagery, field surveys, and secondary data. The data sources and their descriptions are outlined below:

Satellite remote sensing data: multi-temporal, multi-spatial, and multi-spectral satellite remote sensing data spanning the entire Rapti River Basin from 1975 to 2024 were acquired from the U.S. Geological Survey (USGS) Earth Explorer platform. These data include Landsat imagery with a spatial resolution ranging from 30m to 60m, which were used to analyze land use changes, river morphology, and vegetation dynamics. The satellite images were carefully selected based on their temporal coverage and spatial alignment with the study area.

- Landsat-2 MSS: 1975
- Landsat-3 MSS: 1980
- Landsat-5 TM: 1988, 1990, 1998, 2004, 2006-2010
- Landsat-7 ETM+: 2001, 2011-2012
- Landsat-8 OLI: 2013-2024
- Source: U.S. Geological Survey Earth Explorer, http://earthexplorer.usgs.gov

Elevation data: Digital Elevation Model (DEM) data from the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) was used to generate elevation and terrain information for the Rapti River basin. The DEM data, with a spatial resolution of 12.5 meters, were used to assess the topography of the river basin, identify slope variations, and derive hydrological and hydraulic models. This data provides critical information for understanding floodplain dynamics and the influence of elevation changes on river morphology.

- Source: ALOS PALSAR DEM Data, https://vertex.daac.asf.alaska.edu/
- Acquisition Date: 02 December 2007

River infrastructure data: Data on riverine infrastructure, including the locations and physical characteristics of bridges, embankments, spurs, and studs, were digitized using high-resolution satellite imagery from Google Earth©. These infrastructure elements are essential for understanding the impact of human interventions on the river system's hydrodynamics and sediment transport. The data was updated based on the most recent imagery available and provides detailed spatial coordinates of various river structures.

- Source: Google Earth© Satellite Imagery
- Acquisition Date: 26 September 2024

Barrage details: Information regarding the Rapti and Banganga barrages, including their locations and technical specifications, was obtained from the India-WRIS (Water Resources Information System) website. The data provided insights into the operational characteristics of the barrages, their role in flow regulation, sediment transport, and their influence on river morphology.

- Source: India-WRIS Website, http://indiawris.gov.in/wris/#/

Each of these data layers was processed and analyzed to provide a comprehensive understanding of the geomorphological processes within the Rapti River system, as well as the influence of infrastructure and hydrological modifications on its natural behavior.

3.2. Methodology

The methodology encompasses a comprehensive analysis of river morphology, focusing on the classification of meander bends, and assessing the impacts of hydraulic interventions such as barrages, embankments, and spur structures. Additionally, the development and morphological implications of embayments

between spur structures are systematically examined.

Classification of meander bends: Temporal changes in bankfull width and sinuosity were analyzed for nine meandering reaches of the Rapti River from 1992 to 2024 using Landsat satellite imagery and geospatial techniques. Meander patterns were classified based on modified Brice [84] criteria, with width measured at 1 km intervals and sinuosity calculated as the ratio of channel to valley length.

Several researchers have categorized river meanders according to their morphological processes and sinuosity characteristics [84-88]. The Rapti River system exemplifies a meandering river, and a modified version of the meander classification proposed by Brice [84] has been applied. The classification is largely derived from observational criteria and effectively distinguishes three levels of confinement commonly observed in meandering rivers. Nine types of meander patterns, as suggested by Brice, have been identified in the Rapti River system, as illustrated in Figure 2. Furthermore, the bankfull widths and sinuosity ratios of the selected nine river reaches were systematically analyzed.

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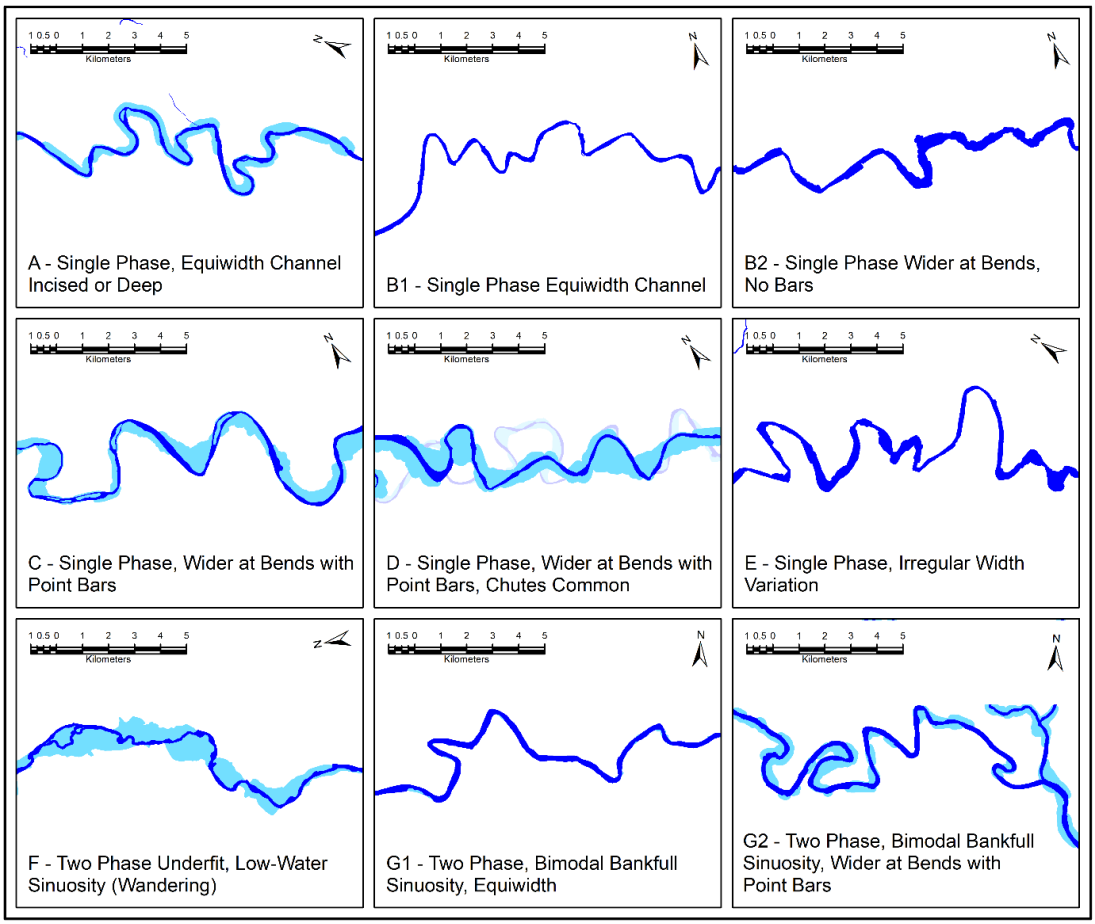


Figure 2. Modified Brice classification of Rapti river system

Sinuosity is a key index used to quantify river meandering and serves as a distinctive feature of river patterns [89-91]. It is intrinsically linked to the morphological, sedimentological, and hydraulic properties of alluvial channels [92]. Sinuosity has been widely employed in functional, comparative, and historical studies.

