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Analyzing Channel Planform Dynamics through Geospatial Approaches over Gandak River Basin, India

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ABSTRACT

The Gandak River, a significant transboundary river in the Indo-Gangetic plains, exhibits complex fluvial processes with frequent planform adjustments. This study examines the river's morphological dynamics from 1975 to 2024, focusing on changes in total length and sinuosity index to analyze spatiotemporal variations. The river's length fluctuated significantly, ranging from 309.79 km in 2010 to a peak of 343.88 km in 2005, highlighting patterns of elongation and contraction influenced by natural and anthropogenic factors. The sinuosity index declined from 1.57 in 1975 to 1.04 in 2024, indicating a shift toward a more linear flow regime. These changes reflect the interplay of sediment transport, hydrological variations, erosion, tectonic influences, and human activities, such as land use changes and infrastructure development. The reduced sinuosity suggests declining floodplain connectivity and altered sediment transport, with implications for river basin management, water resources, and habitat stability. This study underscores the importance of geospatial and hydrological assessments in understanding long-term river morphology trends and informing sustainable river management strategies.

Keywords: River morphology, Sediment transport, Hydrological variations, Floodplain connectivity, River management.

INTRODUCTION

The Gandak River, one of the significant tributaries of the Ganga River, plays a vital role in the socio-economic and ecological landscape of northern India and Nepal (Mehta et al., 2023a). Originating from the Tibetan Plateau and flowing southeast through Nepal and Bihar, it spans over 37,000 square kilometers, covering parts of the Himalayan foothills and the Indo-Gangetic plains. The river, which eventually joins the Ganga at Patna, provides water for irrigation and domestic use, and supports agriculture, which is the backbone of the local economy (Annayat & Sil, 2020; Ghosh & Mukhopadhyay, 2021; Monegaglia et al.,2018a; Shekhar et al., 2022). However, the dynamics of the Gandak River's centerline, the deepest part of the river channel, are of particular interest to hydrologists, geo-morphologists, and river management experts due to their direct implications on sedimentation patterns, flood behavior, drought analysis (Gond, Gupta, Dikshit et al., 2023; Gond, Gupta, Patel et al., 2023; Gupta, Gond et al., 2022) and long-term changes in the river's morphology (Agnihotri et al., 2020). Centerline dynamics refer to the shifting or movement of the river's centerline due to factors, such as flow variations, sediment transport, natural erosion, and deposition processes, as well as human interventions, like embankments, dams, and land-use changes. Understanding the movement of the centerline is critical in the context of flood management and sustainable river basin management, especially for regions vulnerable to the vagaries of seasonal floods, bank erosion, and shifting channels (Basnayaka et al., 2022). This introduction explores the complex interplay of natural and anthropogenic factors that influence the Gandak River's centerline dynamics, providing a comprehensive framework for understanding these processes and their implications for the future of the river basin (Jodhani, Patel, Madhavan, Soni et al., 2024).

One of the primary natural drivers of the Gandak River’s centerline dynamics is the seasonal variability in discharge (Gupta, Mahato et al., 2022; Gupta et al., 2021; Shivhare et al., 2016) and sediment transport. During the monsoon season, which lasts from June to September, the river experiences significant increases in flow due to high rainfall and snowmelt from the Himalayas. This surge in water volume results in lateral bank erosion, which pushes the river’s channel to meander or shift its course (Monegaglia et al., 2018). The Gandak River, originating in the steep terrains of Nepal, carries a heavy sediment load consisting of fine particles from the erosion of the Himalayan foothills. These sediments are carried downstream and deposited in the river's lower reaches, particularly during periods of high discharge. The continuous interaction of these hydrological and sedimentological processes causes the river's channel to evolve, (Jodhani, Patel, Madhavan et al., 2023) leading to shifts in the centerline over time. In some areas, sediment accumulation may form new sandbars or islands, altering the river’s course, while in other regions, the force of erosion may result in rapid bank retreat and channel migration. These processes are critical in understanding how the Gandak River's morphology changes over time and the consequences of these shifts on floodplain management, agriculture, and settlement planning. Moreover, such shifts in the centerline dynamics play an essential role in the distribution of water resources within the basin, affecting the water availability for irrigation and domestic consumption, particularly in low-lying areas that are prone to flooding (Jodhani, Patel & Madhavan, 2023; Jodhani, Patel, Madhavan, Gupta et al., 2024; Madadi et al., 2015; Shekhar et al., 2022).

While natural hydrological forces are key to understanding the Gandak River's centerline dynamics, human interventions in the form of embankments, dams, and river training works have altered the river's natural course and flow regime. The construction of embankments along the river, particularly in Bihar, was initially aimed at mitigating flooding and protecting agricultural land from inundation during the monsoon season. Embankments are typically designed to confine the river within a fixed path, preventing lateral erosion and shifting of the channel. However, while embankments have succeeded in providing short-term flood control benefits, they have also led to significant changes in the river's centerline dynamics. By preventing the river from meandering and adjusting its course naturally, embankments restrict the lateral transport of sediments, which can result in sediment buildup in certain sections of the river. Over time, this confinement can increase the potential for localized erosion downstream, as the river is forced to channel its flow into a narrower path, leading to bank failures and sudden shifts in the centerline. Furthermore, the construction of dams, such as the Gandak Barrage, has introduced another layer of complexity (Mehta et al., 2023b). While these dams regulate water flow for irrigation and hydro-electric power generation, they also reduce the variability in discharge, leading to changes in sediment transport patterns and the morphology of the riverbed. The reduction in high-flow events, which are essential for flushing sediments and rejuvenating the river's natural dynamics, has further exacerbated issues related to sediment accumulation, erosion, and the shifting of the centerline in both upstream and downstream sections of the river. Thus, the human modifications to the Gandak River system have been double-edged, providing flood protection and irrigation benefits, while also disrupting the natural processes that govern the river’s hydrology and morphology.

