



Spatio-temporal Variation of Channel Migration and Vulnerability Assessment: A Case Study of Bhagirathi River Within Barddhaman District, West Bengal, India

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Abstract

The channel migration across the floodplain areas is a natural dynamic process, mainly for alluvial rivers, and several geo-hydrological factors are involved in this process of shifting. The river Bhagirathi, the westernmost part of the Ganga–Brahmaputra Delta, often experiences more lateral migration along its course from Ketugram-II to Kalna-II Community Development (C.D.) blocks of Barddhaman district. The present study aims to understand the channel migration of the river from 1930 to 2018 based on the collected database, such as the district administrative map of Barddhaman of 1930, satellite images of Landsat 5 Thematic Mapper (TM) of 1987, 1997, 2008, and Landsat 8 Operational Land Imager (OLI) image of 2018. All the data are processed in ArcGIS 10.3.1 software to prepare maps of the river course of different years, and the meandering pattern of the channel is observed. There is no such prominent pattern of bank line shifting observed and the overall average rate

of erosion of bank lines from 1930 to 2018 shows a declining trend in general. Moreover, an estimation is also made to know the future pattern of the Bhagirathi River course of 2030 adopting the logarithmic regression method. The predicted average bank line erosion rate from 2018 to 2030 is found to be 174 m/year. This possibility of bank line shifting may bring vulnerability to the 17 identified villages adjacent to the river course with a population of around 65,000 of 6 C.D. blocks of Barddhaman district up to 2030.

Keywords

Channel migration · Bhagirathi River · Bank lines · Vulnerability · RS and GIS · Logarithmic regression

14.1 Introduction

Channel migration within its meander belt is one of the common natural processes in the case of an alluvial channel, and the river keeps on shifting its position leaving different imprints (Bhunias et al. 2016; Gregory 1977, 1979, 1983; Hickin and Nanson 1975; Leopold et al. 1995; Lewin and Hughes 1976; Mondal and Mandal 2018; Philip et al. 1989; Thorne 1992, 2002). Several geo-hydrological factors of a river, such as lithology, channel gradient, river discharge, sediment load, velocity and bed materials, etc. control the channel

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migration. The cumulative effects resulting from some processes, like higher rate of seepage, direct corrosion, and bank failure may produce lateral shifting of channel or meander migration and channel expansion or channel avulsion (Charlton 2008; Hickin and Nanson 1975; Kotoky et al. 2005; Kumar et al. 2010; Yang et al. 1999). Channel migration is a natural dynamic hydro-logic condition that cheers up during high discharge events. The riverbanks, mainly the meander part used to experience rampant erosion in its outer bend, and sometimes the water spills over the floodplain. Channel migration in the Bhagirathi River almost invariably follows the bank failure that mostly takes place on the outer bend of the meanders (Ghosh 2007). Consequently, the morphology of the river channels has been changed with the constant operations of riverbank erosion and accretion processes (Alexeevsky et al. 2013; Chakraborty and Mukhopadhyay 2015; Duran et al. 2011). Many a time, it is observed that the flow patterns of the river get changed due to alterations in channel morphology and fluvial architecture. It is quite obvious that the entire fluvial environment is altered due to channel migration at reach scale (Church 1992; Leopold et al. 1995). Several in-depth studies have been carried out worldwide to evaluate the activities of channel migration and its associated morphological changes (Beechie et al. 2006; Bisson et al. 2011; Das et al. 2007; Dury 1977; Ghosh and Sahu 2018; Gregory 1977; Hickin and Nanson 1975; Knight 1975; Millar 2000; Thorne 1982, 1992; Újvári et al. 2009; Yunus et al. 2019). Channel migration is a dynamic process that changes in response to a variety of inputs. Hydraulic action, abrasion (corrasion) and attrition are well-known geomorphic processes involving running water, which continuously controls the fluid dynamics and sediment entrainment processes. The alluvial river like the Bhagirathi used to keep on shifting its position over the floodplain within the meander belt laterally by the riverbank erosion. Riverbank shift is a subject matter of fluvial morpho-dynamics because fluid dynamics and fluvial architecture are mutually adjusted with each other. Riverbank erosion refers to the separation and entrainment of

bank materials in the form of grains, aggregates, or blocks by fluvial, subaerial, and/or geo-tectonic processes. It is a common form of geomorphic hazard associated with meandering or braided river systems and floodplains (Ghosh 2007). The resulting channel migration from combined hydro-geomorphic actions can take a faster speed by human interventions. Therefore, a combination of natural and anthropogenic drivers increases the spatial extension and severity of channel migration (Chakraborty and Mukhopadhyay 2015; Dey and Mandal 2019). On the other hand, certain land-use practices may prepare riverbanks to inhibit erosion. Trampling by grazing animals can reinforce the compactness of the top layer. The right type of vegetation increases resistance to erosion manifold by their elaborate and condense root systems. However, in rivers with high banks, common in the middle and lower reaches of large rivers, the effect of vegetation in arresting bank erosion tends to be limited (Ghosh 2007).