Sinuosity, defined as the ratio of channel length to valley length, quantifies the degree of curvature in a river's course when observed in plain view. According to Leopold [93], Schumm [85], and Chorley [94], a meandering reach is characterized by a sinuosity greater than 1.5. A ratio of 1 corresponds to a straight river course, while a sinuosity ratio between 1 and 1.5 indicates a sinuous course, and values ranging from 1.5 to 4 suggest a meandering course.

Impact of barrage on river morphology: The influence of the Rapti barrage on river morphology was analyzed using Landsat satellite imagery and geospatial techniques spanning 1975-2024. Remote sensing data were processed and interpreted within a GIS environment to assess temporal variations in channel planform and sediment dynamics. Pre- and post-installation periods revealed significant changes in meandering patterns, river width, and sediment deposition has been analysed.

Impact of embankment on river morphology: Morphological changes in the Rapti River system were analyzed using Landsat imagery (1975-2024), data, and geospatial techniques to evaluate the impacts of embankments. Remote sensing data were processed and interpreted within a GIS environment to extract planform changes, monitor sediment dynamics, and assess bankline shifts over time.

Channel stabilization and bank protection works, including embankments, groynes, spurs, and other structures, are used to control erosion and ensure flood safety [95-97]. While these measures address river instability, they also impact hydro-geomorphic processes [98-99]. They alter channel width, roughness, and bed slope, leading to changes in sediment transport, potential floodplain aggradation, riverbed erosion, and decreased water conveyance capacity [100-101]. Embankments and levees can exacerbate peak flows, causing downstream impacts [102].

Multi-temporal satellite imagery, including Landsat-2 MSS (1975), Landsat-3 MSS (1980), Landsat-5 TM (1990, 2000, 2003, 2006, and 2009), Landsat-7 ETM+ (2012), and Landsat-8 OLI (2015, 2018, 2021, and 2024) for pre-monsoon periods, were analyzed. Four distinct morphological active areas were identified: (i) Regions with partially implemented bank protection structures, (ii) Regions lacking bank protection measures, (iii) Regions with bank protection installed along one bank, and (iv) Regions with bank protection implemented on both banks. Erosion and deposition patterns, along with sinuosity indices, were assessed for these areas. The Rapti River, being morphologically dynamic, poses a flooding risk to surrounding areas in the absence of embankments, which limit bankline movement. This pattern was observed in several vulnerable regions.

Impact of spurs on river morphology: The impacts of spur structures on the Rapti River's channel morphology were assessed using GoogleEarth satellite imagery (2005-2024), field data, and geospatial analysis techniques. Remote sensing imagery was interpreted within a GIS environment to identify, map, and evaluate changes in bankline position, channel configuration, and sediment deposition patterns associated with spur construction. Of 187 identified spurs, 163 were under 90 m, limiting detailed visibility in satellite data.

Embayment development between spurs: The development of embayments between spur structures along the Rapti River was analyzed at Duhiya village near Gorakhpur using GoogleEarth satellite imagery (2005-2024), integrated with remote sensing and GIS techniques. Erosion, deposition, river segment lengths between spurs, and bankline migration rates were studied before and after the installation of five repelling spurs (2008-2009).

4. Result and discussion

4.1. Meander classification

Remote sensing data were processed and analyzed using ArcGIS 10.7 for automated planform extraction and spatial measurements. An inverse correlation

between bankfull width and sinuosity was observed in certain reaches, where wider channels displayed lower sinuosity. The application of remote sensing and GIS tools provided critical insights into the morphological dynamics influencing the Rapti River's meandering patterns over time.

The temporal variations in bankfull width and sinuosity ratio for nine selected meandering patterns of the Rapti River were analyzed using multi-temporal satellite remote sensing data. The study utilizes Landsat archive data spanning approximately thirty-three years (1992–2024) at a spatial resolution of 30 meters to assess temporal changes in the river's morphological characteristics. River width was measured at 1 km intervals along each of the nine defined river reaches, and the average widths are presented in Figure 3(a). In addition, channel and valley lengths were derived from satellite remote sensing data using ArcGIS 10.7, enabling the calculation of sinuosity ratios to evaluate meandering dynamics. The computed sinuosity ratios for each reach over the study period are summarized in Figure 3(b).

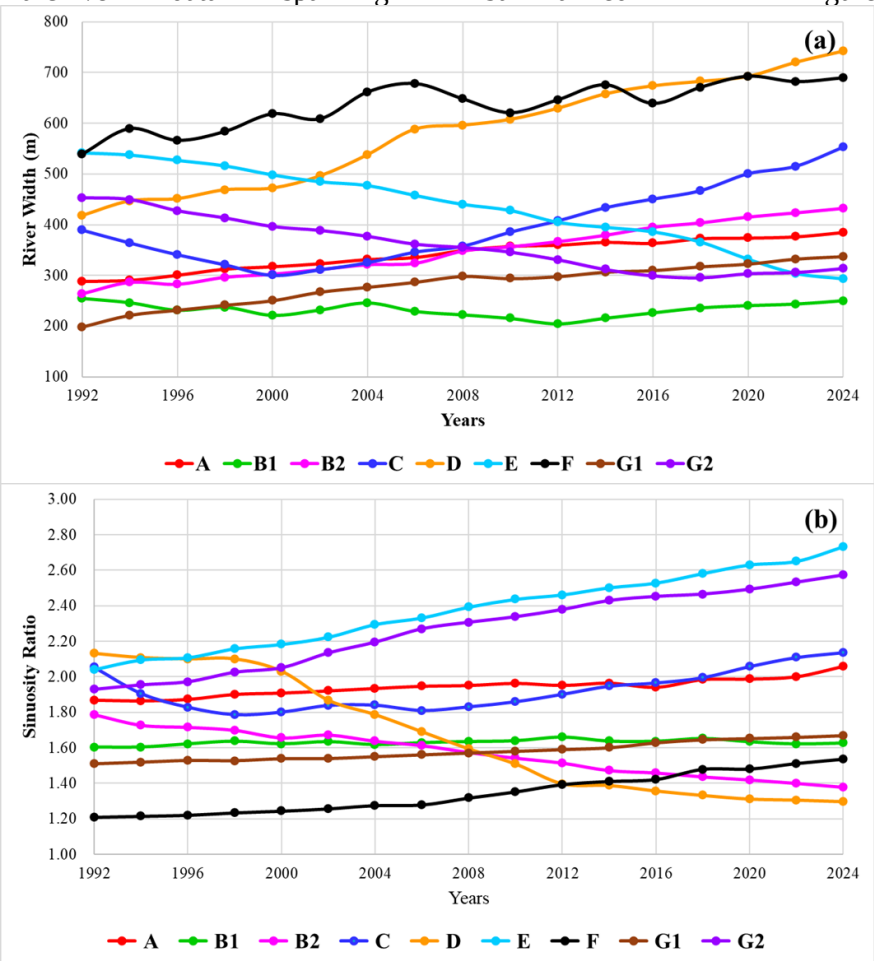


Figure 3. (a) Temporal changes in average river width (RW) and, (b) temporal progression of river sinuosity (SI) over the years

The evolution of bankfull river width in a meandering river is illustrated in Figure 3 (a), while the increasing sinuosity of the river over time is shown in Figure 3 (b), except for reach-E and reach-G2. Initially, the Rapti River exhibited low sinuosity (Si = 1.21 in 1992, reach-F). As the planform developed, the river valley length increased while the channel length remained relatively stable, resulting in a progressive increase in sinuosity, reaching a maximum value of

2.73 in reach-E by 2024. The analysis of bankfull river width and sinuosity ratio for each reach reveals a strong correlation between these two parameters.