The study addresses several key challenges in managing the Gandak River, primarily related to morphological changes, hydrological variability, and anthropogenic interventions. One of the major concerns is the significant fluctuation in the river's total length and sinuosity index over the past five decades, indicating dynamic channel instability. The implications of shifting centerline dynamics in the Gandak River are not limited to flood risks and sedimentation. These dynamics also have far-reaching consequences for local agricultural practices, land use, and the overall sustainability of the river basin. The movement of the centerline, caused by changes in flow, sediment deposition, and bank erosion, can lead to the formation of new floodplains, the erosion of fertile land, and the alteration of water courses used for irrigation. In the lower reaches of the Gandak River, where the landscape is relatively flat, the river is prone to lateral migration, leading to changes in the availability and distribution of agricultural land. For instance, new channels or oxbow lakes may form in some areas, resulting in the abandonment of agricultural land that was once fertile, but has now become waterlogged or inaccessible. Conversely, the sedimentation that occurs as a result of shifting centerlines can create fertile land, ideal for crop cultivation, but these lands can also become vulnerable to flooding, especially when the river's course changes abruptly. Therefore, the study's main objectives are to analyze the morphological changes in the Gandak River from 1975 to 2024 by assessing variations in channel length and sinuosity index using geospatial techniques, and to identify the natural and anthropogenic factors influencing these changes. To evaluate the implications of river morphological changes on hydrological stability, sediment transport, and floodplain connectivity, providing insights for sustainable river basin management and mitigation strategies against potential environmental and socio-economic impacts is important. The flooding risks associated with shifting river courses pose significant challenges to settlement planning and infrastructure development, particularly in regions located close to the river's banks. As the river's centerline shifts, it impacts the local water distribution system, particularly for irrigation channels and domestic water supply systems, leading to potential conflicts over water resources in an already water-scarce region (Annayat & Sil, 2020e; Chen et al., 2024; Earnst et al., 2012a, 2012b; Hoseini & Soltanpour, 2022; Jourgholami, 2012a, 2012b; Mehta et al., 2023f; Monegaglia et al., 2018f; Rowland et al., 2010a, 2010b; Shroyer et al., 2015a, 2015b; Tanizawa et al., 2004a, 2004b; Trofa et al., 2019; Wu et al., 2017; Zhang et al., 2023).

Study Area

The research papers above would fit well into a combined study of the different aspects of flood management and adaptation strategies within the context of the Gandak River basin mainly in Bihar, India. The study area selected covers the whole Ganak River basin which ranges from parts of Tibet, Nepal, and India. The study area is a geographical extent, with latitudes spanning between 25.6° N and 29.4° N, and longitudes between 82.8° E and 85.82° E (see Figure (1)). The river originates near the frontier of Nepal and Tibet at about an altitude of 7,620 m. Further down, at the Triveni confluence, it enters the district of Champaran in Bihar; its catchment area is around 40,713 km², with mixed topography: mountainous to vast floodplains. In this basin, the elevation is also largely variable, ranging from about 18 meters above sea level for the plains to about 7,745 meters high in mountains. The region has a monsoon climate type, with high precipitation events dominating the period between June and September; hence, notable river flows occur in the full period, but are appreciably lower in the summer and winter months. This variation of rainfall makes for a more intricate hydrology regime to manage water or find control of flooding. It is subsistent agriculture; wherein local communities rely on seasonal rainfall events for their means of livelihood. Because their nature is subsistent, they are more vulnerable to the effects of flooding, because extreme weather conditions may affect the crops and weaken the food security. In, such places, flooding affects agricultural productivity much more destructively and has adverse implications for public health. Flooding of lands often leads to an increased number of cases of waterborne diseases, among others, due to polluted sources of water and a lack of proper sanitation facilities. This is often faced by populations at higher risk, who have exacerbated the impact of flood on pre-existing health disparities and catapulted the demand in health care services locally. Hence, flooding research is based on focusing on key issues in the subject of flood management in explorations over time series analysis of rainfall frequency data from sources, such as Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE) and the Indian Meteorological Department (IMD). These analyses fit statistical methods to normal and generalized extreme-value distributions of maxima for rainfall and enlighten on future potential flooding.

