Chapter-4

DECADAL CHANNEL PLANFORM DYNAMICS

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4.1 Introduction

Satellite-based remote sensing data are globally used to study the earth surface dynamics. Remote sensing has the advantage to monitor the fluvial environment due to its large area coverage, synoptic view and continuously data capturing ability [104,105].High spatial resolution data are suitable for monitoring the fluvial environment, mainly the river planform dynamics, especially for large and highly dynamic rivers.

The fluvial environment isa continuous system which required the continuous-time series data for in the detailed analysis of its structure and function [123].Fluvial geomorphologist faced difficulties during long term analysis of channel planform dynamics due to the limited availability of continuous data.Thus, remote sensing data provide an excellent opportunity for standardised mapping and monitoring of channel planform dynamics at regular intervals.

Landsat satellite launched in 1972, which started the era of spaced based earth observation with high spatial and temporal resolution. This remote sensing data gives wonderful opportunity to study the earth surface dynamics on the bases of available spatially continuous, synoptic and temporally repetitive data in multi-spectral bands. Initially, due to the high cost, the accessibilityof Landsat data was very limited to the scientific community to study and monitor the Earth surface dynamics. Now, the Landsat data archive becomes freely available to the global scientific community by NASA and USGS for mapping and monitoring of earth surface dynamics [124].

The focus of this chapter is to analyse one of the first major tributary of the Gangariver, which is Ramganga, and particularly, the downstream of the Ramganga river. A minimal number of studies have been carried out on this section. Landsat images supplemented by historical topographic maps were processed to produce a time-series over a more extended period of nearly 237 years.

It is well known that channel planform dynamics is one of the main problems of alluvial rivers in the world, which causes natural hazards like lateral channel shifting, flooding, bank erosion, and damage to hydraulic structures, transport network, agricultural land, and settlement, etc. A proper understanding of the historical planform change in rivers through time is critical to many water resources scientists, managers, and policymakers engage in river management activities [3, 4]. During the last three decades, significant efforts have been made to study thechannel planformbehaviour locally and globally [108, 109]. Numerous geospatial technology-based studies have been carried out globally, e.g. in the United States on the Lower Yuba river and Lower Mississippi river[20, 110]. In China on the Yellow river and along the Ningxia-Inner Mongolia reaches of the Yellow river, in Australia on the lower Pages river[128], in Italy on the Tammaro river[125], in Bangladesh on the Manu river and Jamuna river[112, 113], in the Romania on Someşu Mic river[131], in Spain on Jarama and Tagus rivers and several river reaches on Ebro basin [115, 116] and locally on the Gangetic plains [117, 118] and Brahmaputra plain [109], [136]. Lower reaches of the rivers frequently alter its course due to different tectonic tilting, hydrological variability and sedimentological readjustments [15, 111, 118, 120, 120–122] and lower Ramganga river have no exception.

Nikolakopoulos et al. (2007b)studied the Alfios river in Greece to map the network shape transformation for the period 1977–2000 using PCA and GIS techniques on multitemporal and multisensor satellite images and concluded that these changes in Alfiosriver basin hadbeen caused by human activity. Erskine (2011b) explained historical planform changes of lower Pages river in Australia due to autogenic (inherent in the river regime) or allogenic (driven by external changes) for better focus river management activities and river restoration work[14]. Magliulo et al. (2016) analysed the planform changes of Tammaro river (southern Italy) using GIS and historical maps between 1870 and 1955 and reported these changes took place because of scarce human impact on channel morphology[125]. Yang et al. (1999) demonstrated the utility of remote sensing data with GIS for investigating the channel migration in the active Yellow river Delta, China and concluded that these changes are related to modifications in the proportion of water discharge and sediment load caused by the complicated interaction between humans and the environment[142].

Geomorphologists have noticed that the channel planform dynamics is a major problem in Himalayan rivers which always shifted channel in their lower reaches [16, 24, 26]. Satellite remote sensing data and historical topographic maps provided an enormous opportunity for fluvial geomorphologists to understand the channel planform dynamics, particularly for long and extremely moveable rivers due to the broad areal coverage, synoptic view and frequent data acquisition capability [117, 118]. Remote Sensing and Geographic Information System (GIS) becomes suitable for analysing and monitoring the rivererosion and its central line shifting [12, 130–133]. The development of GIS has enhanced the capacity of the researcher to determine planform characteristics, e.g., changes in length, centerline migration, and sinuosity index, etc. by combining the images on river planform from different sources. Ramganga has a meandering nature in its lower reach due to frequent floods. In each channel shift, a large number of the population of that area got affected concerning the loss of land, life, property and they had to settle elsewhere. This area has remained underdeveloped due to infrastructure damage by the meandering river [150].

The main objectives of this chapter are to (i) analyse the planform dynamics occurring in the lower reaches of the Ramganga and to (ii) understand the role of flood plain topographyin channel planform dynamics. Analysis of these dynamics will be useful to provide information for future management activities like construction of bridges, roads, embankments and other infrastructure activities.

4.2 Data

In this study, historical topographic maps of Rennell's Map (1780) and US Army survey maps (1923) are used along with Landsat data. Numerous scholars used topographic maps to delineate the historical river course of that time, which gives evidence about historical planform changes [14, 128, 135–137]. SRTM based digital elevation models are also used to generate topographic profiles across the Ramganga river and the adjoining floodplain. A major problem with the Landsat data is gaps in the time- series to present the study area. The river is a dynamic system, and the major planform changes take place during the monsoon season (June-September). Post-monsoon, cloud-free images have been collected for decadal assessment of channel planform dynamics in the study reach. The satellite-based remote sensing and the historical topographic map are useful in investigating river dynamics over a natural fluvial system spatially and temporally [143, 144].

In the present study, various thematic maps of the study area have been prepared from the historical topographic data and high-resolution satellite images collected from different sources as given (Table.4.1).

Table 4.1 Spatial data source

Data	Scale/ Resolution(Meter)	Year/date	Source
A map of the north part of Hindostan	1:480,000	1780	A map of the north part of Hindostan
Topographic sheets	1:2,50,000	1923	US Army Map
Landsat MSS	80 m	1973	USGS
Landsat MSS	80 m	1981	USGS
Landsat TM	30 m	1990	USGS
Landsat ETM+	30 m	2000	USGS
Landsat TM	30 m	2010	USGS
Landsat OLI	30 m	2017	USGS
SRTM Dem	30m/1-ARC	2014	USGS
Geological Quadrangle Map	1:2,50,000	1977	Geological Survey of India
Topographic sheets	1: 50,000	2006	Survey of India

4.3 Methodology

Geoinformatics based tools and techniques provide an excellent opportunity to measure the properties of the natural fluvial environment and model the channel planform dynamics in a GIS environment.Assessment of channel planform dynamics required a standard spatial data sets, for this following remote sensing data processing step were fallowed.

4.3.1 Controlling for Discharge

As the planform of a river at a given point in time is dependent on discharge (and consequently stage), it was necessary to control the discharge in the channel to allow comparison between the two remote sensing image[8]. The ideal condition for such comparison is found in the month of November and December, so mainly images were downloaded for these months. In this period the river stages are sufficient to fill the main channel with the water. In some images, widespread cloud cover existed, so data were not useful. The data between January and May of the next year were considered for channel planform mapping. To check the flow stability in downstream of Ramganga river, the discharge data from Dabri gauging station covering 34 years period from 1985-2018 were collected from the central water commission (CWC) (Fig. 4.1). This figure shows the discharge is a constant inflow to fulfil the channel during the post-monsoon period, e.g. November to May. So, these months are suitable for the collection of remote sensing images.

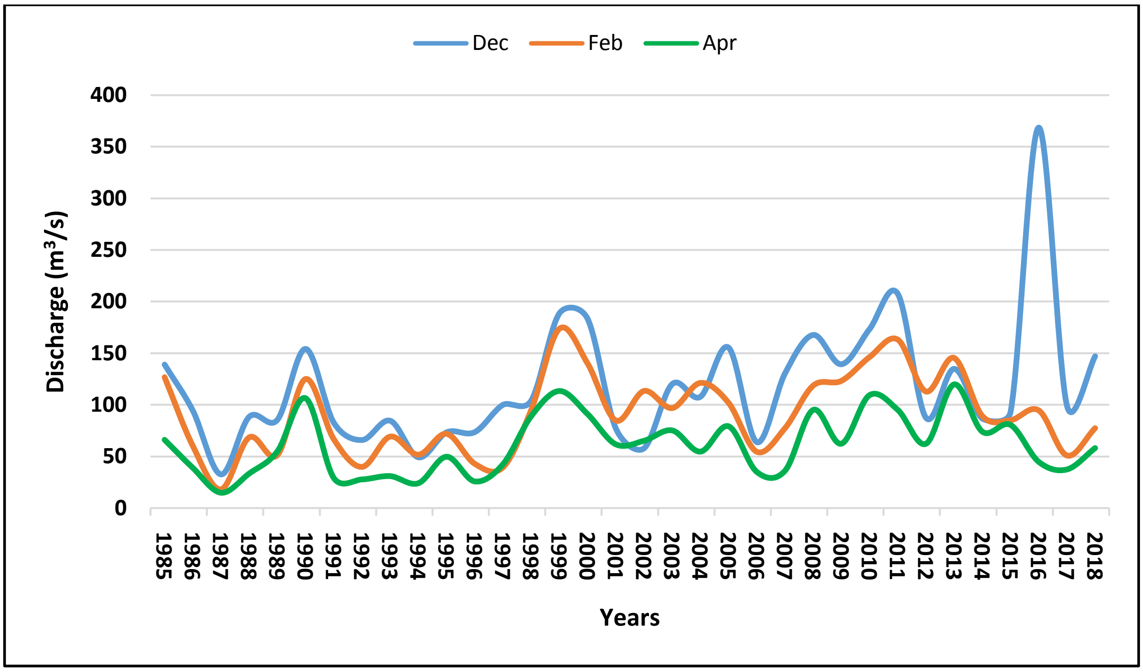

Figure 4.1 Monthly average discharge for three months plotted against the year from 1985 to 2018 for the Ramganga river at Dabri hydrological station (Data Source: CWC,2019)

