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Integrating geospatial techniques and field survey to assess the changing nature of meander movements and meander geometry of Raidak-I River in the Himalayan foothills, West Bengal

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Abstract. Channel migration and resultant meander movements are the two important fluvial processes found in the riparian environment of a river basin. The present research explores the changing nature of the meander movements and meander geometry of the Raidak-I River in the Himalayan foothill region using geospatial tools. The study incorporated Landsat data (satellite imageries) for the years 1972, 1980, 1988, 2004, 2012 and 2021 and the whole study has been segmented into five periods i.e., 1972–1980, 1980–1988, 1988–2004, 2004–2012 and 2012–2021 to examine which type of meander movement dominates in the Raidak-I River within a particular time frame and how the nature of the meander movements is being changed over time. Bank lines of different periods have been superimposed with the help of the overlay analysis method in ArcGIS software (Version 10.8) to obtain the results. Furthermore, Arc-Extension tools have also been used to measure the meander geometry. Twelve active river bends have been identified to study meander geometry of sinuosity indices, meander length, meander width, meander-ratio, channel width and radius of curvature from 1972 to 2021. Initially, lateral movements predominated but, in the late-stage, rotational movement became much more prominent, which indicates dynamicity of the river channel in recent time. The cross-sectional study revealed that a convex bank has frequently been replaced with a concave bank and vice versa. The study finds human intervention – especially the construction of embankments – is the main reason behind such meander dynamics. The method we have used here is very simple, and thus can be considered for any part of the world and is very beneficial for identifying suitable sites for embankment construction, river restoration and channel management.

Key words:
meander geometry,
meander movement,
embankment,
Raidak-I River

Introduction

River meanders are amongst the most common (Howard 1992) and most dynamic fluvial features (Hooke 2007) and display progressive changes in the location of the river channel because of their migration over the floodplain (Hickin and Nanson 1984; Hooke 1984). Natural rivers experience a meandering process that produces a non-uniform planform pattern in the form of a series of bends (Mohamad et al. 2015). The meandering process usually entails channel instability, where slight perturbation results in erosion and deposition, which leads to lateral migration of the river channel (Odgaard and Abad 2008). The planform dynamics of meandering rivers have produced significant interest in fluvial geomorphology (Hickin and Nanson 1975; Hooke 1984; Furbish 1991). These studies include the intriguing complexity of planform changes, the spatial extent of channel changes, floodplain development through channel migration and the socio-economic impact of river channel migration and bank erosion (Hooke 1995). Meander migration is one of the simplest processes of river mechanism. It involves flowing water being directed towards the outer bank by centrifugal forces, leading erosion on the outer bank and the transportation of eroded sediment towards the inner bank (Gilvear et al. 2000). There are various types of meander movements. Some are primary and some may be the result of up-and-down movement of primary movements, i.e. one- or two-directional, increase or decrease, and right or left (Kotoky and Dutta 2015). According to Hooke (1980), translation, rotation and extension were simple meander bend development models, though he suggested nine types of meander movements. The technical explanation of a meander in a river course is called "meander geometry", which is characterised as an uneven waveform (Deb et al. 2012). Meander geometry includes sinuosity, meander length, meander width, meander ratio, channel width, the radius of curvature, and other parameters. Himalayan Rivers are characterised by varying discharges and sediment loads, shifting of river courses, polishing of bed and banks, and large-scale deposition of sediments (Kale 2002; Dhali et al., 2020). Ahmed (1969), Dutta (1980), Naik and Sing (1996), Goswami et al. (1999), Bezbaruah et al. (2003), Kotoky et al. (2012), Dey and Mandal (2018), Pati et al. (2019), Dhali et al. (2020), Hasanuzzaman et al. (2021) and Maya et al. (2022) have analysed various aspects of fluvial geomorphology in India, including meander development, meander movements, bank line shifting, river instability and others.

The current research deals with the meander movements of the Raidak-I River, which is a right-bank tributary of the Brahmaputra River. In recent time, remote-sensing (RS) and a geographic information system (GIS) comprise an efficient and significant tool for mapping and analysing channel-course change at reach scale (Winterbottom 2000). Moreover, the application of GIS provides not only a spatial dimension to morphometry, but also helps to understand the difference between quantitative morphometric parameters (Thomas et al. 2012). Consequently, it is very helpful in dealing with the changing detection of rivers in India (Pal et al. 2016).

The study has mainly focused on various types of meander movements of the Raidak-I River, and how these movements have changed in the last 49 years, which has still not been studied. The study also explores parameters of meander geometry of the active meander bend using geospatial and field-based cross-sectional data, which fill a gap in the existing research in the Himalayan foothills.

Materials and methods

Study area

An 81.9-km river stretch of the Raidak-I River is selected for the present study. This river is a branch of the Raidak River that originates in the Himalayas and eventually meets the Brahmaputra River in Bangladesh. The Raidak-I falls under two districts of West Bengal, i.e. Cooch Behar and New Alipurduar. The latitudinal and longitudinal extension of the study area is 26º34´30.18´´N to 26º12´57.58´´N and 89º43´12.12´´E to 89º41´38´´E (Fig. 1). The total catchment area of the river up to Tufanganj is about 635 km². The Raidak River is the main right-bank tributary of the Brahmaputra River. This river is a trans-boundary river and flows through the countries of India, Bhutan and Bangladesh (Hasanuzzaman and Mandal 2020). The Raidak is a combination of three courses: the middle part is known as old Raidak, the western flow is named Raidak-I or Dipa Raidak; and the eastern part is named Raidak-II. The river Raidak-I or Dipa Raidak flows through Alipurduar District and enters Tufanganj Subdivision in Cooch Behar District. The river flows through the villages of Balabhut, Bansraja, Debogram, Dhalpal, Rajarkuthi, Shalbari, Dwiparpar, Andaranfulbari, Nakkatigachh, Kamatfulbari and Chamta of Tufanganj Block I and enters Bangladesh, to finally meet the Brahmaputra River.

