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Meander Classification and Trend Analysis using Multi-Temporal Landsat Series Satellite Imagery

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ABSTRACT

The Rapti River and its tributaries are a small River, with a large number of meanders bent, changing their locations and sizes every year. Meanders are the result of erosion-deposition processes that occurred in River bends. Due to the centrifugal force brought by the bend, the winding current movement gives rise to high velocities that outward direction at the outer curve of the bend, and low velocities that perform in an inward direction. Because of the generated current components, the outer part of the bed piece, and the bank erosion, and the sediment deposit is closer to the bend interior. Migration of bed material and deposition affects sediment movement and imperils streams banks and cross sections security. The focus of this study is on the meander migration of alluvial channels, which results primarily from bank instabilities. The migration in meandering Rivers is a result of erosion at the outer bank combined with the equivalent sedimentation near the inner bank. In this paper multi-temporal, multi-spatial, and multi-spectral Landsat series satellite imageries from 1996 to 2020 have been used, which is provided by USGS. For trend analysis of meander bends, we have selected various meander bends within the Rapti River basin, while for meander classification, we have identified the nine type of meander patterns (A to G2) within the Rapti River basin. Rapti River at its initial formation have typically a low sinuosity (Si = 1.21 in 1996, reach-F), while the planform development increases the River valley length with a rather stable channel length resulting in a progressive increase of the River sinuosity, which was observed maximum in reach-E as 2.73 in 2020. We have established a very important relationship between meander patterns, sinuosity ration and bankfull River width.

Keywords: Meander classification, meander trend analysis, Rapti River, Landsat satellite imagery and GIS

1. INTRODUCTION

Meandering Rivers are one of the most widely studied systems on earth, although the knowledge on their actual dynamics is still limited, but these are most intriguing and highly dynamical processes. Basically, meander Rivers carve their shape into the floodplain by alternating processes of bank erosion and deposition respectively at the inner and at the outer banks. Riverine systems in which the centreline of the channel exhibits a curvilinear structure while flowing from upstream to downstream. The process of meandering occurs as freely evolving Rivers with curvilinear planforms wander through their floodplains, carving the landscape and reworking its sediments through the mechanisms of Riverbank erosion and accretion (Leopold et al., 1960; Edwards et al., 2002; Hooke 2003; Hooke et al., 2011). Large-scale sediment bedforms called bars usually develop at the inner banks of meander bends (point bars), gently connecting the floodplain with the Riverbed (Nanson et al., 1983; Legleiter et al., 2011; Kasvi et al., 2013).

Meanders are among the important features that can change the morphology of floodplains (Lagasse et al., 2004; Güneralp et al., 2009; Güneralp et al., 2012). The behavior of meander is related to serious issues for human existence, for example, obliterating inhabited and cultivated lands in the floodplain territories. River geomorphic properties are important factors for identifying environmental changes and are particularly associated with changes in River frontier and marginal areas (Dai et al., 2008). These morphological changes are attributed to changes in water and sediment load regimes due to climate, anthropogenic activities or LULC changes (Lagasse et al., 2004; Gordon et al., 2006; Cserkész-Nagy et al., 2010). Changes in the meander parameters can also be attributed to local management activities, as for instance the urbanization expansion, levees, riprap, dam, and road constructions (Nelson et al., 2013). In addition, meanders can naturally evolve and change shape over time even without human intervention (Brice 1960, Hooke 2013).

In the last four decades, several studies on meandering Rivers demonstrated that water flow in the meander bend from centrifugal force can cause an intensive increase in water depth and helicoidal flow in the outer arc (Blanckaert 2003; Frascati et al., 2010; Chen et al., 2012). Erosion and sedimentation processes have been observed at the front edge of the meander arcs (Frothingham et al., 2003; Rhoads et al., 2009; Riley et al., 2012). Bank erosion and channel migration can occur on different timescales i.e. hours, days, years, decades (Simon et al., 2002; Hooke 2004; De Rose et al., 2011; Michalková et al., 2011). In recent decades, there has been an emphasis on the economic, social, and environmental importance of River alteration and deformation i.e. narrow, wide, incision (Kondolf 1994; Allan 2004; Rinaldi et al., 2005; Boix-Fayos et al., 2007; James et al., 2013; Belletti et al., 2016). Related to the meander classification and trend analysis, many studies have been done by several researchers (Yang et al., 1999; Timár 2003; Chu et al., 2006; Wolfert et al., 2007; Ollero 2010; Hooke 2013; Nabegu 2014; Ashour et al., 2017; Bertalan et al., 2018; Pareta et al., 2019; Finotello et al., 2020). Several classification and models of meander change have been suggested, but most of these methods are empirical, derived from case studies (Brice 1982; Peixoto et al., 2009; Van De Wiel et al., 2011; Güneralp et al., 2012; Hooke 2013; Fuller et al., 2013; Pirot et al., 2014; Pareta et al., 2019). The main objective of this study is to analyze the meander morphology changes, meander classification and trend analysis of Rapti River, a major left bank tributary of the Ghaghara (Ganga) River. Comprehensively, multi-temporal Landsat series satellite imageries from 1996 to 2020 has been used.