4.3.2 Georectification

Open series topographic map (OSM) of SOI for the year 2006 were georeferenced and used as a base map, and all other images of Landsat MSS and ETM+ were georectified to the topographic map. Any differences with respect to the topographic maps in the positions of permanent features in the MSS and ETM+ images were corrected by polynomial georectification (image warping coupled with pixel re-sampling) based on ground control points (GCPs) [161]. All the topographic sheets were individually ‘georeferenced’ using the second-order of polynomial transformation with the nearest neighbour resampling method based on the selected 135 GCPs (Ground control points) along the river course [162]. GCPs were assigned to characteristic objects (road intersection, villages near to the course of the river, fort, bridge, etc.), which are common in both the existing and the historical maps[163]. The root mean square (RMS) error was estimated to evaluate the georeferencing of toposheets, which was found 0.946. The topographic sheets were registered on the satellite image in a GIS environment using the standard parameters like Projection Type-UTM Zone 44 N, Spheroid-WGS 84, and Datum-WGS 84. All remote sensing images resampled 30 m to bring them on the same spatial resolution [161]. The majority of satellite images were taken in November and December when the river discharge is sufficient to fill the main channel but comparatively constant from year-to-year, and the area is generally cloud-free, as it is the dry season [12]. Riverbank line was digitized using the water boundary to denote the edge of the channel because this boundary is clearly defined in Landsat images and in the topographic sheets [164]. The superimposed bank lines provide the complete channel migration configuration of the river from 1780 to 2017.

The georeferencing process involved three steps (i) matching the GCPs with common features in the base layer, (ii) transforming the GCPs to the UTM WGS 84 coordinate system and (iii) pixel re-sampling. The GCP selection was made using the well-established technique of hardpoint selection along the river[149, 150].The GCPs were evenly distributed along the river to provide a stable image warp. When choosing

GCPs, both hard (road crossings, canals, etc.) and soft points (corners of waterbodies, features with fuzzy edges) were considered. Hardpoints should be considered in preference to soft points to increase georectification accuracy [63], but in the fluvial environment,all soft points could not be excluded. During polynomial transformation,second-order of polynomial transformation was selected with the nearest neighbour resampling method. The differences in location between GCPs on the transformed layer and the base layer were represented by the root-mean-square error (RMSE) equation given below (Eq. 4.1)[167].

$$RMSE = [(X_s - X_r)^2 + (Y_s - Y_r)^2]^{1/2} \quad (4.1)$$

Where X_s and Y_s are geospatial co-ordinates of the point on the source image, and X_r and Y_r are co-ordinates of the same point on the transformed image.The RMSE for an image with *n* validation points is assessed as follows (Eq. 4.2)[168].

$$RMSE = \left[\frac{\sum_{i=1}^{n}[(X_s - X_r)^2 + (Y_s - Y_r)^2]}{n}\right]^{1/2} \quad (4.2)$$

The average RMSE of the whole image was less than 1 pixel. Resampling of the pixels then was conducted using the nearest neighbour function as it retains the original pixel values [63].

4.3.3 Controlling the Variation in Spatial Resolution

The time-series data from the Landsat archives have images of multiple spatial resolutions varying from 80 m to 30 m. Thus, it was, necessary to standardize the spatial resolution so that meaningful comparisons could be made [169]. To facilitate comparison between images of different dates, all remote sensing image resampled 30 m to bring them on the same spatial resolution.This meant that the spatial complexity was reduced in all images, and 30 m spatial resolution was adequate to reveal the significant thematic and spatial characteristics required for the study[170].

4.3.4 Vectorization of river planform

Riverbank line was digitized using the water boundary to denote the edge of the channel because this boundary is clearly defined in Landsat images and in the topographic sheets [164]. Initially, mapping of the wetted channel was tested using digital image classification techniques (supervised/ unsupervised classification techniques).This digital image classification was not found suitable for mapping of such dynamic rivers. The riverbank line and channel bar boundary could not be accurately mapped due to mixed pixels and similarities in the spectral signature of the sand in the point bars and wetland areas which are highly moisture-laden. The channel backlines, as well as the channel bar boundaries, were digitized as polylines in ArcGIS editing environment and the data were also checked for cartographic accuracy and topology errors such as overshoot, undershoot and unresolved line segment intersections.

4.3.5 Channel shifting

River channels centerlines are a common mechanism for replacing wide rivers channels with equivalent narrow rivers in a network[171].The rive centerlines can be traced manually and also generated automatically in the GIS environment. In this research, channel centerline is mapped at 20m interval in FluvialCorridor toolbox in Arc GIS 10 [172]. The centerline of a river describes the midpoint along the length of the river and measurements of lateral shifting can be done based on river centerline movement. The lateral channel shifting between two dates is calculated as the difference in the position of the channel centerline across the floodplain. The two-channel centerlines referring to the two dates are placed in a unique map from this map its configuration of channel planform dynamics can be studied. The superimposed bank centerlines of two different dates provide the complete channel migration configuration of the Ramganga river from 1780 to 2017.

The ratio of the curvilinear length to the straight (shortest) length between the endpoints of the river is known as the sinuosity index. Sinuosity is used as an indicator of channel behaviour which determines whether a channel is straight or meandering. Sinuosity index of the present studies was measured using the method given by Friend &Sinha (1993). In this method, the reach was divided into equal-length reaches. The river in window A is divided into seven reaches, and in window B the river is divided into five reaches.Further, the actual channel length and the straight path length were measured, and then the sinuosity index was calculated using the following equation for each reach (Eq. 4.16):

$$P = \frac{L_{cmax}}{L_R} \quad (4.1)$$

Where P is sinuosity index, L_{cmax} is the length of the midline of the channel (in single-channel) or the widest channel (in multi-channel) of the reach, and $L_R$is the overall length of the reach. The channel's pattern classification was done according to Rust (1978) and is illustrated in Table (4.2).

Table 4.2 Classification of channel pattern.

River	P	Classification of channel pattern
Single channel	<1.5	Straight
	>1.5	Sinuous
Multiple channels	<1.5	Braided
	>1.5	Anastomosing

The topographic analysis was carried out using SRTM DEM data with 30 m spatial resolution (Fig. 4.2). A DEM (Digital Elevation Model) was also generated using 80 elevation points from Survey of India topographic map (OSM sheet). The accuracy analysis of the DEM data was carried out through 20 random elevation points with the root mean square error of 1.58 m (max vertical error < 4 m) in the present study[143], [174]. DEM shows that the current study area has a maximum elevation of ~167 m in the North direction while an average height of ~106 m in the southwest direction.

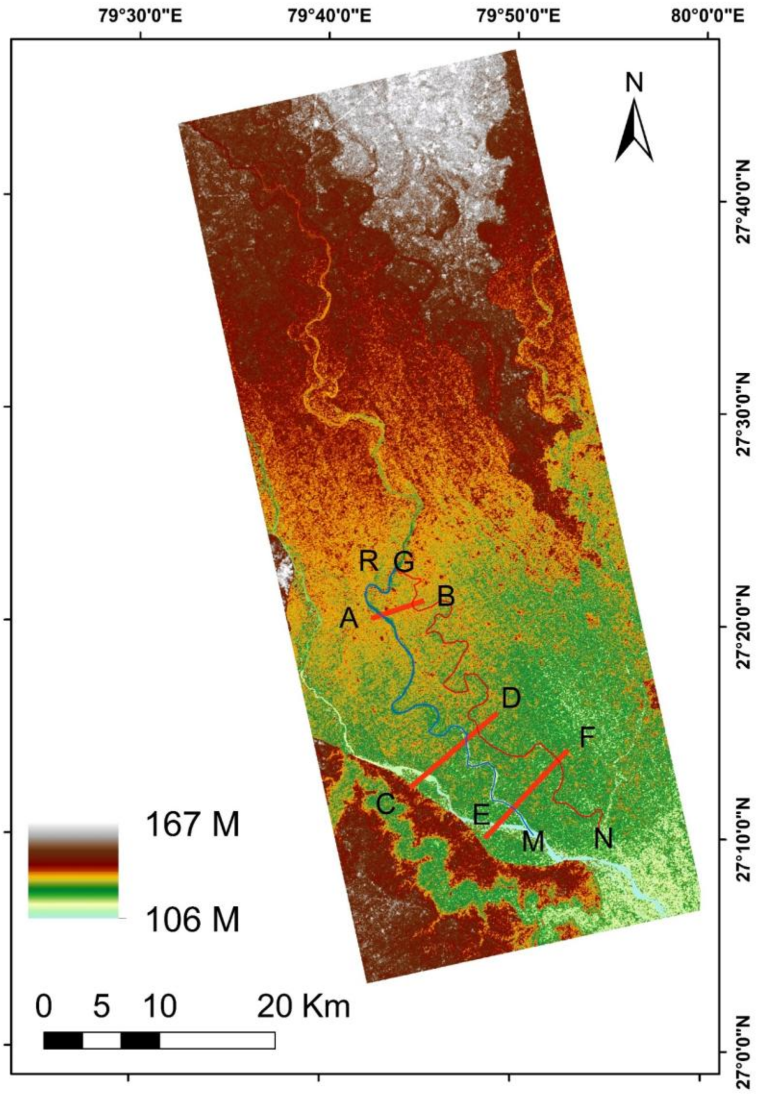

Figure 4.2 SRTM DEM of the Study Area.