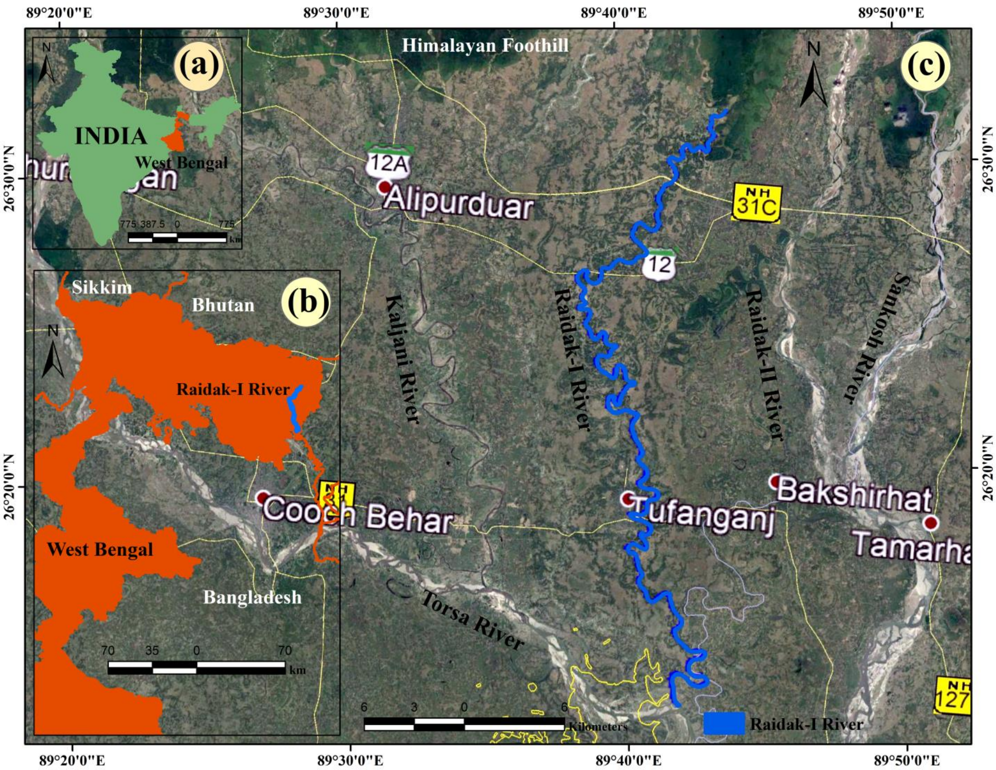

Fig. 1. Location of study area

The foothills region of an active orogenic belt such as the Himalayas is characterized by active faults and complex alluvial morphology with fluvial erosion and deposition (Burbank and Anderson 2001). These rivers brought immense loads from the Himalayas in the form of boulders, gravels, sand and silt, and deposited the coarser ones at the foothills in the extreme north due to the lesser slopes there (Starkel et al. 2008); meanwhile, finer particles accreted in the south to form and shape their wide, flat and almost monotonous floodplains that are subjected to inundation – even multiple times in a single monsoon season – thus hampering the livelihoods of the floodplain dwellers (Bastawesy et al. 2013).

Database and methods

The data sets used in the study includes Landsat-1 MSS images of the years 1972 and 1980, Landsat-5 TM images of the years 1988, 1996, 2004 and 2012, and a Landsat-8 OLI image of 2021. The datasets used in this study are collected from the official website of the United States Geological Survey (USGS) (http://landsate.usgs.gov/). The resolutions of the concerned data sets are not equal. MSS images of 1972 and 1980 have 60×60-metre resolution, while the rest of the datasets of TM and OLI images are of 30×30-metre resolution. Thus, those images are generally collected for the months of February–April to achieve better results. The study periods have been divided into six phases, 1972–1980 (8 years), 1980–1988 (8 years), 1988–1996 (8 years), 1996–2004 (8 years), 2004–2012 (8 years), and 2012–2021 (9 years) for better analysis and interpretation. To validate the results, a cross-sectional study was made with the necessary accessories.

ArcGIS software (version 10.8) was used to digitise the Raidak-I River of different time periods. The superimposed bank lines of successive years reveal meander movements and their changes through time. The study classified eight types of meander movements for understanding the dynamic nature of the meander following Brice (1974) and Hook (1977). These are (1) Lateral movement, (2) Translation, (3) Extension, (4) Rotation, (5)