Description of Study Area

Rapti River basin extends from 26°18′00′′ N to 28°33′06′′ N and 81°33′00′′ E to 83°45′06′′ E and covers an area of 25,793 Km^2 out of which 41% (10,642 Km^2) lies in Nepal and 59% (15,151 Km^2) in India. The Rapti River is the largest tributary of the Ghaghra River, which in turns is a major tributary of the Ganges River system. After flowing through the mountainous and steep path in Nepal region, it enters India at Holiya village and flows in Bahraich, Shrawasti, Balrampur, Siddharth Nagar, Sant Kabir Nagar, Gorakhpur and Deoria districts of eastern Uttar Pradesh before merging into the Ghaghra River at Kaparwaa ghat. The Rapti River basin is diverse in its physiography because Nepal part of the basin is completely mountainous and River flows in deep gorges, while the Indian part is relatively flat. For trend analysis of meander bends, we have selected various meander bends within the Rapti River basin, while for meander classification, we have identified the nine type of meander patterns (A to G2) within the Rapti River basin, which are situated at A - Bolua, B1 - Sukrooliya, B2 - Kakra Kalan, C - Andhra Purwa, D - Gosainpur, E - Shawagunj, F - Sahiapur, G1 - Gadrahia, and G2 - Bangarha Bugurg. The location map is shown in the Figure 1.

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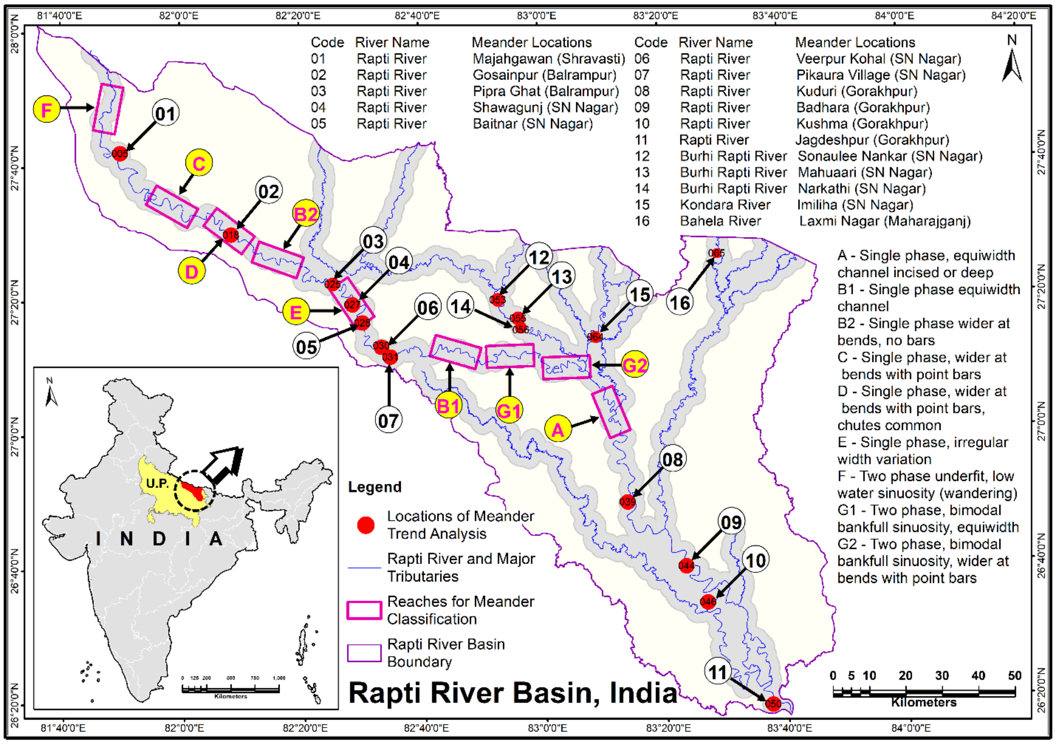

Figure 1. Location Map of Study Area

Data Used and Sources

Data used, and description of data sources are given in Table.

Table 1. Data Used and their Source Description

S.No.	Data Layers / Maps	Description of Data Sources
1.	Satellite Remote Sensing Data	Multi-temporal, multi-spatial, and multi-spectral satellite remote sensing data from 1996 to 2020 have been downloaded for entire Rapti River basin, India from U.S. Geological Survey (USGS), Earth Explorer. Source: http://earthexplorer.usgs.gov Landsat-5 TM: 1996 to 2000, 2002 to 2010; Landsat-7 ETM$^+$: 2001, 2011, 2012; Landsat-8 OLI: 2013 to 2020.
2.	Survey of India Topographic Map @ 1:50,000 Scale	Survey of India Toposheets, 2005 http://www.soinakshe.uk.gov.in/ Toposheet No.: 63E / 10, 14; 63I / 02, 03, 07, 08, 11, 12, 16; 63J / 09, 13, 14; 63M / 08, 12; 63N / 01, 02, 03, 05, 06, 07, 09, 10, 11, 14, and 15.
3.	Elevation Data	ALOS PALSAR (DEM) Data: Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) Digital Elevation Model (DEM) Data with 12.5 m spatial resolution Source: https://vertex.daac.asf.alaska.edu/ Acquisition Date: 02nd December 2007.
4.	Slope Map	Slope map has been prepared using Spatial Analyst Extension in ArcGIS 10.7, and ALOS PALSAR (DEM) Data with 12.5 m spatial resolution.
5.	Morphologically Active River Bankline Reaches	River bankline of Rapti River and its 17 major tributaries have been digitized in ArcGIS 10.7 software from 1996 to 2020. All banklines have been superimposed in one window to find the morphologically active River bankline reaches as shown in Figure 2.