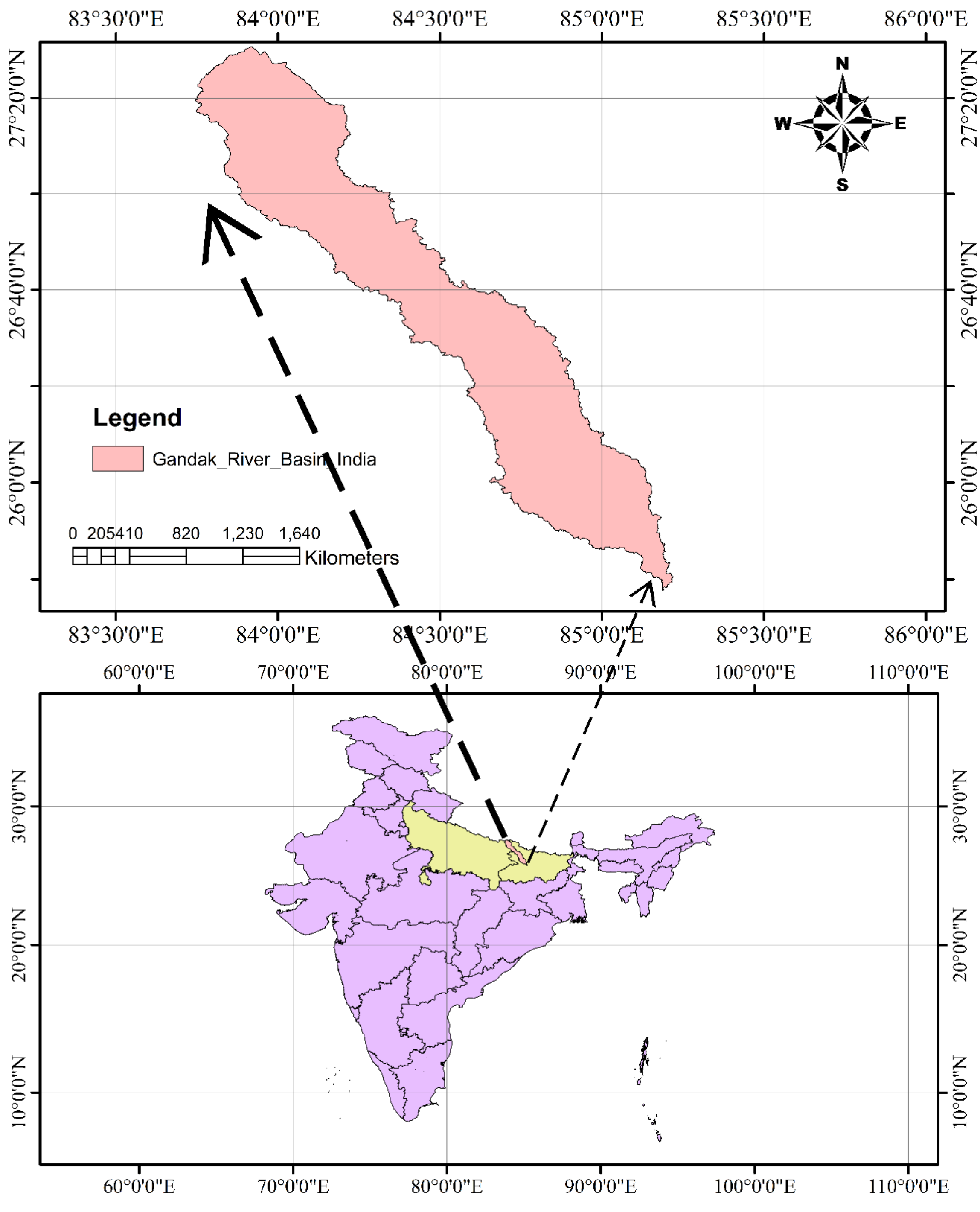

Figure (1): Geographical map of Gandak river basin as study area and map of India

This integration would call for an upscale in the flood forecasting and management strategy within the region. The local communities have insightful historical information about the weather patterns as well as events of flooding that always prove effective supplements in using scientific approaches. Contact with researchers and community members will further bring out more defined paths on which effective early warning systems and adaptive approaches might be developed-suitable approaches for each specific community. Climate change is yet another key input factor in the hydrology of the Gandak River basin, and more elevated temperatures and changed rainfall regimes might add up to the amplification of the flooding in this already vulnerable area., such contexts should be borne in mind while preparing adaptation strategies. An integrated approach will be required, underlining the need for cooperation among local community groups, researchers, decision-makers, and a wide range of stakeholder groups about effective solutions in resilient conditions for floods while promoting sustainable development programs among people and the environment. Addressing the challenges of flooding in the Gandak River basin would finally depict a high opportunity for measures taken for improvement upon the impacts of climate change besides developing a sustainable future for its people through cooperative efforts to improve public health outcomes and agricultural productivity. Therefore, science must integrate the local knowledge and cooperation from all stakeholders, so that only through this blended approach, one can develop comprehensive strategies in light of taking care of flooding concerns temporarily and developing further long-term resilience against climate variability in this critical region of South Asia.

MATERIALS AND METHODOLOGY

This study utilized Landsat satellite datasets obtained from the United States Geological Survey (USGS) to analyze the morphological changes of the Gandak River from 1975 to 2024 (Table 1). The pre-processing of Landsat imagery involved multiple steps to enhance data quality and ensure accurate analysis. First, atmospheric correction was performed using the Fast Line-of-Sight Atmospheric Analysis of Hypercubes (FLAASH) module in ENVI software to remove atmospheric distortions, such as haze and water vapor effects. Radiometric calibration was applied to convert raw digital numbers into surface reflectance values, ensuring consistency across different sensor generations. Geometric corrections were conducted using ground control points (GCPs) and co-registration techniques to align images accurately over time. Cloud masking was implemented using the Function of Mask (Fmask) algorithm to exclude cloud-covered and shadowed areas, minimizing misclassification errors. Principal Component Analysis (PCA) was performed in ENVI software to enhance feature extraction and identify dominant spectral variations in the dataset. Geographic Information System (GIS) tools were used to delineate river center lines and measure the sinuosity index which calculates the ratio of the actual channel length to the shortest path length.

Table 1. Various satellite datasets with their spatial resolution and operating years provided in USGS

Satellite Data	Year	Spatial Resolution (m)	Source
Landsat 8-9 OLI/TIRS C2 L2	2013 - Present	30	USGS
Landsat 7 ETM+ C2 L2	1999 - Present	30	USGS
Landsat 4-5 TM C2 L2	1982 - 2012	30	USGS
Landsat 8-9 OLI/TIRS C2 L1	2013 - Present	30	USGS
Landsat 7 ETM+ C2 L1	1999 - Present	30	USGS
Landsat 4-5 TM C2 L1	1982 - 2012	30	USGS
Landsat 1-4 MSS C2 L1	1972 - 1993	80/30	USGS

The method employed for the comprehensive analysis of channel planform dynamics typically involves a systematic approach integrating various geo-spatial techniques and data sources. Initially, historical data, including topographic maps, and satellite imagery, were collected and processed to establish a baseline understanding of the river's planform characteristics. Subsequently, Geographic Information System (GIS) tools (Issa et al., 2023) were used to delineate the river's centreline, measure & analyse the sinuosity index over a period of 48 years.

