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MEANDERS OF THE KABODAK RIVER, BANGLADESH

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Abstract

The study explores the meandering patterns of the Kabodak River and investigates the relationship among geometric aspects like sinuosity, width, amplitude, radius of curvature, and wavelength. The variables like basin area, river length, and longitudinal profile were measured, and the geometric aspects such as sinuosity, radius of curvature, meander wavelength, and meander amplitude were interpreted and calculated using Google Earth Pro and ArcGIS 10.5. With the aid of the software SPSS and unscrambler X, the relationship among the geometrical aspects was examined. Besides, different meander patterns have been identified by analyzing the meander form. The result reveals that the upper and lower parts of Kabodak appear more sinuous than the middle. Nodal patterns in river sections vary, with the upper and lower sections experiencing increased sinuosity due to lower gradients, reduced flow, and blockage. In contrast, the middle section exhibits less sinuous characteristics because of neotectonics upliftment. Among the variables, meander wavelength, amplitude, and radius of curvature have weak positive correlations between and among them, except for the wavelength-amplitude relation. The relationship between wavelength and amplitude is inversely proportional. The variable width appears non-responsive with other variables, which makes sense as the river's width is already structuralized due to human interference. Theoretically, the Kabodak River's meandering pattern deviated from other meandering river studies due to human interference. Similar types of work on other meander rivers of the delta may be explored to see if the result corroborates. Besides, the effect of human intervention on meandering patterns and morphological processes needs further study.

Keywords: Meander, Kabodak river, Sinuosity, Longitudinal profile, Geometric aspects.

Introduction

Though a common sight in a deltaic environment, Meander rivers may also occur in other parts of Bangladesh (Bagchi, 1944; Chowdhury, 1959). Because of its winding nature, it appears sinuous when seen from the sky. Such a unique plan-view is deeply connected

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with a wide range of human activities like economic, ecological, environmental, and cultural activities (Alam *et al.,* 2022). In densely populated parts of the world, humans use river courses for habitation and livelihood (Kusratmoko, 2017; Kusratmoko *et al.,* 2019). Therefore, managing the functions of the rivers is essentially linked with the welfare of the population living along the river. In nature, the river bends due to numerous independent factors, like geology, climate, gradient, and time. (Montgomery, 1999; Schumm, 1967; Hogan and Luzi, 2010). These factors, again, are linked with the dependent variables, like river discharge, vegetation, hydraulic characteristics, and sediment transport (Buffington *et al.,* 2003; Montgomery and Buffington, 1993). The meandering rivers constantly change their banking because of this interaction between independent and dependent variables. In the short term, the gradient, energy (water discharge), and matter (sediment transport) affect the shape of a meander river channel. However, Church and Ferguson (2015) note that these variables' interactions typically serve as their guides.

The formation and persistence of river meanders have intrigued multiple scientific disciplines, including geomorphology, fluid dynamics, sedimentology, mathematics, and engineering. As a result, several theoretical frameworks have been put forward in the extended scholarly literature to provide a comprehensive understanding of the phenomenon of meandering (Morisawa, 1968; Leopold *et al.,* 1964). While disagreements persist regarding the classification and identification of meanders, some commonalities shed light on the mechanisms driving meander development. Early attempts to quantify meander processes identified consistent geometric ratios, such as the relationship between radius of curvature, meander length, and channel width (Thorne *et al.,* 1997). The relationships between meander length, channel width, and curvature radius are independent of bed and bank materials and connected to an unspecified mechanical principle (Knighton, 1977). The ratio of curvature to channel width is crucial for understanding flow resistance and offers insights into why channels of different sizes exhibit similar geometric patterns (Leopold and Wolman, 1960; Dury, 1970). Scientists developed statistical models rooted in heuristic reasoning, treating meanders as a type of random walk aimed at minimizing changes in flow direction through in-depth, velocity, and slope adjustments. However, while valuable for understanding large-scale meander patterns, these models do not fully predict the intricate details of meander evolution (Komatsu and Baker, 1994; Schumm and Khan, 1972).