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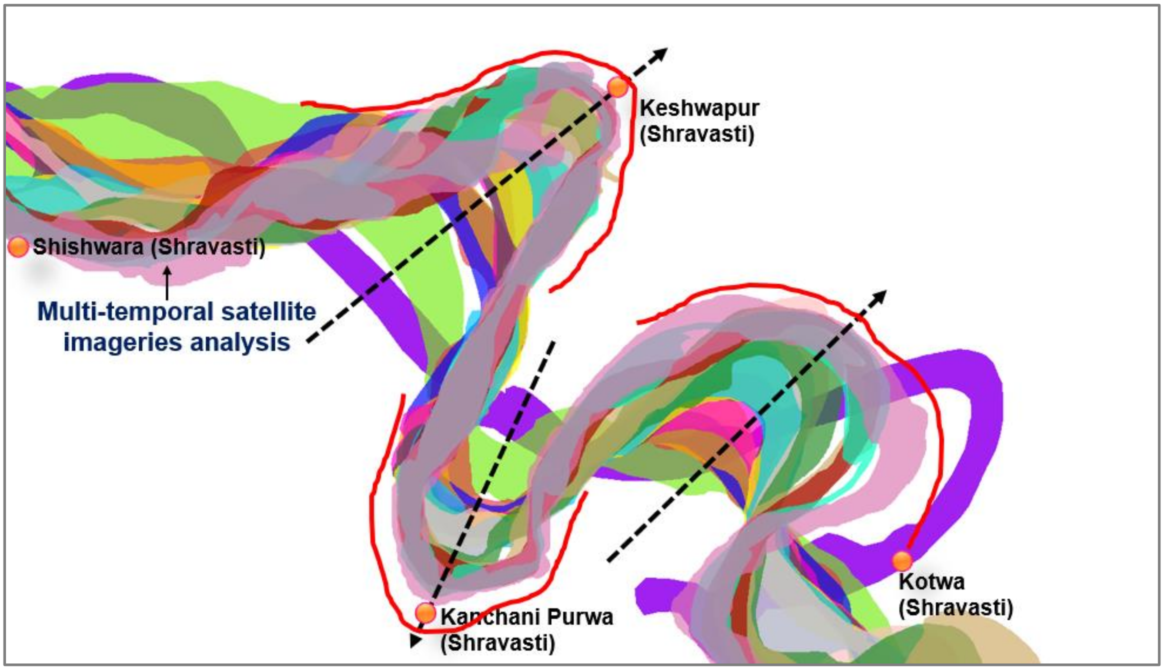

Figure 2. Multi-Temporal Satellite Imagery Analysis or extraction of Morphologically Active River Bankline Reaches

2. METHODS

GIS was used to identify the historical meander changes. Topographic maps with a scale of 1:50,000, which is a set of topographic maps of 2005, were combined to the Landsat series satellite imageries i.e. Landsat-5 TM (30 m), Landsat-7 ETM+ (30 m), and Landsat-8 OLI (30 m) have been used. As the study requires high accuracy, the validation of the geo-reference process was conducted before the digitalization process was carried out in this process to ensure total RMS error is minimized and adopted based on the scale used (Pareta et al., 2020). River bankline and River meander bends have been digitized at a similar scale by using ArcGIS 10.7 software on Survey of India toposheets of 2005 at 1:50,000 scale, and Landsat series satellite imageries (30 m spatial resolution) from 1996 to 2020, and store in geodatabase. These datasets were superimposed to detect reaches which registered changes. These changes were stored as new themes for the subsequent sinuosity and River width analysis. One of the advantages of using GIS is that highly accurate measurements between points can be obtained. It also provides a rapid and convenient technique to compare the datasets from 1996 to 2020.

Quantitative analysis then was undertaken in order to examine meander morphology changes, meander classification and trend analysis of Rapti River and its 17 tributaries. It involved determining and measuring the channel sinuosity which is the channel length over valley length. In this respect, sinuosity index is a key indicator to identify the stability of a River channel (Hooke et al., 1992; Rosgen 1994).

The process of sinuosity measurement involved measuring the valley length as a straight line drawn from the starting point to the end point of each sub-reach and the channel length which was a meandering line along the channel axis. The calculation of sinuosity index which was carried out using the database was analyzed through GIS and this formula: Sinuosity Index (SI) = Channel Length (CL) / Valley Length (VL).

3. RESULT AND DISCUSSION

Techniques of Meander Analysis

A Number of polarities in approach and methodology can be recognized in the strategies found in the literature. An important distinction is between those techniques in which a bend or loop as a whole is considered and those in which certain parameters of form or change are analyzed. The latter tend to be more highly quantified but do have limitations, particularly in analyzing changes. Another division is between techniques that use direct planning maps and that involve further processing to generate data, although varying degrees of processing are involved. A distinction in the data used that may profoundly affect the interpretation of the results, whether a full Meyer trace is analyzed, or a sample bend is selected (Hickin, 1977).

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Five major types of approaches that have been used in the literature are identified in Figure 3. The groups are not distinguishable, some can be classified as subsets of others and many have common starting points or finishing points. Of these five approaches, three are essentially techniques for the analysis of mender morphology (A-C) and it is from the comparison of results for courses of different dates that the changes are apparent. The other two approaches involve the examination of direct changes (D-E). The basic information required for all these techniques is a combination of plans for River courses at different dates. These can be obtained from older maps (Hooke, 1977), aerial photographs or other historical documents (Hooke et al., 1982), from evidence of the meander scrolls, vegetation and area of older channels and their associated deposits (Eardley, 1938; Everitt, 1968; Hickin, 1974), or from direct observations (Hooke, 1980).

