



Understanding planform dynamics of the Ganga River in eastern part of India

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Abstract To understand the natural processes of planform change, meandering and formation of braid bars, satellite sensor data of few decades play a significant role. The present research focuses on the planform dynamics of Ganga River from Sahibganj (Jharkhand) to Jalangi in West Bengal, India. This study is based on the sequential river planform maps. These maps were prepared using Landsat 1, Landsat 3, Landsat 4, Landsat 5 and Landsat 7 data for the period 1975–2015 at an interval of 5 years. The sinuosity index, braiding index and spatial analysis of maps were used to assess and classify the river into straight, braided and meander categories. This was observed that braiding index is continuously increasing and the meandering index has decreased from 1.6 to 1.24 during 1975 to 2015. The results showed the changes in channel migration with time and space. From the analysis, it is observed that the factors causing shifting of the Ganga River in some areas are natural and anthropogenic. Landsat images were found to be effective in determining the meandering index, braiding index and planform change of a river.

Keywords Meandering index · Sinuosity index · Braiding index · Farakka barrage · Sahibganj · Ganga River

1 Introduction

A River is a dynamic and crucial part of the physical environment. Study of the behaviour of a river gives prime importance to wide variety concerns, like flood control, navigation and water resource development to recreation. Meandering is very common to most of the rivers in the world nowadays, which is occurring due to various natural and human activities [1]. Excess of turbulence, slope of the river, streamflow, bed and side resistance capacity are the natural causes of most of the meandering rivers. Human activities also influence the river meandering by constructing a dam, settlement and adopting faulty agricultural practices [2]. Meandering property of a river has attracted many engineers and researchers over the last few decades. In alluvial planes, a meander of rivers consists of a number of consecutive curves connected with short straight stretches crossing. In a plan view, the appearance of a reach describes the pattern of a river. Based on a plan view of a major river, the pattern of a river reach is broadly categorized into three patterns such as straight, braided and meandering [3]. A straight river follows almost a straight-line course. A meandering channel follows a sinuous course of Y-shaped or U-shaped, consists of alternating bends. Generally, braided rivers are formed due to poorly defined unstable banks. Ganga River basin covers about 26% of India's total landmass. This river basin supports livelihoods of millions of people of India. The basin extends through the countries like India, Bangladesh, and Nepal with a catchment area of about 1,086,000 km². On the north side of the basin, there is Himalayas and on the west side there is Aravalli. South side of the basin is surrounded by Vindhyas and Chhotanagpur plateau and east side Brahmaputra Ridges [4]. In India, the Ganga River has

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a length of about 2525 km along Bhagirathi and Hooghly up to the outlet into the Bay of Bengal.

Previous research works have addressed the meander planform geometry, bending in flow, bending in migration dynamics, and lateral sedimentology [5]. Some rivers of India such as the Ganga, Kosi and the Brahmaputra River show the special temporal shifting of their channels [6–8]. The changing meander behaviour of river Ganga in West Bengal was studied from the past two centuries [9]. The author opined that the migration of the Ganga River is towards east appreciably and a mighty bend is formed because of the Farraka barrage construction in West Bengal. This recent change has occurred due to the trapped sediment load above the barrage. After several studies, it was observed that the upstream channel of Farakka barrage had been moved eastward, but downstream part is erratic [10]. The morphology of river Jamuna was examined using remote sensing and Geographic Information System (GIS) technique [11]. Thematic Mapper (TM), Landsat Enhanced Thematic Mapper Plus (ETM+) and Multi-Spectral Scanner (MSS) images for five different years were used to identify vulnerability and morphological changes. Analysis of bank erosion hazard at upstream part of Farakka barrage was done and measurement of different morphometric parameters was done using Landsat and IRS satellite images for six different years from 1955 to 2005 [12]. Drastic change in all the parameters were observed over the period of time. The authors further observed bank failure due to certain factors such as soil stratification in the bank of the river, higher sediment load, presence of hard rocky areas, dredging difficulties and obstructions to the natural flow caused by the construction of Farakka barrage. Sinuosity is increased on the left bank of the river. Study of lower reaches of Ganga–Padma River for the years 1972–2010 was done [13]. The study of avulsion threshold and planform dynamics in the Kosi River was carried out [14]. Several reaches along Kosi River were found to be avulsion prone. Hossain et al. [15] also observed that avulsion threshold in the alluvial river reaches influenced by planform dynamics of the river. Assessment of the morphological changes of the Ganges in the upstream of Farakka barrage was done using Landsat MSS, Landsat TM and IRS LISS images [15]. It was observed that left bank of Ganges was more accretion prone than the right bank. Due to the presence of highly erodible materials in the river banks and higher discharge rate during monsoon season, Ganges has higher probability of erosion rate than the other major rivers in India. The study of morphological changes in the Ganga River at Varanasi was carried out by considering the long and cross profile [16]. The results showed that sinuosity varies from 1.66 to 1.26. The analysis of sinuosity and channel shifting in river Ganga of Uttarakhand was done using satellite images in the transect

method from 1972 to 2005 [17]. Kumar et al. [18] suggested flood protection measures for west side banks of the river. The sinuosity and meandering of the Ganga River near Allahabad were determined [18]. It was observed that Landsat images could be effectively used for classifying the lengths of the river. Recently a study on the analysis of meandering and braiding characteristics was carried out by considering middle-lower part along river Ganga as study reach [19]. The analysis of planform changes of the Ganga–Padma river system in Bangladesh was done for the period of 1973–2011 with the help of Landsat images and streamflow data for a longer period [20]. After studying erosion–deposition statistics of the Ganga River, it was found that during the assessment period that about 57 km² of the land is lost on the right bank and 59 km² of land is deposited on the left bank. From the previous works, drastic change in the morphology of the Ganga River after the construction of Farakka barrage can be observed. Studies related to the upstream part of the Farakka barrage in the Ganga River have been carried out. But no recent works on the morphological changes of the Ganga River considering both upstream as well as downstream part of the Farakka barrage have been studied. Thus present study aims at the identification of historical changes in planform of the Ganga River with the help of dynamic fluvial characteristics by using Landsat images for different periods from Sahibganj in Jharkhand to Jalangi in West Bengal. In this particular portion of Ganga River, the meandering values are not known, hence determination of various morphometric parameters like sinuosity, tortuosity and braiding index of reach from Sahibganj to Jalangi and its analysis are the mainstay of the research paper. The output of the study can be of great help for better planning in flood protection, and river training works in this area.