4.4 Results

4.4.1 Channel morphology and topographic analysis

The satellite images and topographic maps displayed that the lower Ramganga is a meandering river (Fig. 4.8). The river length increased and decreased during several phases historically, leading to corresponding changes in the sinuosity index.

In segment A, the Ramganga River observed to be straight single-channel in a small-scale map of Rennels (1780) with a sinuosity parameter <1.5 in both reaches (Fig. 4.3). Several scholars used the map of Rennels (1780) to delineate the historical river course of that time, which gives evidence about historical planform changes in that section[128,147,148,159,160].From 1923 to 2017 the Ramganga is displaying meandering nature at all sections. The given figure depicts the sinuosity index of the Ramganga river in the upstream area (Window A) for different years (Fig 4.3). In 1923 the sinuosity index varied (1.32–2.40) in all segments. In 1973, the sinuosity parameters were relatively high, and all the values were more than 1.50. In 1981 the sinuosity showed relatively low values (1.09–1.31) except in segment 3.

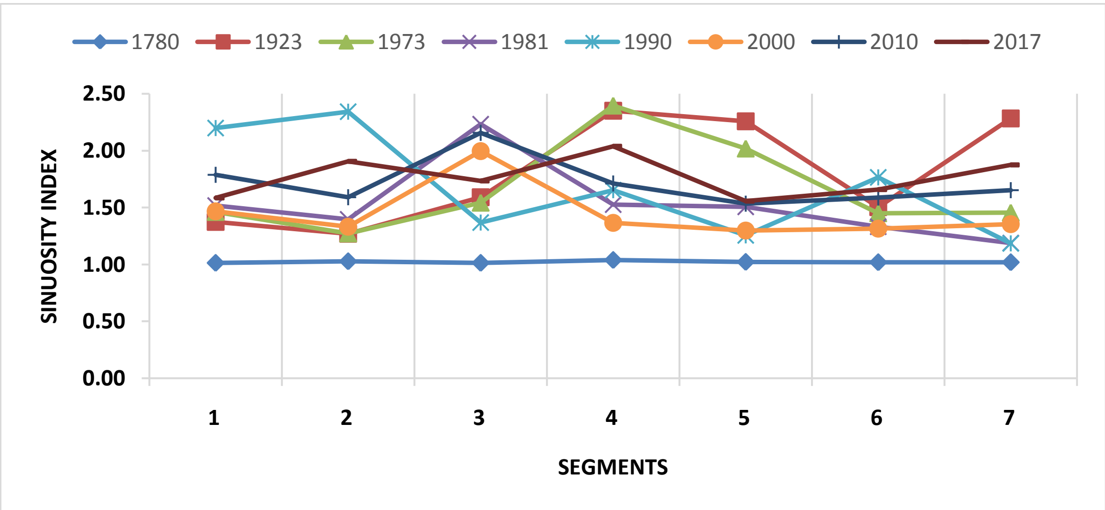

Figure 4.3 Temporal changes of sinuosity in the upstream area.

In 1990, the sinuosity parameters decreased sharply except segment 1 and 2 with a change in the channel pattern. In 2000 only segment 3 shows the high sinuosity index (>1.5) and all other segment are straight in nature. In 2010 and 2017 relatively high values of sinuosity (>1.5) are observed in all segments which show the present meandering nature of Ramganga in the present study.

Segment B, displays the sinuosity index in the downstream area for different years, Fig. (4.4). In 1780 the river showed straight nature in all segment with sinuosity index ~1. In 1923 the sinuosity index varied (1.35–2.30) during the period of study for all segments. In 1973, the sinuosity parameters were relatively low (<1.5) from segment two to the confluence of Ganga and Ramganga. In 1981 the sinuosity showed relatively high values (1.35-2.0) in all segment. In 1990, the sinuosity parameters increased sharply except segment 2, which shows highly meandering nature in the downstream area. In 2000 only segment 3, shows the high sinuosity index (>2.0) and all other segment displays the sinuosity parameter between (1.30-1.50). In 2010 sinuosity parameter varies from 1.30-1.60 and 2017 shows relatively high values of sinuosity (>1.5) in all segment except downstream segments, which shows the present meandering nature of Ramganga.

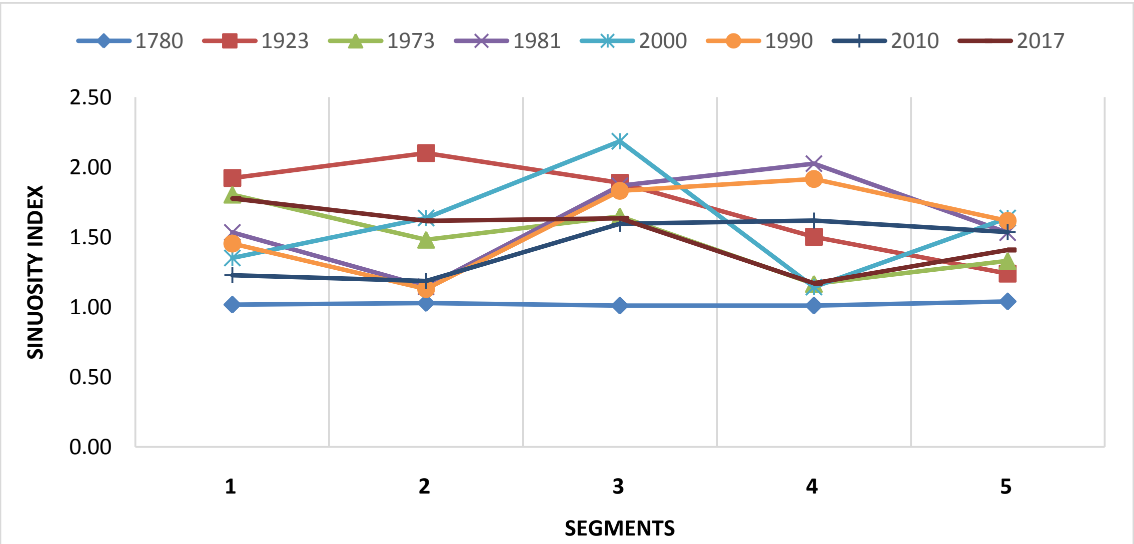

Figure 4.4 Temporal changes of sinuosity in the downstream area.

Digital Elevation Model (DEM) is a quantitative representation of terrain and is important for hydrological applications [177].The horizontal topographic profiles mapped from DEM data in the lower reach of Ramganga display the average topographic elevation in the downstream area (Fig. 4.5). Elevation profile along AB transect shows the valley of Ramganga is deep and wider than the Gambhiri river. Elevation profile CD shows the relative depth of all channel in which the Ganga is shown deepest followed by Ramganga, Sota nala, and Gambhiri naddi (Fig. 4.7).