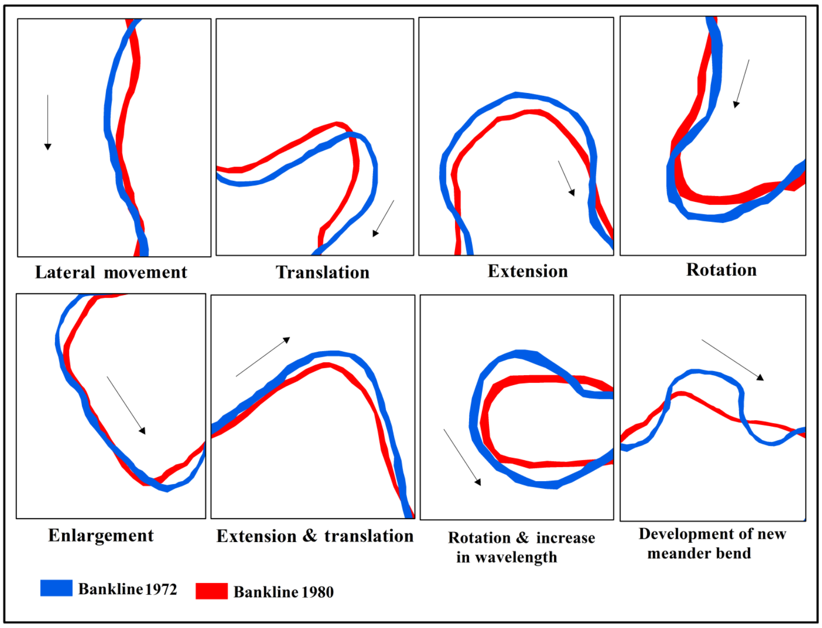

Fig. 2. Schematic diagram of different meander movement types

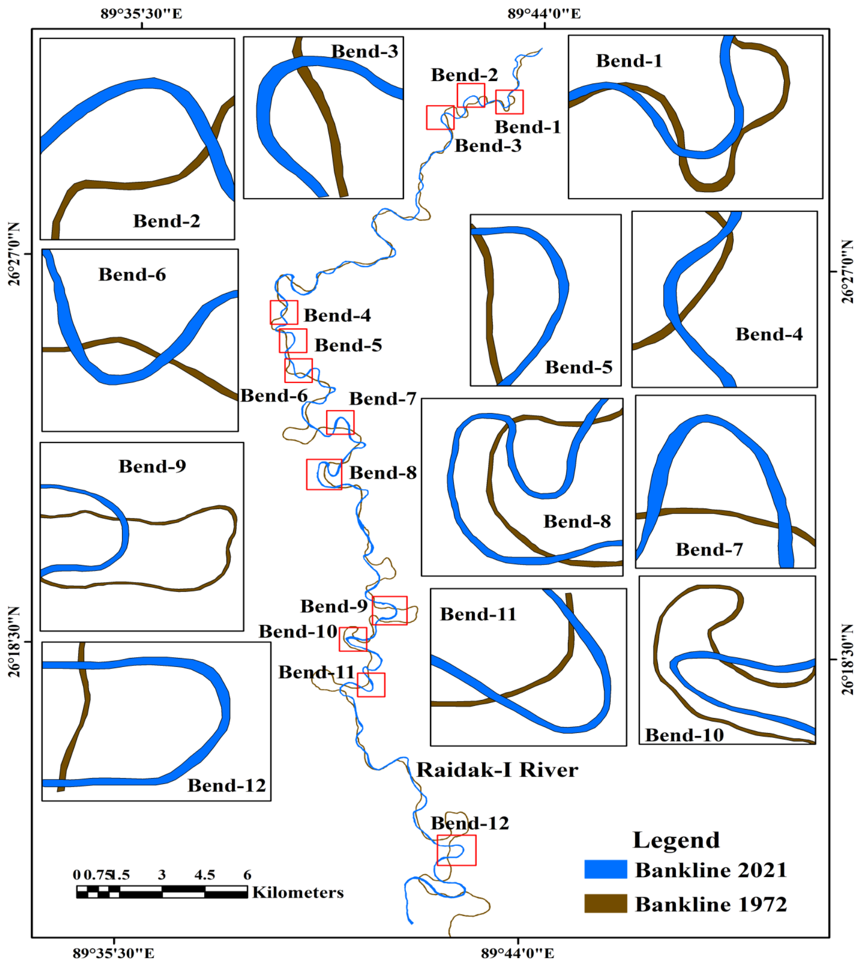

Fig. 3. Location of the 12 selected bends of the Raidak-I River

Enlargement, (6) Extension and Translation, (7) Rotation and increased length and (8) Development of new meander bends (Fig. 2). To assess the meander geometry, 12 river channel bends were considered, being selected based on differences in dynamicity (Fig. 3). Furthermore, 12 cross-sectional studies were made at the selected 12 bends. Cross-sections were made at the middle part of each bend (Fig. 3). The location of bend apex, actual length, axial or straight length, sinuosity, radius of curvature, meander ratio and channel widths were estimated using River Bathymetry tools in ArcGis platform. In addition, distances of movement of the bank line, specifically maximum, minimum and apex movement, were measured directly for each bend using ArcGIS 10.8.

The parameters of meander geometry include sinuosity, meander wavelength, meander width, channel width, radius of curvature and meander ratio. The sinuosity of the river is defined as the ratio between the valley length and the length of the channel. Schumm (1963) opined that there is a close relationship between channel pattern and sinuosity. The distance between two consecutive concave banks on the same side of a channel is called "meander wavelength", while the distance between two consecutive concave banks in a direction transverse to meander wavelength is called "meander width". Meander ratio is the ratio of meander width to meander length, where the channel width is measured on the basis of the surface width of the channel. This dimension can be determined as the crossover between two bends. In contrast to sine waves, the loops of a meandering stream are nearly circular. The radius of a loop is considered to be the straight line perpendicular to the down-valley axis intersecting the sinuous axis at apex. The curvature was measured by digitising the centerline for every year of the channel. The

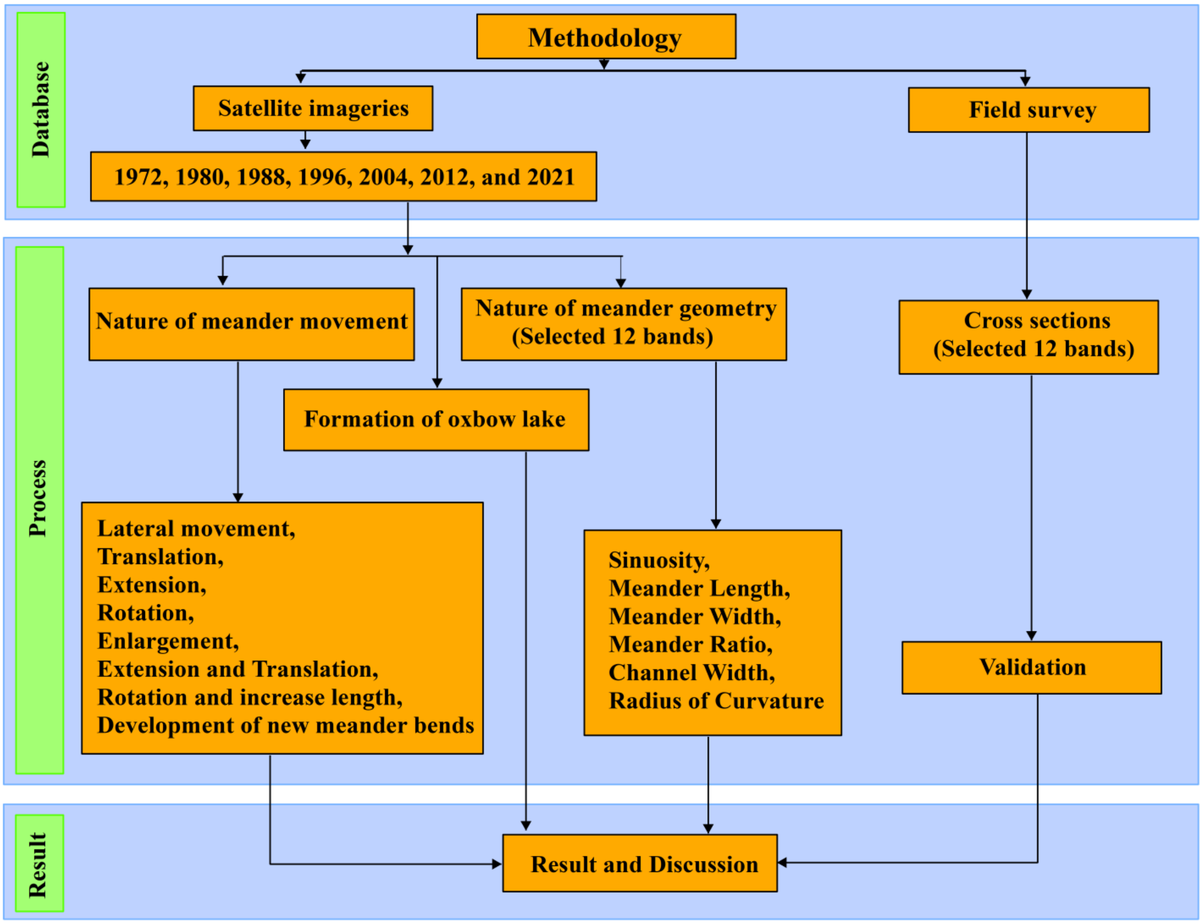

Fig. 4. Conceptual framework of study methodology

conceptual framework of the method applied in this present study is depicted in Figure 4.