2 Materials and methodology

2.1 Study area

The Ganga River is considered as the longest river as well as the largest river basin of India. The river flows starting from the Himalayas to the Bay of Bengal. The Ganga basin covers almost 26.3% of the total geographical area of India [16]. The drainage pattern of river Ganga is braided in nature and in the upper Gangetic plain straight course can also be found. Southwest Monsoon plays a vital role in the hydrological properties of the basin [21]. During the months of June to September, about 84% of total rainfall events take place. Substantial seasonal variation can be observed in this basin. Due to seasonal variation in the basin many problems may occur in land and water resources management. The variation of seasonality is so

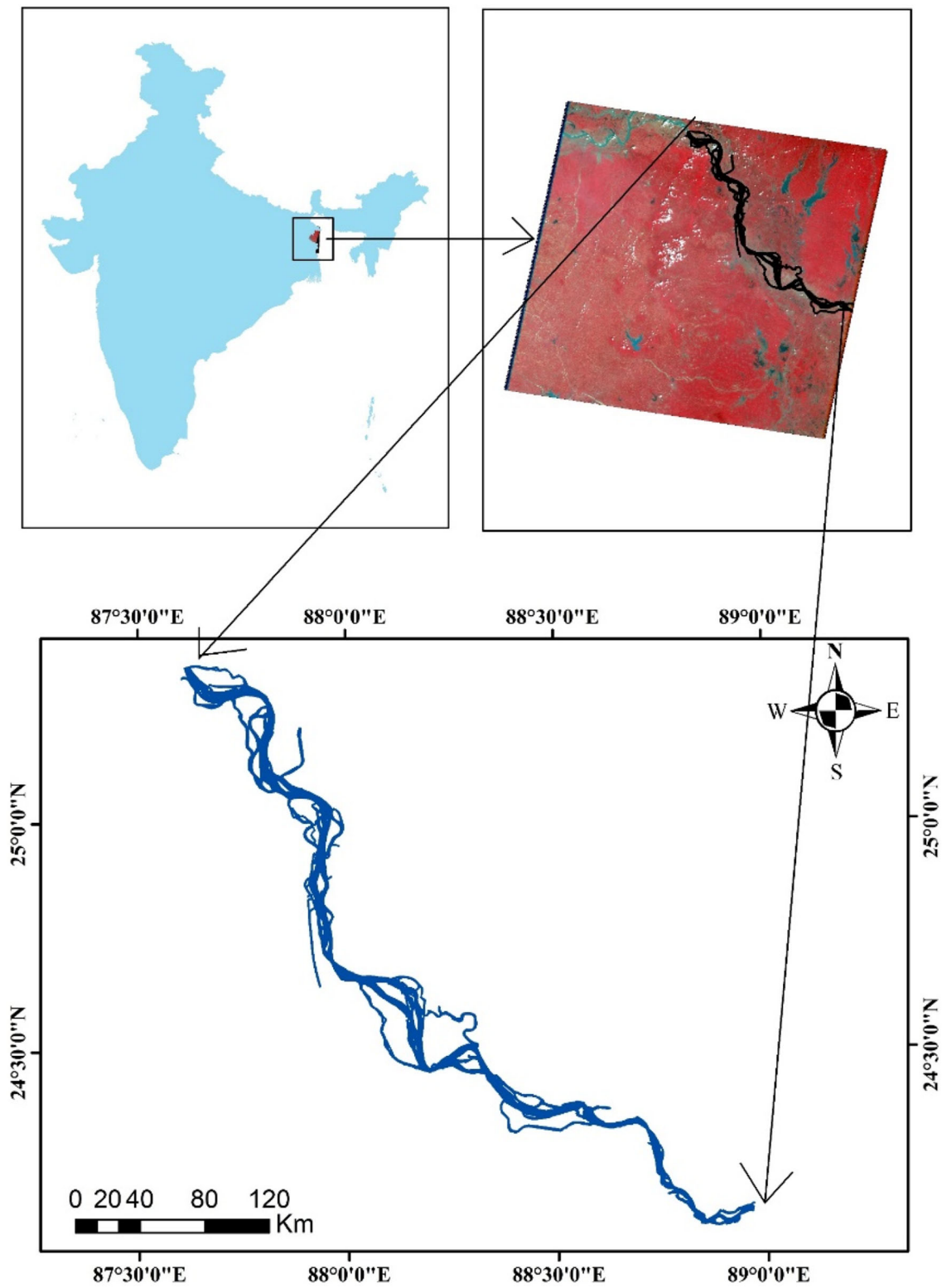


Fig. 1 Location of study (reach of river Ganga) area from Sahibganj (Jharkhand) to Jalangi in West Bengal

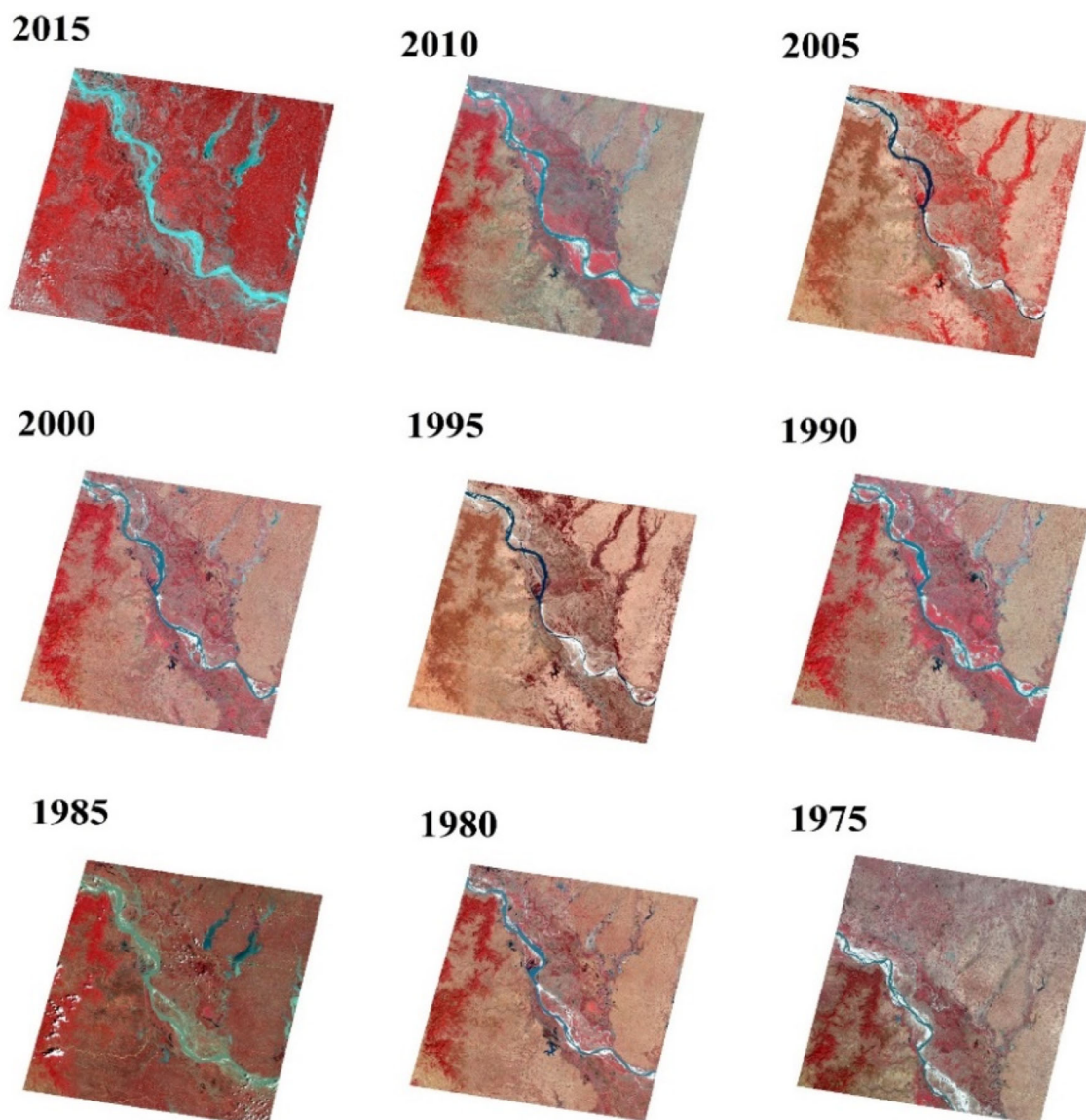
much that it can cause drought as well as flood. Farakka Barrage is located in Murshidabad district in West Bengal near Sahibganj. It was constructed to maintain the water

