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Meandering-braiding aspects of the middle-lower part of the Ganga River, India

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ABSTRACT
The present study is focused on the analysis of some geometric characteristics regarding meandering and braiding of the middle-lower part of the Ganga River at different axes. The middle-lower part of the Ganga River is the study reach and it ranges from Bhagalpur to Jangipur. The methods that applied in this study are: braid-channel ratio, sinuosity index and different parameters of maximum asymmetry. The relationship between the relative bend-entry curvature or channel width ratio and relative bend curvature is very strong and positive. The relationship between bend-entry curvature and meander wavelength is positive along with the positive relationship between relative bend curvature and meander wavelength. In the study reach sinuosity ranges from 1.08 to 1.90 and braid-channel ratio ranges from 1.21 to 4.26. The sinuosity index and range of sinuosity are not very high compared to the braid-channel ratio and its range. Statistically the relation between sinuosity and the braid-channel ratio is negative but the value is not significant in the reach. Hence, the channel lies in between the sinuous-braided structure or the meander-braided structure in the study reach.

Key words: Ganga River, channel geometry, braid-channel ratio, sinuosity index, maximum asymmetry.

INTRODUCTION

While carrying out geomorphologiocal changes along big rivers researchers recreate in a geographic information system (GIS) environment using data obtained from Landsat TM/ETM+/OLI satellite images. This helps to have proper knowledge of the temporal changes in the sinuosity and braiding characteristics of the river during different periods. This further helps the right and left banks morphology of a river, the shorelines of islands and bars within the river channel automatically from the satellite images by integrating the normalized difference water index (NDWI) and modified normalized difference water index (MNDWI) (Derya Ozturk and Faik Ahmet Sesli, 2015). Due to various limitations in the present study the above technique could not be used. While admitting non utilisation of satellite imagery data and gathering information in GIS environment has lessened quality of the study the systematic data acquisition procedures used in the present study have helped in getting useful information about Ganga river dynamics. The detailed study has been carried out to bring into focus floodplain morphology dynamics, floodplain structure, channel geometry, meandering and sediment depositional characteristics of Ganga river system.

In the study of floodplain morphology dynamics, channel avulsion is a considerable complex response event, which modifies floodplain structure, channel geometry, meandering and sediment depositional characteristics of a river system (Keen-Zebert et al., 2012). To explain meandering-braiding complexities and floodplain formation a single mechanism can't be taken as perfect. In order to understand the meander character of modern channels, scientific analysis and explanation of many palaeo sequences of mud-silt-clay dominated facies is important (Keen-Zebert et al., 2012). The explanations for meandering has been done based on sedimentation in a braided (Leopold and Maddock, 1953), on autocyclic-stochastic movements (Wells and Dorr, 1987), instability of channel that is a sudden movement around a concave point (divergence point) and vertical accretion (shallow or deep inundation) including large breaches during a flood with a magnitude near to avulsion threshold (extrinsic or intrinsic) (Schumm, 1977). For the last six decades, in the tenet of fluvial geomorphology, several mathematical models have been proposed for the analysis of channel pattern especially for the identification of threshold between meandering-braided forms of a river. The channel pattern includes the empirical researches (Lane,1957) based on discharge-slope; discharge, slope and stream power based on Leopold and Wolman (1957); the physical interpretation of Begin (1981) based on flow shear stress and the physical and statistical analysis of Henderson, (1966) and Chitale (1973) based on bed material size and Leopold-Wolman analysis. Apart from these, many concepts of descriptive classification have also been proposed, mainly based on multi-channel form and sinuosity (Rust, 1978; Magdaleno and Fernández-Yust, 2011), river meandering and channel size analysis