Results and discussion

Nature of meander movements

The Raidak-I is a significant right-bank tributary of the Brahmaputra River. The river represents high dynamics and meandering. Meandering assigns fundamental characteristics of discharge or velocity of the river, erodibility of the riverbanks, size and shape of the channel, and the ratio of suspended to bed loads of the rivers. The meandering increases the channel length between two points and thus the slope of the channel is decreased. The resultant slope therefore controls the river velocity and sediment transporting capacity (Kotoky and Dutta 2015). Hooke (1977) presented nine such types of meander movements. Out of nine, eight types of meander movements can be considered for the Raidak-I River, i.e. (1) Lateral movement,

Table 1. Meander movement in Raidak-I River in the study period 1972–2021

Types	1972–1980	1980–1988	1988–1996	1996–2004	2004–2012	2012–2021
Lateral movement	54	41	16	29	17	4
Translation	3	1	4	5	3	1
Extension	18	16	12	15	5	5
Rotation	2	1	4	4	8	15
Enlargement	1	1	0	2	3	0
Extension and translation	2	3	2	1	2	0
Rotation & increasing length	2	4	6	3	2	0
Development of new meander bend	1	4	2	4	3	1
Total	83	71	46	63	43	26

Source: own elaboration

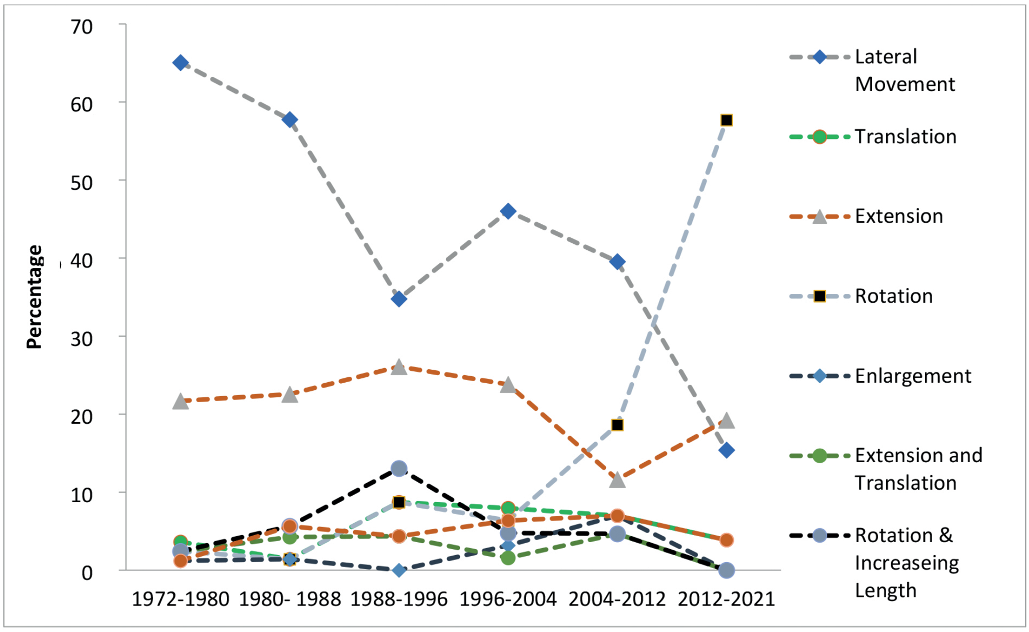

Fig. 5. The changing nature of meander movements during the study period

(2) Translation, (3) Extension, (4) Rotation, (5) Enlargement, (6) Extension and Translation, (7) Rotation and increased length and (8) Development of new meander bends (Fig. 3).

The highest number of meander movements (83) was recorded for 1972–1980 and 1980–1988, which experienced 71 meander movements (Table 1). The fewest (26) movements were found in recent years (2012–2021). After 2000, an embankment was constructed along the banks of the river. Thus, the numbers of meander movements have decreased significantly. Out of eight movements, lateral movement is the most common, followed by extension and rotation. The descending order of those movements is: lateral movement (48.49%) > extension (21.39%) > rotation (10.24%) > translation and rotation &increasing length (5.12%) > development of new meander bend (4.25%) > extension and translation (3.01%) > enlargement (2.11%) (Figs. 4 and 5).

As time proceeds, lateral movements decrease significantly, and rotation increases rapidly after 2004 and dominates over other movements; thus, with time, the Raidak-I River has significantly