flow in West Bengal. Due to the presence of the barrage as well as other causes such as higher discharge rate, weaker soil texture, sediment deposition, presence of Rajmahal

Table 1 List of satellite images for the different years 1975–2015

Year	Acquisition date	Satellite	Sensor	Band
1975	24/12/1975	Landsat 1	MSS	1, 2, 3, 4
1980	17/01/1980	Landsat 3	MSS	1, 2, 3, 4
1985	15/12/1985	Landsat 4	TM	1, 2, 3, 4, 5, 6
1990	23/12/1990	Landsat 5	TM	1, 2, 3, 4, 5, 6
1995	21/21/1995	Landsat 5	TM	1, 2, 3, 4, 5, 6
2000	10/12/2000	Landsat 7	ETM+	1, 2, 3, 4, 5, 6, 7, 8
2005	24/12/2005	Landsat 7	ETM+	1, 2, 3, 4, 5, 6, 7, 8
2010	04/11/2010	Landsat 7	ETM+	1, 2, 3, 4, 5, 6, 7, 8
2015	20/12/2015	Landsat 7	ETM+	1, 2, 3, 4, 5, 6, 7, 8

hilly areas on the right as well as left-bank erosion of the Ganga River becomes one of the most severe Geo-hazard in West Bengal. The main part of the study area is stretched from Sahibganj (Jharkhand) to Jalangi in West Bengal. Sahibganj and Jalangi are the two reaches of the Ganga River situated on the upstream and downstream side of the Farakka barrage respectively. The study area lies between 87°30'E to 88°40'E longitude and 23°40'N to 26°00'N latitude. The study area includes main tributaries like Gandak, Ghagra, Sone, and Kosi which affects the plan form of River Ganga. The location of the study reach from Sahibganj to Jalangi is shown in Fig. 1.

**Fig. 2** Satellite images of the Ganga River from Sahibganj to Jalangi from the year 1975–2015

2.2 Data preparation and analysis

In order to identify the trend of morphological changes in the Ganga River over a period of the last 40 years, nine satellite images from the year 1975 to 2015 in 5 years of the interval are analyzed. The Landsat data with year and acquisition dates are shown in Table 1. Digital remote sensing data of Landsat images with spatial resolution of 30 m having Thematic Mapper (TM), Multi-Spectral Scanner (MSS) and Enhanced Thematic Mapper Plus (ETM+) sensors are obtained from USGS earth explorer as shown in Fig. 2. The downloaded satellite images with the corresponding sensor for the years 1975–2015 at an interval of 5 years are listed in Table 1. A topographic map with 1:50,000 scale of the study area has been imported to ERDAS Imagine 9.0 to for georeferencing. Topographic maps, Landsat MSS and TM images are georeferenced and projected into UTM Zone 45 based on the Ground Control Points (GCP) generated from the Landsat images. As ETM + data is subjected to scan line correction-off since 2003, the focal analysis is applied to de-strip the images [22]. Resampling of all the images is done using Nearest Neighbor Method to 30 m resolution. All the spatial input maps are also converted to a common scale. These maps are later superimposed in ArcGIS to observe deviation from the bank line of the river during this period. After digitization of the river, sinuosity and tortuosity index along with braiding index are estimated to observe the change in plan form of the Ganga River. The flow chart of the data analysis is shown in Fig. 3.

2.3 Meandering Indices

Two indices have been used here to measure the intensity of meander of a river. They are Sinuosity index and Tortuosity index. Sinuosity index is a measure of channel curvature. It is the deviation from a path defined by the direction of maximum downslope. The sinuosity ratio is defined as the ratio of distance between two points on the stream measured along the thalweg and the valley length between the two points. The sinuosity index of bedrock stream is 1, as it flows directly downslope. On the other hand, sinuosity index of meandering streams is greater than 1 [23]. The value of sinuosity ratio of a channel with 1.5 or greater is considered as a meandering channel. Tortuosity is the property of a channel or river having curve being tortuous or twisted. The value of tortuosity ratio for a meandering channel is less than 1. The sinuosity and tortuosity are determined with the following formula.

$$\text{Sinuosity} = \frac{\text{Thalweg length}}{\text{Valley length}} \quad (1)$$

$$\text{Tortuosity} = \frac{(\text{Thalweg length} - \text{Valley length})}{\text{Valley length}} \quad (2)$$

2.4 Braiding index

A braided river consists of a network of a number of small channels separated by small and often temporary islands called 'braid bars'. The braiding index can be determined by using the following formula [24].