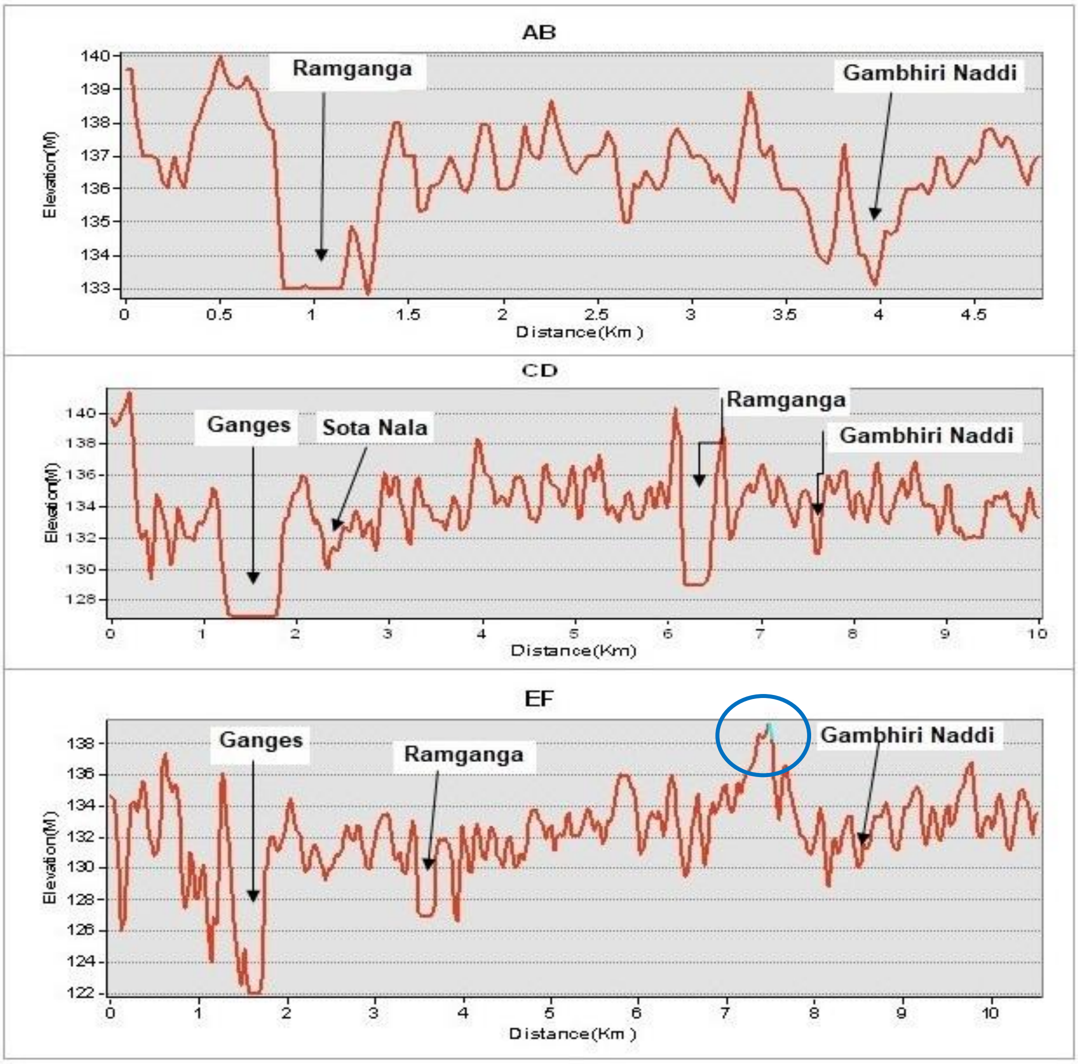

Figure 4.5 Topographic profiles extracted from SRTM DEM (vertical error < 4 m) along the selected sections (AB, BC, and CD).

The Sota Nala is separated bya natural levee which is approximately 0.5 km wide. These natural levee is eroded during high flood then it joins Gangariver or sometimes it allows to join Ramganga further downstream in Ramganga. The natural levee deposits acted as a natural embankment, and once the embankment was breached due to floods, the river started to follow the through deeper channel[174]. Elevation profile (EF) shows that due tothe presence of natural levee (represented by the blue circle) between Gambhiri Naddi and Ramganga it joins the Garra River in further downstream.

Moreover, the channel flowing south of the Patipalpur village Ramganga (Kunda Nala) displays a depression inits longitudinal profile in comparison to the upstream channel (Gambhiri Naddi) (Fig. 4.6). Longitudinal profiles display that topographic elevation along the new channel (Kunda Nala) is 3.0–4.0 m lower than that of the older channel (Ghmbhiri Naddi). This difference in slope between the two channels is the main cause of shifting the planform of the Ramganga river (Gambhiri Naddi).

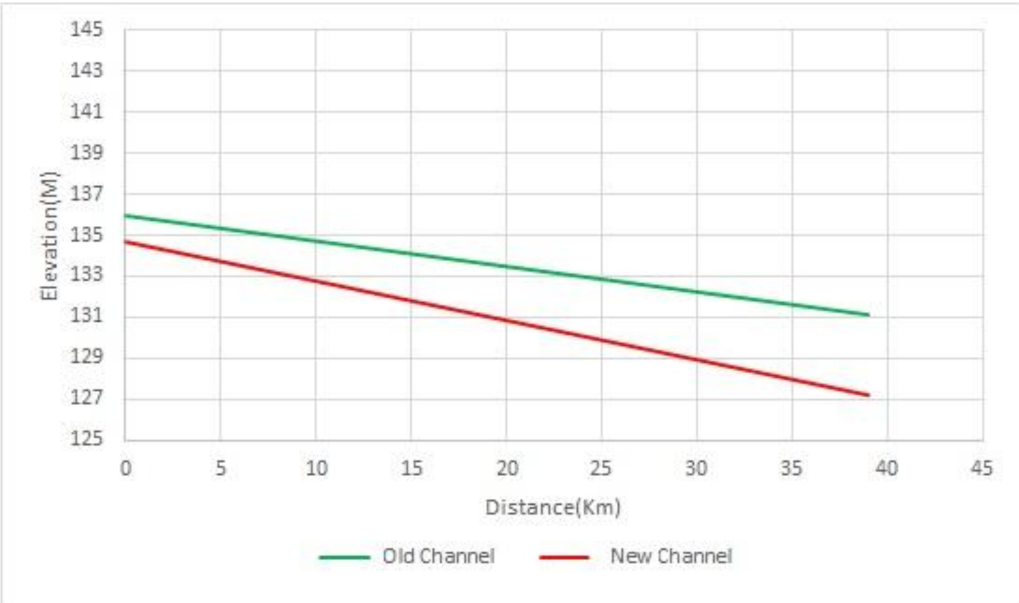

Figure 4.6 Longitudinal profile of a segment of Ramganga river of old (Gambhiri river) and new course (Kunda nala).

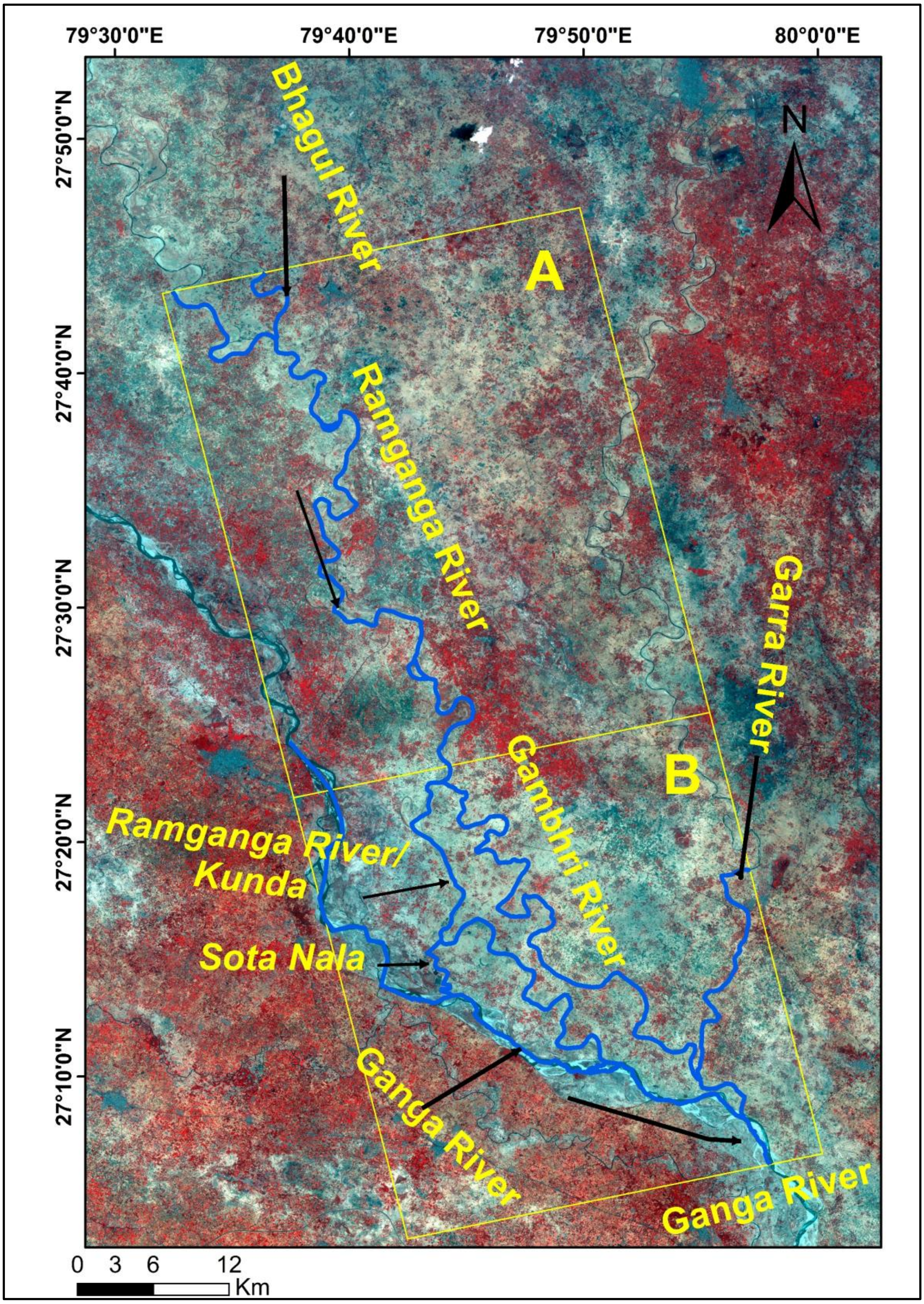

Figure 4.7Channel configuration in the lower course of Ramganga river

4.4.2 Centerline migration

The centerline of a river describes the midpoint along the length of the river and measurements of lateral shifting can be done on the basis of river centerline movement. The centerline of a channel changes temporally due to the siltation problem of the channel, whereas the width of a channel may shift due to the bank erosion [109].The overall shifting of the Ramganga river is towards the south-west direction, which follows the regional slope towards the Ganga river. The upstream in segment A is showing the continuous shifting and meandering in its floodplains while downstream in segment B showing south-west direction (Fig. 4.8). The variation of the channel centerline is very high from 1780 to 2017 and observed 7.18 km shifting near the confluence of Ramganga and Baghul river as shown in segment A,(see inset map (Fig. 4.8)).While the planform change between 1922 and 2017 was comparatively high (~4 km) and repeatedly oscillated in its floodplain. The river centerline displayed significant shifting at the upstream. Further, itwas observed that the river left its course in 1780 and moved towards south-west in 1922.So that Baghul river occupied its previous channel in 1972. The confluence of Baghul river and Ramganga river shifted 4.96 km upstream side from 1972 to 2017.