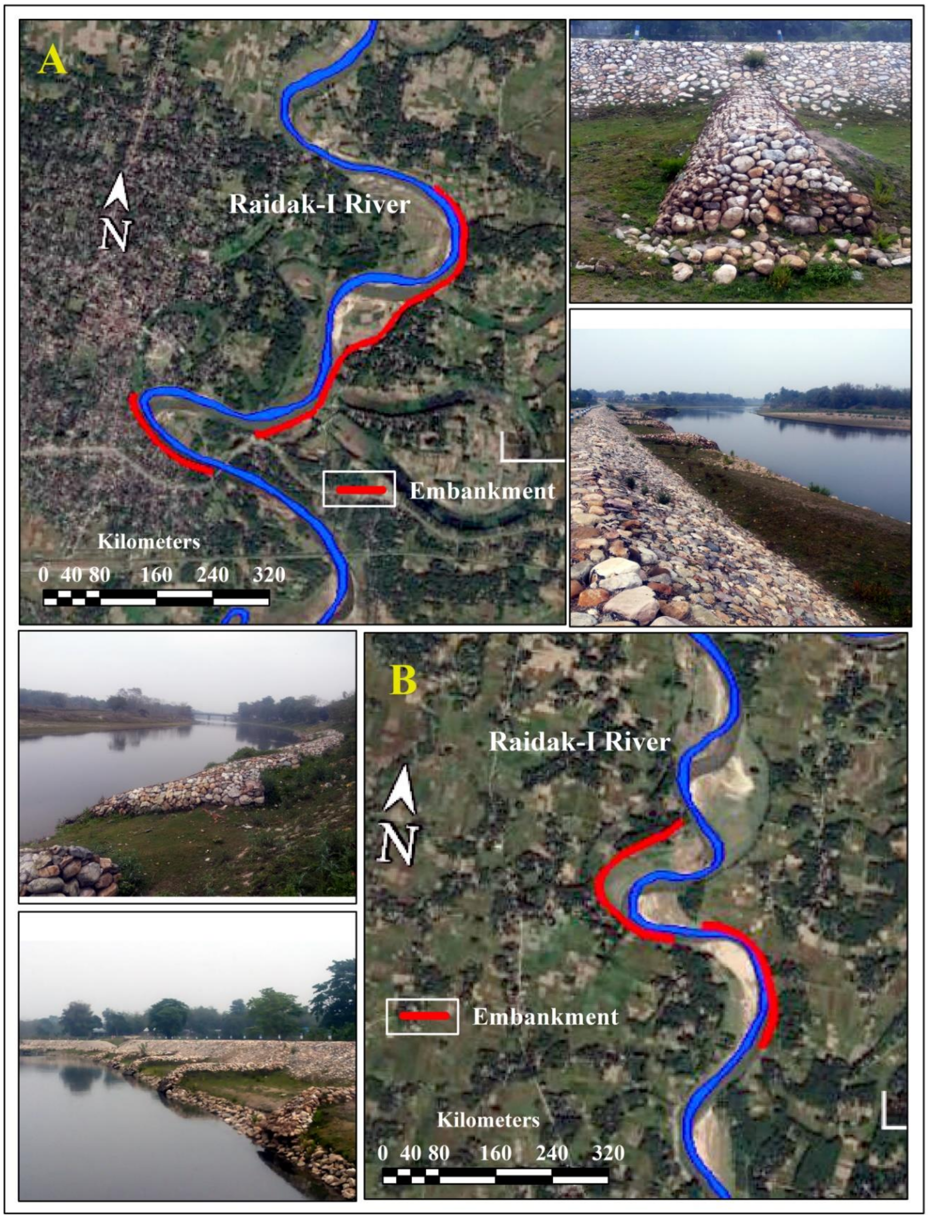

Fig. 6. Embankment along Raidak-I River

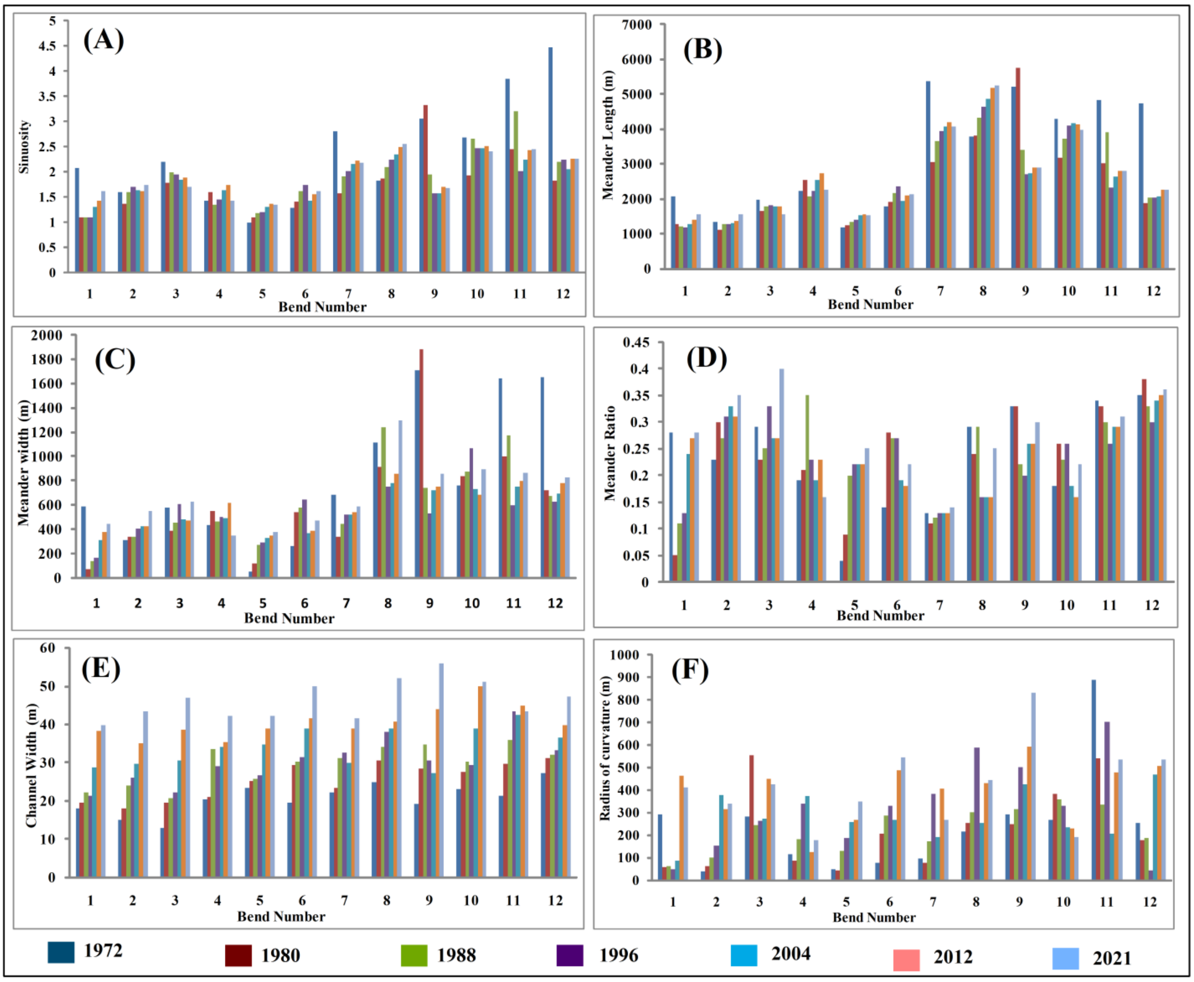

Fig. 7. Variation in geometric parameters of 12 selected bends, (A) Sinuosity, (B) Meander Length, (C) Meander Width, (D) Meander Ratio, (E)Channel Width, (F) Radius of Curvature

changed its meanders. Initially, lateral movements and extension dominated the movements in the stipulated time periods, but, in the later stage, these have been replaced by rotation and extension. Moreover, other meander movements have also decreased in the later stage. Construction of embankments is the determining factor, because the river cannot shift laterally after their construction, but its channel can rotate (Fig. 6).