Despite the abundance of scholarly literature on the subject matter, several academics have agreed that a comprehensive and satisfactory explanation for meandering remains elusive (Leopold *et al.,* 1964; King, 1966; Morisawa, 1968). The Gulf Stream and other streams characterized by straight sections with meandering thalwegs, sediment-free streams situated on glacial ice, and sediment-free streams located on solid rock formations much above base level all show meander patterns. This observation implies that natural streams have an inherent tendency to meander (Knighton, 1972; Zhang *et al.,* 2008). Therefore, sediment's role in erosion, transportation, and deposition during the creation and migration of meanders is mostly secondary (Leopold *et al.,* 1964; Davis, 1913). In Bangladesh, meandering rivers are common regarding availability, followed by braided rivers and linear channels (Chowdhury, 1959). In his 1959 work 'Morphological Analysis of the Bengal Basin,' Chowdhury covers both parts of Bengal, encompassing a wide range of studies that delve into the erosional, depositional, and transportation activities of the Bengal rivers (Rob, 1989). The greater floodplains and the Ganges deltaic plains are low-lying, and valley gradients are low; thus, channel meanders occur quickly (Banglapedia, 2015). Furthermore, a second arc on the perimeter of the simple loop gradually forms to create compound loops (Brice, 1974). Over time, each meander slowly grows to greater and greater size, increasing in arc and radius, until the neck of a valley-side spur or a floodplain lobe is narrowed and worn through (Schumm, 1963).

Knowledge about meandering rivers is essential, as many economic activities are associated with these rivers. Learning about the nature and behavioral pattern of the meandering river will help in river management. The researchers chose the Kabodak River as a case study because of its unique characteristics. The river flows through a moribund delta, a mature delta, and terminates near a tidally active deltaic region. This makes it an ideal river for investigating the process of meander formation (Fig. 1). The Kabodak River originated from the Mathabhanga River and disconnected from its source in the Chuadanga district (Banglapedia, 2021). The river flows through the Jhenaidah, Jessore, Satkhira, and Khulna districts and finally meets the Shibsha River at Paikgacha upazila in the Khulna district. Along the whole length of the Kabodak River, it exhibits different subsurface lithologic conditions and hydrogeomorphologic settings. The objective is to identify the meandering patterns of the different parts of the Kabodak River and investigate the relationship among geometric aspects like sinuosity, width, amplitude, radius of curvature, and wavelength.

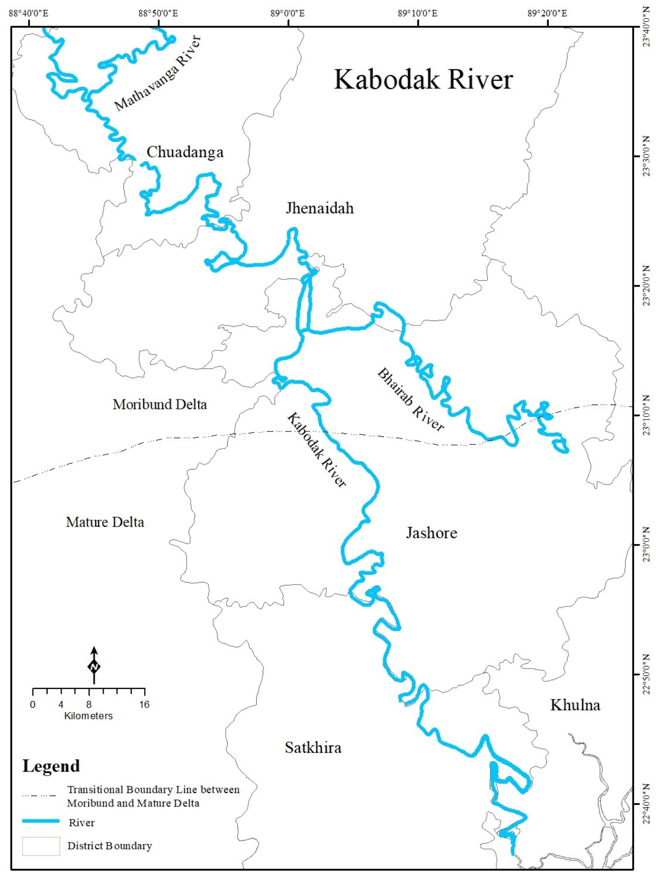

Fig. 1. The Kabodak river.
Complied by the authors, 2023.