Meander Classification

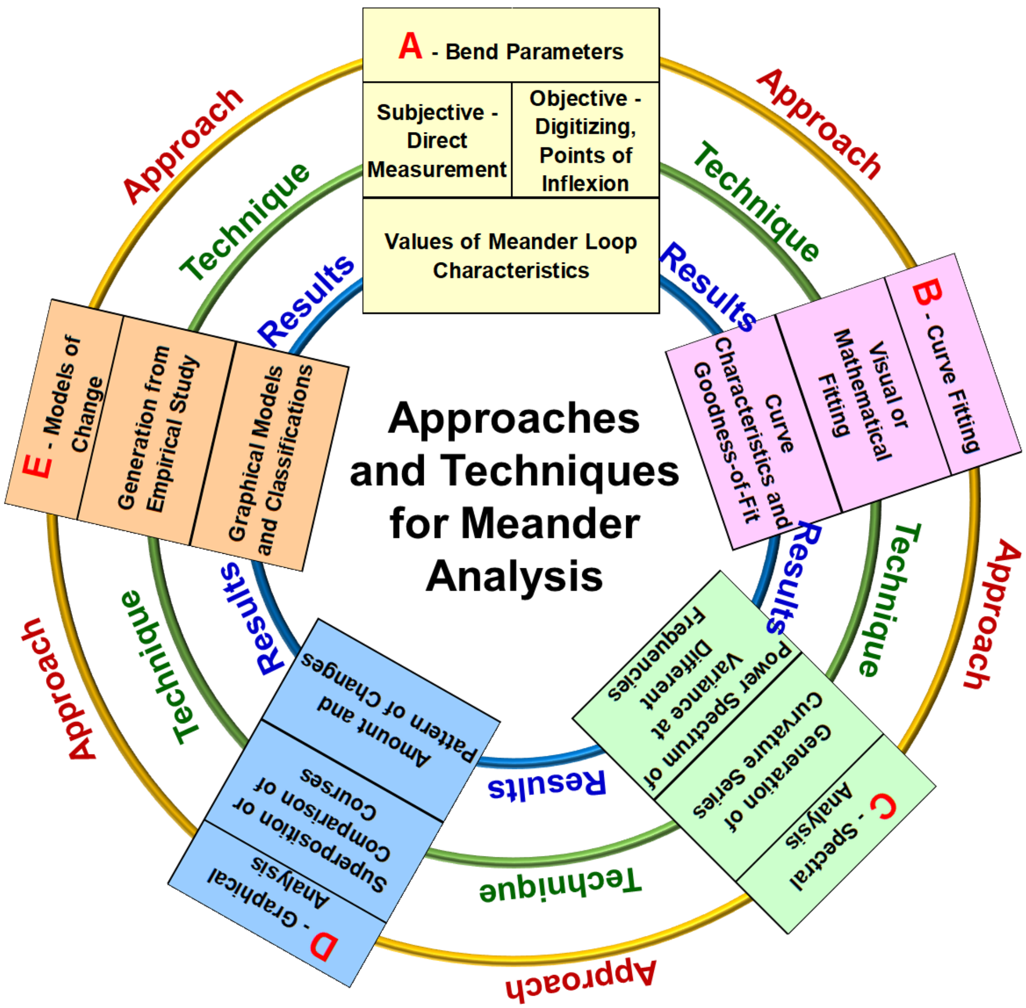

Figure 3. Approaches and Techniques for Meander Analysis

Researchers continue to mystery over the still elusive question of why Rivers meander in alluvium, but still there remains a common problem as to why the flow of any restricted Riverain should be meander. The idea is that there is a response to self-decomposed transverse oscillations against several types of theories of the mass of water flowing into water (Exner, 1921; Fujiyoshi, 1950; Anderson, 1967). Several researchers link meandering the sediment transport, stream loads, and orderly debris transfers between bank and flow (Matthes, 1941; Ackers et al., 1970; Hooke, 1975). These processes express an essential condition for meanderings, but one of those ideas has not yet predicted the meander scale. Meandering may be a response to River flow deviating to secondary flow (Thomson, 1876; Leliavsky, 1955; Tanner, 1960; Komura et al., 1967). Several researchers treat meandering as a stability problem (Reynolds, 1965; Callander, 1969; Engelund, 1971; Parker, 1976). Meandering is sometimes associated with the Coriolis force (Eakin, 1914). However, this may not be a necessary control, as Rivers have much more water in

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the equator as high latitudes. The possibility that wandering amplifies stream energy misfortunes has gotten little help (Jefferson, 1902; Inglis, 1949), however, its direct opposite, that meandering minimizes the misfortune and that wanders are in this manner the most probable form of a River, is for some persuasive (Chatley, 1940; Leopold et al., 1960; Langbein et al., 1966; Chang, 1979).

A number of researchers have classified the River meander based on their morphological process, and character of sinuosity (Brice, 1975; Schumm, 1977, 1981; Montgomery et al., 1997, Rosgen, 1994). The Rapti River system is a typical example of a meandering River. We have adopted the meander classification proposed by Brice (1975) with some modification i.e., modified Brice classification. It is mainly based on observational criteria and efficiently identifies the three degree of confinement that are commonly observed in meandering Rivers. He has been suggested nine type of meander pattern, which we have found in Rapti River system and shown in Figure 4. Future, we have analysed the bankfull River widths and sinuosity ratio of these selected nine River reaches.

We have investigated the temporal evolution of bankfull River width and sinuosity ratio of selected nine meandering patterns of Rapti Rivers through multi-temporal satellite remotely sensed data. The data is taken from the Landsat archive (https://earthexplorer.usgs.gov/) which provides multi-spectral information spanning roughly the last 25 years between 1996 and 2020 with a spatial resolution of 30 m. The analysis of the Landsat imagery is performed through the ArcGIS 10.7 software, which allows for the fully automated extraction of meandering River planforms from sets of temporally subsequent Landsat images. Cluster classification tool in Spatial Analyst of ArcGIS 10.7 software is able to define the local bankfull channel width by performing a binary cross-segmentation of vegetation, sediment, and water indexes from the multi-spectral datasets: banklines are located at the interface between vegetation and water or bare sediment, being the latter included within the channel body. We have measured the River width at 1 Km interval of each River reaches, and then taken an average of River width for these nine Rivers reach, which is shown in Figure 5 (a).