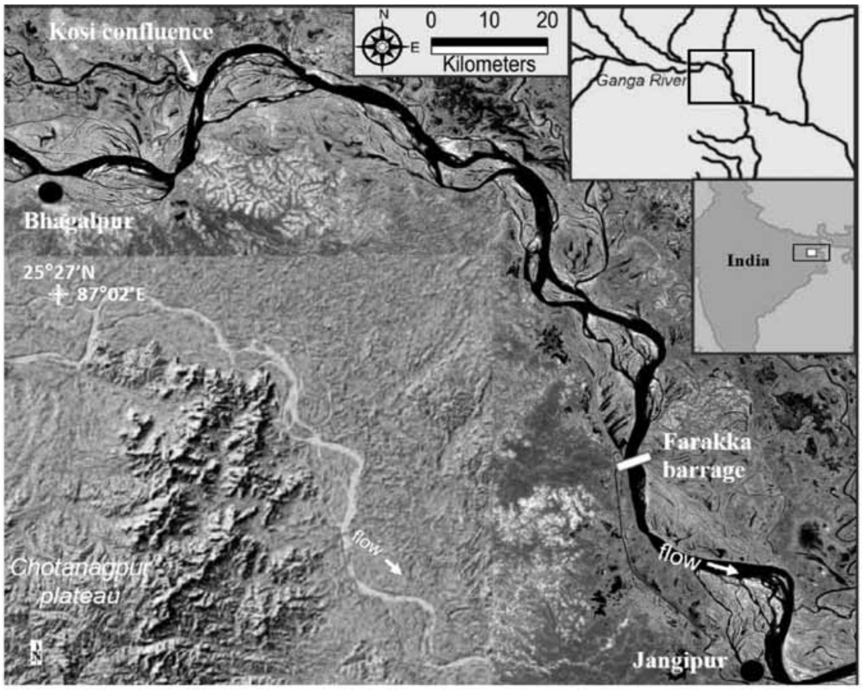

Figure 1. Location map of the study reach of the Ganga River.

(Williams, 1986). Others include channel bar forms (Brice, 1975), sedimentary controls and channel stability (Schumm, 1985) and floodplain and valley characteristics (Nanson and Croke, 1992; Alabyan and Chalov, 1998). Williams (1986) used an enlarged data set to (1) compare measured meander geometry to that predicted by the Langbein and Leopold (1966) theory, (2) examine the frequency distribution of the ratio radius of curvature/ channel width, and (3) derive 40 empirical equations (31 of which are original) involving meander and channel size features. He has further pointed out that the Langbein-Leopold sine-generated-curve theory for predicting radius of curvature agrees very well with the field data.

The study reach of the Ganga River is highly complex in terms of its meandering-braiding coexistence. A complex formation of channel meanders, channel braiding and ana -branching is a channel corridor complexity as well as a geomorphic asset. In order to demonstrate the meander-braiding complexities or single-multithread channel coexistence, it is necessary to find out the underlying causes and mechanics that shape the channels into single-multithread form (Knighton, 1998). It has been observed in the study reach, the meander portions of the channel are single thread and the braiding portions are multithread. Carson (1984) has pointed out two arguments that explain the meander-braiding complexity: i) braiding primarily depends on local shoaling of the thalweg rather than on the hydraulic threshold (e.g., stream power) and ii) it is worthless to find out a threshold for meandering and braiding. Moreover, the study by Nanson and Croke (1992) points out that the processes involved in floodplain formation range from a vast extension and diverse floodplain types. Such a range of flood plain processes support the need to building a specific model for each floodplain. The present study is mainly focused on the investigation of some geometric properties of the Ganga River at different axes in the considered reach.

Alea Yeasmin and Nazrul Islam (2011) carried out systematic studies to understand changing trend of channel pattern of the Ganges-Padma River. The study analyzes the changing trends of channel pattern of the Ganges-Padma River. A time series of satellite images in the period of 1973-2006 are compiled for analysis. It is believed that the Ganges-Padma River is a meandering river. But lately the Ganges-Padma has become a braided river due to high sediment transportation by Jamuna and deposition of Ganges-Padma River bed. For the purposes of study, the sinuosity ratio and braiding index were calculated in different time series. The analysis shows that the sinuosity ratio is increased over time. In 1973, it was 1.31 and in 1984, 1996, 2006 it was 1.33, 1.37, and 1.43, respectively. In 2006, though it was sinuous, since it is very close to 1.5 it indicates meandering. In case of braiding index, it has been observed that in 1973, the braiding index was 1.3 and in 1984, 1996, 2006 it was 1.43, 1.62, and 1.92, respectively.

I give below a detailed analysis of the study carried out by me.