Methodology

In this study, the Kabodak River of Bangladesh is selected to measure the types and number of meander patterns developed by the river and the relationship among the geometric aspects like width, amplitude, radius of curvature, and wavelength. The specific activities carried out as a part of this study are summarized below:

Identification and delineation of the Basin area of the Kabodak River: The study uses high-resolution DEM data downloaded from USGS (2019) to identify and delineate the river basin. Then, the study computes the flow direction with the Flow Direction tool. To find the contributing area, we used a flow accumulation threshold. The output is a raster displaying the delineated watersheds for the Kabodak River.

Measurement of the River Length: The Kabodak River's length was determined using Landsat OLI images. To pinpoint the precise initiation and termination points of the Kabodak River, a reference was made to Banglapedia 2021. Subsequently, a transect was drawn across the middle section of the Kabodak River, and the river length was measured accordingly.

Drawing the longitudinal profile: The river's geometric attributes were extracted from the Digital Elevation Model (DEM) dataset. This involved identifying and delineating the thalweg line, which corresponds to the river's lowest point. To obtain the longitudinal profile of the Kabodak River, the elevation profile tool was utilized. This tool facilitated the generation of a comprehensive representation of the river's elevation changes along its entire course. (Fig. 2).

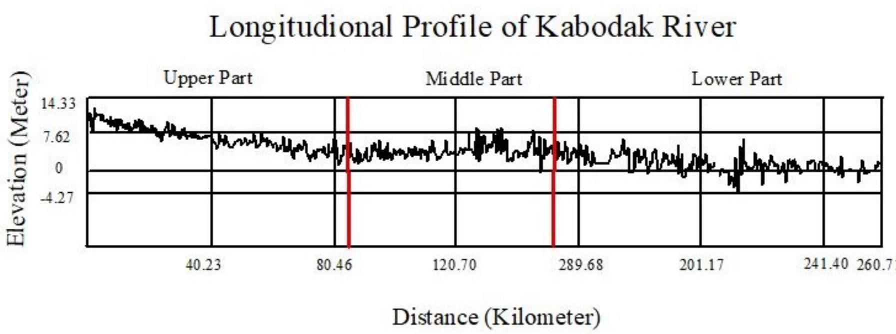

Fig. 2. Longitudinal profile of the Kabodak river, 2023.
Source: Compiled by the authors, 2023)

Measuring geometric aspects of the meander: Sinuosity, width, amplitude, radius of curvature, and wavelength are quantified as geometric aspects (Fig. 3). sinuosity was calculated as the along-channel distance divided by the Euclidian distance per bend and meander. Using the ruler tool in Google Earth Pro, the channel length is measured from the centerlines. In the wet season, meander width is measured in Google Earth Pro by measuring from bank to bank. The meander amplitude was calculated as the highest normal distance of the channel position from the meander belt centerline as defined by the inflection points. The radius of curvature was determined from the meander belt centerlines using Google Earth Pro's ruler "circle" tool, and the meander wavelength was estimated using the centerlines of two sequential meander bends. Finally, the relationship among geometric aspects is measured using the SPSS and unscrambler X software.

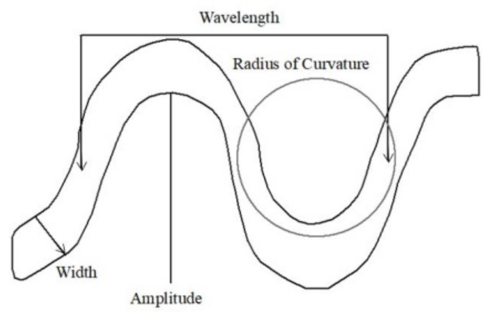

Fig. 3. Geometric Aspects of a River.
Source: Compiled by the Authors, 2023.

Assessing meander pattern: Based on the meander node and complexity, the authors of this paper divided the shapes into four major groups (Fig. 4).