The sinuosity index is defined as the proportion of the curved length to the straight (shortest) length between the river's endpoints. As an indicator of channel behaviour, sine curvature distinguishes between straight and meandering channels. Sinuosity index of the study reach was determined utilizing Friend and Sinha's approach (1993). This method involved dividing the reach into reaches of equal lengths. After measuring the actual channel length and the straight path length, the sinuosity index for each reach was computed using the subsequent equation (Jodhani, Patel, Madhavan, Soni et al., 2024).

$$P_{SI} = L_{cmax}/L_R \quad (1)$$

where, P_{SI} is the sinuosity index, L_{cmax} is the length of the channel's midline (in single channel) or the broadest channel of the reach (when multi-channel), and L_R is the reach's total length. According to Rust (978), the channel's pattern categorization was performed and is illustrated in Table 2.

Table 2. Classification of channel pattern of rivers based on sinuosity index value

River	P_{SI}	Classification of channel pattern
Single channel	<1.5	Straight
	>1.5	Sinuous
Multiple channels	<1.5	Braided
	>1.5	Anasomosing

To facilitate a comprehensive statistical analysis, principal component analysis (PCA) and multi-variate regression, are often applied to interpret complex geo-spatial datasets and identify significant trends or anomalies in the planform dynamics. Additionally, spatial interpolation techniques are used to generate detailed maps highlighting the spatial distribution of channel migration, erosion, and deposition patterns. These methodologies enable the identification of key factors influencing channel planform changes, such as hydrological variations, sediment transport, and anthropogenic activities.

The calculation of the sinuosity index was based on several key assumptions to ensure consistency and accuracy. It was assumed that the satellite imagery captured the river's morphology under comparable hydrological conditions, minimizing seasonal variations. The analysis primarily focused on the main channel, disregarding minor branches or temporary floodplain shifts. A uniform measurement scale was applied across all time periods to maintain consistency in reach length and sinuosity calculations.

RESULTS AND ANALYSIS

The analysis of channel sinuosity, utilizing Landsat satellite datasets from 1975 to 2024 and processed through ArcGIS 10.3, highlights significant spatio-temporal changes in flow dynamics over nearly five decades. The sinuosity index and the corresponding map revealed progressive alterations in meandering patterns, providing insights into the intricate interactions between natural geomorphic processes and anthropogenic influences on channel morphology. The observed changes underscore the importance of understanding historical trends to assess the evolution of water channels accurately. The integration of advanced geo-spatial tools, such as ArcGIS, with remote sensing techniques enhanced the precision and depth of the analysis, enabling a detailed examination of channel behavior over time. This approach uncovered critical patterns, including the rate and extent of sinuosity variations, which have implications for sediment transport, floodplain development, and aquatic habitat sustainability. Furthermore, the findings contribute valuable baseline data for predicting future channel shifts, which is essential for effective water resource management and planning. By combining historical data with cutting-edge spatial analysis, this study provides a robust framework for monitoring and managing the evolving dynamics of fluvial systems, ensuring their ecological and hydrological sustainability in the face of ongoing environmental changes.

The Landsat satellite datasets, pre-processed for atmospheric correction in ArcGIS 10.3, were utilized to identify and analyze the flow channels using specific bands (B3, B4, B5). Shapefiles were created to accurately trace the channels, facilitating the digitalization of water features into a comprehensive digital format. The digitalization process included assigning attributes, such as channel width and length, enabling detailed spatial analyses. Calculations of lengths and areas provided quantitative insights, while the results were visualized through mapping to capture spatio-temporal dynamics. This systematic process, supported by documentation of Landsat dataset details and pre-processing steps, enhanced the understanding of spatial relationships and channel behavior within the study area. Figure (8) compares the Gandak River's flow channels from 1975 to 2023, revealing significant topographical shifts in the river's flow path during this period. These findings highlight the dynamic nature of channel morphology, offering critical insights for understanding and managing the river's evolving hydrological patterns.