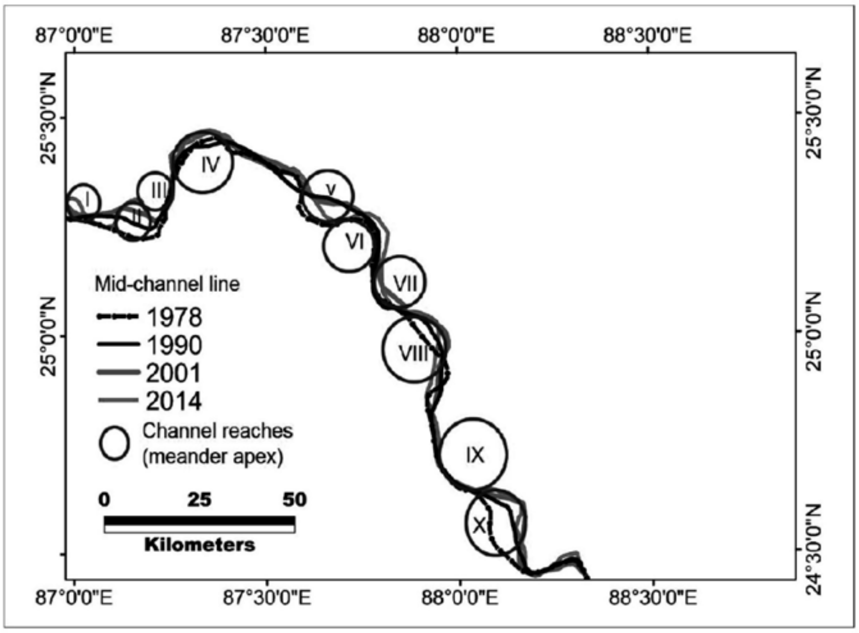

Figure 2. The position of mid-channel lines in 1978, 1990, 2001 and 2014. The circles are the meander apex or channel reaches (meandering axes).

Study Reach:

Out of ~2525 km of the flows of the river ~217 km stretch has been considered in this study. It is the middle-lower part of the river that ranges from Bhagalpur to Jangipur. The river drains up to the Kosi confluence in the north-east direction, then it flows in the east direction in Bihar. Finally, it flows in the south-east direction in West Bengal. The Ganga River bifurcates into two segments neat the edge of the Ganga-Brahmputra delta, one is the Hugly-Bhagirathi that drains in a southern direction joining the estuary of the Bay of Bengal. Another one is the Padma that drains through Bangladesh in the south-east direction to join the Brahmputra River and finally the estuary of the Bay of Bengal (Singh, 1971; Rudra 2010). The study reach is architectured by a basement high, two fault lines (the Rajmahal Fault and the Malda-Kishnaganj Fault), the Kosi confluence, the northern edge of Ganga-Brahmputra delta and Farakka barrage (Singh, 1971; Singh, 1996; Sinha and Ghosh, 2012) (Figure 1). The hydrology of the river in the study reach is extensively controlled by seasonal forces, the construction of Farakka barrage and annual-decadal flood events (Pal and Pani, 2016).

METHODOLOGY

The channel centreline of different years i.e., 1978, 1990, 2000 and 2014 has been taken into consideration to identify different axes. Landsat satellite images of the mentioned years have been used for the axis identification. Ten axes have been identified across the channel reach on the basis of Landsat images of different years (Figure 2). Figure 3 shows a detailed view of meandering geometry that has been incorporated in this study. However, following methods have been applied to explore geometric properties of the river in the study reach:

Braid-channel index (*Bfd*): The braid- channel ratio may be derived as (Friend and Sinha, 1993)

$$Bfd = L_{ctot} / L_{cmax} \qquad \text{............ (1)}$$

Where, *Bfd* is the braid-channel ratio, L_{ctot} is the total of the mid-channel length of all the channels in a reach and L_{cmax} is the length of the prime channel, in that reach. A high value shows multiplicity of the channel and high braidness where, a low value shows single flow of the channel.

Sinuosity index (P): It is a measure of the curvature of a channel. It can be formulated as (Friend and Sinha, 1993)

$$P = L_{cmax} / L_R \qquad \text{............ (2)}$$

Where, L_{cmax} is length of the primary channel in a reach and L_R is the straight line length of the channel for the same reach. A high value shows high meandering and a low value indicates the straightness.