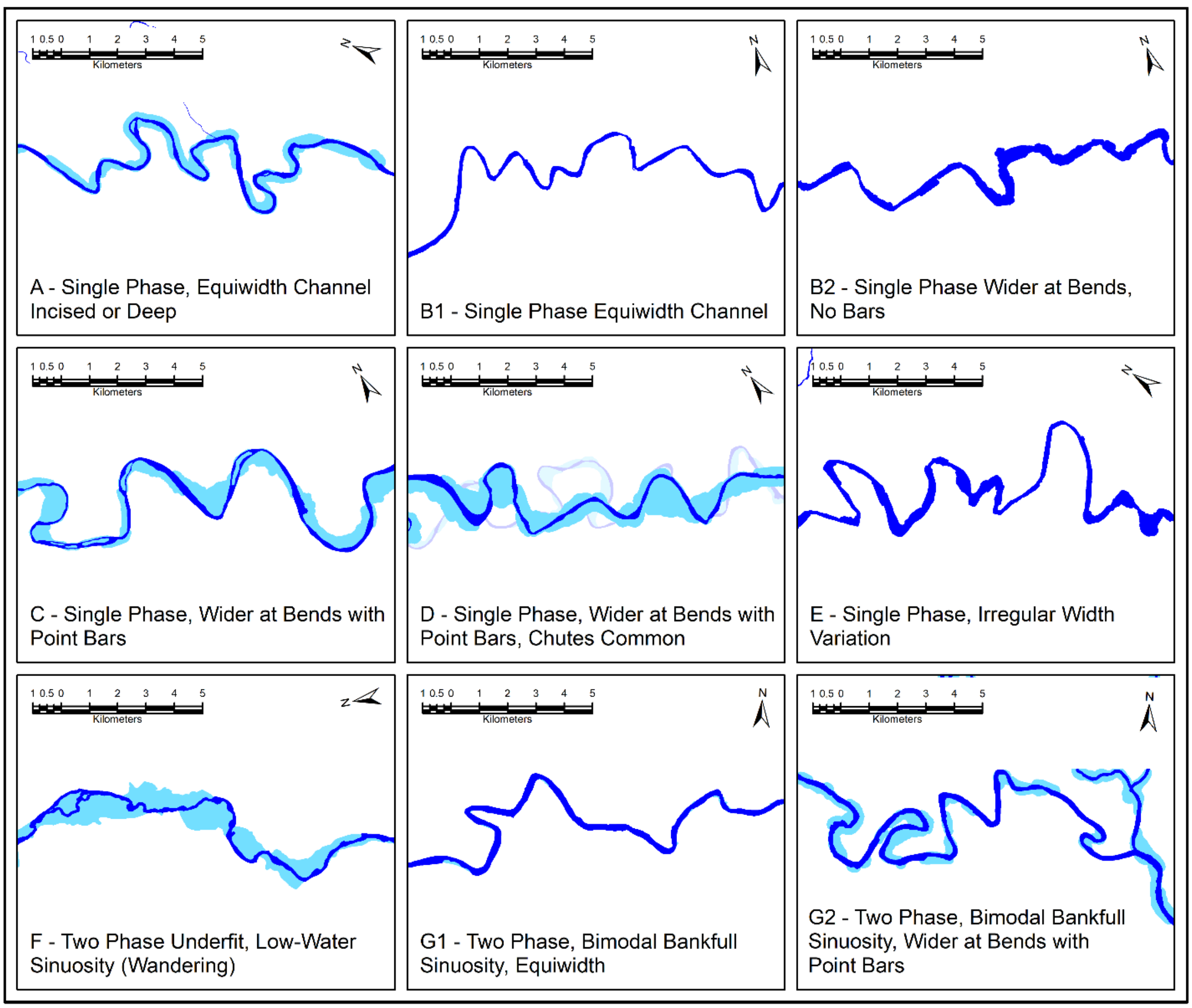

Figure 1. Modified Brice Classification for Rapti Meandering River

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Sinuosity is a quantitative index of River meandering and a distinctive property of River pattern. Among the variables involved in the geometry and dynamics of alluvial channels, sinuosity is functionally related to morphological, sedimentological, and hydraulic characteristics. Sinuosity has been used in practical, near, and verifiable examinations. River sinuosity, the ratio of channel length to valley length, refers to the sinuous path of a channel as shown in plain view. It is one of several variables involved in the geometry, dynamics, and dimensions of alluvial channels (Leopold et al., 1957; Schumm, 1977; Chorley et al., 1984) defined a meandering reach as one with a sinuosity of 1.5 or more noteworthy. For a straight River course this ratio is equal to unity. A proportion fluctuating from 1 to 1.5 characterizes the stream course as crooked and from 1.5 to 4 as meandering. Nine River reaches wise channel length and valley length from 1996 to 2020 has been measured using satellite remote sensing data and ArcGIS 10.7 software and generate the sinuosity ratio of these nine Rivers re ach, which is shown in Figure 5 (b).

Figure 5 (a) illustrates an example of evolution of bankfull River width of a meander River, and Figure 5 (b) provides a visual example of an evolving meander River increasing its sinuosity over time, except reach-E, ad reach-G2. Rapti River at its initial formation have typically a low sinuosity (Si = 1.21 in 1996, reach-F), while the planform development increases the River valley length with a rather stable channel length resulting in a progressive increase of the River sinuosity, which was observed maximum in reach-E as 2.73 in 2020. Reaches wise bankfull River width and sinuosity ratio have been analysed and found the below stated (Table 2) relationship between these two parameters.