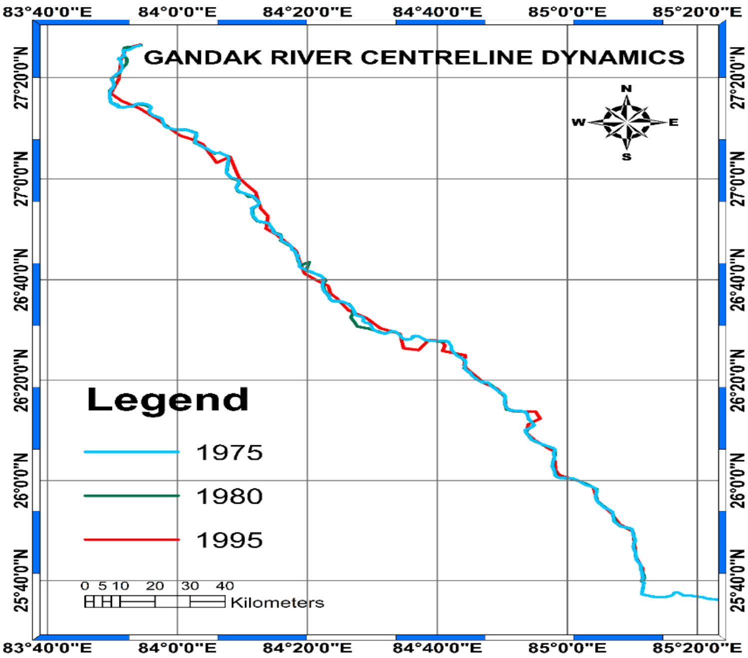

Figure (2): River centreline dynamics from 1975 to 1995

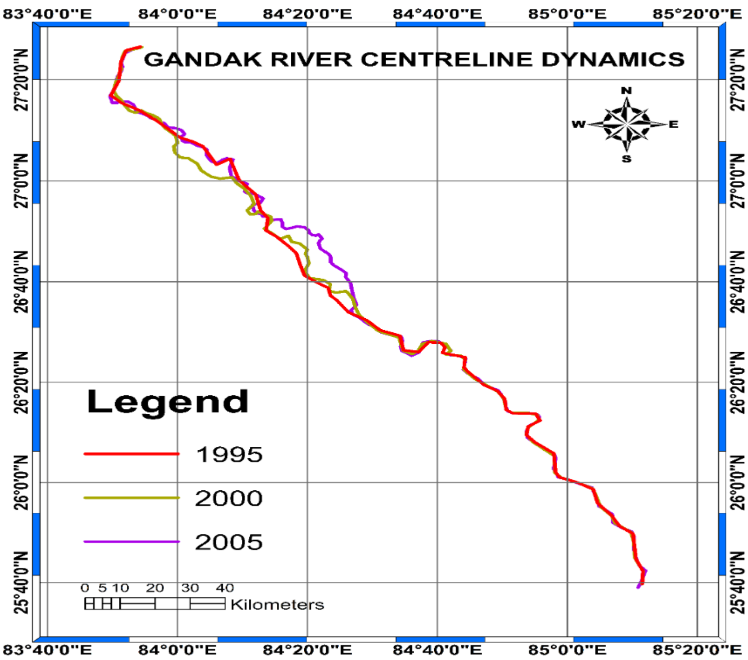

Figure (3): River centreline dynamics from 1995 to 2005

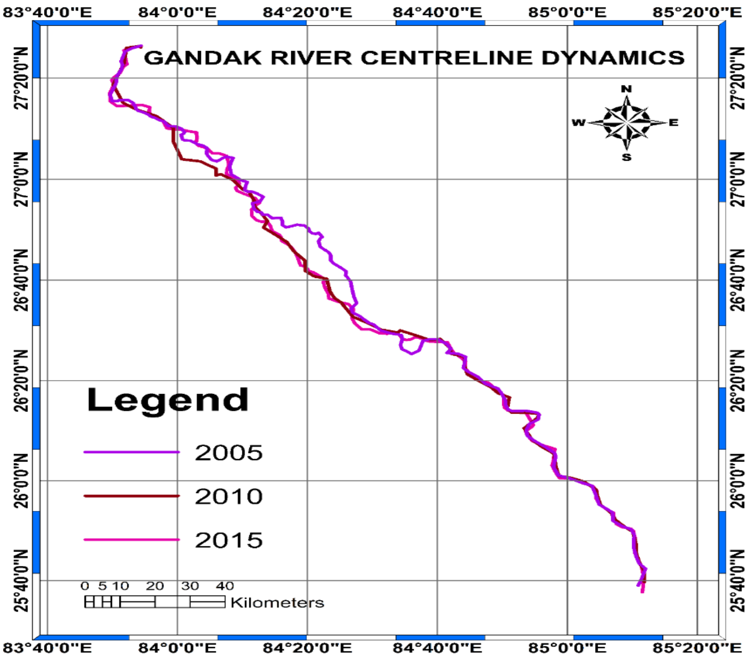

Figure (4): River centreline dynamics from 2005 to 2015

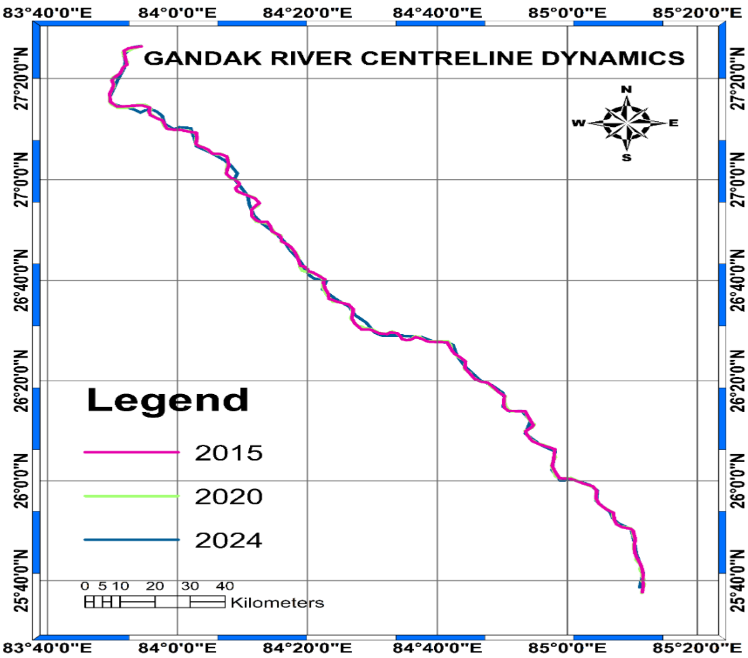

Figure (5): River centreline dynamics from 2015 to 2024

The centerline of the Gandak River was digitized for various years between 1975 and 2024 to analyze changes in its length and sinuosity index over time. In 1975, the river's total length was 326.72 km, which fluctuated over the years, reaching a peak of 343.88 km in 2005 and decreasing to 312.09 km in 2024, as depicted in Figs. (2-5). These changes in river length can be attributed to both natural processes, such as sediment transport, erosion, and deposition, as well as anthropogenic factors, like changes in land use, agricultural development, urbanization, and infrastructure construction. Additionally, the study highlights variations in the sinuosity index over time, with the index starting at 1.57 in 1975 and declining to 1.04 in 2024 (Table 3), indicating a shift from a highly sinuous river system to a more linearized channel. The observed patterns, including changes in river length and sinuosity, are illustrated in Figs. (2-5) and highlight the dynamic nature of the Gandak River's planform and hydrological processes. These findings underscore the role of environmental changes and human activity in driving morphological transformations and emphasize the importance of continuous monitoring and analysis to assess the river's evolution and inform effective management strategies.

