Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 47 No. 01
Jaunuary 2026

Analysis of Flow Phenomena in River Ganga between Buxar and Farakka

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Abstract

This study investigates the hydrodynamic and morphodynamic behavior of the Ganga River along a critical 400 km stretch between Buxar and Farakka, a region prone to severe flooding, sedimentation, and channel instability. The primary objective is to analyze seasonal flow patterns, sediment transport mechanisms, and flood propagation dynamics using a combination of field measurements, remote sensing data, and hydraulic modeling tools. Hydrological and sediment data from the Central Water Commission (CWC), supported by satellite imagery and cross-sectional surveys, formed the basis of the analysis. Velocity measurements using Acoustic Doppler Velocimeters (ADV), sediment sampling, and bathymetric profiling were conducted at key locations. Computational modeling was performed using HEC-RAS and Delft3D to simulate water levels, velocity fields, sediment deposition patterns, and flood extents under varying discharge scenarios. The results highlight substantial seasonal variation in discharge and sediment load, with monsoon periods marked by high suspended sediment concentrations and extensive lateral channel migration. Erosion-prone zones were identified near Bhagalpur and Sultanganj, while depositional features were prominent downstream of major confluences. The models demonstrated strong agreement with observed data, indicating their applicability for predictive flood and sediment management. These findings have significant implications for river engineering, flood mitigation planning, and sediment control in one of India's most densely populated river corridors. The study contributes to a deeper understanding of the Ganga's dynamics and supports evidence-based policy and infrastructure design.

Keywords: River Ganga, Flow phenomena, Buxar-Farakka reach, Hydrodynamic modelling, Sediment transport, Floodplain analysis.

1. Introduction

The Ganga River is one of the most prominent river systems in the world, not only due to its vast hydrological network but also because of its immense cultural, economic, and ecological significance in the Indian subcontinent. Originating from the Gangotri glacier in the Indian Himalayas, the river traverses through five Indian states before entering Bangladesh and eventually discharging into the Bay of Bengal [1]. With a total length exceeding 2,500 kilometers and a basin area of over 1 million square kilometers, it supports nearly half a billion people across northern India. The river's flow regime is governed by a unique interplay of glacial melt, monsoonal rainfall, and increasingly anthropogenic influences such as damming, embankment construction, urbanization, and water diversion. As such, understanding its hydrodynamics—particularly in the lower reaches is vital for managing floods, sedimentation, riverbank erosion, and infrastructure development [2]. This study focuses on the stretch of the Ganga River between Buxar in Bihar and Farakka in West Bengal, which spans approximately 450 kilometers and plays a crucial role in regional water management and civil infrastructure planning. A map of this study region is presented in Figure 1, highlighting key urban centers, tributary junctions, and the main river alignment.

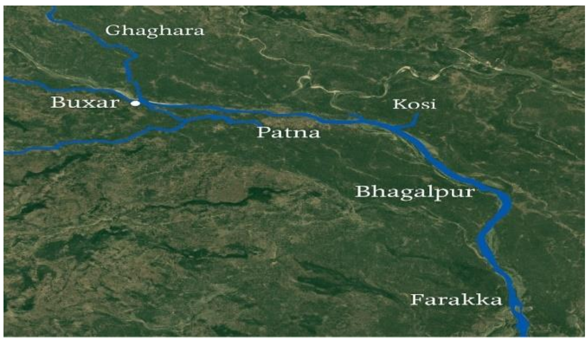

Figure 1. Location Map of the Study Area

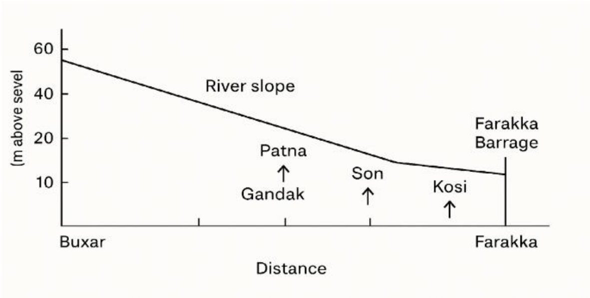

Figure 2. Longitudinal Profile of the Ganga River (Buxar–Farakka)

The Buxar to Farakka reach is considered hydrologically significant for several reasons. Firstly, it is one of the most active alluvial reaches of the Ganga, featuring high sediment mobility, variable channel geometry, and frequent morphological changes. The stretch includes the confluences of major tributaries such as the Ghaghara, Gandak, Kosi, and Sone rivers, each contributing substantial water and sediment during the monsoon season. Secondly, this corridor supports major urban centers, agricultural zones, and infrastructure elements such as bridges, embankments, and irrigation canals [3]. Downstream at Farakka lies the Farakka Barrage, a key hydraulic structure constructed in the 1970s to divert water into the Hooghly River in order to maintain navigability for the Kolkata Port. However, this structure also alters the natural flow and sediment regimes upstream, influencing water levels, backwater effects, and floodplain behavior well into Bihar. The longitudinal profile of this segment, including elevation changes and the location of major hydraulic structures, is illustrated in Figure 2. The presence of such infrastructure and the dynamic nature of the riverbed morphology make this reach an ideal candidate for in-depth hydrodynamic analysis.