Maximum asymmetry (z): It is a function of relative meander amplitude (r_e/W), relative bend-entry curvature (a/W) and inclination angle (ω). It can be defined as (Carson and Lapointe, 1983)

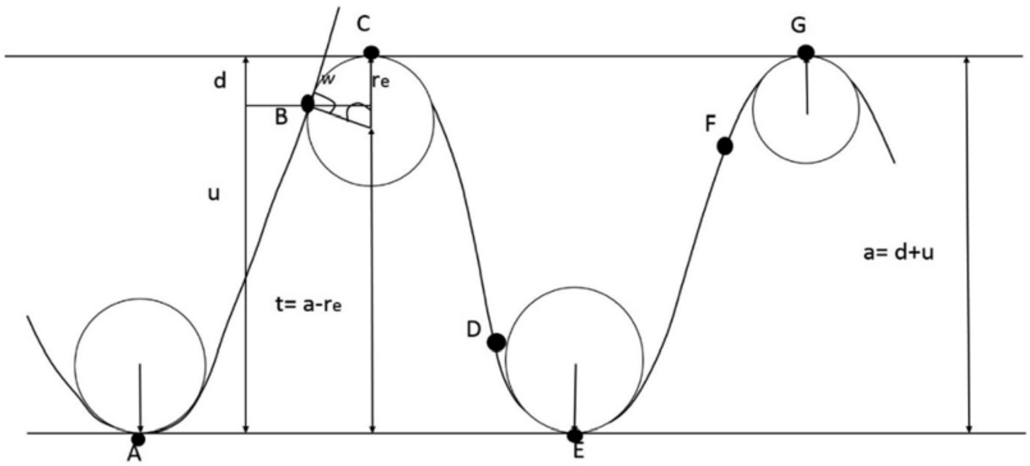

Figure 3. A view of simple geometry of meandering and its aspects (adopted from Carson and Lapointe, 1983).

$$z = 100\ (1\text{-}(r_e/a)(1\text{-}\cos\ \omega)) \qquad \text{............ (3)}$$

Where, z is the maximum value of asymmetry or magnitude of delayed inflection asymmetry, r_e is the bend entry curvature or radius of curvature and r_e/a can be defined as

$$r_e/a = (r_e/w)\ /\ (a/w) \qquad \text{............ (4)}$$

Where, *a* is the amplitude of meander trace or mean meander length and *W* is the channel width (Figure 3).

ANALYSES AND DISCUSSIONS:

The study reach of the river exists with a complex coexistence of the meandering-braided (expansion) and single thread forms (contraction). The channel where it meanders is also braided. The single thread portions across the reach are very small in length and most of them exist in the apex of some meanders. So, it is difficult to classify the channel into meander and braid form or a single thread. Hence, the use of discharge, slope and sediment size is not helpful to classify the channel into such forms. Figure 2 represents the position of the mid-channel lines in 1978, 1990, 2001 and 2014. The circles in the figure are the channel reaches where the channel has meandered. In the reach, there are ten meander apexes that have differences in various geomorphic characteristics.

Seven physical as well as mathematical parameters have been taken into consideration for the study: channel inflection angle (ω), meander wavelength (λ), relative meander amplitude or Channel width ratio (*a/W*), relative bend-entry curvature (*a/W*), braid-channel ratio (*Bfd*), sinuosity (*P*), maximum asymmetry or magnitude of delayed inflection asymmetry (*z*). All these factors have been measured and calculated with respect to the mid-channel lines (Figure 3 & 4).

The channel inflection angle (ω) is not same at the different meander apexes. It ranges from 40° to 110°. Apex III and IX have the highest degree of inflection viz. 110 and 105, respectively. The lowest value of channel inflection is for the axis VIII. Table 1 indicates that meander wavelength of the meander apex has also varied. It is maximum for the axis VIII (46.5) and minimum for III (11.2 km). The wavelength is lowest in the case of the axis III, because of the sudden change in the flow of the river in the north-east direction near Kahalgaon. It is so, as even at the axis III the maximum inflection angle exists (Figure 2). However, there exists no relationship between the inflection angles and the meander wavelengths. The relationship between the relative bend- entry curvature or channel width ratio (*a/W*) and relative bend curvature (r_e/W) is very strong and positive (R^2=0.9323) (Figure 4).