$$\text{Braiding Index} = \frac{2 \sum L_r}{L_m} \quad (3)$$

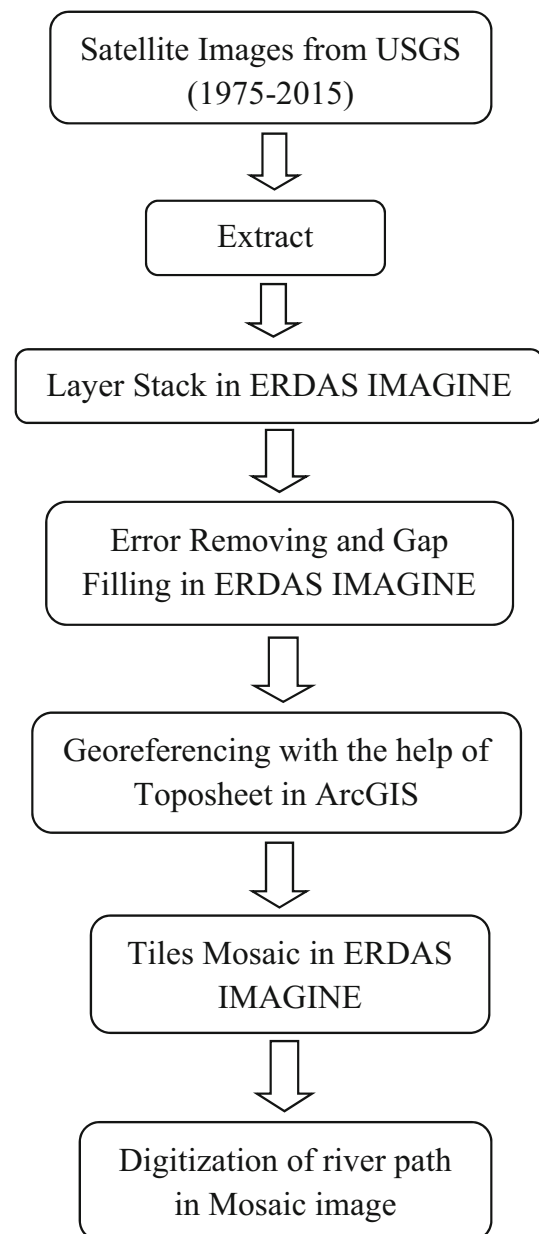
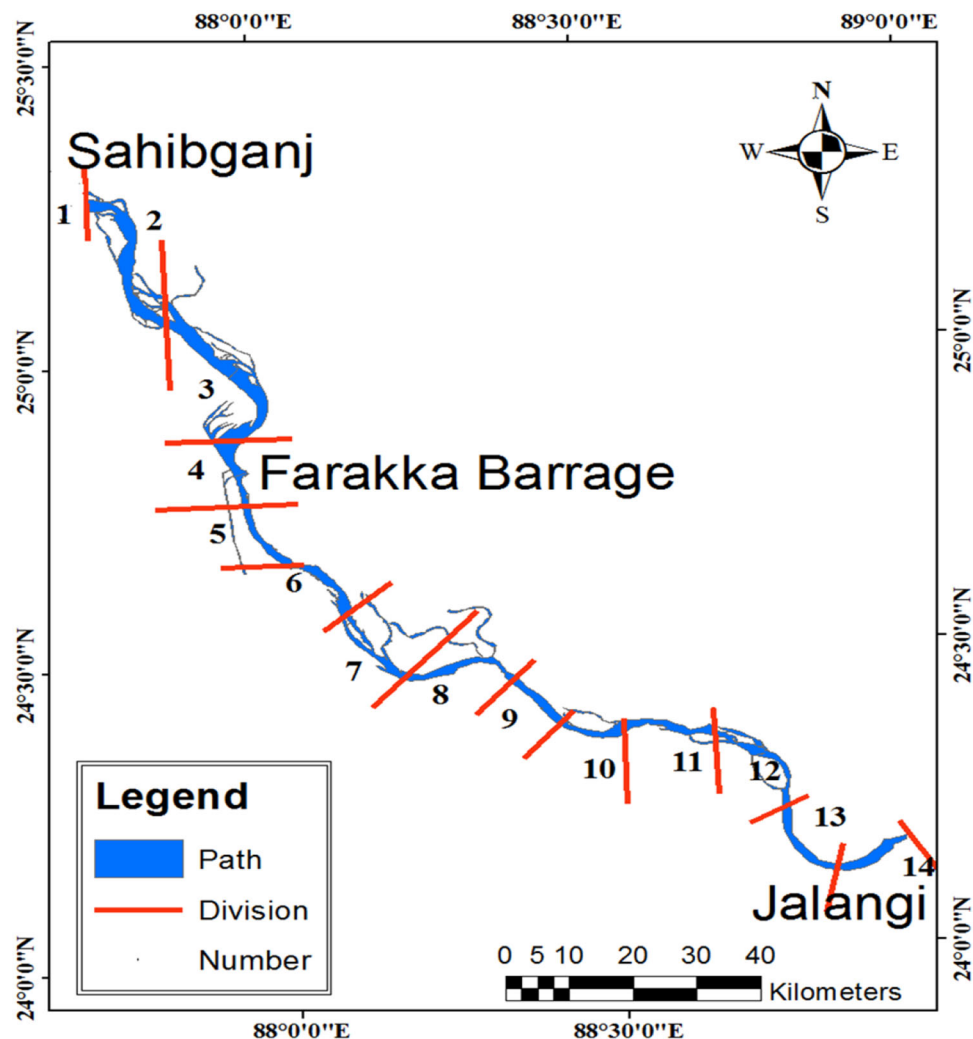


Fig. 3 Flow chart of the data analysis

Fig. 4 Division of study area into 14 number of reaches from Sahibganj to Jalangi



where, L_r = Length of all the islands and/or bars in a river reach, and L_m = Length of a river reach measured midway between the banks of the channel belt.

A revised formula has been proposed for the determination of braiding index, which varies between 0 and 1. The formula is given hereunder as Eq. (4) and depiction of methodology for estimation of braiding index is given in [25]. The whole study area is divided into 14 different reaches at the interval of 10 km in order to calculate the braiding index (Fig. 4).

$$\text{Braiding Index} = 1 - \frac{\sum B_r}{B_m} \quad (4)$$

where, B_r = distance between inner bars and B_m = distance between outer bars. In the present study, Eq. (4) has been used for calculating the braiding index.

3 Results and discussions

The course of River Ganga around the Farakka barrage was studied using Landsat images. The digitized paths of river Ganga from Sahibganj to Jalangi are shown in Figs. 5a, b and 6 for the periods from 1975–1985, 1990–2000 and 2005–2015, respectively. These figures reveal morphological changes in river Ganga during the last few decades. Variations in morphological parameters such as sinuosity and tortuosity indices are estimated (Table 2). It is observed that the meandering indices have decreased from 1.60 to 1.24. The tortuosity index is decreased from 0.60 to 0.24 due to the sedimentation process on the banks of the river. The variation of sinuosity and tortuosity indices is shown in Fig. 7.