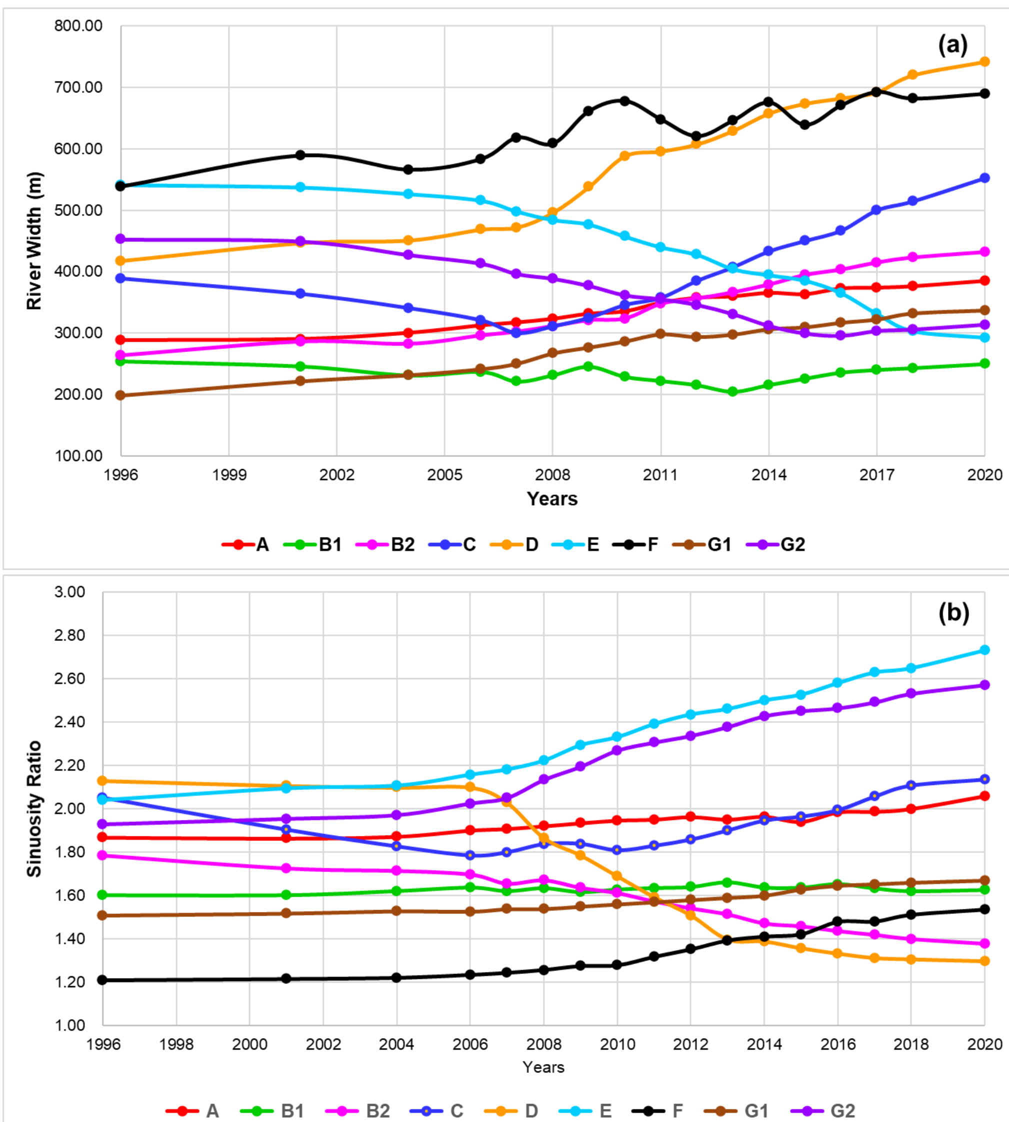

Figure 5. (a) Evolution of the average River width over the years, (b) Evolution of River Sinuosity Ratio Over the Years (1996-2020)

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Table 2. Relationship between bankfull River width and sinuosity ratio

S. No.	Modified Brice Classification for Rapti Meandering River	Bankfull River width		Sinuosity ratio	
		Width#	In/St/De*	Sinuosity#	In/St/De*
A	Single phase, equiwidth channel incised or deep	M	In	M	St
B_1	Single phase equiwidth channel	L	**St**	M	**St**
B_2	Single phase wider at bends, no bars	**L**	**In**	**H**	**De**
C	Single phase, wider at bends with point bars	M	**In**	H	**In**
D	Single phase, wider at bends with point bars, chutes common	M->**H**	**In**	H->**L**	**De**
E	Single phase, irregular width variation	H->**L**	**De**	**H**	**In**
F	Two phase underfit, low water sinuosity (wandering)	**H**	**In**	**L**	**In**
G_1	Two phase, bimodal bankfull sinuosity, equiwidth	L->M	**St**	L	**St**
G_2	Two phase, bimodal bankfull sinuosity, wider at bends with point bars	M->**L**	**De**	**H**	**In**

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

According to Brice (1982), it should be possible to identify stable meander by their width characteristics, which we have seen in equiwidth channel especially in reach-B_1 and G_1. The majority of actively migrating channels exhibit spatial bankfull River width variation. River reaches that are systematically wider at bends apexes (where curvature is highest) tend to exhibit the highest migration rates. They also identify another class of Rivers for which bankfull River width variation is uncorrelated with curvature, and migration rates are low (Brice, 1982; and Lagasse et al., 2004). On the basis of the observations of nine reaches of Rapti River, we are suggesting the following: meandering Rivers may evolve so as to (i) have little systematic width variation, (ii) show apexes that are slightly narrower than crossings or (iii) show apexes that are slightly to significantly wider than crossings. Case (iii) appears to be most common in Rivers that show significant rates of migration (Lagasse et al., 2004).

We have also observed that, the bankfull River width maximum is located specially in downstream of bend apex, while the percentage of bends for which the width minimum is located upstream of the bend apex, but this behaviour is not universal is illustrated in Figure 5 (a). We have observed the direct correlation between River width and sinuosity ratio, which if River width increased, the sinuosity ratio is decreased, and the same in inverse also (refer to reach-B2, D, E, and G2, Table 2). Sinuosity increments when, inside a channel twist, the bank at the external curve dissolves quicker than at the inward twist. Alluvial wander hypothesis relates this lop-sidedness in parallel disintegration to hydrodynamics. Although channel narrowing is observed, especially in reach-D, the channel continues to develop sinuosity until incipient neck cutoff.