Table 3. Temporal variations of total length and sinuosity index of the Gandak River (1975 to 2024)

Year	Total Length (km)	Sinuosity Index
1975	326.72	1.57
1980	336.66	1.48
1985	314.99	1.34
1990	335.47	1.36
1995	314.85	1.07
2000	330.01	1.15
2005	343.88	1.05
2010	309.79	1.09
2015	328.61	1.08
2020	329.43	1.09
2024	312.09	1.04

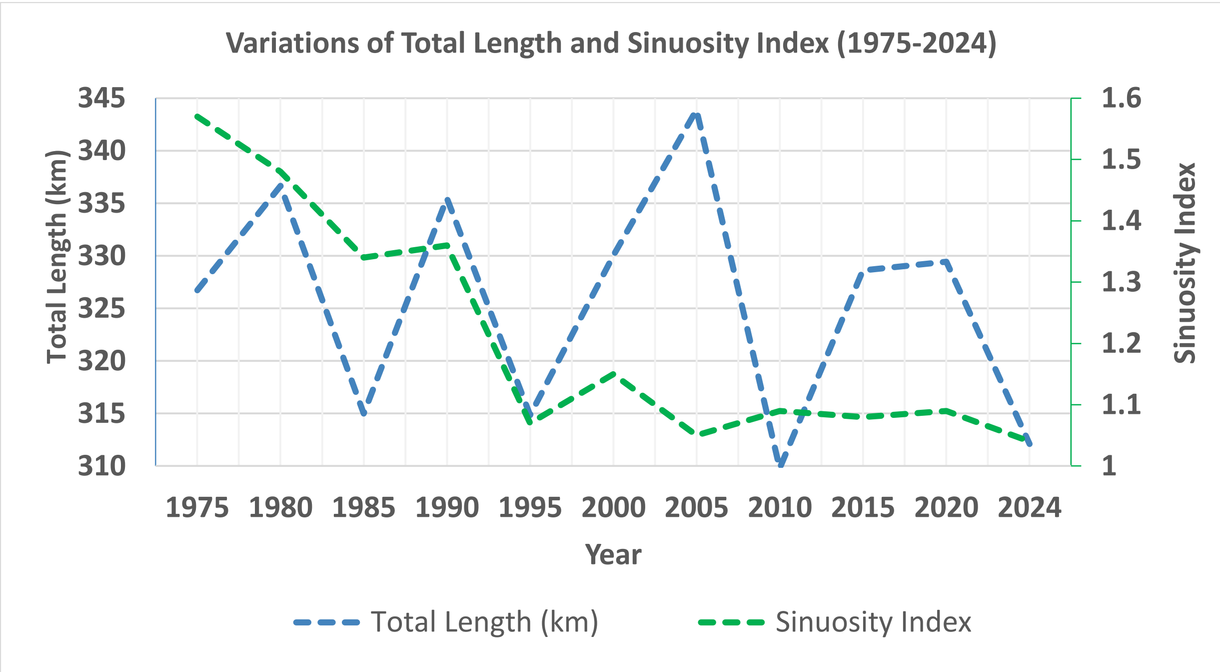

Figure (6): Variations of total length and sinuosity index (1975-2024)

The analysis of the Gandak River's total length and sinuosity index from 1975 to 2024 provides a comprehensive understanding of its morphological trends and the underlying hydrological processes over time (Figure (6)). The total length of the river exhibited notable variations during the study period, ranging from 309.79 km in 2010 to a peak of 343.88 km in 2005, demonstrating changes in meandering patterns, sediment deposition, and river migration. Between 1975 and 2024, the river showed alternating patterns of elongation and contraction, which can be influenced by natural factors, such as sediment load variations, tectonic activity, and hydrological regime shifts, as well as human activities, like dam construction, agricultural encroachment, and urbanization.

The sinuosity index, a measure of the meandering tendency of the river, revealed a decreasing trend from 1.57 in 1975 to 1.04 in 2024. The high sinuosity in the earlier years indicates a meandering river system with pronounced bends and floodplain interactions. However, the declining trend suggests a gradual shift toward a more linear flow regime, likely influenced by sediment deposition patterns, erosion, river channel modifications, and hydrological regulation. The drop in sinuosity may also indicate a reduction in floodplain connectivity, potentially impacting aquatic habitats and sediment transport patterns.

From 1980 to 1990, the river length fluctuated around 336 km, while the sinuosity index stabilized at 1.36. However, a significant reduction in the sinuosity index was observed post-1995, coinciding with the river's transition toward a straighter and less sinuous course, implying changes in the river's sediment transport and geo-morphological behavior. Similarly, the most recent years (2020-2024) show the river achieving its lowest sinuosity index at 1.04, emphasizing a highly linearized channel morphology.

These observed morphological trends over time highlight the complex interactions between natural processes, such as changes in sediment transport and hydrological flow, and anthropogenic interventions, including land use changes, deforestation, dam construction, and urban development. The river's changing sinuosity and total length have critical ecological and hydrological implications, including the potential for increased bank erosion, sediment reworking, and shifts in aquatic habitat availability. Furthermore, these changes have socio-economic consequences for communities dependent on the river for water resources, fisheries, and agricultural irrigation. Understanding these dynamics provides valuable insights for future river management strategies, ecosystem restoration planning, and climate change adaptation efforts.