The braiding index from Sahibganj to Jalangi is calculated from reach 1 to 14 and shown in Fig. 8. The variation of braiding index is presented in Table 3. It is observed that after the construction of Farakka barrage in 1972, the braiding index has increased up to 0.94. In Jalangi, the

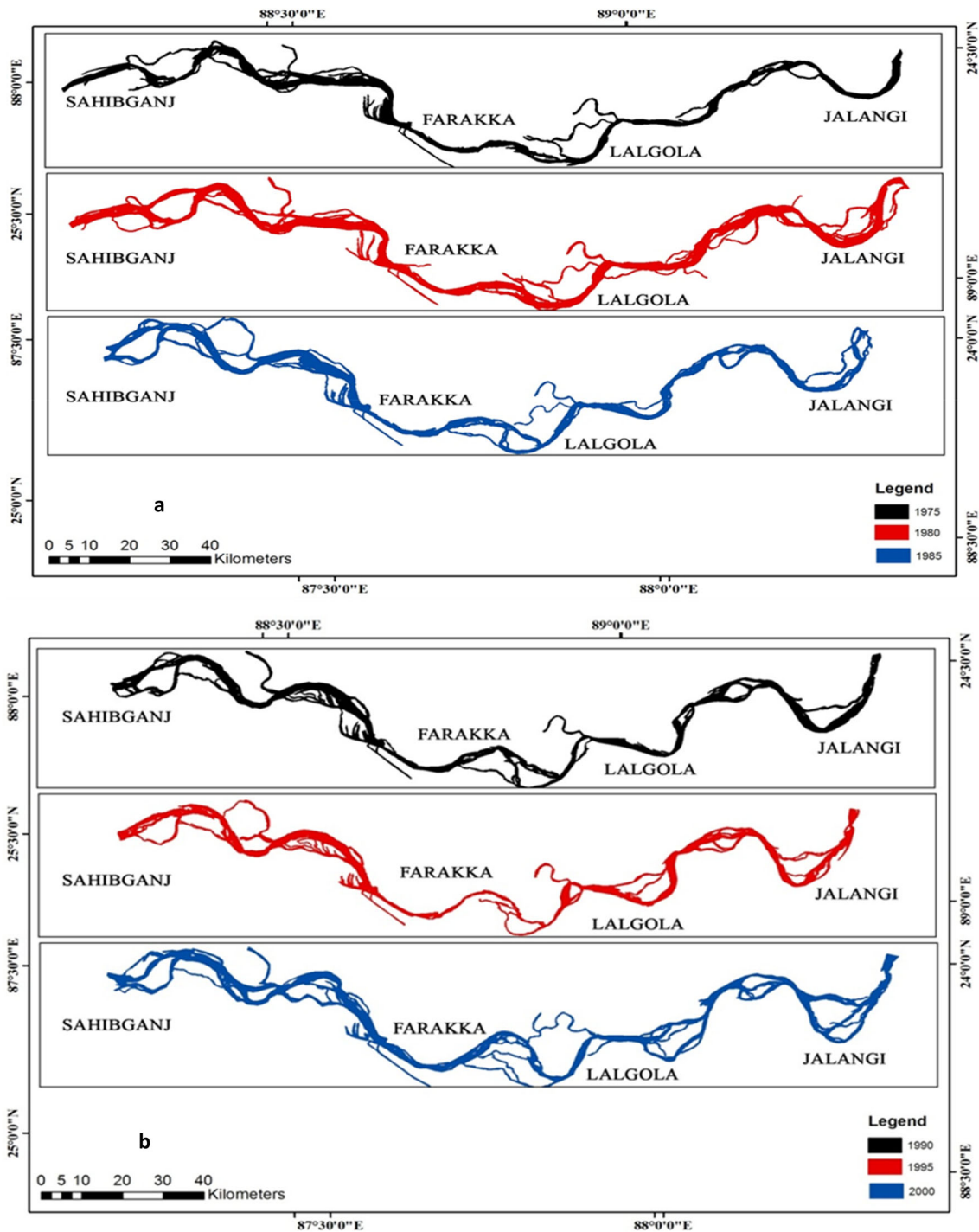


Fig. 5 Digitized path of river Ganga from Sahibganj to Jalangi **a** Digitized path of river Ganga from Sahibganj to Jalangi (1975–1985) **b** Digitized path of river Ganga from Sahibganj to Jalangi (1990–2000)

tendency of braiding is decreasing. The morphometric changes in river Ganga in the upstream area of Farakka barrage up to Ramajahal hills are shown in Fig. 9. Downstream of Farakka barrage, the river changes its direction towards the north, thus resulting in the shift of the Ganga River to eastwards. The historical sinuous channel

around Farakka barrage has become a straight channel resulting in an overall sinuosity reduction from 1.60 to 1.24 between 1975 and 2015. Moreover, the channel around the Farakka region changed the direction towards the east by about 10–11 km, forming a large meander loop also. A remarkable change in the study area is observed when the