Meander Trend Analysis

GIS techniques (spatial-temporal analysis of satellite imageries), using advanced remote sensing data over the last 20 years, have been used to identify changes in the River course (both River and tributary channels) and further computation has analysed River shifting and bank erosion. The multi-temporal remote sensing data were individually processed and analysed in a GIS environment for pre-monsoon. Delineation of River course and identification of deposits were digitized into shapefiles. By overlaying this database locations of bankline shifting of Rapti River and tributaries have been identified. The shifted parts of the River are mapped by vectorisations in GIS. The change is detected by superimposing various data sources by mapping calculations. Quantitative data generation and thematic maps have been produced outlining hot spots of high bank erosion at meander. Where the curvature of a River is higher, often there is a higher bank erosion of fertile soil due to active water forces (water velocity is higher). Low vegetation cover increases erosion rates on curvature of bank. Human activities including dredging, agriculture and deforestation may contribute to bank erosion and bankline shifting.

The trends of channel migration have been established by comparing satellite images from 1996 to 2020. The approach is based on geospatial analysis of bankline changes along the River. The bank line shifts are digitized manually using Landsat-5, Landsat-7, LISS-III and Landsat-8 satellite images for the respective years. Examination of the bankline shifts of Rapti River and its tributaries have been carried out into several reaches. Bankline shifting trends for various meander reaches have been measured by using the cumulative River bankline shift data and given in Table 3. Meander trend analysis maps of various reaches is shown in Figure 6.

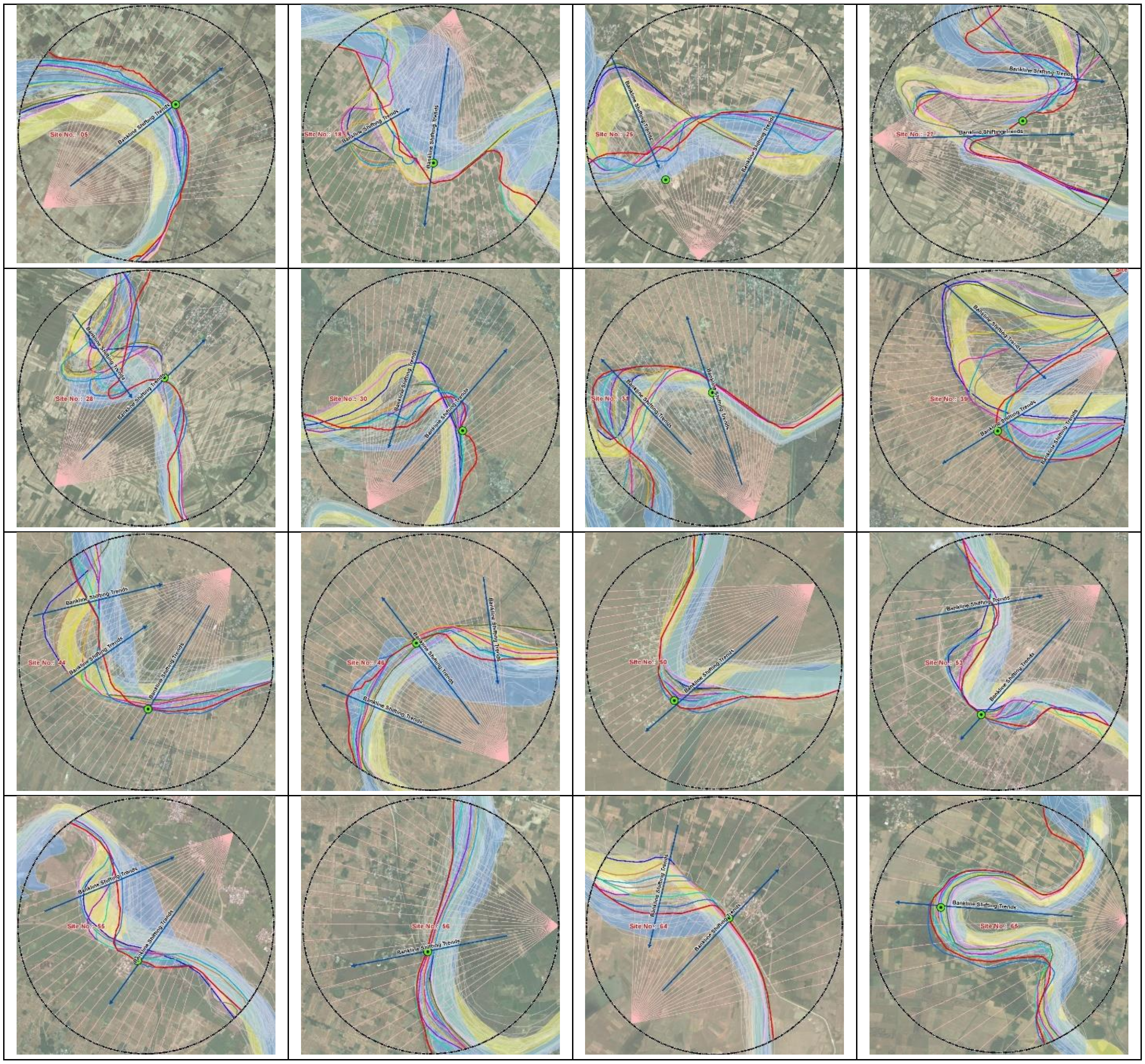

Figure 6. Meander Trend Analysis Map (1996-2020)