The relationship between bend-entry curvature and meander wavelength is positive along with the positive relationship between relative bend curvature and meander wavelength (Figure 4). All z-values indicate whether the traverses are convex (>55) or concave (< 45), down-valley structure (Carson and Lapointe, 1983). The value in between 45 and 55 indicates more or less the symmetric form of the traverse. The meander apex III, VII and IX have experienced convex-down-valley form and I, IV, V, VI, VIII and X have concave down-valley form. Only meander apex II has a little symmetric form of the traverse. Thus about 50% of the channel reaches is under the concave down-valley traverse.

The braid-channel ratio and the channel sinuosity index are probably the most important factors for the analysis and understanding of river morphology especially for meandering-braided channels. The study reach is highly complex in the context of the formation of meander and braid. The analysis suggests that the study reach planform does not maintain the conventional rules of the channel pattern classification proposed by Leopold and Wolman,

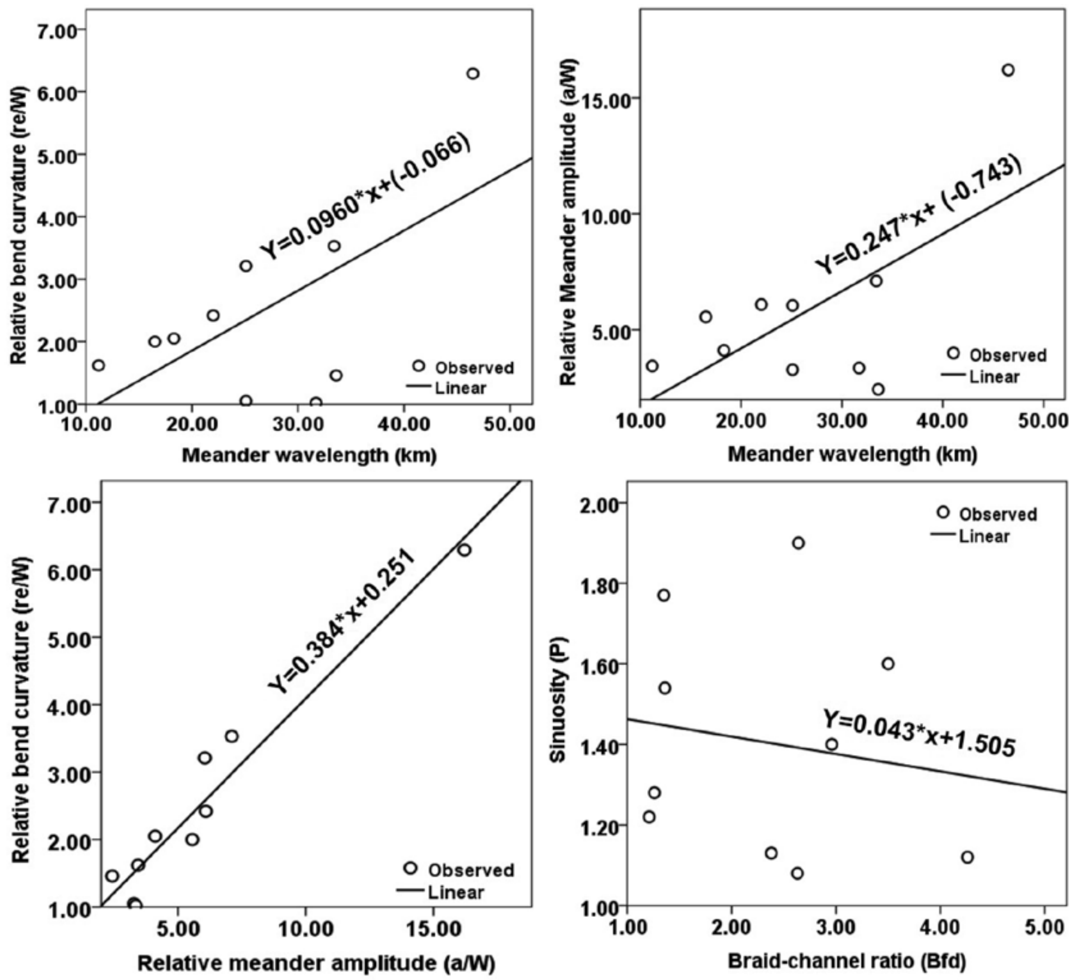

Figure 4. The four graphs indicate the linear relationships between a couple of variables viz. relative bend curvature and meander wavelength, relative meander amplitude and meander wavelength, relative bend curvature and relative meander amplitude & sinuosity and braid-channel ratio.

(1957).Visually it can easily be observed that the channel trough is tortuous and continuously flowing in a wave style. In the study reach, the channel's source is at Bhagalpur, where the trough is too broad because of point bars and channel bars. Then the channel trough narrows and becomes a single thread near Kahalgaon. After that the channel again becomes multi-threaded near Barari and maintains that pattern even beyond. There are six locations in the channel reach where the channel becomes multi-threaded. In between each two multi- threaded formations one can notice formation of a single thread. The study reach of the channel experiences meandering structure along with the single and multi-thread structure. It is mentioned earlier that significantly wherever the channel is braided the channel also meanders. The average sinuosity of the study reach is 1.48.The value is near to the threshold value of meandering (1.50 and more). In the study reach sinuosity ranges from 1.08 to 1.90 and braid-channel ratio ranges from 1.21 to 4.26. Hence, the channel in the study reach somewhere lies in between the sinuous-braided structure and the meander-braided structure. The apex III, IV, VIII, IX and X have both high channel sinuosity index and high braid-channel ratio. Another aspect is that both the sinuosity index and range of sinuosity are not very high compared to the braid-channel ratio and its range.