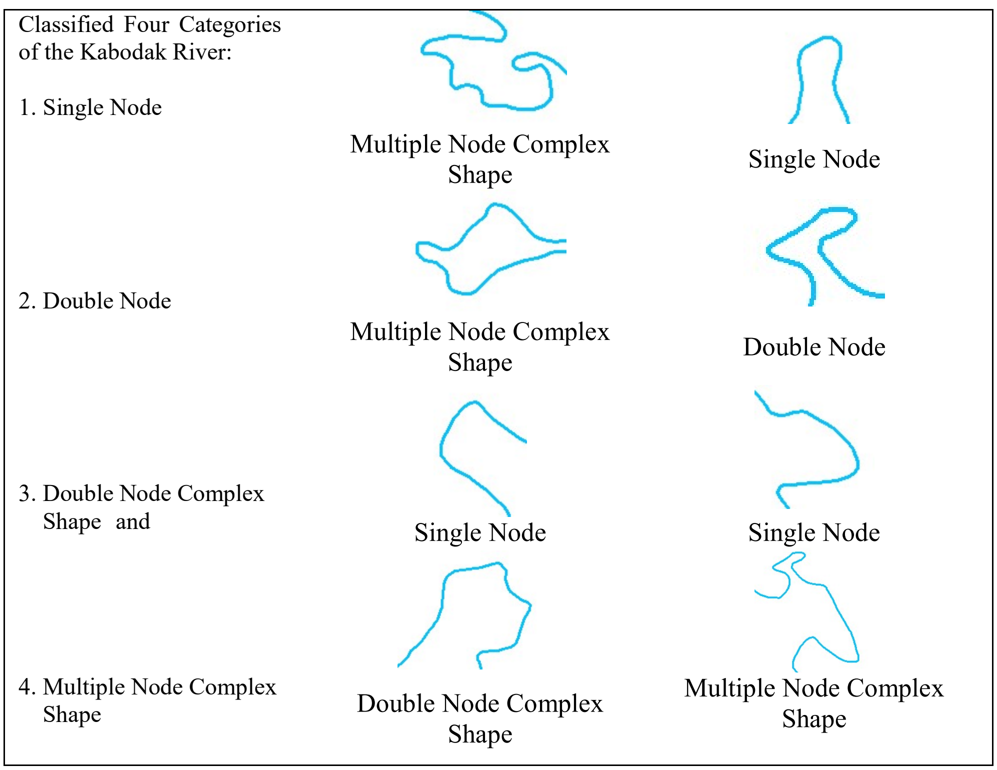

Fig. 4. Complex Shape of Meander Bend of Kabodak River.
Compiled by the authors, 2023.

Results

Basin area and length of the Kabodak River: The orientation of the river is north-south directed. The current measurement of the river's entire length is around 262.5 km, while the basin area of the Kabodak River is roughly 2,918.67 square kilometers.

The Kabodak River now relies mainly on channeling its tributaries for its flow. The first-order stream within the Kabodak river basin (Fig. 5) has accounted for the highest proportion of contribution, namely 50.24%. The subsequent notable contribution is derived from the 2nd Order stream, which accounts for 24.88% of the total. The third-order stream accounts for 10.14% of the total contribution, while the fourth-order stream exhibits the lowest contribution at 6.28%. The contribution exhibits a reduction of 8.45% in the fifth-order stream. This implies that this river's primary water source is derived mainly from smaller tributaries. Fig. 5 demonstrates that the middle part has the greatest quantity of order streams.

On the contrary, the upper part exhibits a shortage of primary and secondary streams, leading to an exceedingly sinuous configuration due to diminished energy levels. In addition, a substantial quantity of first-order streams in the middle part of the river contributes to its heightened flow rate relative to other segments. The lower part of the river is situated inside a region characterized by tidal activity, resulting in partial flow from backwash water that aids in the river's continuation.

Longitudinal Profile of the Kabodak River

The sinuosity of a river is contingent upon its gradient. The longitudinal profile of the Kabodak River provides an overview of the gradient decline pattern seen along the whole river. The depiction of the upper, middle, and lower sections of the Kabodak River (Fig. 2) is based on the observed gradient decline. Upon analysis of the comprehensive profile of the Kabodak River, it is evident that the river exhibits a consistent downward trend, except for a notable deviation in the middle part. The upper part of the graph depicts a state of equilibrium, but notably, the central part exhibits erratic fluctuations, suggesting an unstable state inside this interval. This fluctuating state reaches a peak elevation of around 7.6 meters above sea level and then descends towards sea level. The data exhibits significant fluctuations. The underlying cause of this precarious state may be attributed to indistinct refraction close to Jhikargacha. Also, near the midpoint of the lower part, it eroded below sea level (-4.27 meters) because of extensive bed scouring during high flood incidence in 2000 and 2011.