A number of research works have already been done on the geomorphic and environmental effects of the Farakka barrage related to the shifting of the lower course of the river Ganga and its distributaries including Bhagirathi in the downstream areas of India and Bangladesh. Some of the important works carried out on different aspects, such as sedimentation on the river bed of the Bhagirathi (Basu et al. 1996); channel shifting of the Bhagirathi (Bag et al. 2019; Basu 2001; Islam and Guchhait 2017; Laha 2015; Rudra 1996, 2014; Sarkar et al. 2003); channel morphology of the Ganga (Majumder 2004; Sarkar et al. 2003) and the Padma (Ophra et al. 2018; Sarkar 2004); loss and quality deterioration of agricultural field adjacent to the Padma (Gain and Giupponi 2014; Pal et al. 2016). In this context, it becomes more important to generate a digital database based on measuring spatial shifting of riverbanks over a longer period of time to understand lateral migration of river and to estimate the future trend of channel shifting (Das et al. 2012; Philip et al. 1989). It will help to formulate proper management plans for the entire area well in advance. To understand the nature of lateral shifting of the river, the application of Remote Sensing (RS) and

Geographical Information System (*GIS*) techniques has been using more popularly worldwide (Aher et al. 2012; Ahmed et al. 2018; Alexeevsky et al. 2013; Beechie et al. 2006; Bisson et al. 2011; Das et al. 2012; Debnath et al. 2017; Dey and Mandal 2019; Duran et al. 2011; Guite and Bora 2016; Hamid et al. 2017; Islam and Guchhait 2017; Kotoky et al. 2005; Laha and Bandyapadhyay 2013; Mandal et al. 2017; Mukherjee et al. 2016; Ophra et al. 2018; Rudra 2014; Saleem et al. 2020; Thakur et al. 2012; Yunus et al. 2019). A number of research works have been carried out by several researchers adopting *RS* and *GIS* techniques to prepare channel migration zones of the river Ganga (Ghosh and Sahu 2018; Philip et al. 1989), the river Torsa (Dey and Mandal 2019), the river Pravara (Aher et al. 2012), the Bhagirathi (Pal et al. 2016) using different techniques.

But there is no such work done on identifying the chronological changes of the Bhagirathi River channel for a larger time span along with the future prediction of channel shifting, rate of erosion and accretion of both banks, and assessment of future vulnerable areas with human settlements and agricultural lands. Thus, the amalgamation of *RS* and *GIS* with statistical techniques may be used to assess the channel migration with a scope of estimating future shifting. Here, the present study tries to understand the pattern of channel migration of the river Bhagirathi along the eastern boundary of Bardhaman district for the last 88 years and based on that, a future estimation of shifting of the river course is computed for the year 2030. In addition to this, the vulnerable riparian villages resulting from lateral migration of the river Bhagirathi from 2018 to 2030 of the Bardhaman district are recognized.

14.2 Study Area: General Geographical Settings

West Bengal is susceptible to a varied range of Natural Environmental Hazards (NEH) because of its unique physical setting that stretches from the Himalayas to the Bay of Bengal, which no

state of India has to cope with. The Ganga is India's largest river in terms of annual discharge ($522 \times 10^9 \text{ m}^3$), length (2,158 km), and drainage area ($861.40 \times 10^3 \text{ km}^2$: 78.60% of the total basin area) (Ghosh 2007). The Ganga originates from the Gangotri glacier in the Himalaya at 4,000 m above mean sea level beyond the mountains. It enters into West Bengal at the northern border of Manikchak Community Development (C.D.) block of Malda district ($25^\circ 13' 13'' \text{ N}$, $87^\circ 47' 40'' \text{ E}$; altitude: 29 m), 19 km north of Rajmahal town. In its deltaic course, the general trend of the Ganga follows a south-southwest ward trend for the first 100 km up to the off-take point of the Bhagirathi and then takes up an east-southeast ward course to its confluence with the Brahmaputra and beyond. The broad physiographic divisions of the area through which the Ganga flows in West Bengal are the lowlands, the Pleistocene terraces/piedmonts, and the hills. In the lowlands, the altitude reduces in the same general direction in which the Ganga flows—from northwest to southeast. It is widely believed that the Bhagirathi-Hugli river represents the earliest course of the Ganga in the delta. Subsequently, the alignment of the river shifted to its present position by successive development and abandonment of several distributary channels that can be traced as off-shoots of the present river. From west to east, they include the Bhagirathi, Kalkali, Bhairab, Silamari, Jalangi (in India), Mathabhanga, Garai-Madhumati, Chandana and Kumar (in Bangladesh). At present, all these rivers are in various stages of degeneration. The only exception is the Bhagirathi-Hugli, which is artificially resuscitated by the Farakka barrage (Ghosh 2007; Ranjan and Ramanathan 2018; Rudra 2012, 2018).