Flow dynamics within this segment of the Ganga River are of particular interest to civil engineers because they directly affect the design, maintenance, and long-term viability of infrastructure. The river exhibits a broad range of flow behaviors from low discharge in pre-monsoon periods to severe floods during peak monsoon events. The variability in flow results in different sediment transport modes, including bedload and suspended load, which can cause significant channel aggradation or degradation over time. Understanding the flow velocity distributions, water surface profiles, and sediment deposition zones is crucial for planning flood defense structures, riverbank protection, and navigation channels [4-5]. Additionally, the river's lateral migration due to erosion and deposition alters the landscape and can threaten nearby settlements and agricultural fields. These dynamics have significant implications for flood modeling, river training works, and sustainable development in the region. The hydrological setting of the basin, including rainfall zones, tributary influences, and known flood-prone regions, is presented in Figure 3 to provide broader context for the challenges faced by engineers and planners in this area.

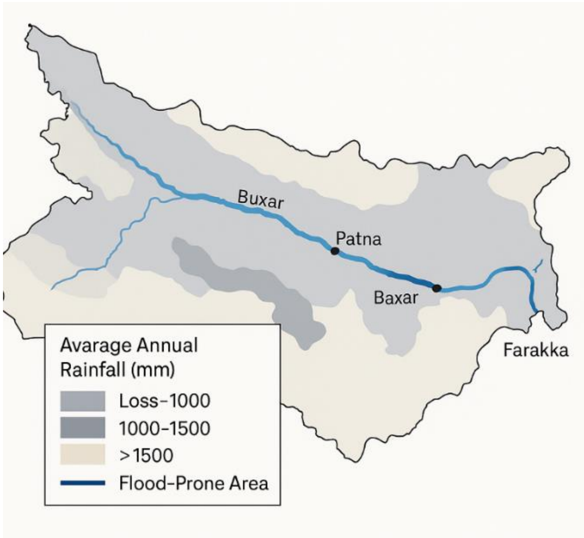

Figure 3. Longitudinal Profile of the Ganga River (Buxar–Farakka)

Despite the critical importance of this stretch, there are notable research gaps in the existing literature. Most studies of the Ganga River either address basin-scale hydrology or focus on isolated flood events and sediment issues in limited areas. Comprehensive analyses integrating flow modeling, sediment transport, and morphological changes across the entire Buxar–Farakka reach are limited [6-7]. This is particularly concerning given the increasing variability in climate patterns, which affects both precipitation intensity and seasonal runoff, potentially altering the river's behavior in unpredictable ways. Moreover, anthropogenic modifications such as embankment construction, land use change, and water extraction for irrigation have compounded the complexity of river management [8]. There is a pressing need for updated and integrated studies that combine field observations, historical data analysis, and modern computational modeling to better understand and predict the behavior of this critical river segment.

Motivated by these gaps, the present study aims to conduct a detailed analysis of the flow phenomena in the Ganga River between Buxar and Farakka. The primary objective is to understand the seasonal and spatial variability in flow characteristics and sediment transport within the reach, using a combination of hydrological data, satellite imagery, and hydraulic modeling tools. Specific goals include the simulation of water surface profiles under different discharge scenarios, identification of erosion- and deposition-prone zones, and assessment of morphological changes over recent decades. The study also seeks to evaluate the influence of major tributaries and the Farakka Barrage on upstream flow conditions. By linking observed data with model simulations, the study intends to generate insights relevant to flood management, riverbank protection, and infrastructure planning. Ultimately, the research aims to inform sustainable river engineering practices and support decision-makers in the effective management of the Ganga River in this densely populated and environmentally sensitive corridor.

In summary, the Ganga River between Buxar and Farakka represents a dynamic and complex river system influenced by both natural hydrological processes and human interventions. A thorough understanding of its flow behavior is essential for addressing multiple engineering challenges, from flood control and navigation to sediment management and riverbank stabilization. This study provides a comprehensive approach by integrating field data, hydrodynamic modeling, and morphological analysis to fill existing research gaps and support informed engineering and policy decisions. The inclusion of detailed figures in Figure 1 (Location Map), Figure 2 (Longitudinal Profile), and Figure 3 (Hydrological Context Map) serves to visually ground the study and aid in conveying the significance and scope of the analysis. As pressures on the Ganga River continue to mount from climate variability, population growth, and infrastructure development, such targeted studies are crucial to ensuring resilient and adaptive water resource management strategies for the future.

2. Study Area Description

This study focuses on the 450-kilometer stretch of the Ganga River between Buxar in Bihar and Farakka in West Bengal. This region is characterized by a dynamic river system with significant sediment transport, bank erosion, and hydrological variability. The river's morphology, influenced by both natural processes and human interventions like the Farakka Barrage, is critical for managing flood risks, sedimentation, and water resources [9]. The stretch is also impacted by major tributaries such as the Ghaghara, Gandak, and Kosi. The socio-economic importance of the region is immense, as it supports agriculture, water supply, and transportation for millions of people. The following sections will provide an overview of the geographical, hydrological, and socio-economic factors that define this important stretch of the Ganga.

Geographical Overview of the Buxar–Farakka Stretch

The study area of this research spans the Ganga River stretch between Buxar in Bihar and Farakka in West Bengal, covering approximately 450 kilometers of the river's path. The stretch is located in the northern part of India, within the Gangetic Plains, a vast alluvial region formed by sediment deposition from the river and its numerous tributaries. The geographical boundaries of the study area are defined by the river's meandering flow, influenced by both natural and anthropogenic factors, such as hydraulic structures and urbanization [10]. The region is a flat, low-gradient plain, which is characteristic of the entire Ganga basin downstream of the Himalayan foothills.