According to Brice [103], stable meanders can be identified based on their width characteristics, particularly in equiwidth channels, as observed in reaches B1 and G1. Actively migrating channels generally display spatial variability in bankfull width, with the widest sections often occurring at bend apices, where curvature is most pronounced, and migration rates tend to be highest. Brice [103] and Lagasse [104] identified a distinct category of rivers where variations in bankfull width are independent of curvature, leading to reduced migration rates. Based on observations from nine reaches of the Rapti River, the following classifications for meandering river evolution are proposed: (i) rivers with minimal systematic width variation, (ii) rivers with apexes narrower than crossings, and (iii) rivers with apexes wider than crossings, with case (iii) being the most common in rivers exhibiting significant migration rates [104]. Observations indicate that the maximum bankfull width typically occurs downstream of the bend apex, while in some instances, the minimum width is found upstream. However, this pattern is not consistent across all cases, as illustrated in Figure 3 (a). A direct relationship between river width and sinuosity ratio was identified, wherein an increase in river width is associated with a decrease in sinuosity, and conversely, a decrease in width corresponds to higher sinuosity (see reach-B2, D, E, and G2, Table 3). Sinuosity tends to increase when the outer bank of a bend erodes faster than the inner bank, a process explained by alluvial meander theory in terms of hydraulic dynamics. Although channel narrowing was evident, particularly in Reach-D, the channel continued to increase in sinuosity until the initial formation of a neck cutoff.

Table 3. Correlation between bankfull river width and sinuosity ratio

S. No.	Adapted Brice classification of the Rapti River meandering patterns.	Bankfull river width		Sinuosity ratio	
		Width#	In/St/De*	Sinuosity#	In/St/De*
A	Single-phase, uniform-width channel characterized by incision or significant depth.	M	In	M	St
B_1	Single-phase channel with uniform width.	L	St	M	St
B_2	Single-phase channel with increased width at bends and absence of bars.	L	In	H	De
C	Single-phase channel characterized by increased width at bends and the presence of point bars.	M	In	H	In
D	Single-phase channel exhibiting greater width at bends, characterized by the presence of point bars and frequent chutes.	M->H	In	H->L	De
E	Single-phase channel with irregular variations in width.	H->L	De	H	In
F	Two-phase underfit channel with low-water sinuosity, exhibiting a wandering pattern.	H	In	L	In
G_1	Two-phase channel with bimodal bankfull sinuosity and uniform width.	L->M	St	L	St
G_2	Two-phase channel with bimodal bankfull sinuosity, exhibiting greater width at bends and the presence of point bars.	M->L	De	H	In

*Increasing (In) / Stable (St) / Decreasing (De) order. # H = High, M = Medium, L = Low

4.2. Impact of Rapti barrage on the river morphology

Upstream, the river transitioned from a meandering to a more straightened flow, gradually reverting to a meandering state, while downstream shifts in meandering direction were constrained by riparian vegetation. Disturbances in sediment transport and deposition were prominent between 1981 and 2005, stabilizing post-2006. The analysis highlights potential long-term impacts of the barrage, including sediment accumulation upstream, reduced water velocities, and enhanced downstream erosion caused by the release of sediment-depleted water. The application of remote sensing and GIS provided a robust framework to detect and quantify these

morphological transformations over time.

River width upstream and downstream of the Rapti barrage was analyzed before and after its construction. Prior to the barrage installation, the river width was relatively consistent. Disturbances began in 1981 with the start of barrage construction, and it took approximately 25 years (until 2006) for the river to readjust. After 2006, the river width upstream and downstream became more balanced (Figure 4 a). Geomorphic response times to river engineering works vary, typically requiring 20 to 100 years for the river to reach a new equilibrium, depending on the extent of flow alterations, sediment supply, and vegetation cover. Sediment deposit upstream and downstream of the Rapti barrage was analyzed. From 1981 to 2005, sediment deposition was disrupted, with increased deposition upstream and reduced deposition downstream. However, between 1975-1980 (pre-barrage) and 2006-2024 (post-barrage), sediment deposition patterns were more-or-less balanced upstream and downstream (Figure 4 b), supporting the previous observations.

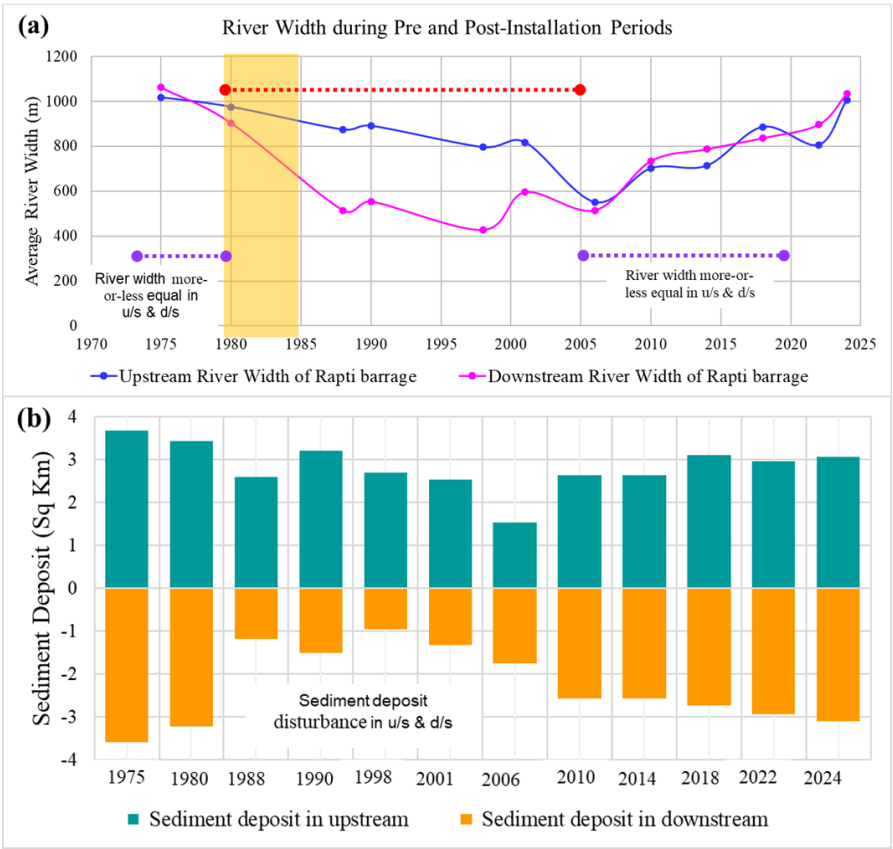


Figure 4. (a) Variation in river width before and after the installation of the Rapti Barrage, and (b) Sediment deposition patterns upstream and downstream of the Rapti Barrage

Prior to the construction of the barrage, the Rapti River exhibited a uniform channel width of approximately 1000 meters both upstream (U/S) and downstream (D/S). However, following the commencement of barrage construction, a divergence in channel width between the upstream and downstream sections became evident. The downstream width progressively decreased relative to the upstream width, reaching a maximum disparity of approximately 400 meters in 1998. By 2006, this difference further widened, with the upstream width exceeding the downstream width by nearly 800 meters. Projections indicate that by 2024, the downstream width is expected to

revert to its pre-construction condition, aligning with the width observed in 1975.