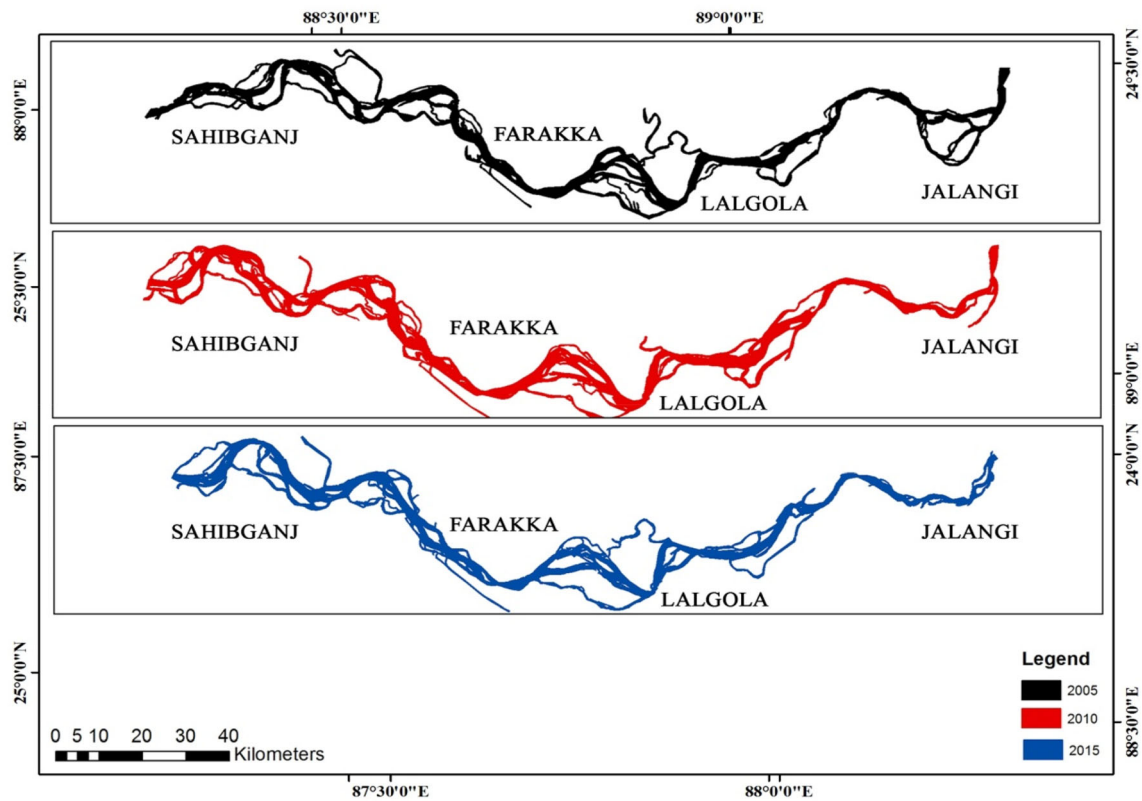


Fig. 6 Digitized path of river Ganga from Sahibganj to Jalangi (2005–2015)

Table 2 Observed meandering indices from Sahibganj to Jalangi

Year	Sinuosity	Tortuosity
1975	1.60	0.60
1980	1.61	0.61
1985	1.25	0.25
1990	1.14	0.41
1995	1.35	0.35
2000	1.42	0.42
2005	1.41	0.41
2010	1.23	0.23
2015	1.24	0.24

maps of 1975 and 2015 are compared (Fig. 10). Also on the downstream of Rajmahal, the meandering has become more pronounced by the year 2015. The river system is greatly influenced by the construction of dams and barrages resulting in the change in the natural ecosystem of the river due to the change in sedimentation as well as erosion. Figure 10 indicates that the bankline is shifting near Lalgola as observed for three years i.e. 1975, 1985, 2015. The oscillating nature of bank line is seen near Lalgola. Lalgola is located in the Jalangi–Bhagirathi interfluvial region in Murshidabad district. The plan-dynamics are changing due to the effect of the construction of Farakka barrage, moreover, the tendency of braiding is also increasing. In

Jalangi, it has been observed that the channel is showing a straight pattern rather than meandering which indicates that the sinuosity index is decreasing (Fig. 11). Due to continuous bank erosion occurring over last few decades, the course of the Ganga River in the northern part of West Bengal is changing. Presently the river has shifted away from Jalangi as shown in Fig. 11.

The study reveals the recent change in planform of river Ganga. The river is shifting towards eastward as a result of hydrological processes. The modifications that occurred in the channel form is due to the construction of Farakka barrage and also due to the confluence of river Kosi, Gandak in Bihar. A significant amount of sediments are getting trapped in the downstream of Farakka Barrage because of this the river has started to wander and developed a conspicuous bend towards the northeast which is still continuing. Therefore, the bend has raised concern of the adjoining river and the barrage leads to bank protection measures on both the upstream and downstream of the barrage. Though the Farakka barrage project was constructed for navigational class of Calcutta Port, but it has resulted into enormous devastation in Malda on upstream part and Murshidabad on downstream part. The major impacts due to this project are huge sedimentation, increase in flood intensity and tendency of bank failure.

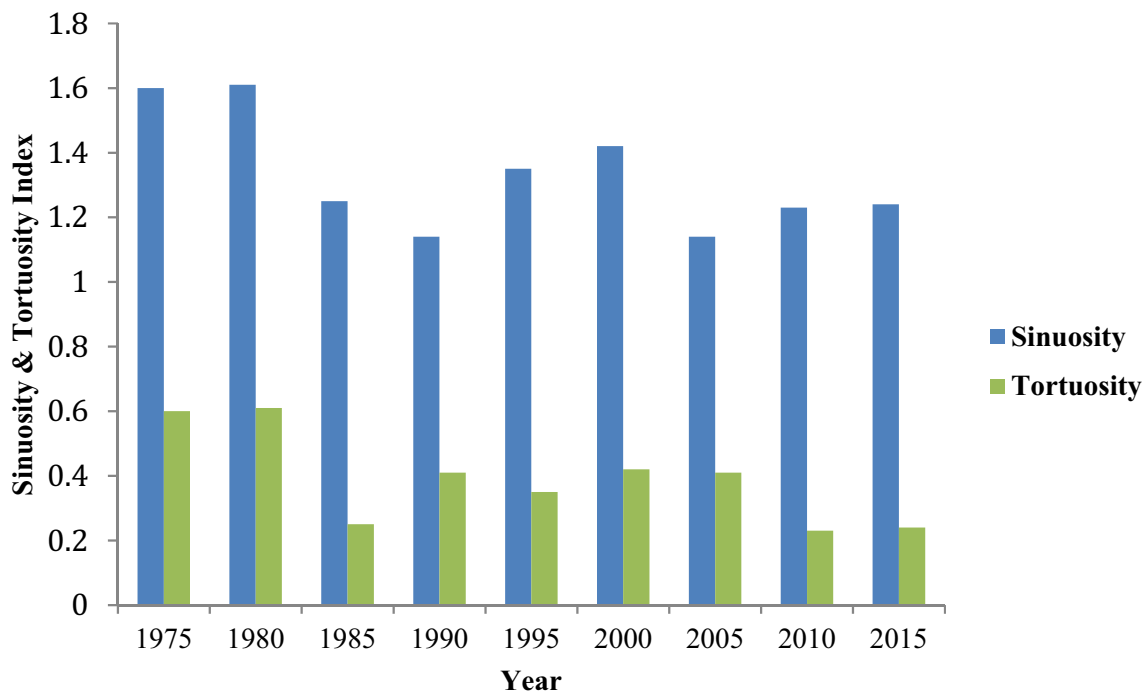


Fig. 7 Variation of Sinuosity and Tortuosity index of river Ganga from Sahibganj to Jalangi over the period of 1975–2015