In segment B, Ramganga river shows the migration trend towards the south-west direction in downstream where the lower segment showed the large-scale dynamics of planform in which river left its old course and occupied a new channel (Fig. 4.8). This shifting was considered as the major evolutionary stage of the river. During, 1922 there was a narrow distributary of Ramganga called *Kunda nala,* bifurcated from the western side of Rampura village, which become a major channel in 1972.The previous channel of Ramganga is now known as Ghambhiri, which becomes the abandoned channel of Ramganga.

The dynamics of meander migration from 1972 to 2017, which is shifting towards the south-western side and maximum shifting is 2.5 km (see inset map (Segment B)). Segment B shows the maximum migration of centerline from 1780 to 2017 is 7.36 km. Roy and Sinha (2007) have studied about confluence dynamics of Ganga and Ramganga rivers and concluded that Ganga and Ramganga confluence shifted approximately 20 km towards west from 1911 to 1970. In the present study, the confluence shifted 10.58 km toward the west from 1780 to 2017. It shows a highly dynamic nature of confluence of Ganga and Ramganga rivers.

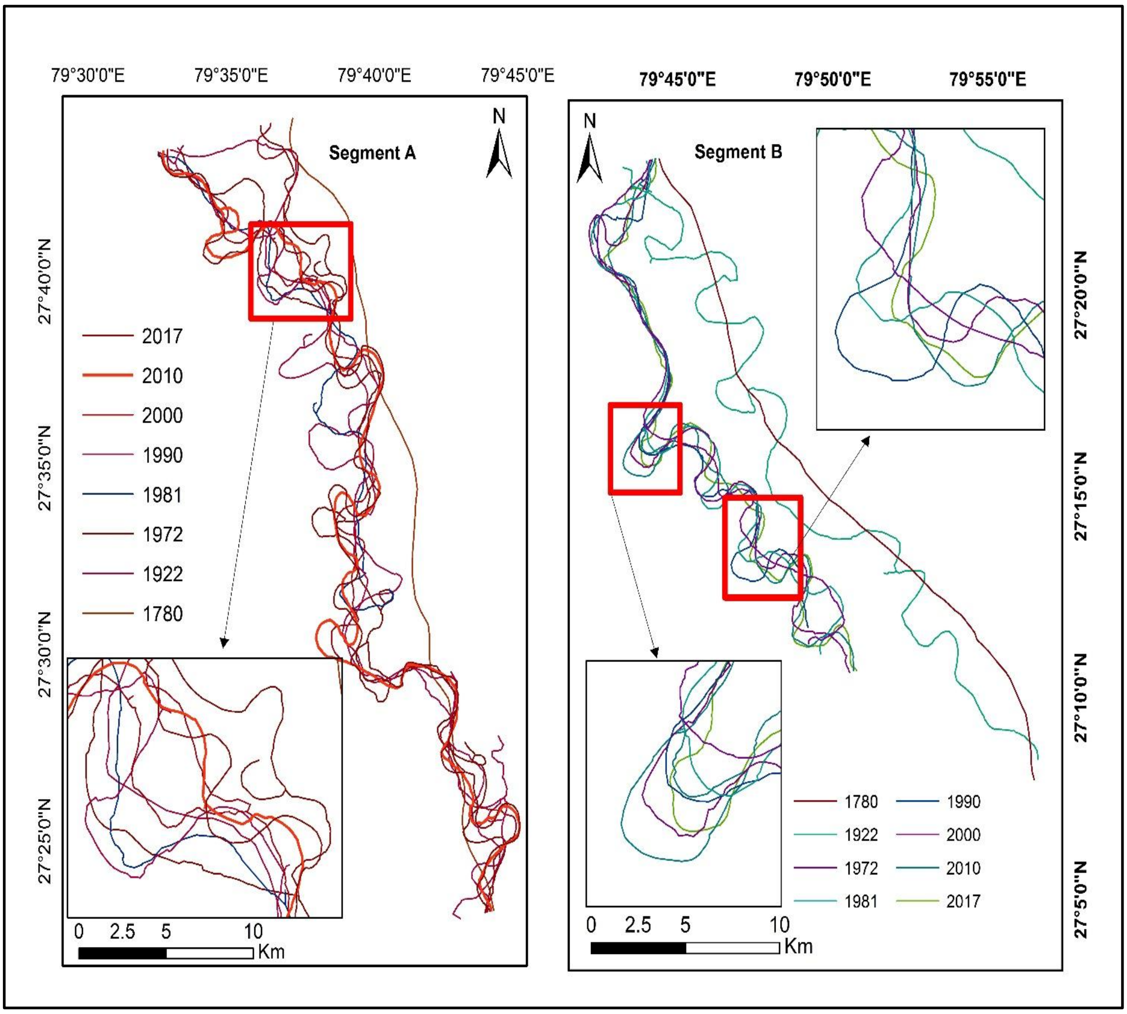

Figure 4.8River Centerline dynamics in two Segment over a 237-year period.

4.4.3 Planform Dynamics in Segment A

The channel of the Ramganga expanded, contracted, and adjusted its planform to response the occurrences of high and low flow during the study periods. Systematic mapping of river planform for the period 1780-2017 shows the gradual movement of the Ramganga river towards the south-western side during 1780 to1923 (Fig. 4.9). The upper reach of the Ramganga river movestowards the west while south reach moves towards the east, and due to this shifting few meanders was developed (A of Fig. 4.9). Furthermore, the old river was changed into a sinuous channel which displayed as an overall increase of sinuosity from 1.05 to 2.06. The settlements between this shifted channel, e.g., the village Garhi Aurangabad (Ga) and Kundauli (K) have been completely eroded due to westward shifting of the channel from 1780 to 1923. (B of Fig. 4.9). On the other hand, the confluence of River Bhghul river moves southward in the upstream reaches near to the Garhi Aurangabad (Ga) village between 1923 and 1973. However, two cutoffs have taken place near the village Rulapur (R) and Ratanpur Pamaran (Rp). It moved ~ 5 km towards the west and made a huge meander loop near to the village Miyan Patti (Mp).

Further, an assessment between 1973 and 1981 (C of Fig. 4.9) reveals that the channel displays a significant shift in the upstream reaches near Kundauli (K) village. It shows shifting of ~4km towards the south-west of the Ratanpur Pamaran (Rp). A cutoff has been formed near the village of Miyan Patti (Mp) which makes it straight in this region. One another cutoff has been formed and shifted ~3 km towards the west in the downstream part near the Barhauli (B) village. A remarkable change has been observed from 1981 to 1990 in the study area (D of Fig. 4.9). The confluence of Baghul river and Ramganga have moved ~ 5 km towards upstream. A cut-off, of ~5 km has been formed between Rulapur (Ru) and Ratanpur Pamaran (Rp), where river shifted towards the west to its previous course of 1922. The stretches between the Ratanpur Pamaran (Rp) and Rampur Patti (Rp) were relatively stable, showing less fluctuation in planform.

Further, by studying the maps of the year 1990 to 2000, a more important shifting has been observed in the present study area (E of Fig. 4.9). One cutoff has been formed in the upstream of Bhagul river near Garhi Aurangabad (Ga) village and follows a straight path. One meander loop is formed near Rajepur (R) village. The downstream channel doesn't show any significant change. There was a substantial shift of the channel planform during 2000–2010 (F of Fig. 4.9). The movement was observed toward the west and with an outward shifting of the river in upstream of Aurangabad (Ab). During this period an extreme movement has been taken place near to the village Rampur Patti (R), and the west bankline moved 1.2 km towards the west. An assessment of images between 2010 and 2017 displays that river did not shift much more, but two cutoffs have been formed, one near to the Aurangabad (Ab) village and another to the Rajepur (Rj) village which reduced the length of the channel from 81.73 km to 80.47 km (F of Fig. 4.9). Ratanpur Pamaran (Rp), Miyan Patti (Mp) and Kamaluddeen Pur (Kp) villages were located outside the channel belt while Aurangabad (Ab), Barhauli (B) and Kundauli (K) are located in flood region which area is prone to erosion.