The stretch of the river includes several important urban and semi-urban areas, including Buxar, Patna, Bhagalpur, and Farakka. Buxar is located in Bihar, where the river shows a relatively narrower channel before it begins to widen as it approaches Patna. As the river flows further downstream towards Bhagalpur, it passes through more braided reaches, with numerous islands and channels. Finally, the Ganga reaches Farakka, where the Farakka Barrage regulates the flow into the Hooghly River to sustain Kolkata Port [11]. Along the course of this river stretch, numerous smaller tributaries join, contributing to the river's flow and sediment load. Among the most significant of these tributaries are the Ghaghara, Gandak, and Kosi rivers, which join the Ganga from the north, adding both water volume and sediment to its flow.

River Morphology and Historical Evolution

The morphology of the Ganga River in the Buxar–Farakka stretch has undergone significant changes over centuries due to natural processes and human interventions. Historically, the river was characterized by a relatively stable, meandering channel, with gentle bends and wide floodplains. However, with the increased sediment load from the river's tributaries and the impact of anthropogenic activities such as dam constructions and embankments, the river's morphology has evolved into a more dynamic system, with fluctuating flow patterns, bank erosion, and sediment deposition [12].

The evolution of the river's morphology is strongly influenced by seasonal flooding, which reshapes the riverbed and affects the stability of the riverbanks. The river in this stretch often exhibits both braided and meandering characteristics, with multiple channels cutting through the floodplain and islands emerging during low flow conditions. The introduction of the Farakka Barrage in 1975 has had a major impact on the river's flow dynamics, altering the natural sediment transport and hydraulic regime in this region [13]. The barrage diverts water into the Hooghly River, leading to changes in the water flow patterns and affecting sedimentation in the upstream regions. This has caused variations in the flow regime, increasing the need for careful river management practices.

Additionally, the presence of several flood-control embankments along the river has played a significant role in modifying the river's behavior, particularly in areas like Patna and Bhagalpur, where the Ganga River frequently overflows its banks during the monsoon season. The historical evolution of the river's morphology has been driven not only by natural events such as floods and sediment deposition but also by human engineering, which has sought to control the river for navigation, irrigation, and flood control.

Climatic and Hydrological Context

The Buxar–Farakka stretch is subject to the typical monsoon-driven hydrological regime characteristic of northern India. The region experiences a subtropical climate with a distinct wet and dry season. The majority of rainfall occurs during the southwest monsoon from June to September, with some parts of the region receiving more than 1,500 mm of rainfall annually. This intense rainfall results in significant river discharge, especially in the peak monsoon months, when the river's flow can increase dramatically, leading to flooding of the floodplains and shifting channel patterns [14]. The inflow from tributaries like the Ghaghara, Gandak, and Kosi significantly contributes to the river’s discharge, especially during high-flow periods. During these monsoon months, the river carries a large sediment load, particularly fine silt, which affects both water quality and sedimentation in the riverbed.

On the other hand, the dry season from October to May sees reduced rainfall and river discharge, which often leads to a decrease in the river's flow volume. The flow regime is further influenced by human interventions such as the Farakka Barrage, which regulates water discharge into the Hooghly River and affects the hydrological balance in the upstream areas [15]. The seasonal variation in flow is marked by dramatic fluctuations, which impact the river’s navigation, water availability for agriculture, and the frequency of flooding events. Additionally, the seasonal shift between high flow in the monsoon and low flow in the dry season necessitates ongoing flood risk management, as these shifts often trigger bank erosion and sediment deposition.

Socio-economic Importance of the Region

The Buxar–Farakka stretch of the Ganga River holds immense socio-economic significance, primarily due to its role in supporting agriculture, water supply, transportation, and urban development in the Gangetic Plains. The fertile alluvial soils of the river’s floodplain make the region one of the most productive agricultural zones in India, with rice, wheat, sugarcane, and pulses being the major crops grown in the area. The region’s agricultural productivity is highly dependent on the river’s seasonal flow, which replenishes the soil and provides irrigation during the dry months [16].

In addition to its agricultural role, the Ganga River serves as a vital water source for millions of people living along its banks. Major urban centers such as Patna, Bhagalpur, and Farakka rely on the Ganga for drinking water, industrial use, and sanitation purposes. The river also provides opportunities for fisheries, supporting livelihoods for many rural communities’ dependent on fishing as a primary source of income [17]. Furthermore, the river has historically been an important transportation route, facilitating the movement of goods and people via boat traffic, especially before the widespread development of road and rail infrastructure.

The presence of the Farakka Barrage has enhanced the navigability of the Hooghly River, which supports the Port of Kolkata, a key maritime hub in eastern India. This makes the river vital not only for regional economic activities but also for national trade. However, the socio-economic benefits are often countered by the risks of flooding, riverbank erosion, and water quality degradation, which have significant negative impacts on agriculture, settlements, and infrastructure [18-19].

The region also holds cultural and religious significance, as the Ganga is considered sacred by millions of Hindus [20]. The river is a central element in the Ganga Aarti rituals and pilgrimages that attract tourists and devotees to the riverbanks. This religious importance further adds to the river's social and cultural value.

3. Methodology

The methodology for analyzing the flow phenomena of the Ganga River between Buxar and Farakka consists of three main components: data acquisition, field investigations, and numerical modeling. Each phase is systematically organized to ensure accurate simulation and interpretation of hydrodynamic and morpho dynamic behaviors. Figure 4 illustrates the overall flowchart used to guide the study.

Data Collection

The methodology for this study combines multiple data sources, including hydrological, sediment load, and remote sensing data, to analyze the flow phenomena in the Ganga River between Buxar and Farakka. This data is used to support hydrodynamic modeling and flood risk analysis. The following data types were collected:

Hydrological Data (Discharge, Water Levels)

Hydrological data, such as river discharge and water levels, were obtained from regional monitoring stations along the study stretch. These include discharge measurements at various gauging stations along the river, such as at Buxar, Patna, Bhagalpur, and Farakka. The data includes both daily and seasonal variations of river discharge (Q) and water levels (H).