4.3. Impact of bank protection structure - embankment on channel morphology

Erosion, deposition, and sinuosity dynamics were examined across four zones: unprotected areas, partially protected sections, one-sided protection, and fully embanked stretches. A detailed 25 km river segment was divided into five sections for comparative analysis of pre- and post-embankment conditions. Results showed reduced meandering and localized erosion near embankments, while downstream areas experienced intensified erosion and altered sediment deposition due to modified flow dynamics. The integration of remote sensing and GIS enabled a systematic evaluation of spatial-temporal morphological responses to embankment interventions. The different types of morphological active areas are illustrated in Figure 5.

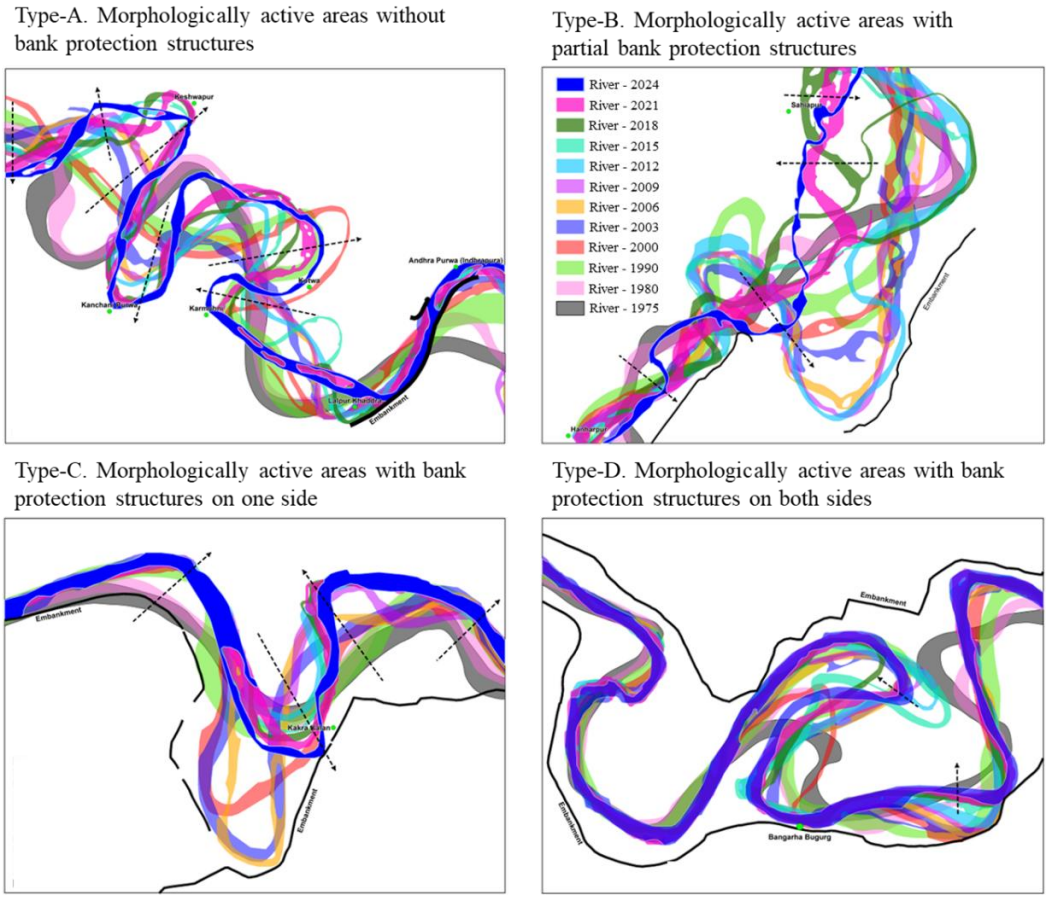


Figure 5. Four distinct morphological activity zones within the Rapti River system

It was observed that embankments restrict the Rapti River from meandering to the left or right. In areas without embankments, the river exhibits a greater tendency to meander freely. In multiple flood-prone areas, embankments restrict the natural meandering dynamics of the river, thereby safeguarding settlements and agricultural land from erosion and inundation. In certain areas, where embankments are present on both sides, the river's meandering occurs within the confines of the embankments. These embankments prevent the river from altering its course beyond their boundaries, thus safeguarding the land outside from

flooding and submergence. Consequently, embankments on both sides of the river effectively limit its meandering to within the embankment limits. Statistical analysis and graphical representations of erosion/deposition patterns and sinuosity indices for four types of morphological active areas. Figure 6 illustrates the classification of morphological activity zones within the Rapti River system, categorized as follows: (i) partially protected regions, (ii) unprotected regions, (iii) areas with bank protection on one side, and (iv) areas with bank protection on both sides.

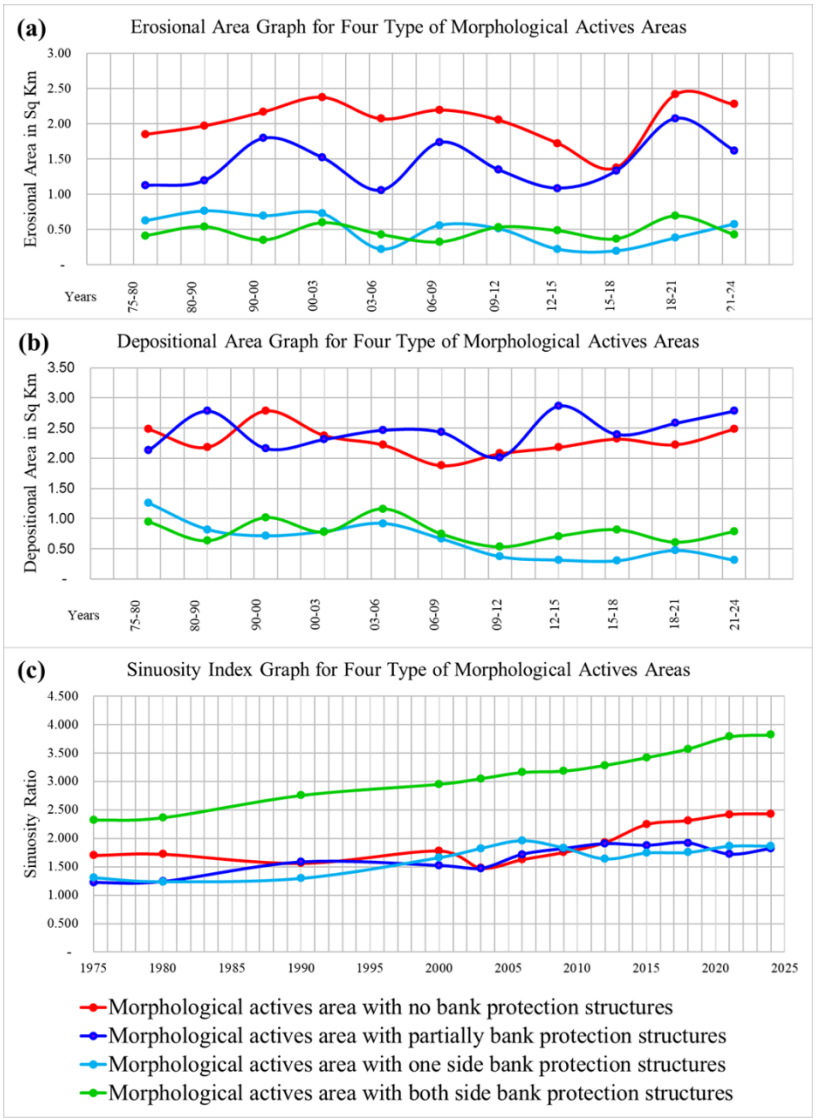


Figure 6. Analysis of (a) erosion patterns, (b) sediment deposition, and (c) sinuosity index across four distinct morphological activity zones within the Rapti River system.