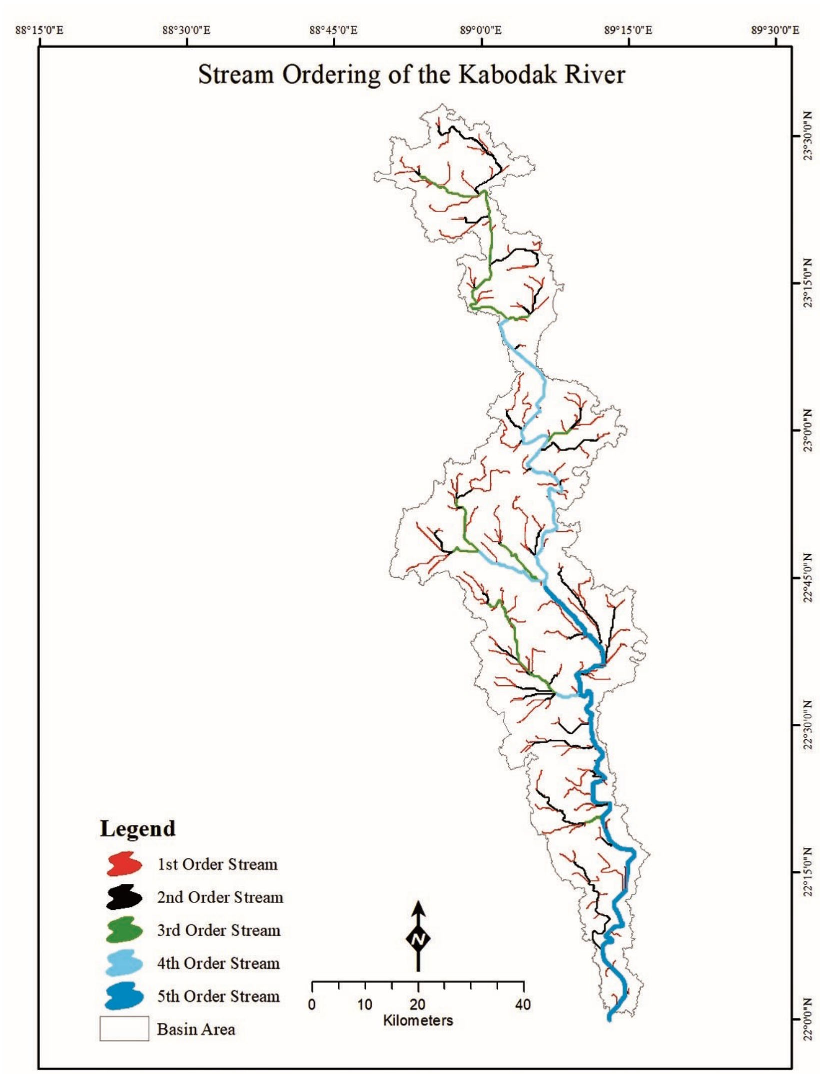

Fig. 5. Stream order map in Kabodak river basin, 2023.
Compiled by the authors, 2023.

This river's lower reach is tidal and exposed to heavy siltation, thus covering lower gradients and a high sinuosity ratio. On the other hand, the lower part has a sinuosity of 2.34, whereas the sinuosity of the whole river is 2.32. The central part would follow the same sinuosity trend if the middle part didn't face the fault line.

- Sinuosity Ratio of Kabodak River: 2.32;
- Sinuosity Ratio of the Upper part: 3.18;
- Sinuosity Ratio of Middle part: 1.66;
- The Sinuosity Ratio of the Lower part is 2.34.

The complex shape of the meander bend of the Kabodak River

The present categorization scheme classifies several forms of meander bends based on the number of nodes and the level of shaping complexity. The intricate formations of the Kabodak River can be classified into four primary categories (Fig. 4).