Changing nature of meander geometry of Raidak-I River

The range of sinuosity at various bends of the Raidak-I River varies from 1.1 to 4.48. Among the bends, bend 12 displays the highest sinuosity ranges (from 1.83 to 4.48) within the study periods. Conversely, the lowest sinuosity is found at bend 2 (ranging from 1.38 to 1.76). Moreover, Figure 6 reveals that the sinuosity of bend 1, bend 3, bend 9 and bend 11 have decreased slightly, whereas bend 5, bend 6 and bend 8 indicate increasing trends of sinuosity during 1972–2021.

The axial length of one meander or the tangential distance between the corresponding points of a meander or the meander length of the selected 12 bends of the Raidak-I River vary through time. Figure 7 indicates that the maximum length is 5,747.1 m at bend 9 in the year 1980 and the minimum length is recorded as 1,117.5 m at bend 2 in the same year. So, the maximum fluctuation in meander length is found in the year 1980. Consequently, it is found that there is no significant change at bends 4, 7, 8, 9, 10 or 11. Figure 7b also shows that the meander length of different bends gradually increases over the study period. The distance between the outer edges of clockwise and anti-clockwise loops of the meander or meander width of the selected 12 bends of the

Raidak-I oscillates. The maximum and minimum meander width are 1,884.37 m at bend 9 and 68.89 m at bend 1 – both in 1980, which reveals that, like meander length, maximum fluctuation of meander width was also recorded in the year 1980. The tremendous decrease in meander width at bend 9 indicates the formation of an oxbow lake. The width of the river is defined as the distance between the two banks. Here, the width of the river was measured from the images, taking into account the point bars and active corridors. The minimum width (12.78 m) is found at bend 7 in 1972, whereas the maximum width of the Raidak-I River is recorded as 55.79 m at bend 9 in 2021. The channel width gradually increases at maximum bends during the study periods. Figure 7 reveals that bend 7 represents the least variation in meander ratio, whereas bend 1 shows maximum fluctuations. Bend 10, 11 and 12 revealed more-or-less similar trend in meander ratio. The maximum meander ratio is recorded as 0.4 at bend 3 in 2021 and the minimum meander ratio is 0.04 at bend 1 in 1972. A sudden decrease in meander ratio was recorded at bend 1 during 1972–80, which may be the result of the formation of an oxbow lake at that bend. Bends 2, 3 and 5 represent positive growth, whereas the meander ratio of bends 8, 9 and 11 decreased in early periods but increased later in the study period. Figure 7 represents the variation in the radius of curvature of the Raidak-I River over time. The radius of curvature at bends 2, 3 and 6 continuously increased. A sharp variation in radius of curvature is observed at bends 4, 7, 9 and 11. The maximum radius of curvature is 36.22 m, recorded at bend 2 in 1972, and the minimum is 890.21 m at bend 11 in the same year. The figure also indicates that the radius of curvature gradually increases at different bends from upstream to downstream during the study periods.

Discussion

The present study reveals the formation of 15 oxbow lakes during the study periods, which certainly depicts rapid shifting of the river channel. The present research work finds that meander movements of the Raidak-I River significantly decreased after 2004. Out of a total of 332 meander movements, 263 are recorded during 1972–2004 at an average of 8.4 per year (263 movements in 31 years). However, after 2004, the meander movements took place at an average rate of 4.6 per year (69 movements in 15 years). Consequently, the type of the meander movements also changed after 2004 (Table 1). Primarily, lateral movement was the most common meandering type, but, after 2004, the scenario changed and rotation movement became very much active. Out of a total of 332 movements, the river moved laterally 161 times and by rotation 34 times. However, after 2004, the river laterally migrated only 21 times (i.e., only 12.21% of total lateral movements), whereas the river migrated 23 times after 2004 by rotation (i.e. 67.65% of total rotation movements). It is evident that significant and rapid changes in the river channel have occurred in the last 44 years. The oscillation of the Raidak-I River is the outcome of various factors. There is a lacuna of literature regarding the Raidak-I River, so the present results cannot be compared against existing knowledge. Hasanuzzaman and Mandal (2020) demonstrated that insufficient discharge in the channel, nature of bed load, bar formation within channel and attached to the banks, and changes of channel thalweg are the main factors behind such changes.

During the field survey, we observed some imprints of an older thalweg line and a deep narrow channel along the convex slope (Fig. 8), which proves that the river has frequently changed its thalweg and that concave banks have been replaced by present-day convex banks and vice versa. The cross-sectional study uncovered changing thalweg lines and older concave banks (Fig. 9). As a result of the construction of embankments, the banks have been stabilised at different sections. Constructions of embankments certainly obstruct bank erosion processes, and, consequently, the total number of meander movements significantly decreased after 2004. Moreover, these embankments reduced lateral movements of the river, which was very common in the entire river. Due to obstruction on one side, the river started to erode in the opposite direction, leading to changes in the thalweg. After some years, eroded material from the opposite bank is deposited along the concave banks and concave banks are transformed into convex. These constructions also allow the river to erode more in areas without manmade constructions. Some active bends of the Raidak-river were taken into account to assess the meander types. Bend 1 is a newly developed segment