The evaluation of the presented figures demonstrates notable correlations among the four distinct morphological activity zones, as summarized in Table 4.

Table 4. Key relationships among the four types of morphological active areas

S. No.	Categories of morphological active areas and their parameters	Erosion	Deposition	Sinuosity index
1	Morphologically active areas without bank protection structures	High	High	Low
2	Morphologically active areas with partial bank protection structures	Moderate	High	Low
3	Morphologically active areas with bank protection structures on one side	Low	Low	Moderate
4	Morphologically active areas with bank protection structures on both sides	Low	Low	High

Morphologically active areas lacking bank protection structures - such as embankments, spurs, or studs - exhibit significant fluvial dynamics characterized by intense lateral erosion and sediment deposition. The absence of confinement allows for unrestricted channel migration, promoting the formation of broad meander loops between natural or anthropogenic stabilization points, and yielding a lower sinuosity index (Table 4). In areas with partially bank protection, structures interventions constrain the river's lateral mobility only at select locations. This localized confinement results in upstream and downstream morphological instability, marked by moderate bank erosion and substantial sediment deposition. Consequently, the channel develops moderate to large meander loops, maintaining a low sinuosity index.

Where bank protection is present unilaterally, channel migration is impeded on the protected bank while remaining unrestricted on the opposite side. This asymmetrical constraint induces differential morphological evolution, limiting erosional and depositional processes along the protected margin. The resulting adjustment in flow direction and sediment transport dynamics typically produces a moderate sinuosity index.

In fully confined reaches, where embankments are present on both banks, lateral channel migration is substantially restricted. This confinement minimizes fluvial erosion and deposition beyond the embankments. However, despite these structural controls, the highly dynamic nature of the Rapti River permits limited in-channel adjustments. Analysis of temporal changes from 1975 to 2024 reveals an increasing trend in channel sinuosity, attributed to elevated discharge events and continued meander development within the confined corridor. Therefore, the sinuosity index in these reaches is projected to remain high due to persistent intra-embankment morphological activity.

From 1975 to 2024, the sinuosity index exhibited an increasing trend across all four morphological activity types. Among these, reaches with partially bank-protected structures recorded the lowest average sinuosity index (1.665), indicating relatively less channel meandering. In contrast, reaches confined by bank protection structures on both sides exhibited the highest average sinuosity index (3.139), reflecting a pronounced increase in meandering despite structural constraints.

A 25 km river segment, comprising 12 km upstream and 12 km downstream of the Right-Balrampur embankment, was selected to assess the embankment's influence on river morphology. Constructed between 2004 and 2007, this embankment is situated upstream of the Aghenpurwa Bridge in Sidharth Nagar district. Composed of earthen materials with boulder pitching, the embankment divides the study reach into five equal 5 km sections: Sections A and B are upstream, Section C aligns with the embankment location, and Sections D and E are downstream. Statistical analyses, along with graphical representations of erosion-deposition trends and sinuosity index, were conducted for both the pre-installation (1975–2004) and post-installation (2007–2024) periods, as illustrated in Figure 7.

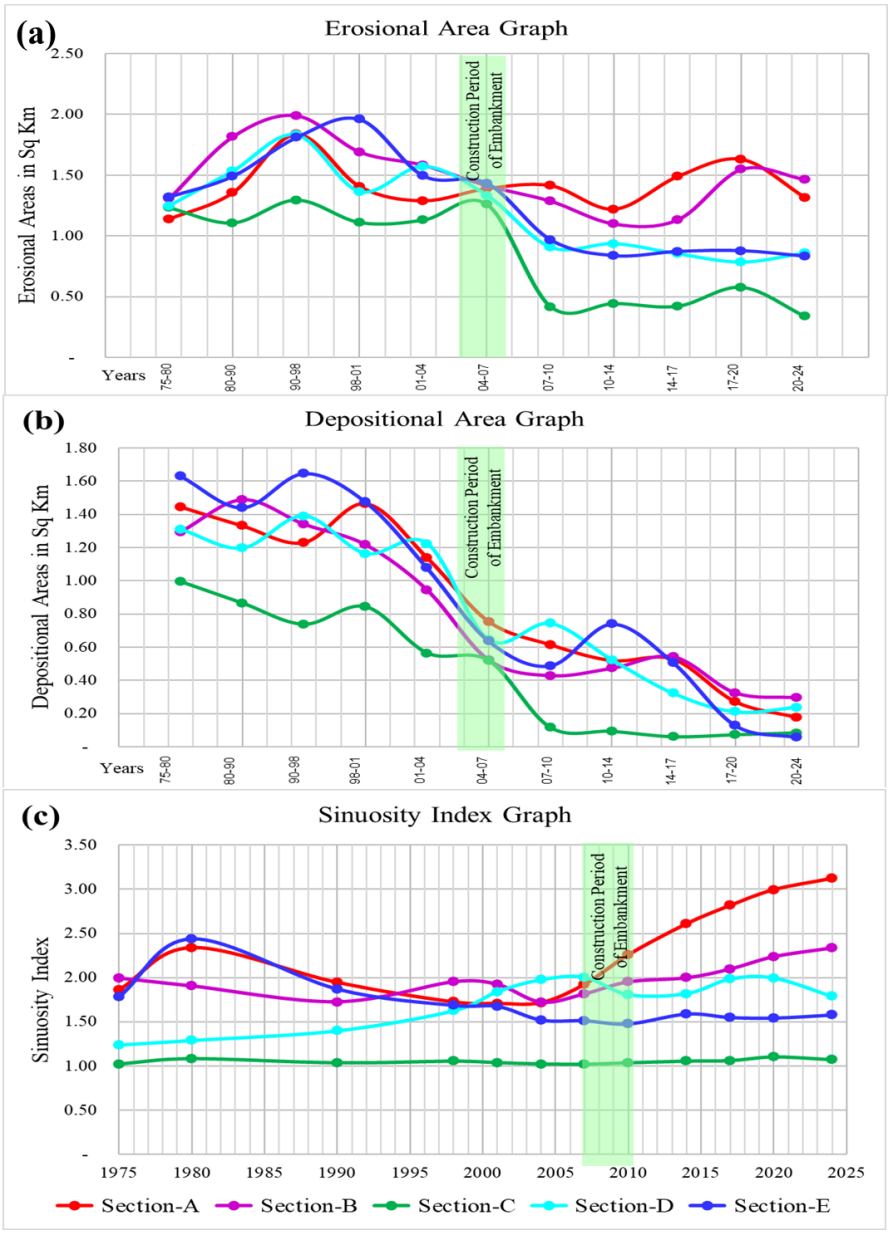


Figure 7. (a) Erosion, (b) sediment deposition, and (c) sinuosity index analysis for evaluating the impact of embankment construction on river morphology