This research examines and analyzes 31 meander nodes within the Kabodak River. The complexity of the structure is attributed to the significant decrease in sedimentation and water flow originating from the top source. On the other hand, the lower portion is subject to elevated sedimentation and retrograde discharge due to tidal impacts. The energy diminishes, forming a lower gradient that gives rise to a complex meander in the upper section. Likewise, a significant sedimentation process leads to a complicated meander in the bottom section. Classifying a meander's form involves shape matching, sinuosity, radius-of-curvature, breadth, amplitude, and wavelength. The meander forms have been classified into four distinct groups. Thirty-one different shapes and planform photographs were analyzed to characterize each particular meander. This analysis was conducted to identify the specific shape type used in the present research, as shown in Table 1.

Table 1. Different shapes of the meander bend of the Kabodak river.

Node types	Upper part	Middle part	Lower part
1. Single Node	8	3	4
2. Double Node	2	0	1
3. Double Node Complex Shape	1	2	0
4. Multiple Node Complex Shape	4	0	6

Source: Compiled by the Authors, 2023.

Table 1 reflects a visual representation of the variation in meander form along different river sections. The upper portion of the river exhibits the most complexity in meander shape (48.39%). In contrast, the middle section displays the lowest diversity (16.13%), which may be attributed to the inflow of several tributary streams and a relatively steep gradient compared to other parts of the river. The complicated structure of the bottom section is mostly attributed to its low gradient and the backwash effect resulting from the tidal activity in the area (35.48%).

Relationship among the Geometric Aspects of the Meander Pattern

It's important to know how the four geometric properties (width, radius of curve, wavelength, and amplitude) relate because any change in one affects the other three differently. Primary concerns in studying geometric aspects of meandering rivers include point bar development and concave bank erosion (Harvey, 1988). For example, the water-holding capacity will decrease as the river's width decreases, just as accretion will rise in the point bar. In some areas, such as along riverbanks, erosion will accelerate, and the amplitude is expected to increase. This can be understood better from the chronological changes of the Kabodak River (Fig. 6). In 1780, the higher river width exhibited lower sinuosity and amplitude; in contrast, during 2019, with decreasing width, sinuosity increased, and amplitude widened along the whole length of the river.

For assessing the relationship among the geometric aspects of the Kabodak River, 54 meander bends are counted and analyzed. The relation among and between width-radius of curvature (A), width-wavelength (B), and width-amplitude (C) are almost non-responsive as the width of the river has been partly regulated because of human interferences (Fig. 7). The link between wavelength and radius of curvature (D) demonstrates a responsive correlation. A positive correlation exists between the wavelength and the radius of curvature of a river. The research posits that an increase in the wavelength of the river corresponds to an increase in the radius of curvature. The result corroborates a similar study undertaken by Dury in 1970. However, as the values of these two particular meander factors increase, it becomes challenging to forecast the characteristics of the wavelength accurately.

The correlation between the radius of curvature and amplitude (E) implies a similar outcome for the relationship between wavelength and radius of curvature (D). An inverse-proportional connection exists between the wavelength and amplitude (F). An increase in wavelength results in a reduction in amplitude. Conversely, a decrease in wavelength will increase amplitude. This relationship applies to all meandering rivers.