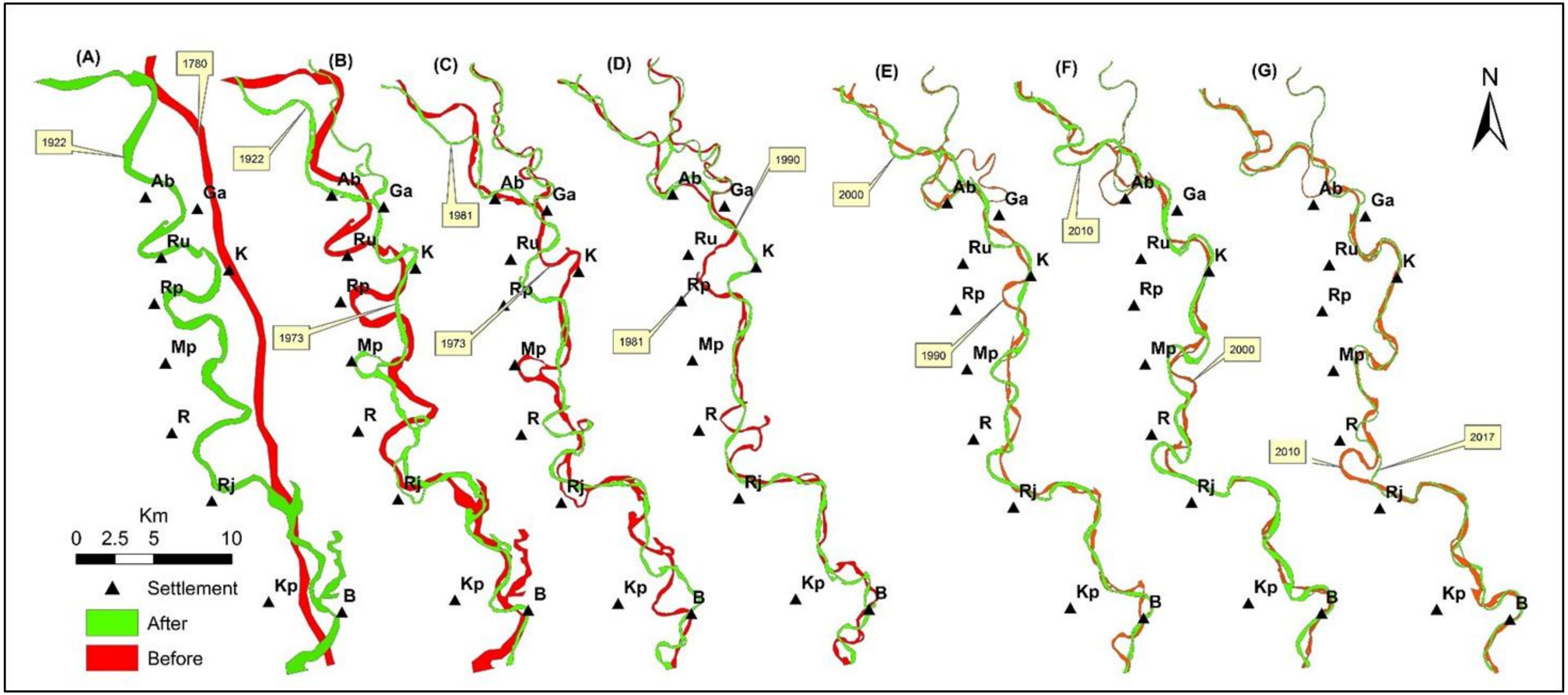

Figure 4.9 Systematic reconstruction of Planform dynamics in Segment A for the period 1780 to 2017 (Miyan Patti-Mp, Garhi Aurangabad-Ga, Rulapur-Ru, Auranga Bad-Ab, Kundauli-K, RatanpurPamaran-Rp, Rajepur-Rj, Kamaluddeen Pur-Kp, Ramapur Patti-R, Barhauli-B)

4.4.4 Planform Dynamics in Segment B

Temporally assessment of river planform in segment B shows a gradual movement of the channel towards the south-west direction for the period 1780 to 1922 (A of Fig. 4.10). In the year 1780, the channel was wide and straight, but in 1922 it displays a significant change in planform. Ramganga river bifurcated into one more minor channel near to the village Patti Palpur (Pp) called *KundaNala*. The Gambhiri *Naddi* currently occupies the abandoned channel of the Ramganga river. Gambhiri*Naddi* started to meander in 1922 (Fig. 4.10 (A). The Ramganga river avulsed by about 7 km into *Kunda Nala* to its west in between 1911 to1973 (Fig. 4.10 (B)) [47].

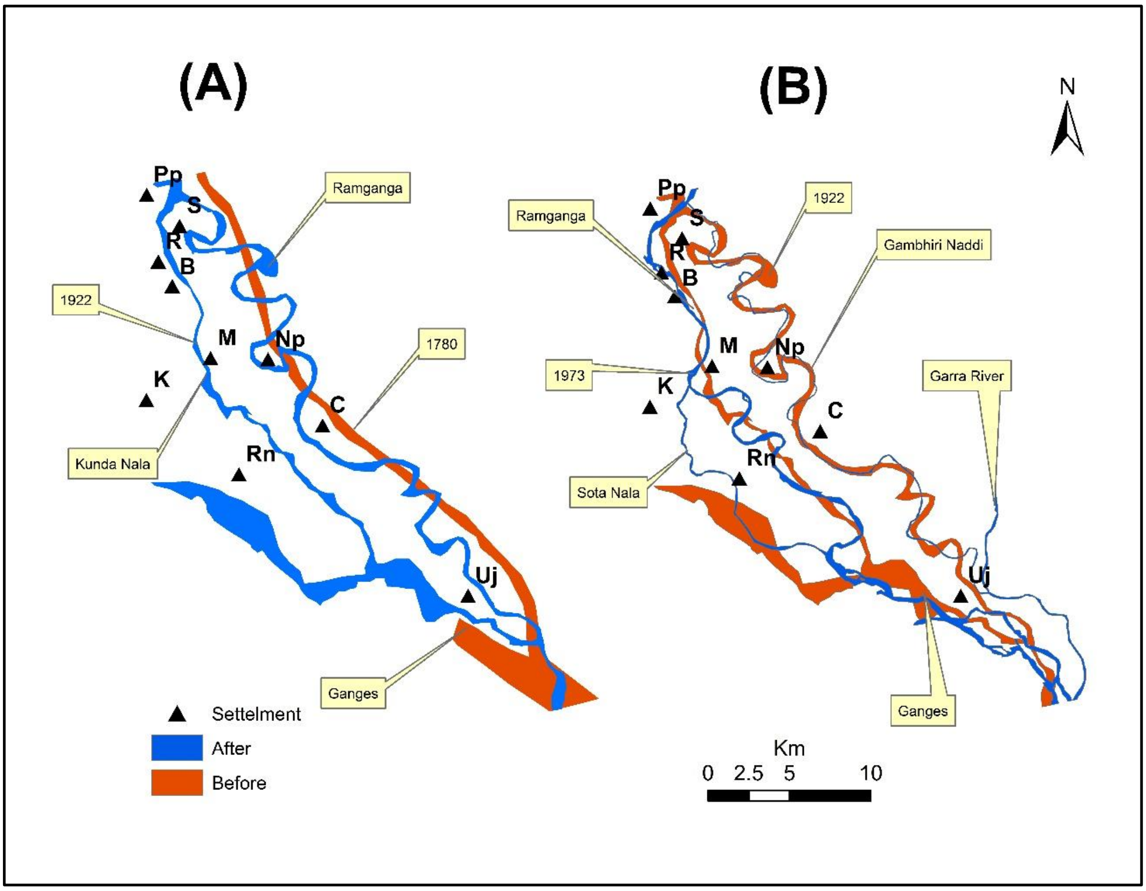

Figure 4.10 Systematic reconstruction of Planform dynamics in Segment B for the period 1780 to 1922 (Patti Palpur-Pp, Shyampur-S, Bari-B, Kurhar-K, Chaunsar-C, Umrauli Jaitpur-Uj, Ram Nagar-Rn, Rabiyapur-R, Mastapur-M, Naun purwa-Np).

In 1973, the width of Gambhiri*Naddi* river was narrowed down due to a decrease in the flow because of one a channel called *Sota Nala* bifurcated from its downstream near the village Kurhar (K). The 1973 maps display two huge meander bends of the Ramganga between Mastapur (M) and Ram Nagar (Rn) (Fig. 4.10 (B)) .Gambhiri*Naddi* joined the Ganga river downstream in 1922, but in 1973 its confluence is shifted towards the north and joins the Garra river.

An evaluation of maps between 1973 and 1981 shows that river planform did not significantly change (Fig. 4.11 (A)). Between village Mastapur (M) and Ram Nagar (Rn) sinuosity increases due to the formation of meander near to these two villages. *Sota Nala* shifted southward in downstream near to the confluence of Ganga and Ramganga river.