Prior to the construction of the embankment, the erosion pattern within the studied river segment exhibited irregular behavior, enabling the Rapti River to erode different land areas. After the embankment was installed (2004–2007), erosion upstream (Sections A and B) decreased but mostly remained unaffected. In Section C, where the embankment is located, the erosion process significantly reduced, as the embankment restricted the river's meandering. In the downstream sections (D and E), comparable patterns were observed, with the river experiencing greater impacts than the upstream sections due to modifications in flow dynamics and direction. These changes compelled the river to develop moderate to large meandering loops. In terms of deposition, a noticeable reduction was observed downstream, particularly in Section C, where deposition decreased substantially.

The embankment influenced deposition downstream, with no significant change observed upstream, indicating that embankments promote erosion downstream. Changes in the sinuosity index were significant post-installation. In Sections A, B, and D, the sinuosity index increased, reflecting changes in water flow and direction caused by the embankment, leading to the formation of moderate-to-large meandering loops. In Section C, where the river became relatively straight, the sinuosity index remained near 1.0, indicating limited meandering.

Prior to the construction of embankments, the Rapti River exhibited a relatively low average sinuosity index of 1.64. Following the implementation of embankment structures, the average sinuosity index increased to 1.83, indicating enhanced meandering within confined boundaries. Spatially, the sinuosity index is higher in sections A, B, and C (1.93) compared to sections D and E (1.72), suggesting varying degrees of channel adjustment along different reaches.

Furthermore, the embankment construction has significantly mitigated fluvial dynamics, leading to a marked reduction in both erosion and deposition rates. The average annual erosion decreased from 1.05 km²/year to 0.38 km²/year, while deposition declined from 1.22 km²/year to 0.37 km²/year post-embankment construction, highlighting the stabilizing influence of these structural interventions on river morphology.

4.4. Impact of bank protection structure - Spurs on channel morphology

A critical site at Duhiya, near Gorakhpur, was analyzed, focusing on a 2.1 km segment divided into seven sections. Spurs constructed between 2008 and 2009 reduced erosion along the left bankline downstream, promoted upstream deposition, and redirected flow, intensifying erosion on the right bankline downstream. Deposition was most pronounced where spurs were arranged in ascending order. The integration of remote sensing and GIS allowed for a spatially explicit assessment of morphological responses to spur interventions.

Spurs are structures constructed perpendicular or at an angle to the dominant flow direction along the riverbank, designed to achieve several objectives [105-107]. They guide the river along a specified course, reducing the concentration of flow at vulnerable points and directing the flow's axis [108-109]. Spurs also create areas of slack flow, promoting sediment deposition near the riverbank and assisting in bank stabilization [110-111]. Additionally, they protect eroding banks by diverting flow away from them, facilitate sediment deposition where necessary, and trap bed load to encourage the formation of new riverbanks [112].

Data on spurs, including their locations and lengths, was obtained from the Irrigation and Water Resources Department of Uttar Pradesh for the Rapti River system. The records show a total of 187 spurs, with 163 of these having a length of less than 90 meters (approximately three pixels in Landsat-8 imagery), which makes identification on satellite images difficult. When these structures were overlaid on Google Earth, 32 spurs were not visible above the water surface, possibly having been washed away by the flow. Due to this, Google Earth satellite imagery was used for the analysis; however, continuous imagery from 2006 to 2024 was not available for the study area. Consequently, Duhiya (Harijan Basti) near Gorakhpur was identified as a critical site for analysis due to the availability of extensive satellite imagery from Google Earth. Between April 2008 and March 2009, a series of five repelling spurs were constructed along a 300-meter stretch adjacent to the Maloni embankment. These structures were designed to alter flow direction, induce sediment deposition, and reduce flow velocities along the riverbank. For the analysis, a 2.1 km river segment was selected, extending 900 meters upstream and 900 meters downstream from

the spur series. The segment was divided into seven equal sections to assess erosion and deposition patterns. Statistical analyses and graphical representations of erosion and deposition patterns along the right and left banklines across all seven sections were conducted, as illustrated in Figure 8.