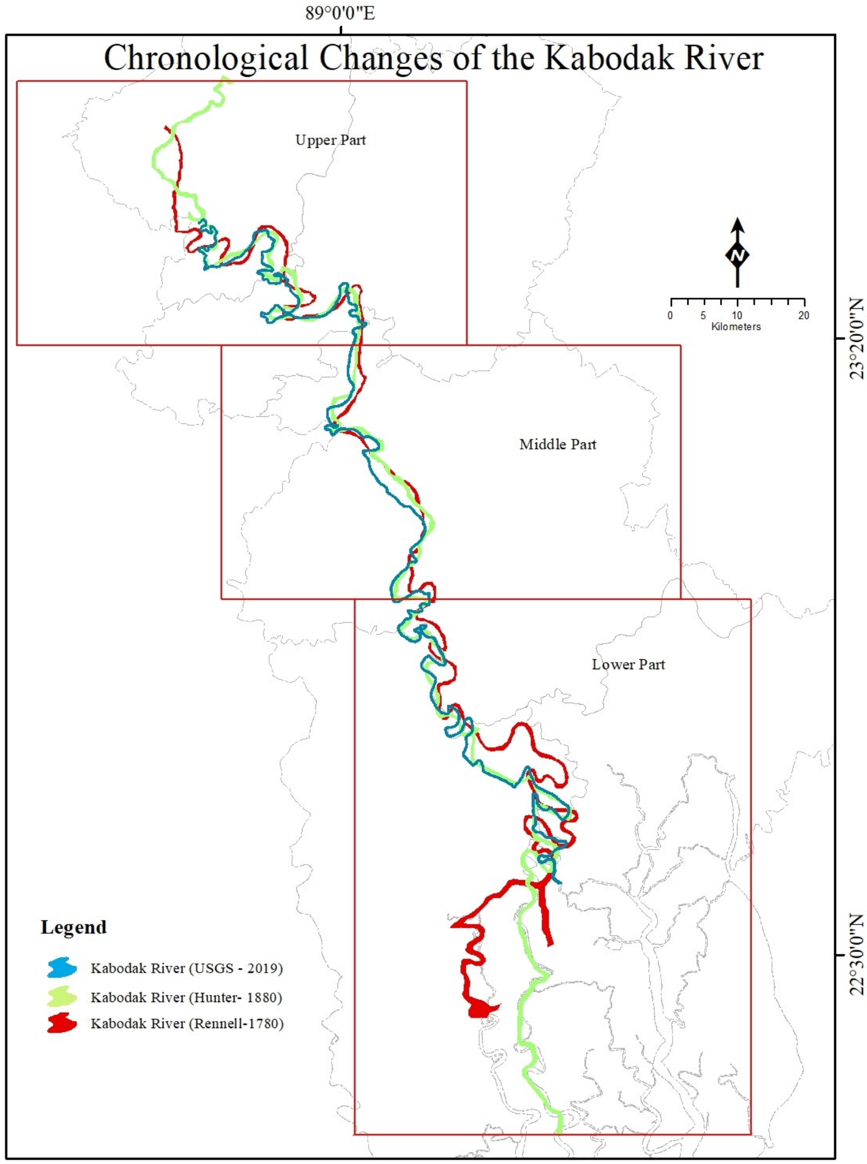

Fig. 6. Variations in channel shifting tendency at different parts of the Kabodak River between 1777 and 2019

Source: Compiled by authors, 2023

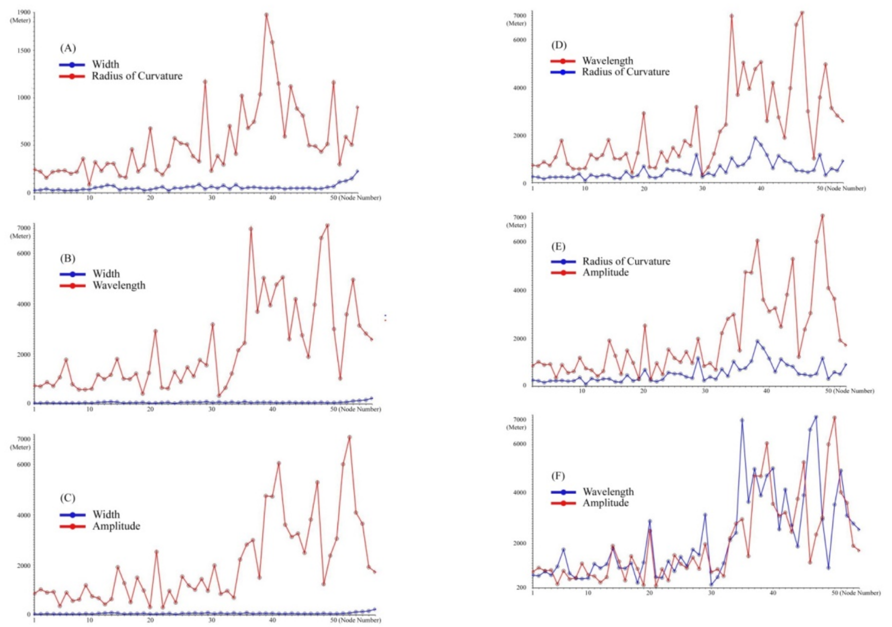

Fig. 7. Relationship among the meander patterns of the Kobodak river.
Source: Compiled by the authors, 2023