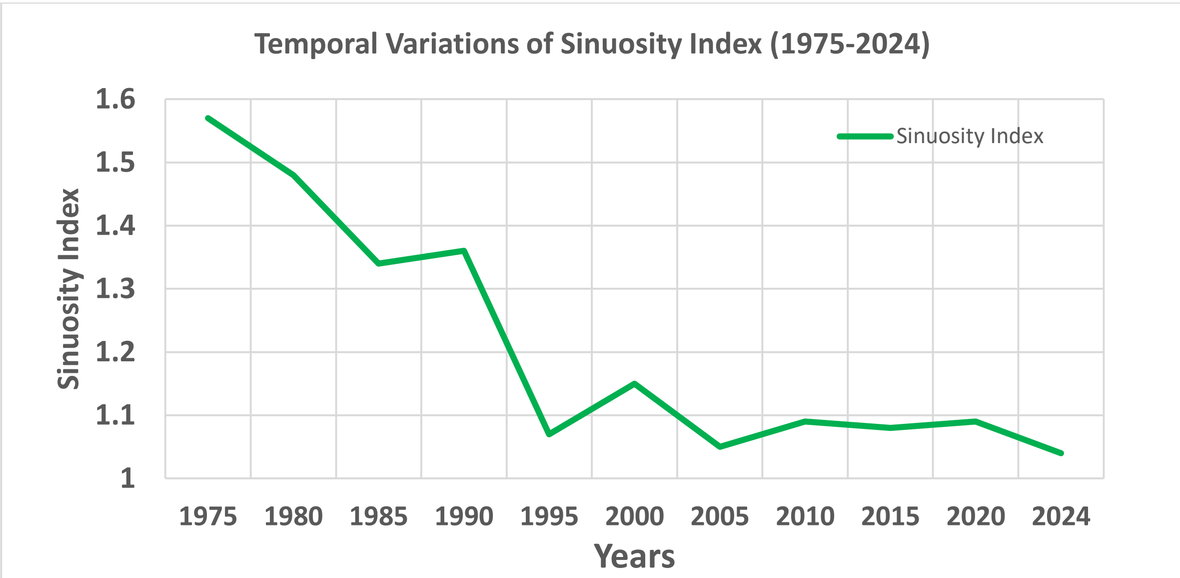

Figure (7): Temporal changes of sinuosity index

The variations in the river centerline dynamics and planform dynamics for the period from 1975 to 2024 are illustrated in Figure (8). Significant changes were observed in the river's total length, which fluctuated between 309.79 km in 2010 (the shortest observed length) and 343.88 km in 2005 (the longest observed length). Similarly, the sinuosity index showed notable variability, ranging from 1.04 in 2024 (the lowest value) to 1.57 in 1975 (the highest value) (Fig. 7). These observed trends underscore the dynamic and evolving nature of the Gandak River's morphology over the study period. The 2008 Kosi Flood, though affecting a neighboring river, led to significant embankment reinforcements along the Gandak River, restricting its lateral movement. Similarly, the construction of the Gandak Barrage in 1968 and subsequent canal networks altered the river's sediment transport and flow dynamics, contributing to reduced sinuosity. The 2017 monsoon floods caused severe bank erosion and localized avulsions, briefly increasing the river's active width. Additionally, rapid urban expansion and embankment strengthening post-2000 have progressively confined the channel, accelerating straightening trends. These events highlight key periods of morphological change that warrant further analysis. The observed changes in the river's total length and sinuosity are influenced by a combination of natural factors, such as sediment transport, hydrological variability, and geo-morphological processes, as well as anthropogenic activities, including urban expansion, agricultural development, dam construction, and changes in land use patterns. The reduction in sinuosity suggests river straightening due to altered sediment transport patterns and human interventions, while the fluctuating river length highlights the complex interaction between deposition, erosion, and hydrological changes. This analysis emphasizes the importance of understanding, such metrics to track river system evolution, predict future morphological changes, and assess the environmental and socio-economic impacts on nearby communities dependent on the river.

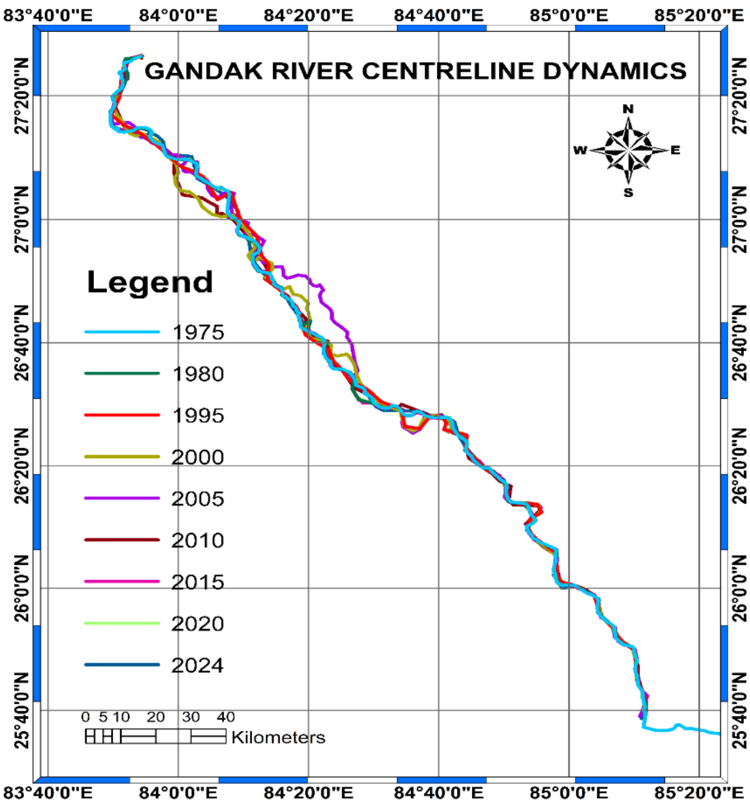

Figure (8): Centerline dynamics of Gandaki river during the period 1975-2024

The Gandak River's morphological trends from 1975 to 2024, as reflected in variations in total length and sinuosity index, reveal a complex interplay of natural processes and human-induced factors shaping its dynamics. The total river length fluctuated between 309.79 km in 2010 and 343.88 km in 2005, indicating sediment transport processes, hydrological variability, and human interventions, such as urbanization, agricultural expansion, and dam construction as key drivers of these changes. Simultaneously, the observed decline in sinuosity from 1.57 in 1975 to 1.04 in 2024 highlights a shift from a highly sinuous river system to a more linearized one, reflecting reduced floodplain interactions and altered sediment transport dynamics. Dam construction, embankments, and urbanization have directly contributed to the Gandak River's reduced sinuosity. The Gandak Barrage altered natural flow regimes, limiting sediment transport and restricting meander formation. Embankments built for flood control have confined the river, preventing lateral migration and accelerating channel straightening. Urban expansion and agricultural encroachments have further reinforced these constraints, reducing the river's ability to adjust naturally. These anthropogenic modifications have collectively led to a more stabilized, but less dynamic, channel, disrupting sediment deposition patterns and floodplain connectivity. These changes suggest both natural processes, like erosion and sediment deposition and anthropogenic activities are contributing to the river's transformation. The findings underscore ecological and socio-economic challenges, such as habitat loss, increased bank erosion risk, and altered floodplain connectivity. Therefore, proactive and sustainable watershed management strategies, including floodplain restoration, sediment management, and integrated hydrological planning, are essential to mitigate these changes and ensure the long-term sustainability of the Gandak River system.