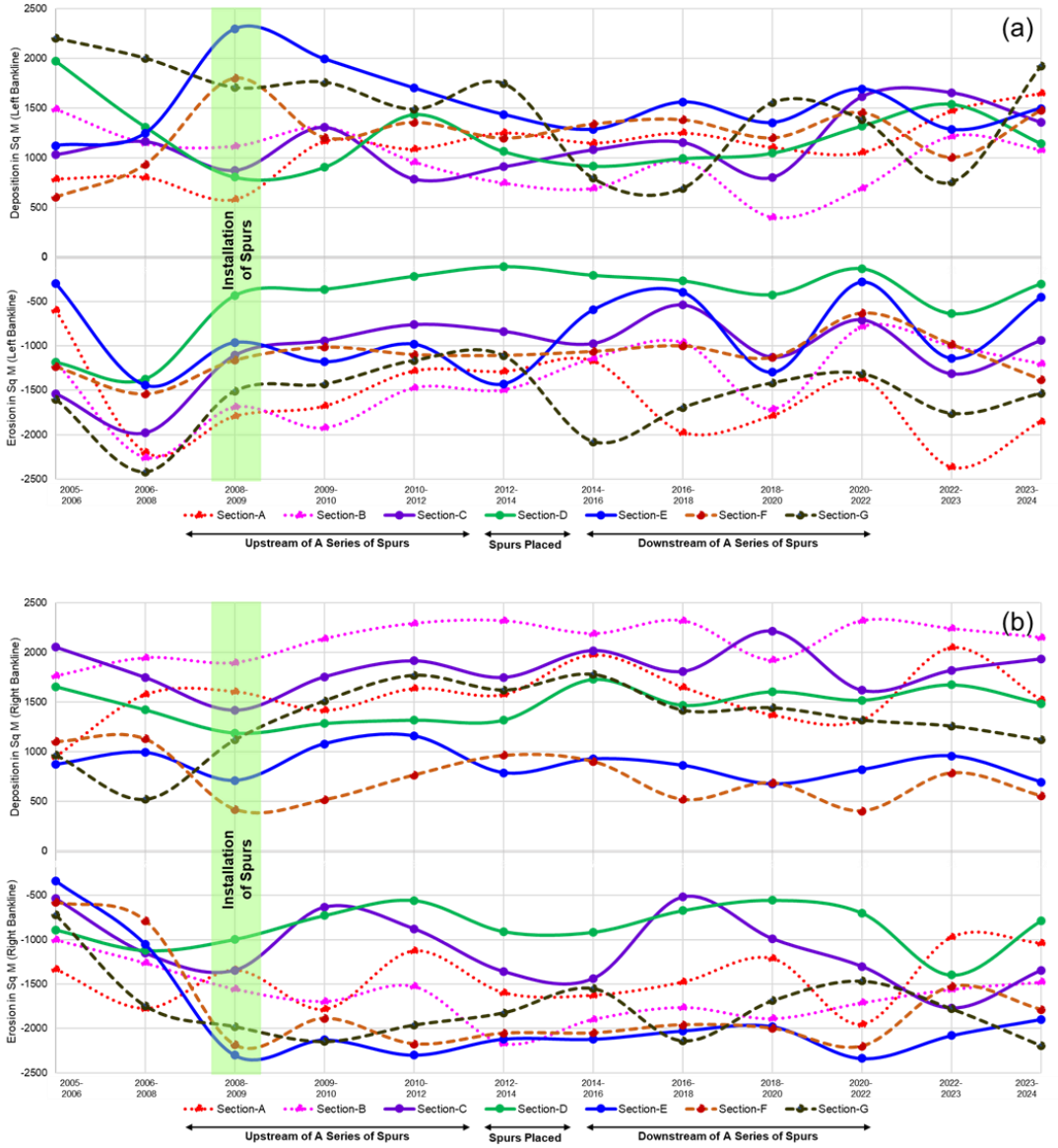


Figure 8. Erosion and deposition patterns along (a) the left bankline and (b) the right bankline

A detailed analysis of erosion and deposition patterns from 2005 to 2024 across the seven sections revealed that deposition predominates in Section-A and Section-B on the right bank (upstream of the spurs), and in Section-F and Section-G on the left bank (downstream of the spurs). Erosion is more prominent in Section-E and Section-F on the right bank (downstream of the spurs). Prior to the installation of the repelling spurs in 2008, erosion and deposition patterns exhibited a zigzag trend without a clear direction. After the installation, erosion significantly reduced in Section-D, particularly on the left bankline (where the spurs were located), as the spurs altered flow dynamics, moving erosive forces away from the bank. The sequential installation of spurs in ascending order led to

increased sediment deposition compared to the reverse arrangement. Along the right bankline, moderate erosion was observed in Section D, while more pronounced erosion occurred in Sections E, F, and G. This pattern is due to the redirected water flow from the left bank, which increased erosion on the right bank, especially in the narrow sections (40-50m wide) of Section-D.

4.5. Formation of embayments between spurs

The analysis, covering three years prior and fourteen years post-installation, divided the river into six sections, with Section-A identified as critical due to its proximity to the first spur. Results highlighted significant alterations in bankline migration and sediment dynamics across the sections.

Spurs are typically constructed in a sequential arrangement to optimize their effectiveness, with each structure facilitating the development of embayments between adjacent spurs [113-114]. These embayments significantly influence flow dynamics and sediment transport, both within the embayment and along the main river [115-116]. Generally, spur dikes reduce flow velocity, leading to sediment deposition between them [117]. As an indirect bank protection method, spur dikes deflect currents away from the bank or reduce flow velocity, thus offering protection against erosion [118]. The key parameters used to describe embayment development are illustrated in Figure 9.



Figure 9. Embayment formation between spurs

GoogleEarth satellite imagery from 2005 to 2024 was utilized to analyze a series of five repelling spurs located at Duhiya (Harijan Basti) near Gorakhpur town, installed between 2008 and 2009. Time-series data spanning three years before and nine years after the spur installation were used to assess erosion/deposition patterns, river segment length between spurs, and bankline migration rates. The spur series was categorized into six sections (A, B, C, D, E, F), with Section A positioned at the critical location where the initial spur is constructed, directly impacting flow

dynamics. The statistical analysis and graphical representation of erosion and deposition patterns for these sections are illustrated in Figure 10.

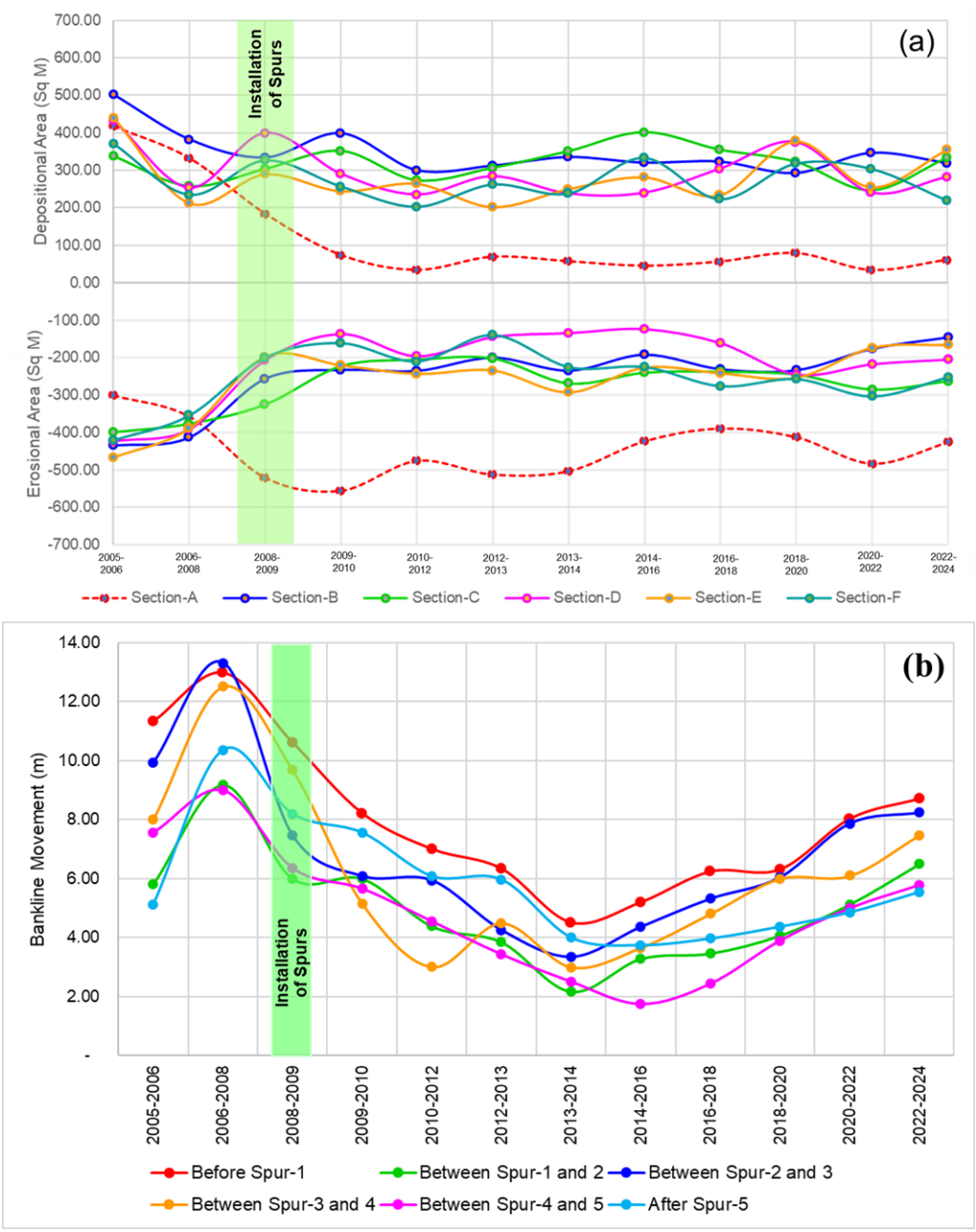


Figure 10. (a) Patterns of erosion and deposition, and (b) Bankline migration in the vicinity of the spur series

Figure 10 (a) shows that before the spur construction (2008-2009), Section-A experienced significant erosion and minimal deposition. After the installation of the spurs, erosion decreased, and deposition increased. Bankline migration analysis reveals that prior to spur construction, the bankline eroded at 13.73 m/year. Following spur installation, erosion slowed to 4.71 m/year, as observed from GoogleEarth images (2005-2024). However, recent images (2015-2024) indicate that erosion has intensified near spur-1, particularly towards the embankment. The analysis of

all five spurs indicates a progressive lateral shift of the river towards the embankment, with an estimated bankline erosion rate of approximately 5.13 m/year (Figure 10 (b)).