The result of planform geometry analysis of the study reach especially, the sinuosity index and braid channel ratio has a different scenario compared to earlier studies. The reason is that most of the former studies were based on temperate small to medium size rivers and the theories were largely developed based on the rivers with the temperate climatic condition. Hence, there is a huge difference in planform geometry of large tropical rivers and temperate rivers. In this study, statistically the relation between sinuosity and the braid-channel ratio is negative. However, the value is not significant (R^2=0.0249) (Figure 2). The planform structure of the rivers is controlled by many factors viz., underlying structural duality (the southern cratonic hard mass and the northern alluvial succession), discharge variability due to high seasonality in rainfall, yearly effect of flood events of different magnitude. This in turn makes the difference between the present study sinuosity index and braid-channel ratio theoretically approximate. The straightening in between the IX and X is due to the channel existence at the edge of Rajmahal Plateau on the right bank, the embankment construction near Farakka and the structural control on the channel trough due to two underlying faults of significant nature (the Rajmahal Fault and the Malda-Kishnaganj Fault) from Rajmahal to Jangipur. The other straight portion of the channel that lies in between the apex IV and V is probably controlled by underlying cratonic basement high that helps the channel to flow in the north-east direction.

CONCLUSIONS

There are numerous new models to explore the geometry of a channel; one or two dimensional models. But, it is difficult to fit either one or two dimensional models in case of large tropical rivers like Ganga because of its meander-braiding complexities. The study reach is highly ambiguous in terms of its meander-braiding pattern, which is shaped by underlying litho-structure, discharge variability and the construction of Farakka barrage. Present study is an attempt to understand the structural form of the channel in the reach with the help of some conventional methods that have been used herein. However, in order to explore the geometric properties of large tropical rivers, more scientific inquiries are needed. As significant monsoon variability is noticed due to global warming related ill effects, it is essential to monitor the entire stretch of Ganga River to take remedial measures to lessen any ill effects due to significant changes in the river morphology. Any artificial or natural obstructions along and across the river could result in flash floods affecting large number of villages and towns existing near the river banks.

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Compliance with Ethical Standards

The author declare that he has no conflict of interest and adhere to copyright norms.

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"It's coming home to roost over the next 50 years or so. It's not just climate change; it's sheer space, places to grow food for this enormous horde. Either we limit our population growth or the natural world will do it for us, and the natural world is doing it for us right now."

David Attenborough

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