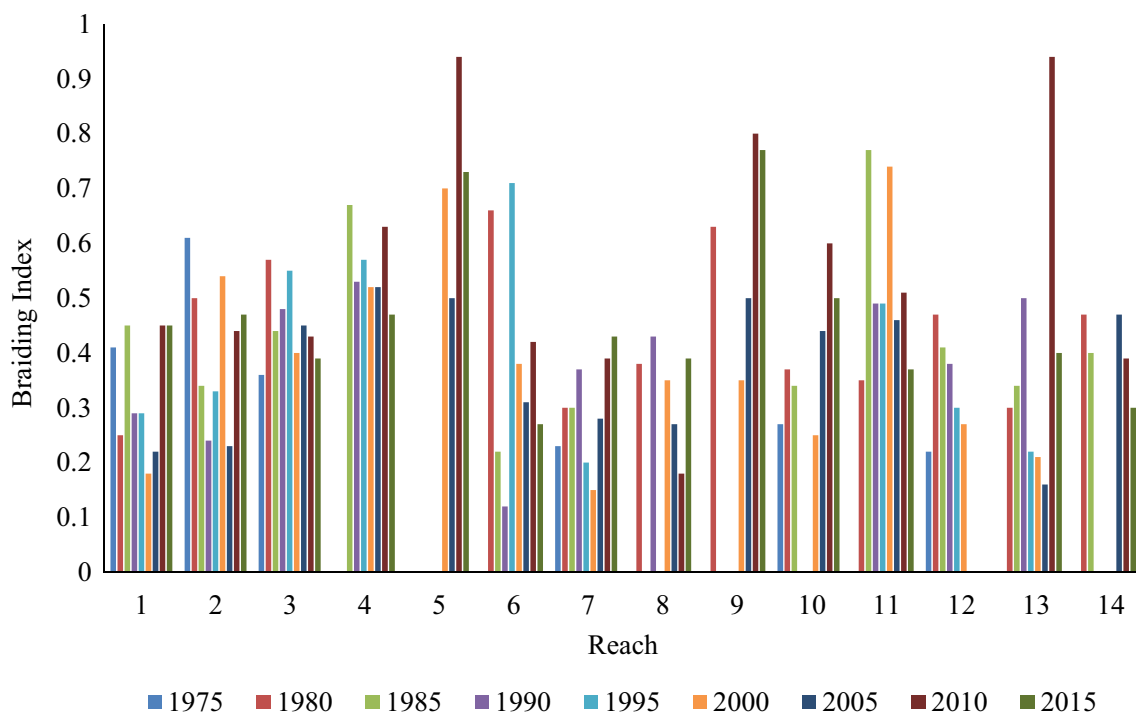


Fig. 8 Plot of braiding index for different reaches from Sahibganj to Jalangi for 1975–2015

From the analysis, it can be seen that there is drastic increase or decrease in the meandering indices like sinuosity, braiding index over the past few decades. Due to increase in sinuosity, the river is affecting larger areas in

the left bank every year. It is found that failure of bank is caused mainly due to engineering interventions and various river confluences on river Ganga.

Table 3 Braiding index from Sahibganj to Jalangi

Reach/year	1975	1980	1985	1990	1995	2000	2005	2010	2015
1	0.41	0.25	0.45	0.29	0.29	0.18	0.22	0.45	0.45
2	0.61	0.5	0.34	0.24	0.33	0.54	0.23	0.44	0.47
3	0.36	0.57	0.44	0.48	0.55	0.4	0.45	0.43	0.39
4	0	0	0.67	0.53	0.57	0.52	0.52	0.63	0.47
5	0	0	0	0	0	0.7	0.5	0.94	0.73
6	0	0.66	0.22	0.12	0.71	0.38	0.31	0.42	0.27
7	0.23	0.3	0.3	0.37	0.2	0.15	0.28	0.39	0.43
8	0	0.38	0	0.43	0	0.35	0.27	0.18	0.39
9	0	0.63	0	0	0	0.35	0.5	0.8	0.77
10	0.27	0.37	0.34	0	0	0.25	0.44	0.6	0.5
11	0	0.35	0.77	0.49	0.49	0.74	0.46	0.51	0.37
12	0.22	0.47	0.41	0.38	0.3	0.27	0	0	0
13	0	0.3	0.34	0.5	0.22	0.21	0.16	0.94	0.4
14	0	0.47	0.4	0	0	0	0.47	0.39	0.3

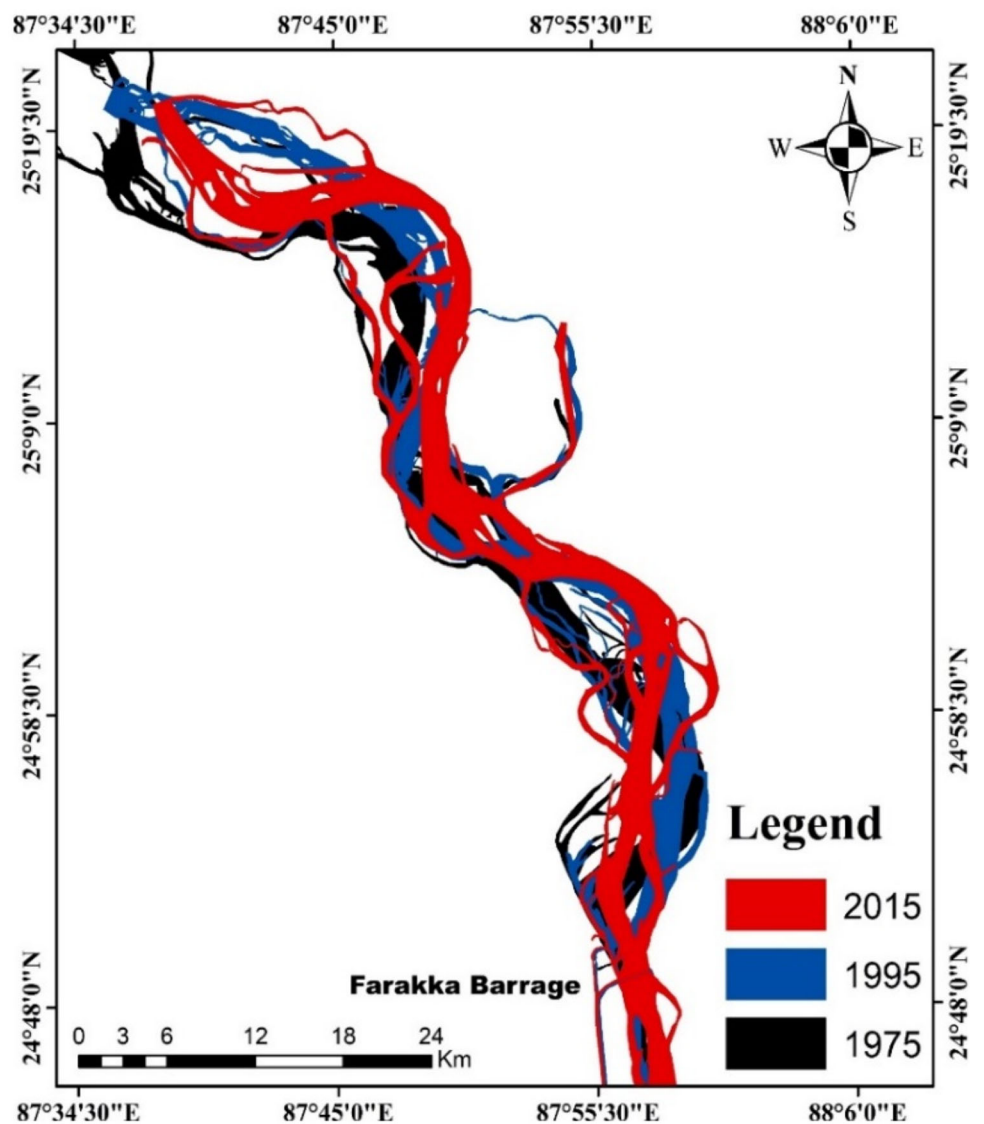
Fig. 9 Channel avulsion near Farakka barrage in West Bengal