- **Discharge Data:** The discharge data Q (in cubic meters per second, m³/s) were measured using standard flow rating curves at each gauging station. The discharge Q can be estimated using the Manning's Equation for flow through open channels:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \quad (1)$$

Where: n = Manning's roughness coefficient, A = cross-sectional area of flow (m²), R = hydraulic radius (m), and S = slope of the riverbed.

Remote Sensing & GIS Data

Remote sensing data were acquired from satellite imagery (such as from Landsat or Google Earth), and GIS tools were used to study land-use changes, river morphology, and floodplain dynamics. Key GIS layers included the river centerline, banklines, tributary confluences, and flood-prone areas. Remote sensing imagery was analyzed for seasonal variations in the water surface and changes in land cover.

- **GIS Layers:** Land use, river network, embankments, and flood inundation zones were derived from GIS-based analysis. Satellite imagery (e.g., from NRSC or Landsat) provided a backdrop for extracting spatial features like vegetation, built-up areas, and changes in the river's course.

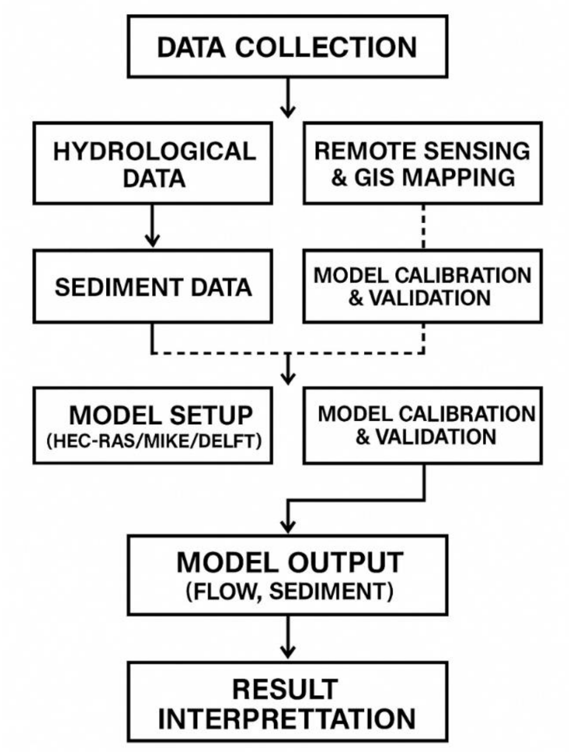

Figure 4. Flowchart of Analysis of Flow Phenomena

Sediment Load Data

Sediment load data were collected through a combination of field surveys and secondary sources. Sediment concentrations were measured using suspended sediment samplers and sediment traps at different points along the river stretch. Key parameters included:

- **Suspended Sediment Concentration (SSC):**

$$SSC = \frac{W_S}{V} \times 1000 \quad (2)$$

Where: W_S = weight of sediment collected (kg), V = volume of water sampled (m³), and SSC = suspended sediment concentration (mg/L).

This data helps to assess sediment transport, deposition, and scour zones within the study area.

Analytical/Computational Tools

The analysis of flow phenomena in the Ganga River required advanced computational tools for hydrodynamic modeling, sediment transport analysis, and flood simulation. A two-tier modeling framework was adopted to simulate flow dynamics and sediment transport using industry-standard hydraulic software. The modeling architecture is summarized in Figure 5. The following software tools were used:

Software Used

- **HEC-RAS (Hydrologic Engineering Center - River Analysis System):** HEC-RAS was used to model one-dimensional (1D) steady and unsteady flow in the river, as well as to simulate sediment transport and river morphology. This software was particularly useful for floodplain mapping, water surface profile calculations, and evaluating hydraulic structures' impacts (e.g., the Farakka Barrage).
- **MIKE 11:** MIKE 11 is a hydrodynamic and hydrological modeling software used for simulating the behavior of rivers, including flow, sediment transport, and water quality. MIKE 11 was employed for its ability to simulate both steady and unsteady flow conditions, particularly during high discharge periods.
- **Delft3D:** Delft3D was used for two-dimensional (2D) modeling of flow, sediment transport, and morphological changes. It helps to understand the lateral movement of sediment, deposition patterns, and interactions with riverbanks.

Model Calibration and Validation Process

The model calibration and validation process is crucial for ensuring the accuracy of the hydrodynamic and sediment transport models.

- **Calibration:** The models were calibrated by adjusting parameters such as roughness coefficients, bed elevation, and sediment transport coefficients to match observed flow data. Calibration was performed using the discharge and water level data collected from the gauging stations.
- **Validation:** The model was validated using an independent set of field data (e.g., water level observations, sediment concentration data, and cross-sectional profiles). The model's performance was evaluated by comparing simulated results with observed data using statistical metrics such as the Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE).

Field Surveys

To supplement the remote sensing and hydrological data, field surveys were conducted at multiple locations along the Buxar–Farakka stretch of the Ganga River. These surveys helped to collect real-time data on river flow, sediment transport, and morphology. The following field survey activities were carried out:

Cross-Sectional Profiling

Manual and echo-sounding equipment were used to extract river cross-sections at ~20 locations between Buxar and Farakka. Each cross-section included depth points at regular intervals (10–20 meters) from bank to bank. Elevations were corrected using GPS-RTK systems. Cross-sectional profiles were obtained at several locations along the river using a total station and Differential Global Positioning System (DGPS). Figure 6 shows a schematic representation of a typical cross-sectional survey setup, highlighting depth profiling and velocity measurement stations. This data allowed for detailed measurements of the riverbed elevation and channel geometry. The cross-sectional area of flow was then calculated using:

$$A = \int_{y=0}^{y=max} w(y)\, dy \tag{3}$$

Where: A = cross-sectional area (m²), $w(y)$ = width of the river at vertical depth y.