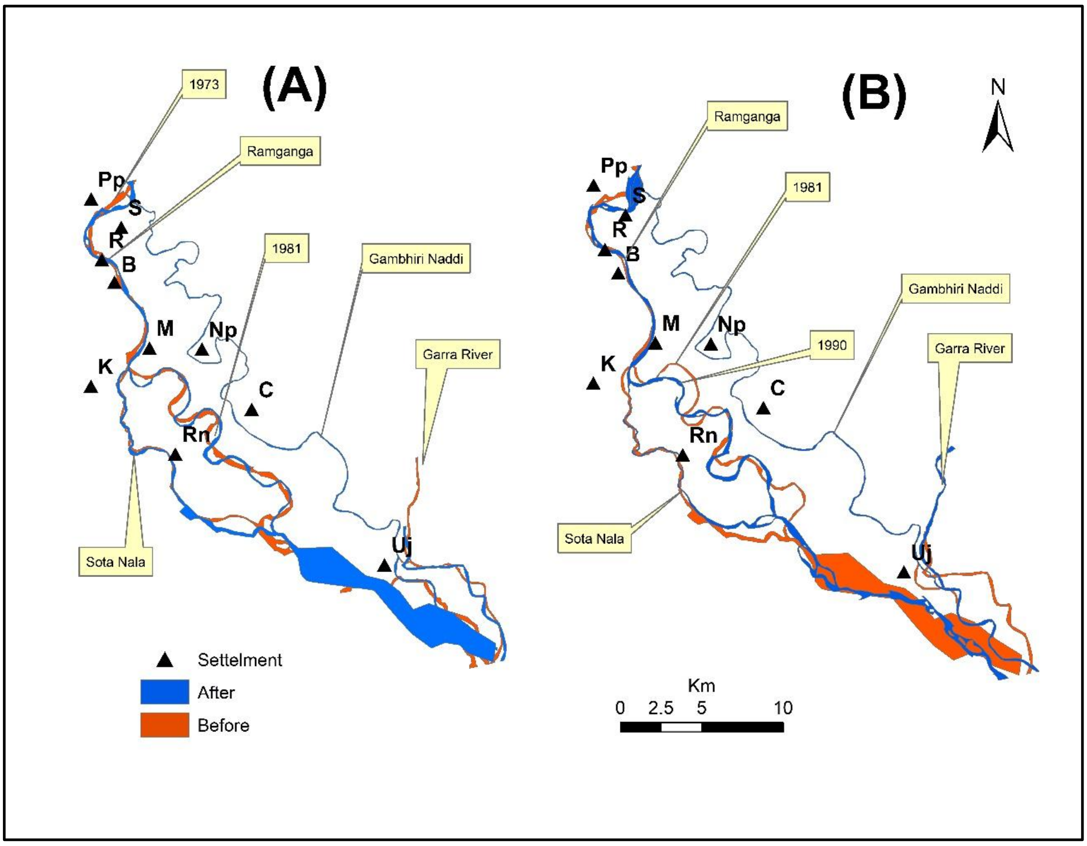

Figure 4.11 Systematic reconstruction of Planform dynamics in Segment B for the period 1773 to 1990 (Patti palpur-Pp, Shyampur-S, Bari-B, Kurhar-K, Chaunsar-C, Umrauli Jaitpur-Uj, Ram Nagar-Rn, Rabiyapur-R, Mastapur-M, Naun purwa-Np)

The confluence of Ganga and Ramganga shifted downstream by 1.5 km. The width of the Gangariver increased and occupied its older channel of 1922. *Sota Nala*further joins Ramganga in downstream then merges into Ganga river.

The channel planform of the river was modified significantly between Mastapur (M) and Ram Nagar (Rn) during 1981 to1990 (Fig. 4.11 (B)). One meander is moving towards village Kurhar (K), which shifted the origin of *Sota Nala* southwards. Further downstream of Mastapur (M) village, meander reduced its size by ~5 km due to cut off. One another meander is moving towards south-west near the village Ram Nagar (Rn) in 1990 which increase the channel length by ~4 km. The confluence of Ganga and Ramganga shifted 2 km upward. There is no significant change observed in the morphology of Gambhiririver in these periods.

The width of the channel significantly increases near the Shyampur (S) during 1990 and 2000 (Fig. 4.12 (A)). One cutoff has been formed in the upstream near the village Rabiyapur (R) while the channel shifted to northwards. Channel follows a straight path between the Bari (B) and Mastapur (M), which is guided by a hidden geological structure (lineament) (Fig. 3.4). The origin of *Sota Nala* again shifted backward due to retreating of the meander to its previous course. *Sota Nala* has been joined the Ramganga river due to downstream movement of Gangariver in further downstream.

The river planform was modified considerably in the upstream near the village Rabiyapur (R) during 2000 to 2010, here one cut off has been formed, and river shifted to its previous channel of 1990 (Fig. 4.12 (B)). Gambhiririver does not show significant changes in this periods due to lack of water flow which is diverted towards the Ramganga river. During this period, there is no movement of the channel observed between the village Bari (B) and Mastapur (M). *Sota Nala* confluence is further shifted northward.

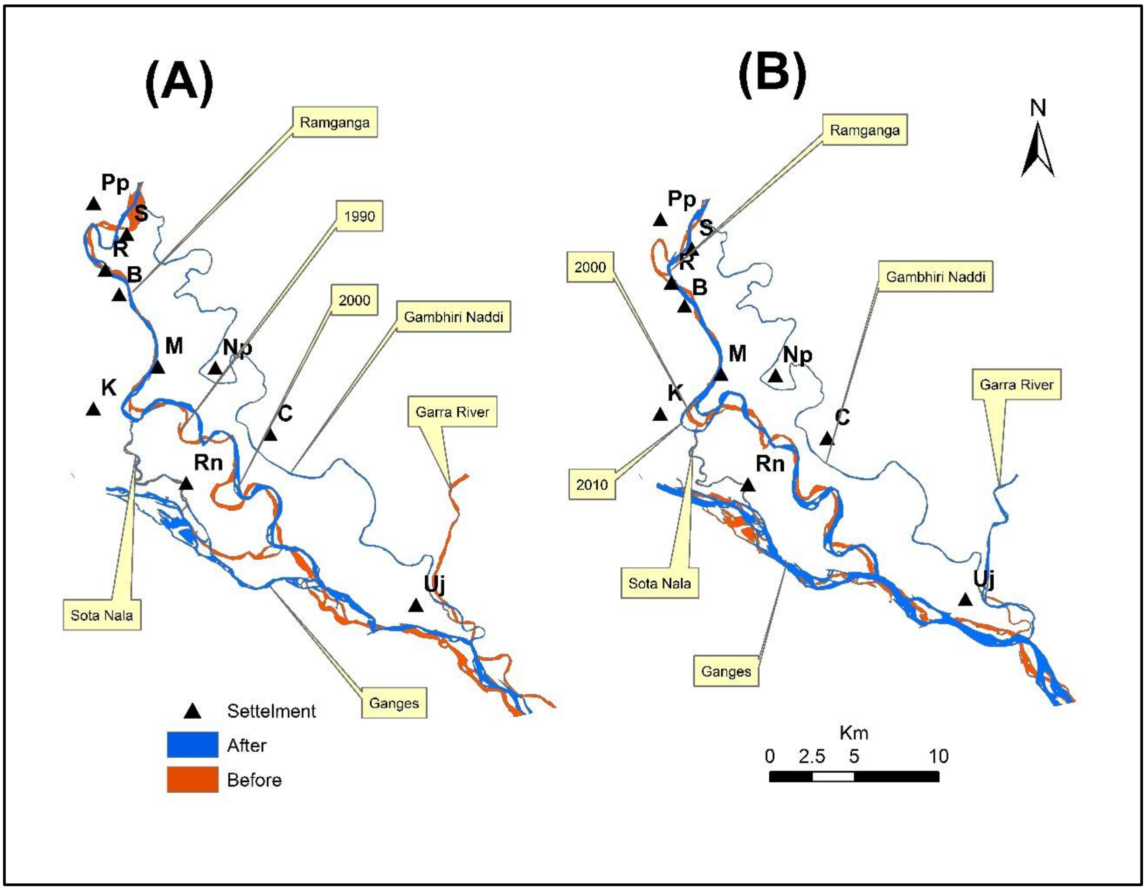

Figure 4.12Systematic reconstruction of Planform dynamics in Segment B for the period 1990 to 2010 (Patti palpur-Pp, Shyampur-S, Bari-B, Kurhar-K, Chaunsar-C, Umrauli Jaitpur-Uj, Ram Nagar-Rn, Rabiyapur-R, Mastapur-M, Naun purwa-Np).

Recently the river does not show any significant change during 2010 to 2017, and only channel meander retreated between the Kurhar (K) and Mastapur (M) village (Fig. 4.13). In this period between the villages, the Bari (B) and Mastapur (M) channel are highly stable and straight. It is the best site for engineering structure, (e.g., bridge road) because in this section very less shifting is observed during the study period.