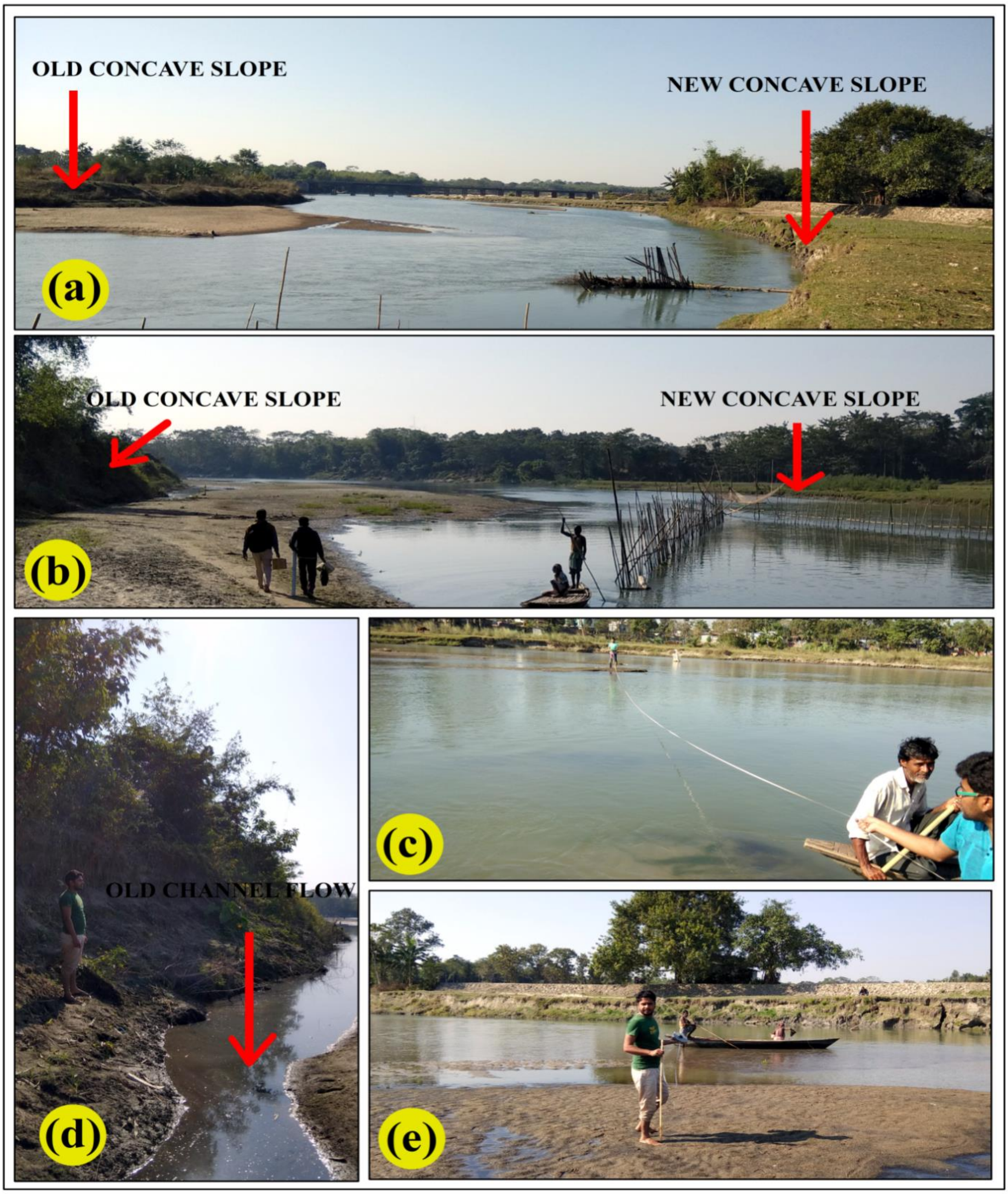

Fig. 8. (a) Rotation of concave slope, (b) Rotation of concave slope, (c) Measuring a cross profile, (d) Remnants of older thalweg line and abandoned concave banks, and (e) Measuring a cross profile

that revealed continuous and sequential development since its inception. Bend 1 and bend 4 have sharp-angled, compound, asymmetric bends confined by bedrock that have migrated downstream by rotation.

Bends 7, 8 and 10 are close to being regular symmetric meanders that have migrated downstream. Bend 9 is a simple symmetric-to-compound meander form that remained almost static during the study. At bend 5, the upstream limb that was almost straight in 1980 is migrating rapidly, but a distinct new bend was found in 2021 that is characterised by moderately high curvature. The radius of curvature