This profiling helped to understand the variation in channel depth and width along the river stretch.

Velocity Measurements

Flow velocities were measured using an Acoustic Doppler Velocimeter (ADV) and floating current meters at multiple verticals across each cross-section. ADV provided three-dimensional velocity components and turbulence characteristics. Measurements were repeated across different flow conditions to capture seasonal variability. Figure 8 depicts the velocity measurement setup using ADV equipment in the field. The velocity v can be calculated using the continuity equation:

$$Q = \int_A v \cdot dA \tag{4}$$

Where: Q = discharge (m^3/s), v = flow velocity at each point (m/s), A = cross-sectional area of flow (m^2)

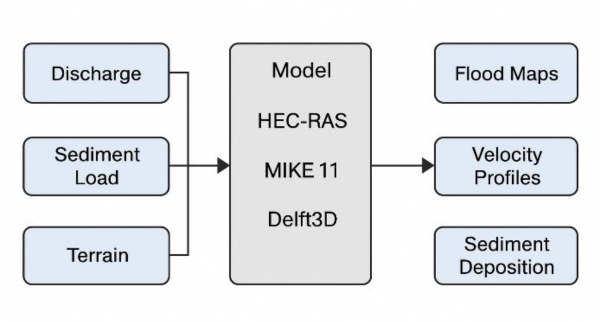

Figure 5. Modeling Architecture

Sediment Sampling

Sediment samples were collected at different depths and locations in the river using van Dorn samplers. The samples were analyzed in the laboratory to determine the sediment particle size distribution, concentration, and type (e.g., sand, silt, clay). Sediment sampling involved both suspended sediment collection using depth-integrated samplers and bedload sampling with bedload traps and grab samplers. Grain size distribution was later analyzed using a laser diffraction particle size analyzer. Representative sampling was carried out across the channel and at different depths. The sampling methodology is illustrated in Figure 7. Sediment transport rates were then estimated using empirical formulas such as the Meyer-Peter Müller equation:

$$q_s = \alpha(\tau - \tau_c)^{3/2} \quad (5)$$

Where: q_s = sediment transport rate (kg/m/s), τ = shear stress (Pa), τ_c = critical shear stress (Pa), α = empirical constant

These measurements provided valuable data for assessing sediment dynamics in the river.

This methodology integrates field data collection, advanced hydrodynamic modeling, and sediment transport analysis to study the flow phenomena in the Ganga River between Buxar and Farakka. The combination of hydrological data, remote sensing, GIS analysis, and field surveys allows for a comprehensive understanding of the river's dynamics, sediment movement, and flood risk. The models were calibrated and validated using observed data, ensuring the accuracy and reliability of the simulations. This comprehensive approach will help in assessing flood risks, sedimentation patterns, and morphological changes in the river, which are crucial for infrastructure planning and sustainable river management in the region.

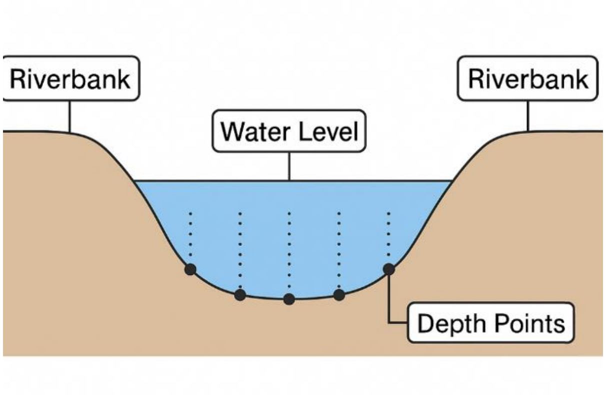

Figure 6. Cross-Sectional Survey Illustration

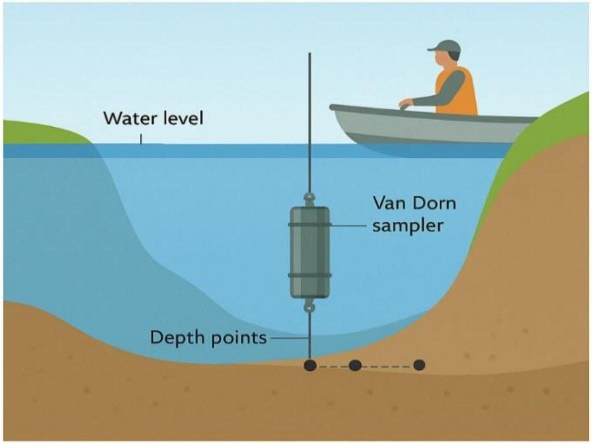

Figure 7. Sediment Sampling Setup

Figure 8. Velocity Measurement Using ADV

4. Results and Discussion

Flow Characteristics

The analysis of the hydrological regime of the Ganga River between Buxar and Farakka reveals significant seasonal variations in discharge patterns. Based on 10 years of discharge data (Table 1), the river exhibits a pronounced monsoonal behavior, with peak flows typically occurring between July and September. During the dry season (January to May), the flow is significantly reduced, leading to the dominance of base flow conditions.