Table 1. Meander Trends Analysis (1996-2020)

S. No.	River Name	Meander Locations	Bankline	Bankline Shifting Trends
1	Rapti River	Majahgawan (Shravasti)	Left Bank	Left Bank Moving to Left Direction
2	Rapti River	Gosainpur (Balrampur)	Right Bank	Right Bank Moving to Right Direction
3	Rapti River	Pipra Ghat (Balrampur)	Left Bank	Left Bank Moving to Right Direction
4	Rapti River	Shawagunj (SN Nagar)	Left Bank	Left Bank Moving to Right Direction
5	Rapti River	Baitnar (SN Nagar)	Left Bank	Left Bank Moving to Left Direction
6	Rapti River	Veerpur Kohal (SN Nagar)	Left Bank	Left Bank Moving to Left Direction
7	Rapti River	Pikaura Village (SN Nagar)	Left Bank	Left Bank Moving to Left Direction
8	Rapti River	Kuduri (Gorakhpur)	Right Bank	Right Bank Moving to Right Direction
9	Rapti River	Badhara (Gorakhpur)	Right Bank	Right Bank Moving to Right Direction
10	Rapti River	Kushma (Gorakhpur)	Right Bank	Right Bank Moving to Right Direction
11	Rapti River	Jagdeshpur (Gorakhpur)	Right Bank	Right Bank Moving to Right Direction
12	Burhi Rapti River	Sonaulee Nankar (SN Nagar)	Right Bank	Right Bank Moving to Right Direction
13	Burhi Rapti River	Mahuaari (SN Nagar)	Right Bank	Right Bank Moving to Right Direction

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S. No.	River Name	Meander Locations	Bankline	Bankline Shifting Trends
14	Burhi Rapti River	Narkathi (SN Nagar)	Right Bank	Right Bank Moving to Right Direction
15	Kondara River	Imiliha (SN Nagar)	Left Bank	Left Bank Moving to Left Direction
16	Bahela River	Laxmi Nagar (Maharajganj)	Right Bank	Right Bank Moving to Right Direction

Causes of Meander Migration

To completely comprehend an issue, it is imperative to know the reason for the issue. In this case, migration is the problem, which occurs as a result of channel instability. For this study, instability is defined as movement in the channel bed and/or banks. Bed instability results from channel aggradation or degradation, leading to a vertical adjustment. Bank instability results from the removal of bank material through grain-by-grain detachment or mass wasting, leading to a width adjustment. Bed and bank instabilities are linked because one can cause or be the result of the other. An example of this would be if a channel had stable banks but was incising through bed degradation, increasing the bank heights to a point exceeding the critical height, where bank sloughing or bank collapse occurs.

The focus of this study is on the meander migration of alluvial channels, which results primarily from bank instabilities. In describing the process of meander migration Julien (2002) states that migration in meandering Rivers is a result of erosion at the outer bank combined with the equivalent sedimentation near the inner bank. In alluvial River systems, it is the rule rather than the exception that banks will erode (Richardson et al., 2001). The eroded bank material is transported downstream to the next point bar, where outer bank erosion is usually balanced by bar deposition and advance.

There are two main groups of bank erosion processes; these include hydraulic action and mass failure (also known as mass wasting). Hydraulic action is commonly associated with high velocity against the bank, particularly along the outside of a bend. The linkage between these two processes is referred to as basal endpoint control (Schumm et al., 1984). This is where the toe of the slope controls the stability of the bank. There are many causes of bank failures, some of which include:

- Parallel flow - stream velocity / shear stress removes granular bank material, causing grain-by-grain detachment of bank particles. This can lead to undercutting of the bank, resulting in a cantilever failure.
- Concentrated or impinging flow - flow occurs at an angle to the bank because of obstructions, debris, or bar formations. Turbulence, velocity, shear stress, and 3-D effects such as bursts and plunges remove bank material. This delivers a more noteworthy impact than that of parallel flow.
- Fluctuating water levels - a quick draw down leaves banks saturated where the weight, lubrication of failure planes, piping, or a combination thereof causes failure.
- Over steepening of bank - bank angle greater than cohesive properties of soil.
- Rilling and gullying - uncontrolled channelized runoff from overbank areas.
- Sheet erosion - unchannelized surface runoff.
- Piping and seepage - flow through the soil may transport soil particles through the bank surface, leaving a void in the bank material. This leads to cave-ins.
- Wave induced failure - erosion generated by vessel forces.
- Animals and humans - grazing, disturbance of riparian vegetation, burrowing may lead to piping.

4. CONCLUSION

Remote sensing and GIS techniques have been utilized genuinely in this study. The free Landsat series satellite imageries from 1996 to 2020 provided by USGS is now used all over the world. With this type of satellite imagery, we can generate and analyze the time series data of the last 50 years (1972-2021). We have been selected various River segments / reaches within the Rapti River system for several type of studies i.e. meander classification, and meander trend analysis in this paper using Landsat satellite imagery from 1996 to 2020. We have classified the meander River Rapti into 9 different type of meander pattern (i.e. A-Single phase, equiwidth channel incised or deep; B1-Single phase equiwidth channel; B2-Single phase wider at bends, no bars; C-Single phase, wider at bends with point bars; D-Single phase, wider at bends with point bars, chutes common; E-Single phase, irregular width variation; F-Two phase underfit, low water sinuosity (wandering); G1-Two phase, bimodal bankfull sinuosity, equiwidth; and G2-Two phase, bimodal bankfull sinuosity, wider at bends with point bars) based on their morphological process, and character of sinuosity. A detailed analysis has done of bankfull River width and sinuosity ratio for these 9-meander pattern, and some important relationship has been established. We have also done the meander trends analysis at 16 meander loops.

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Conflict of Interest:

The authors declare that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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