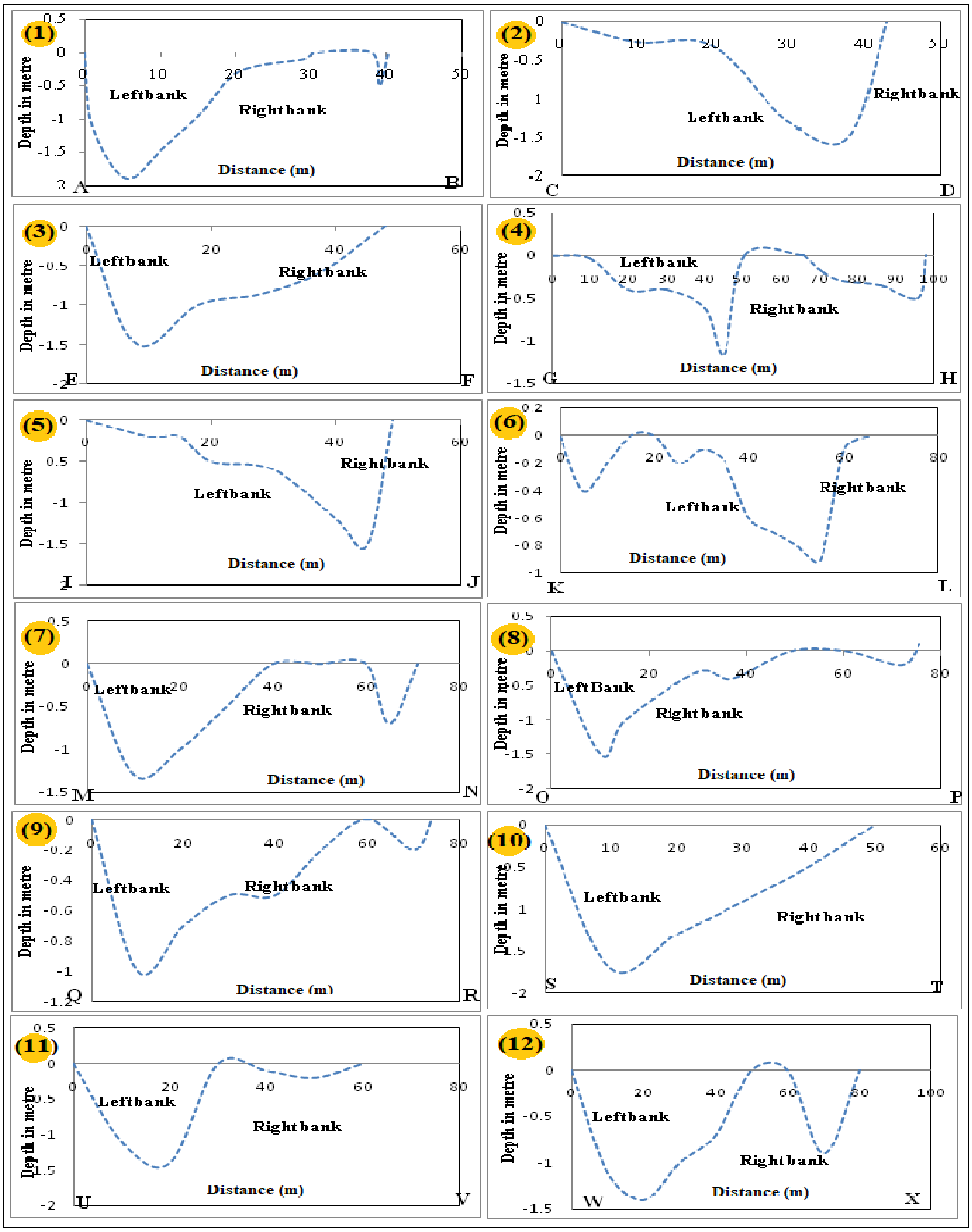

Fig. 9. Cross-sections along Raidak-I showing changing nature of thalwegs and banks

of bend 5 changed and decreased dramatically in 2004. The sudden decrease in radius indicates the formation of an oxbow lake. The morphological changes of bends 12 and 6 are presented in Figure 8 for the period 1972–2021. This symmetrical meander has dominantly migrated downstream, but it has increased in size and has become "flat-headed". Bend 12 is a free alluvial bend, impinging on the sandy-silt low terrace of the valley floor. It showed the classic sequence of migration and then growth and formation of an oxbow lake between 1972 and 1980 (Fig. 10). In the field survey, it was observed that the

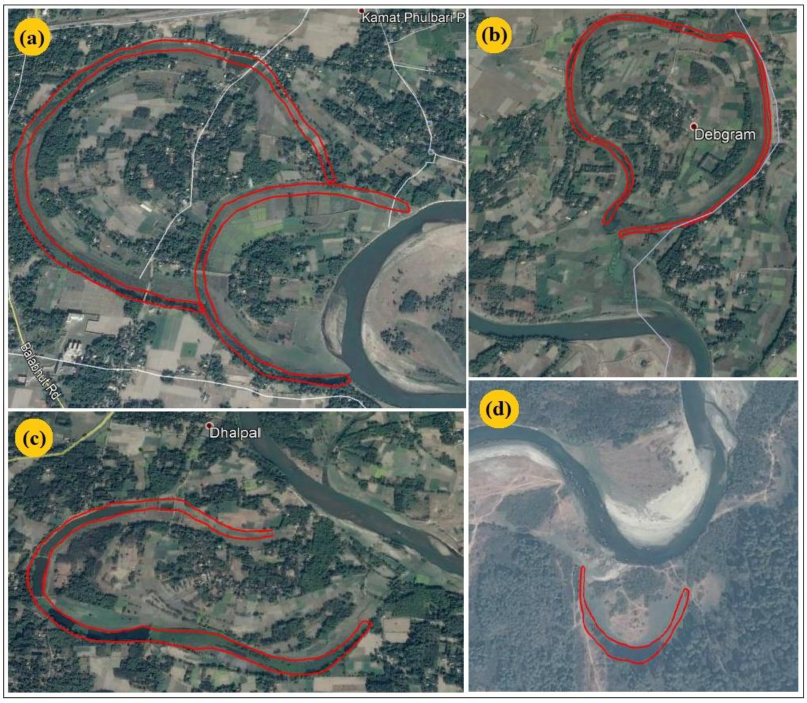

Fig. 10. Formation of oxbow lake, (a) 1972–1996, (b) 1972–1980, (c) 1972–1980, and (d) 1972–1980

satellite data differ to a small extent from the field data. Cross-sections 2, 3, 5 and 10 (Fig. 9) depicted limited fluctuation, and cross-sections 1, 4, 6, 7, 8, 9, 11 and 12 represented maximum variations of bends. Analysis of the evidence of the occurrence and location of processes within the bends indicates that the morphological changes of the Raidak-I River are a common phenomenon that has made the channel more dynamic in nature.

The formation of 15 oxbow lakes in the study area during study periods may be responsible for the morphological changes of different bends. Moreover, the embankment construction and resultant changes in channel are vital for such changes across the bends of the Raidak-I River. The formation of an oxbow lake (Fig. 10) directly reduces the radius of curvature, meander length, meander width and meander ratio of the river bank. So, the meander geometry of the river is largely controlled by various cut-offs, which is observed during the study. The channel width and another parameter of meander geometry may be increased or decreased with the replacement of an old concave bank by a newly formed convex bank. A newly formed concave bank gradually increases channel width.

It is evident that the Raidak-I River has changed its meanders with the passage of time. Numbers and types of meander movements have changed noticeably. The study finds that human interventions along the banks of the river have significantly reduced lateral movements and have increased the rotation process in the meandering system of the river. Field-based cross-sections in twelve different parts of the river and field photographs also indicate the changing nature of meander movements. Moreover, channel migration, along with the formation of oxbow lakes, has also changed the meander geometry of the river. Developments of individual bends are not the same everywhere. Most of the bends are recorded as very dynamic, so their morphological changes have been observed very prominently. It can be stated that because discharge data are unavailable and could not be measured by the authors, a clear-cut conclusion cannot be drawn. But our observation with help of geospatial techniques, field photographs and a field-based cross-sectional study suggests that human intervention (specifically, the construction of embankments) is responsible for the recent changes in the Raidak-I River. The present work enriches the knowledge of meander movements and meander geometry not only in an Indian scenario but also for Raidak-I River, in particular, which fills a gap in the existing knowledge. The integration of geospatial techniques with intense field study provides methods to study meanders even when discharge data is unavailable. Thus, this type of study has some tremendous importance not only in a local case but also in a global perspective. In addition to this, the integration of remotely sensed data, GIS techniques (especially the extension of ArcGIS tools) and field-based cross-sectional study can be very beneficial for identifying suitable sites for embankment construction, river restoration and channel management.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: MH, MHM, SM; data collection: MH, MHM, SM; statistical analysis: MH, MHM, SM; result interpretation: MH, MHM, SM; manuscript preparation: MH; literature review: MH, MHM, SM.

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