Fig. 10 Channel avulsion near Lalgola and Murshidabad in West Bengal

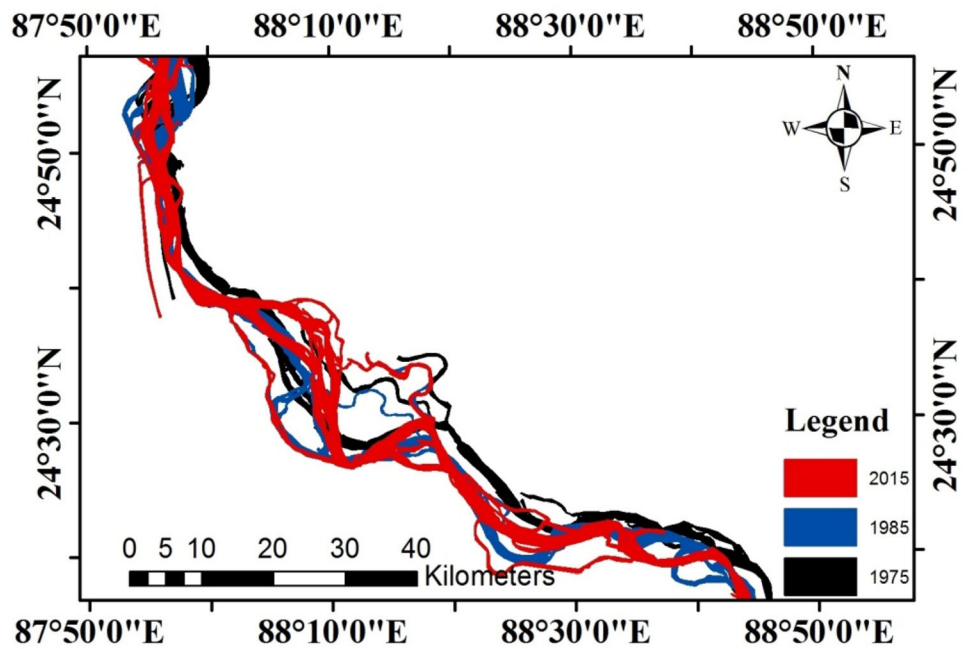
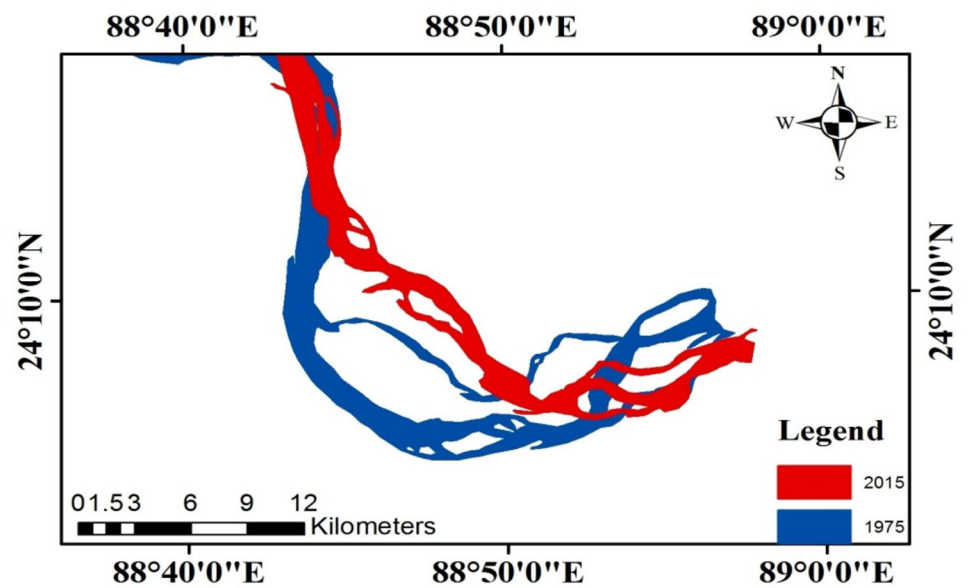


Fig. 11 Planform dynamics near Jalangi



4 Conclusions

In this present study, an attempt is made to monitor the change in the behavior of the course of river Ganga within the study area by using remote sensing techniques and GIS, which includes the identification and mapping of change in the bank line, sinuosity index, tortuosity index and braiding index within the selected area. The channel shifting is caused by the embankment along the river channel in the southern bank which is not allowing natural channel adjustment and leading to migrating to northern direction. Planform dynamics and channel multiplicity significantly

have influenced the avulsion threshold in the downstream of the confluence of river Ganga. The channel migration or change is a significant characteristic of geomorphological change in large alluvial rivers. Although river Ganga migrates naturally in this region, but some engineering interventions like Farakka barrage along with its connected structures seems to have made the situation worse. The construction of Farakka barrage has affected the planform of river Ganga in upstream up to Rajmahal hills. It can be inferred that the changes between different decades, which has been studied for the area are short term or seasonal and are triggered by the natural phenomena like flooding,

avulsion and Ana branching as well as the anthropogenic factors like the construction of the engineering structures along the river course. An analysis of all the available database can be carried out to get a complete coverage of the Ganga River in India which can help in managing disaster and mitigating the natural hazards.

Data availability The datasets used in the findings of this study are mentioned within this article.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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