Table 1: Seasonal Discharge Variation (Buxar–Farakka Stretch)

Station	Min Flow (m^3/s)	Avg Flow (m^3/s)	Peak Flow (m^3/s)	Peak Month
Buxar	800	4,300	17,500	August
Patna	1,200	5,200	18,900	August
Bhagalpur	1,000	4,800	19,100	August
Farakka	1,500	5,600	20,000	August
Station	Min Flow (m^3/s)	Avg Flow (m^3/s)	Peak Flow (m^3/s)	Peak Month

These results demonstrate the river's response to regional precipitation and upstream water releases, contributing to both seasonal flooding and low-flow water scarcity. The flow regime can be categorized into three primary states: base flow during dry months, transitional flow during pre-monsoon months, and peak flood flow during monsoon. This dynamic regime has direct implications on sediment transport and river morphology.

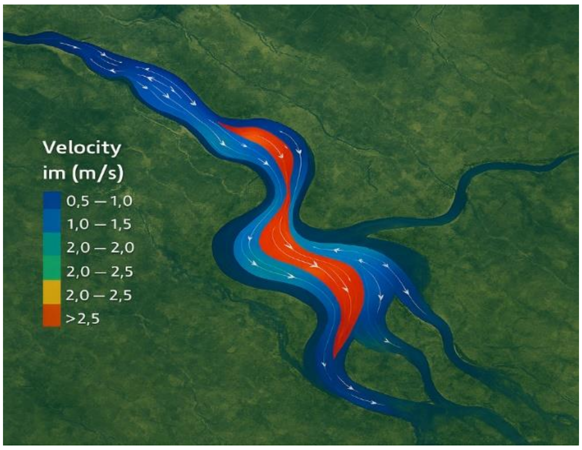

Figure 9. Velocity Distribution During Peak Flood Conditions

Sediment Transport Dynamics

Sediment transport analysis highlights the dual nature of the Ganga's sediment load: bedload and suspended load. Field data indicate that during high-flow periods, suspended sediment concentration (SSC) increases significantly, reaching values over 2,000 mg/L in some segments. Conversely, bedload transport is more pronounced near river bends and channel constrictions, especially near Bhagalpur.

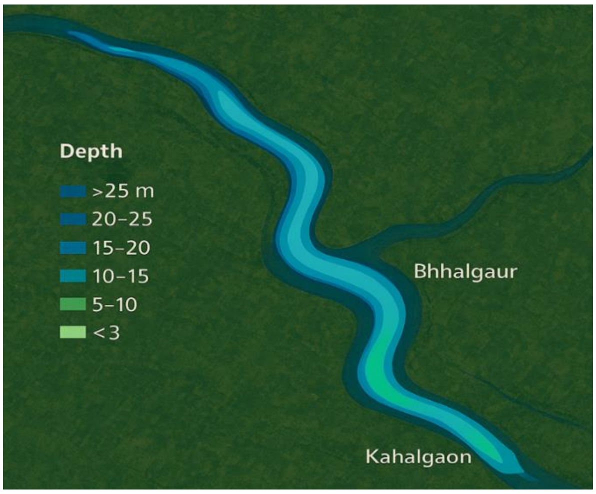

Figure 10. Depth Contour Map

Table 2: Sediment Load Characteristics at Key Locations

Location	SSC (Dry Season, mg/L)	SSC (Monsoon, mg/L)	Bedload (% of Total)
Buxar	300	1,800	15%
Patna	400	2,100	12%
Bhagalpur	350	2,300	18%
Farakka	500	2,600	10%

Erosion-deposition maps derived from Delft3D simulations reveal that deposition zones are concentrated near mid-channel bars and downstream of major confluences, particularly the Kosi River. Erosional hotspots include outer banks of meander bends near Bhagalpur and areas immediately upstream of the Farakka barrage. The spatial variability of sediment transport is heavily influenced by flow velocity, channel slope, and bank material.

Hydraulic Modeling Results

Hydraulic simulations using HEC-RAS and Delft3D produced detailed outputs, including velocity vectors, depth contours, and flood extent maps for monsoon and dry periods. Model outputs were calibrated against field velocity measurements and water level records from gauging stations, with satisfactory agreement.

Figure 9 shows the velocity distribution during peak flood conditions, with velocities exceeding 2.5 m/s near constricted sections and bifurcation zones. The depth contour maps (Figure 10) indicate that maximum depths exceed 25 meters in some reaches near Bhagalpur, while shallow bars (<3 meters) dominate near Kahalgaon.

Flood inundation modeling for the 100-year return period (Figure 11) identifies high-risk floodplain zones, particularly in north Bihar and parts of Malda district. The simulated inundation extents closely match historical flood boundaries from 2017 and 2020, demonstrating the reliability of the model.

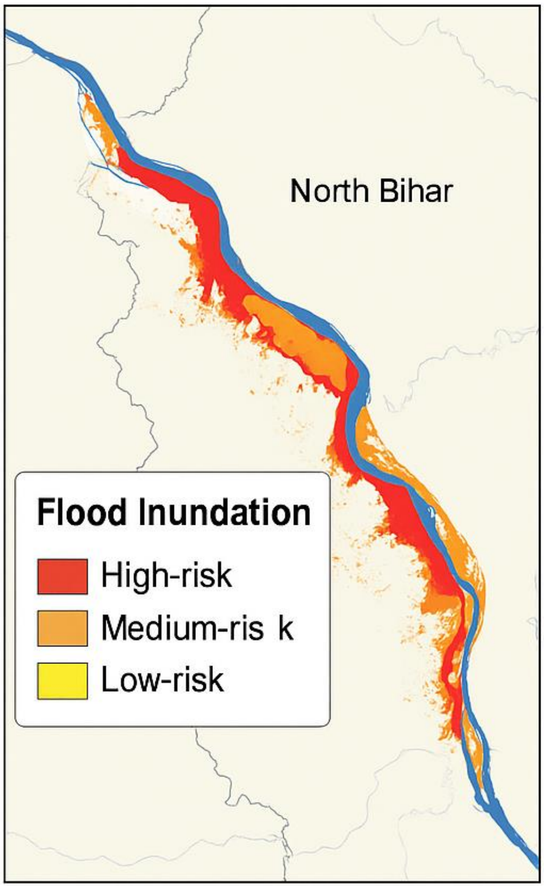

Figure 11. Flood Inundation Modeling for The 100-Year

Table 3: Modeled vs Observed Water Levels (Sample from Patna Station)