Discussion

The Kabodak River has a meandering pattern with a relatively high sinuosity ratio. The upper part exhibits the most sinuosity compared to the other two segments. The upper part of the channel has been disconnected from its main channel, resulting in a lack of water flow (energy) from the upstream and subsequently causing an increase in the sinuosity ratio. In contrast, it can be seen that the middle part of the river has the least sinuosity, having a nearly linear alignment possibly in part due to neotectonics uplift, but the lowest portion has a meandering pattern resulting from exposure to tidal siltation.

The Kabodak River has a consistent, progressive decrease in its gradient, resulting in a concave form. The perfect longitudinal profile of a river has a concave contour. The downstream section of the river is situated close to sea level. The lowest portion of the area experienced significant erosion below sea level (-4.27 meters) due to considerable bed scouring caused by heavy flood events in 2000 and 2011 (Tareq, 2016). The factors contributing to the formation of various meander characteristics include width, radius of curvature, amplitude, and wavelength. The process of altering the form of the radius of curvature, amplitude, and wavelength takes a long time. However, the width of a river may be rapidly altered due to fluctuations in discharge volume or variations in the severity of human interference. Significantly, in the case of the Kabodak River, which has been subjected to human-induced structural interruptions, there is a lack of significant correlation between its width and the radius of curvature, amplitude, and wavelength. Types of human interferences responsible for narrowing the valley width are listed in Table 2.

Table 2. Types of human interferences on river course and their effects in different aspects.

<table>
<tr><th>Aspects</th><th>Human Interferences</th><th>Effects</th></tr>
<tr><td rowspan="2">Geomorphological</td><td>• Constructions of cross-roads
</td><td rowspan="4">• Narrowing the river width to save cost hampers rapid downstream movement.
• Increased upstream siltation
• Decreased water holding capacity
• Flooding in streams due to ponding effects
• Expedite oxbow lake formations
• Narrowing width and
• Altered the natural river systems as well as the ecosystem</td></tr>
<tr><td>• Encroachment of the river through building and bridges construction along and across the river length
</td></tr>
<tr><td>Agricultural</td><td>• Extension of agricultural practices along the river length by landfilling

</td></tr>
<tr><td>Biological</td><td>• Water withdrwal for irrigation purposes</td></tr>
</table>

Source: Compiled by the Authors, 2023

The relationship between amplitude and wavelength is inversely proportional. The inverse relationship between wavelength and amplitude holds for all meandering rivers worldwide. There exists a positive correlation between the radius of curvature in terms of wavelength and the radius of curvature in terms of amplitude, mainly when the values of both parameters are low. As values rise, it becomes challenging to ascertain the precise nature of the link between them. The relationship in question pertains specifically to the Kabodak River, where the lower section of the river is subject to tidal influence and the backwater effect. Predicting this relationship for the lower portion of the Kabodak River presents a challenge.

Based on empirical observations and quantitative measurements, it is evident that the occurrence of nodal patterns and their intricacy is mainly seen in the upper (48.39%) and lower sections (35.48%) of the river. However, it is essential to note that the underlying causes and processes contributing to these phenomena exhibit notable variations. Various factors influenced the sinuosity of the river in different sections. The river showed increased sinuosity in the upper and lower parts due to a lower gradient, reduced flow, and blockage from the source. Conversely, the middle section (16.13%) displayed distinct characteristics resulting from tectonic upliftment, the influx of energy from numerous streams of different orders, and the discharge from the Bhairab River located in the Jessore district.

Conclusion

The Kabodak River, located in the deltaic part, is a deceptively complicated meandering river. Hydro-geomorphological conditions, along with human interference and overexploitation of its resources, distinctly shape the river from other meandering rivers. The relationship among and between geometric characteristics such as width, amplitude, radius of curvature, wavelength, and patterns is more complicated than in any other meandering rivers of Bangladesh. Therefore, the management strategy of the Kabodak River might need a different approach from that of Bangladesh's other meandering rivers. The true nature and behavioral pattern of three distinct meandering sections are entirely different, thus necessitating different sets of measures for each section of the river.

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