DISCUSSION

The findings of this study align with previous research on river morphological dynamics, particularly in South Asian river systems influenced by monsoonal variations and anthropogenic modifications. The observed fluctuations in river length and the declining sinuosity index are consistent with previous studies by Sinha and Friend (1994) and Gupta et al. (2007), who documented similar trends in alluvial rivers subjected to hydrological variability and human interventions. The reduction in sinuosity aligns with Ghosh et al. (2019), who highlighted the role of embankments and channelization in restricting lateral migration. Furthermore, the impact of sediment transport dynamics and erosion patterns corroborates the findings by Singh et al. (2018), who emphasized the influence of changing flow regimes on channel morphology. The results also reflect global studies, such as Best (2019) and Wohl (2020), which indicated that river straightening due to anthropogenic modifications can lead to reduced floodplain connectivity and increased erosion.

The declining sinuosity and channel contraction observed in Gandak River can be attributed to a combination of natural and human-induced factors. Hydrological variations, including monsoonal floods and seasonal flow changes, have significantly influenced sediment deposition and erosion rates. Additionally, human activities, such as dam construction, embankments, and land use changes have restricted the river's ability to meander freely. These modifications have implications for local communities, particularly those reliant on floodplain agriculture, fisheries, and groundwater recharge. Decreased floodplain connectivity and increased erosion can lead to soil degradation, loss of fertile land, and heightened flood risks, adversely impacting agricultural productivity and rural livelihoods. Infrastructure, such as roads, bridges, and settlements in flood-prone areas, may also face increased vulnerability due to changes in river morphology. Beyond physical alterations, the ecological and socio-economic impacts of these morphological changes require further attention. The reduction in sinuosity affects aquatic bio-diversity by altering habitat conditions, particularly for fish species dependent on diverse flow regimes. The straightening of the river channel may also reduce the natural retention of floodwaters, increasing peak discharge events and the severity of floods. Socio-economically, the shifting river course can displace communities, necessitating adaptive measures, such as relocation and improved flood management policies. Effective floodplain management should focus on restoring natural river-floodplain interactions through wetland conservation and afforestation to stabilize sediment transport. Infrastructure planning must incorporate dynamic river behavior by restricting development in vulnerable zones and adopting nature-based solutions, such as vegetative buffers, to mitigate erosion.

Given these findings, adaptive strategies must be developed to ensure sustainable river management. Integrated river basin management (IRBM) approaches incorporating climate resilience, sustainable water use, and ecological conservation should be prioritized. Additionally, community-based river monitoring programs can engage local stakeholders in tracking morphological changes, enhancing both data collection and community preparedness. However, certain limitations of this study must be acknowledged. The reliance on medium-resolution Landsat imagery (30 m) may introduce spatial inaccuracies in detecting smaller-scale morphological changes. While field validation was conducted, the absence of high-resolution hydrological and sediment transport data limits the ability to quantify the exact mechanisms driving channel changes. Similar limitations have been reported in studies, like that conducted by Kondolf et al. (2003), emphasizing the need for integrated field and remote sensing approaches. Future research should explore the integration of multisource remote sensing datasets, such as high-resolution Sentinel-2 imagery and UAV-based observations, to improve spatial precision in change detection. Additionally, incorporating hydro-dynamic modeling and sediment transport analysis would provide a more detailed quantification of the underlying processes driving channel changes. Investigating the socio-economic implications of river morphological changes on local communities would also offer a holistic perspective on river basin management.

CONCLUSIONS

The morphological assessment of Gandak River from 1975 to 2024 reveals significant transformations in channel behavior, evidenced by variations in total length and a marked decline in the sinuosity index from 1.57 to 1.04. These changes stem from a combination of natural factors, such as hydrological variability, sediment transport, tectonic influences, and anthropogenic pressures including dam construction, urban encroachment, and land use alterations. The study emphasizes pressing challenges, such as reduced floodplain connectivity, altered sediment pathways, and ecological disruptions affecting local communities. To mitigate these issues, the study recommends integrated and adaptive management approaches that combine nature-based solutions, community participation, and cross-border cooperation. While the findings provide valuable insights into long-term river dynamics, limitations related to spatial resolution and lack of field-based hydrological validation are acknowledged. Future efforts should integrate high-resolution geo-spatial data and real-time monitoring to enhance predictive modeling and support sustainable river governance. The key points are as follows:

- The river’s sinuosity index declined from 1.57 (1975) to 1.04 (2024), indicating a shift toward a straighter channel.
- Both natural processes and human interventions have driven these morphological changes.
- Key challenges include:
    - Reduced floodplain connectivity.
    - Increased erosion and sediment imbalance.
    - Habitat loss and ecological stress.
- Recommended strategies:
    - Integrated River Basin Management (IRBM) considering climate resilience.
    - Wetland restoration and riparian buffer zones.
    - Sediment monitoring and controlled dredging.
    - Floodplain zoning to control unplanned urban growth.
    - Community-based erosion control through vegetation and local stewardship.
    - India-Nepal collaboration for coordinated transboundary river management.
- Study limitations involve medium-resolution imagery and limited field validation.
- Future work should focus on UAV-based surveys, high-resolution satellite data, and hydro-dynamic modeling for better forecasting and adaptive management.

Declarations

Ethics Approval and Consent to Participate

The authors followed the ethical guidelines and no ethical approval was required and all the authors agreed to participate.

Consent for Publication

All authors are agreeing to publish the content.

Availability of Data and Material

Data and material will be made available upon reasonable request.

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Conflict of Interests

The authors have no conflict of interests to declare.

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