Date	Observed WL (m)	Modeled WL (m)	Difference (m)
15 Aug 2020	51.3	51.1	-0.2
20 Aug 2020	52.1	52.0	-0.1
25 Aug 2020	52.8	52.6	-0.2

The Root Mean Square Error (RMSE) between modeled and observed water levels was calculated to be 0.17 m, and the Nash–Sutcliffe Efficiency (NSE) was 0.89, indicating excellent model performance.

Morphological Changes

Longitudinal analysis using historical satellite images (2000–2022) and modeling outputs demonstrates significant morphological changes along the study stretch. The Ganga has exhibited both lateral and longitudinal channel migration, with notable bank erosion near Sultanganj and accretion near Munger and Rajmahal.

The thalweg the deepest line along the riverbed has shifted over 300 meters in some segments between 2000 and 2020 (Figure 12). These shifts correspond with increased erosion on the outer bank of meanders and suggest significant sediment dynamics driving planform adjustments.

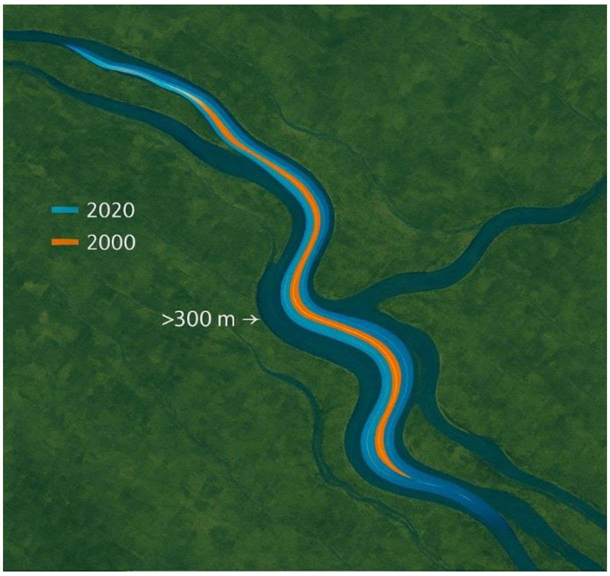

Figure 12. Thalweg Shifts (2000-2020)

Table 4: Bankline Shifts and Erosion/Accretion Rates

Location	Erosion Rate (m/year)	Accretion Rate (m/year)	Net Shift (2000–2020, m)
Bhagalpur	8.5	2.0	-130 (toward south)
Sultanganj	10.0	1.5	-170
Munger	3.2	6.5	+65 (toward north)

Impact on Human Settlements and Infrastructure

The dynamic behavior of the river, especially in terms of flooding and morphological changes, has profound implications for human settlements, agriculture, and infrastructure. Villages near Bhagalpur and Farakka face recurrent threats of flooding, leading to loss of livelihood and forced migration. Moreover, critical infrastructure such as the Farakka Barrage, NH-80, and rail bridges face increased risk due to undermining and toe erosion.

Model simulations estimate that during extreme flood scenarios (e.g., 100-year flood), up to 312 villages and 65,000 hectares of agricultural land could be inundated. The extent of inundation also correlates with poor embankment maintenance and silted drainage channels.

Integrated flood management and riverbank protection measures, such as revetment, riprap, and planned embankments, are crucial to mitigate these risks. Furthermore, early-warning systems based on real-time modeling outputs can significantly improve community preparedness.

5. Conclusion

This study presents a comprehensive analysis of flow dynamics, sediment transport, and morphological evolution of the Ganga River along the critical stretch between Buxar and Farakka. The integration of hydrological data, field surveys, remote sensing, and advanced hydraulic modeling tools (HEC-RAS, Delft3D) has enabled a detailed understanding of the river's complex behavior across different seasons and geomorphic contexts. The investigation revealed significant seasonal variability in discharge, with flows peaking during the monsoon months and diminishing drastically during the dry season. This variation governs not only the hydraulic regime but also the sediment transport mechanisms, with suspended loads dominating during floods and bedload transport influencing channel morphology during transitional periods. The model outputs and field validations showed strong alignment, with high Nash–Sutcliffe Efficiency (NSE > 0.85), confirming the reliability of the simulations in capturing real-world dynamics. Morphological analysis indicated clear trends of bank erosion and channel migration, particularly around Bhagalpur and Sultanganj, which correspond with higher flow velocities and sediment deposition patterns. Shifts in the thalweg and significant bankline changes over the last two decades' point to ongoing geomorphic instability, driven by both natural processes and anthropogenic interventions, such as upstream dam releases and riverfront encroachments. The study's findings contribute meaningfully to the existing body of knowledge on fluvial hydraulics in large alluvial rivers, particularly in monsoon-dominated systems like the Ganga. By identifying critical erosion-prone zones, depositional areas, and vulnerable floodplain sections, the research provides actionable insights for civil engineers, hydrologists, and planners. From a policy and engineering standpoint, the results underscore the urgent need for adaptive flood management strategies, such as dynamic embankment design, periodic sediment flushing, and sustainable land-use planning in the floodplains. The demonstrated utility of coupled field and model-based analysis further supports the integration of real-time data assimilation into early warning systems and disaster preparedness frameworks. In conclusion, the Buxar–Farakka stretch of the Ganga exemplifies the challenges and opportunities associated with managing large river systems under hydrological stress and climatic uncertainty. Continued research, supported by high-resolution data and stakeholder collaboration, will be essential to balance ecological integrity with infrastructural resilience in this region.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding Statement This study didn't receive any funding in any form.