Following the construction of spurs 1 to 5, embayments progressively formed between these structures, becoming more distinct in the years 2010 and 2012. Sedimentation between the spurs increased, and over time, the river's course sometimes shifted abruptly due to high sediment flux. Analysis of historical Google Earth imagery reveals a shift in erosion dynamics and bankline migration following the implementation of bank protection structures. Before the installation of spurs (2005–2009), the average rate of bankline migration was 13.51 m/year. However, after the installation of spurs (2010–2024), this rate significantly declined to 4.22 m/year.

5. Discussion

Multiple studies [119-122] and institutional reports [123-126] have indicated that the construction of the Rapti Barrage (Laxmanpur Barrage) is inconsistent with established international regulations. Nepalese communities argue that the barrage was built only 4.5 km from the Nepalese border, whereas international standards require it to be at least 16.5 km away. These studies attribute the escalation of flood events, intensified bank erosion, elevated sediment loads, and alterations in river course dynamics in Nepal to the construction and operation of the Rapti Barrage. Furthermore, it is argued that the construction of the Rapti Barrage, along with the Kalkaluwa afflux bund, has intensified these challenges by impeding the natural drainage of the West Rapti River [127]. However, it is essential to recognize that the Rapti River basin, extending across both India and Nepal, is inherently susceptible to flooding.

The following factors substantiate this assertion: (i) the Rapti Barrage (Laxmanpur Barrage) is situated 4.5 km downstream of the India-Nepal border, with the submergence zone confined to Indian territory; (ii) the barrage functions as a diversion structure for non-monsoon flows rather than a storage reservoir, facilitating unimpeded water passage during flood events without elevating water levels or exacerbating inundation; (iii) the full reservoir level (pond level) of the Rapti Barrage is 127.60 m above mean sea level (amsl), whereas the general ground elevation on the Nepalese side is 131.00 m amsl, which exceeds the pond level; and (iv) the barrage remains non-operational, as the gates have not been lowered.

Prior to the construction of the Rapti Barrage, the river exhibited a meandering pattern, with a noticeable rightward shift in its upstream course, as observed in satellite imagery from 1975 and 1980. Following the barrage installation, the upstream river channel underwent straightening, as evident in the 1988 and 1990 images. However, in the subsequent years, the river gradually reverted to a meandering morphology. Additionally, before the barrage was constructed, the river made a pronounced 90° rightward bend approximately 5 km downstream. After the barrage installation, the river shifted left but was restricted by riparian vegetation and afforestation (evident in the 1988 imagery). Beyond this vegetative zone, the river adopted a zigzag meandering pattern. Over time, the river gradually moved away from the vegetation, but by 2017, downstream meandering decreased.

The operation of the Rapti barrage will lead to significant changes in river morphology both upstream and downstream. Upstream, reduced water velocities will cause increased sediment accumulation, lowering the riverbed and promoting channel widening or braiding [128-130]. Downstream, the release of sediment-free water will carry more energy, leading to erosion of the channel bed and banks. This "hungry water" will erode the river system, resulting in bed incision and widening, with the river gradually re-adjusting to a new characteristic state over a period of 20 to 100 years.

Sarif et al. [131] conducted a comprehensive morphological assessment of the Ganga River in the vicinity of the Farakka Barrage, the construction of which began in 1961 and was completed in 1975. Their analysis focused on planform dynamics, particularly the sinuosity index, which was observed to range between 1.19 and 1.24 during the period 1965–2017. These values indicate that the Ganga River maintained a sinuous channel pattern in the Farakka region. The study also revealed spatial variations in erosion and deposition patterns before and after barrage construction. Specifically, prior to construction, upstream reaches exhibited relatively low erosion, whereas following the commissioning of the barrage, erosion significantly decreased in the downstream reaches. Conversely, sediment deposition in the upstream decreased after construction, while erosion intensified downstream. These findings closely align with observations from the Rapti River study, where post-construction alterations in flow regime and sediment dynamics led to comparable changes in channel morphology.

6. Conclusion

This study employs remote sensing and Geographic Information System (GIS) techniques extensively for analyzing the Rapti River system. Free Landsat series satellite imagery from 1972 to 2024, provided by the United States Geological Survey (USGS), has been utilized, which is widely accessible and has become a standard tool for monitoring global environmental changes. These satellite images facilitate the generation and analysis of long-term time series data, extending over the past five decades. Various segments of the Rapti River were selected for detailed analysis, focusing on different aspects of river morphology and dynamics. The study encompasses meander classification, an assessment of the Rapti Barrage's influence on the river system, an evaluation of the effects of bank protection measures—including embankments, spurs, and studs—on channel morphology, and an investigation into the formation of embayments between successive spur structures. The time span of the analysis covers the period from 1975 to 2024, using Landsat satellite imagery to monitor and quantify these changes over time.

The Rapti River has been classified into nine distinct meander patterns based on morphological processes and sinuosity characteristics. A detailed assessment of bankfull river width and sinuosity ratio has been performed for all nine meander types, resulting in the identification of significant correlations between these morphological parameters. The study also examined the river width and sediment deposition both upstream and downstream of the Rapti Barrage before and after its construction. Prior to the barrage installation, the river width upstream and downstream was nearly equal. However, disturbances began when the construction of the barrage commenced in 1981. It took approximately 25 years (until around 2006) for the river to readjust to its new morphological state. Post-2006, the equilibrium between upstream and downstream river width was largely reestablished, suggesting that the geomorphic response time to river engineering interventions is influenced by the type of modifications and their effects on flow dynamics, stream power, sediment transport, and vegetation cover. Achieving a new characteristic state may take anywhere from 20 to 100 years, depending on the extent of the engineering works.

The impact of bank protection structures on channel morphology was investigated by studying four types of morphological active areas: those without bank protection, partially protected areas, areas with one-sided protection, and areas with protection on both sides. Significant relationships were established between these four types of areas. The findings provide valuable insights into regions requiring immediate flood protection intervention, facilitating the efficient allocation of resources for river training and flood protection measures. This

study offers essential data for effective budget planning and prioritization of flood protection infrastructure.

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Declations

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AI Statement: The authors did not use any AI tools or services in the preparation of this work.

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