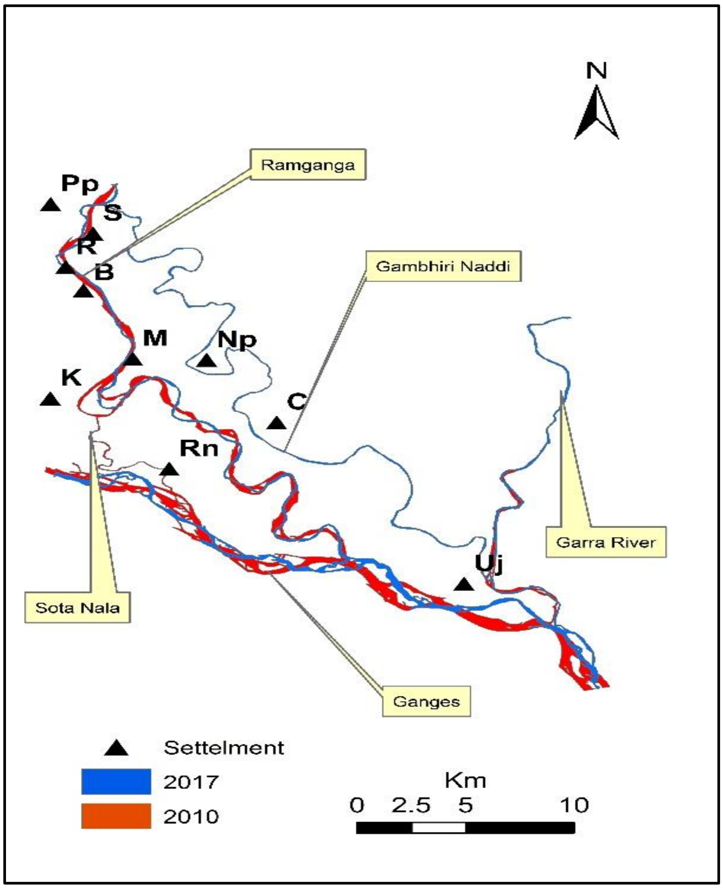

Figure 4.13 Systematic reconstruction of Planform dynamics in Segment A for the period 2010 to 2017 (Patti palpur-Pp, Shyampur-S, Bari-B, Kurhar-K, Chaunsar-C, Umrauli Jaitpur-Uj, Ram Nagar-Rn, Rabiyapur-R, Mastapur-M, Naun purwa-Np).

During the field survey, it is observed that the river has been undergoing extensive fluvial dynamics, as the river bank stratigraphy provide evidence of fluvial dynamics (Fig. 4.14). Different layers in the photographs of fluvial deposits are indicating sequential flood deposits(Fig. 4.14 (a)).One of the oldest flood deposit has taken place in the lower portion and recent one taking place in the upper strata, can be clearly recognized in the photographs. Half of the Barhauli village was eroded by the erosion process so that the major population of the village had shifteddue to the migration of river in the last 15 years (Fig. 4.14 (b)).

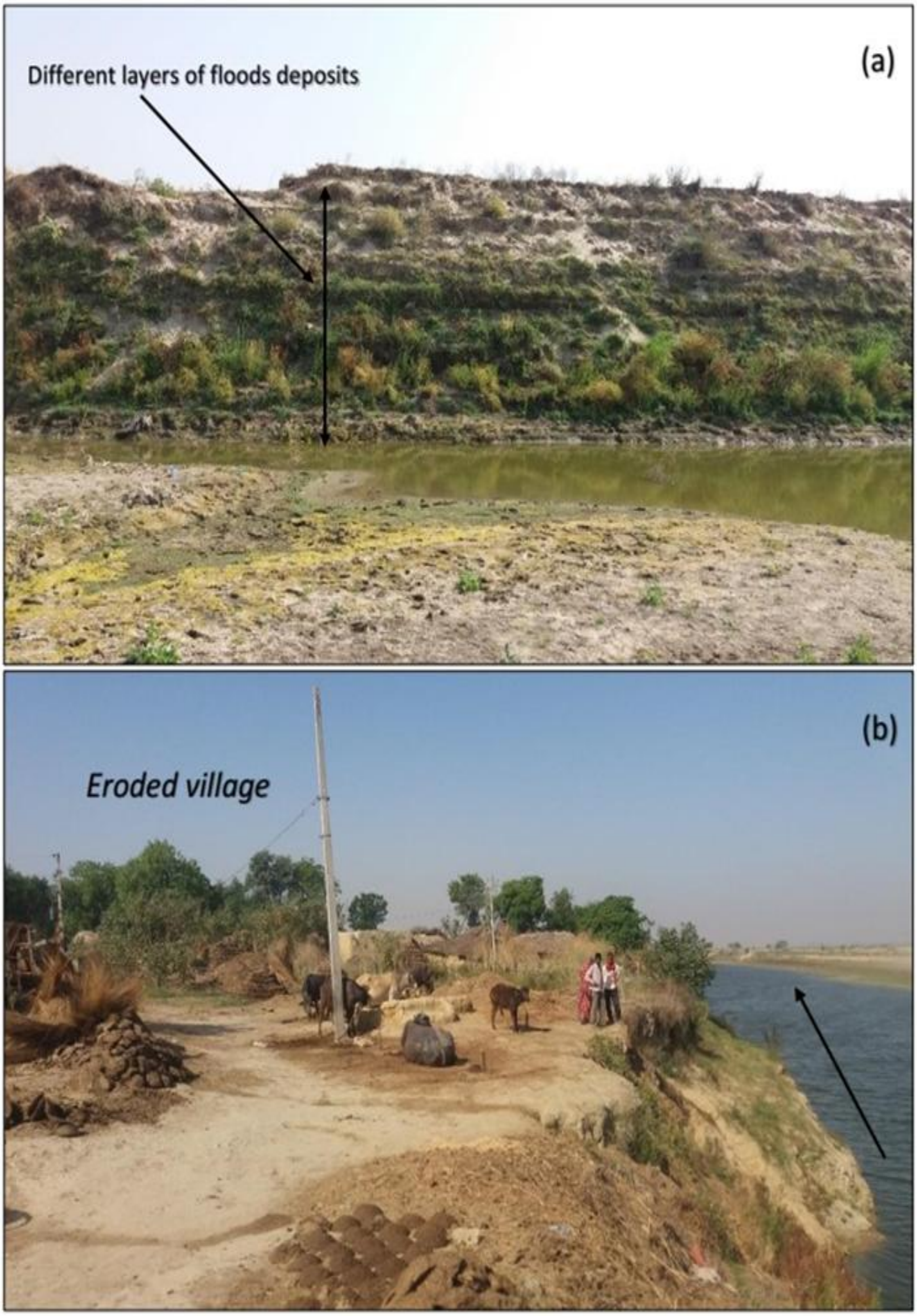

Figure 4.14 (a)Field photographs showing fluvial deposition during major flood events with layers provide clues about recent fluvial dynamics, (b) Severe erosion of left bank near the village Barhauli. The black arrow shows the direction of present-day flow.

The field photographs of the Gambhiri*Naddi* abandoned channel which is activated only during the monsoon season showing the past flow of river near the village Chaunsar (Fig. 4.15(a)). Severe erosion of left bank erosion near the confluence of Ganga and Ramganga has been observed (Fig. 4.16(b)).

Figure 4.15Field photographs showing the abandoned channel of Gambhiri Naddi and width of the channel indicates flow conditions in the past (b) Left bank erosion around the confluence of Ganga and Ramganga rivers

4.5 Discussions and Conclusions

It is evident from the present study that the lower Ramganga river is highly dynamic except for the reaches between the village Bari (B) and Mastapur (M), which is highly stable. Floodplain topography has played a major role in shifting of the river course. SRTM digital elevation models are used to compare the old (Gambhiri*Naddi*) as well as the new elevation profile (*Kunda Nala*) of the Ramganga river, which may have a maximum vertical error of ~4m. Topographic maps and Satellite imageries were used to study the river courses during the study period. In the first segment of lower Ramganga, the general movement of shifting is towards the southwest. The variation of the channel centerline between 1780 and 2017 was very high and observed 7.18 km shifting near the confluence of Ramganga and Baghul river. In the year 1780, the Ramganga river was wide and straight in nature. Ramganga riveris bifurcated into one more minor channel near to the village Patti Palpur (Pp) called *Kunda Nala*, and the abandoned channel of the Ramganga river is currently occupied by the Gambhiri *Naddi*. Gambhiri*Naddi* started to meander in 1922. The planform dynamics of the Ramganga river has primarily been caused by two mechanisms (a) meander migration of sinuous channels and (b) low slope in downstream topography. A dominant westward movement during 1780 and 1922 was primarily caused by meander cut-offs. The SRTM based DEM of the present study area shows a very flat topography which would mean a small change in the hydraulic regime may result in rapid morphological changes [155].

The Landsat archive and historical cartographic data can be used in GIS platform to model geomorphological landform evolution in large alluvial rivers. The lower reaches of the Ramganga in middle Ganga plain display significant changes in terms of channel planform in the last 237 years. The information provided here has increased understanding of the dynamics of lower Ramganga river. It is also important to understand that river planform dynamics is a natural behaviour of the alluvial river. This study will work as a decision support system for local planners and decision-makers for river management activities. Specifically, local concerns over the potential lateral migration of the river Ramganga and consequent erosion and loss of productive agricultural land. It is essential to map the planform dynamics through remote sensing and GIS to save the large population from flood hazards and erosion through river dynamics, and it may also play an essential role for improving the health of Ramganga river.