References

[1] Kumar, A., Bhambri, R., Tiwari, S. K., Verma, A., Gupta, A. K., & Kawishwar, P. (2019). Evolution of debris flow and moraine failure in the Gangotri Glacier region, Garhwal Himalaya: Hydro-geomorphological aspects. *Geomorphology*, *333*, 152-166.

[2] Abdella, K., & Mekuanent, F. (2021). Application of hydrodynamic models for designing structural measures for river flood mitigation: the case of Kulfo River in southern Ethiopia. *Modeling Earth Systems and Environment*, *7*(4), 2779-2791.

[3] Lin, Q., Song, Y., Zhang, Y., Hao, J. L., & Wu, Z. (2022). Strategies for restoring and managing

ecological corridors of freshwater ecosystem. *International Journal of Environmental Research and Public Health*, *19*(23), 15921.

[4] Hamidifar, H., Nones, M., & Rowinski, P. M. (2024). Flood modeling and fluvial dynamics: A scoping review on the role of sediment transport. *Earth-Science Reviews*, *253*, 104775.

[5] Wyżga, B., Kundzewicz, Z. W., Konieczny, R., Piniewski, M., Zawiejska, J., & Radecki-Pawlik, A. (2018). Comprehensive approach to the reduction of river flood risk: Case study of the Upper Vistula Basin. *Science of the Total Environment*, *631*, 1251-1267.

[6] Sinha, R., Singh, S., Mishra, K., & Swarnkar, S. (2023). Channel morphodynamics and sediment budget of the Lower Ganga River using a hydrogeomorphological approach. *Earth surface processes and landforms*, *48*(1), 14-33.

[7] Dey, S., Basu, A., Banerjee, S. N., & Jain, V. (2023). Discharge-driven rapid bank-erosion and its impact on sediment budgeting in the lower Gangetic plains. *Episodes Journal of International Geoscience*, *46*(2), 259-267.

[8] Faisal, B. R., & Hayakawa, Y. S. (2022). Geomorphological processes and their connectivity in hillslope, fluvial, and coastal areas in Bangladesh: A review. *Progress in Earth and Planetary Science*, *9*(1), 41.

[9] Islam, A. R. M. T., Talukdar, S., Akhter, S., Eibek, K. U., Rahman, M. M., Pal, S., ... & Mosavi, A. (2022). Assessing the impact of the Farakka Barrage on hydrological alteration in the Padma River with future insight. *Sustainability*, *14*(9), 5233.

[10] Ielpi, A., Lapôtre, M. G., Gibling, M. R., & Boyce, C. K. (2022). The impact of vegetation on meandering rivers. *Nature Reviews Earth & Environment*, *3*(3), 165-178.

[11] Sinha, R. K., & Prasad, K. (2020). Management of water quality and biodiversity of the River Ganga. In *Ecosystems and Integrated Water Resources Management in South Asia* (pp. 104-132). Routledge India.

[12] Church, M. (2015). Channel stability: morphodynamics and the morphology of rivers. *Rivers–physical, fluvial and environmental processes*, 281-321.

[13] Islam, A., & Guchhait, S. K. (2017). Analysing the influence of Farakka Barrage Project on channel dynamics and meander geometry of Bhagirathi River of West Bengal, India. *Arabian Journal of Geosciences*, *10*, 1-18.

[14] Plink-Björklund, P. (2015). Morphodynamics of rivers strongly affected by monsoon precipitation: review of depositional style and forcing factors. *Sedimentary Geology*, *323*, 110-147.

[15] Sarkar, T., & Mishra, M. (2022). Large Dams, Upstream Responses, and Riverbank Erosion: Experience from the Farakka Barrage Operation in India. In *Applied Geomorphology and Contemporary Issues* (pp. 441-462). Cham: Springer International Publishing.

[16] Choudhary, C. D., Vimal, B. K., Shambhavi, S., & Kumar, R. (2020). Natural Resource Management and Land Use Planning. In *Sustainable Agriculture* (pp. 335-364). Apple Academic Press.

[17] Su, S., Zhao, C., Chen, Y., & Tang, Y. (2024). Unlocking sustainability in China's small-scale fisheries: A case study of livelihood analysis in the Bohai Region. *Ocean & Coastal Management*, *258*, 107405.

[18] Bhuyan, N., Sajjad, H., Sharma, Y., Sharma, A., & Ahmed, R. (2024). Assessing socio-economic vulnerability to riverbank erosion in the Middle Brahmaputra floodplains of Assam, India. *Environmental Development*, *51*, 101027.

[19] Hossain, B., Sarker, M. N., & Sohel, M. S. (2025). Flooded lives: socio-economic implications and adaptation challenges for riverine communities in Bangladesh. *International Journal of Environmental Science and Technology*, *22*(6), 4407-4422.

[20] Singh, R. P., & Rana, P. S. (2020). Faith and place: Hindu sacred landscapes of India. In *The Routledge handbook of place* (pp. 75-87). Routledge.