In the present study, the middle stretch of the Bhagirathi River, flowing along the eastern margin of the Bardhaman district of West Bengal is the study of interest (Fig. 14.1). Many geomorphological features of this river (active channel cutoffs, ox-bow lakes, meander scars, etc.) are frequently observed throughout the studied segment. The river Ajay, a right-hand tributary of Bhagirathi flowing over the Rarh

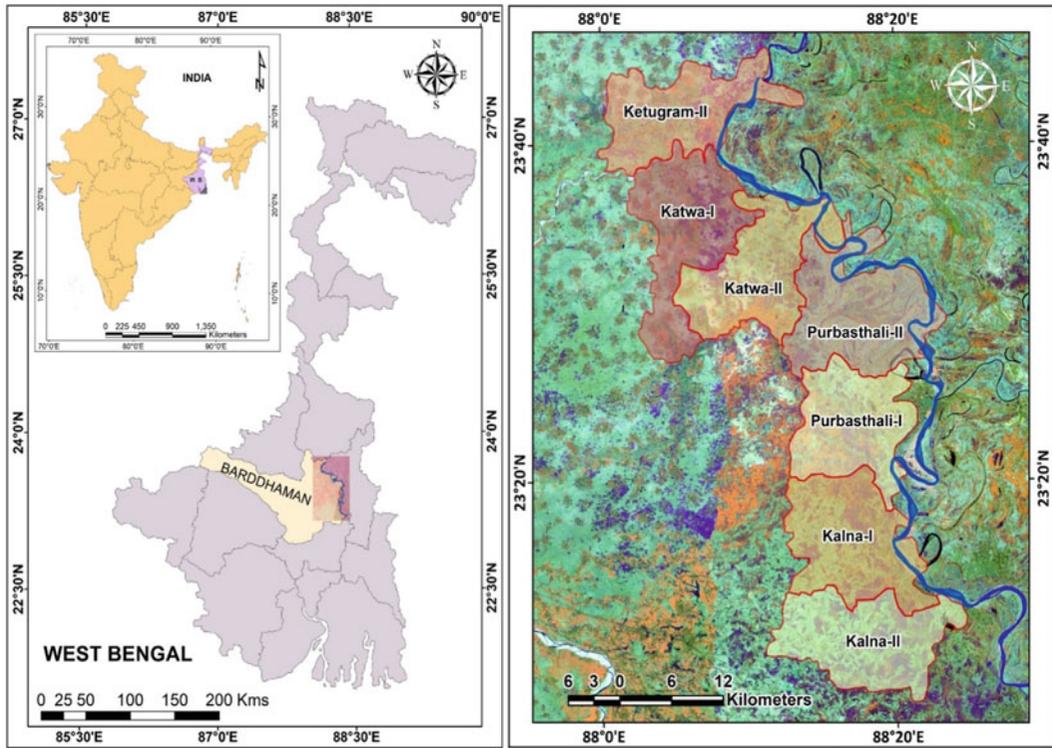


Fig. 14.1 The course of the Bhagirathi River within the study area

Bengal, meets the Bhagirathi near Katwa of Bardhaman district. In the year 2018, the length of the Bhagirathi River within the study area is found to be 114.66 km. The geographical extent of the area of interest lies in between $87^{\circ} 58' E$ to $88^{\circ} 26' E$ and $23^{\circ} 44' N$ to $23^{\circ} 07' N$. The entire area experiences Monsoon climate, hot and humid summer, and dry mild cold in winter. The high discharge condition is experienced by the river only during the period of south-western Monsoon (July to September) (Ghosh 2007; Rudra 2014). A total number of 7 C.D. blocks, namely: Ketugram-II, Katwa-I, Katwa-II, Purbasthali-I, Purbasthali-II, Kalna-I and Kalna-II come under the studied region. The respective total numbers of villages of the C.D. blocks are 56, 66, 68, 95, 90, 99 and 112. The average population density of all 7 blocks is 1010 person/km² in 2011 (Census of India 2011). The eastern portion of the district is a wide alluvial plain enclosed by the river Ajay, the Bhagirathi and the Damodar on the north, south, and east.

14.3 Materials and Methods

14.3.1 Database

The present work has been carried out based on a detailed field survey at several segments of the river Bhagirathi within studied reach. The lateral migration of the river Bhagirathi in its part of the middle reach, mainly in the Bardhaman district, has been portrayed in the present research work using different types of data, such as the district administrative map of Bardhaman, 1930 at a scale of 1.5–10 km collected from Administrative Atlas-West Bengal, 2001 (Census of India 2001); police station map of each C.D. block (total 7 C.D. blocks of the study area) at a scale of 1–10 km taken from Administrative Atlas-West Bengal, 2001 (Census of India 2001); satellite images of Landsat 5 Thematic Mapper (TM) of 1987 (acquired on 24.12.1987), 1997 (acquired on 03.12.1997), 2008 (acquired on

Table 14.1 Detail specifications of the database used in the study

| Data type | Map/Satellite/Sensor details | Acquisition date | Path | Row | Map scale/Spatial resolution | Source |
|-----------------------|--|------------------|------|-----|------------------------------|--|
| District map | Administrative map of Bardhaman | 1930 | – | – | 1.5 cm = 10 km | Administrative Atlas-West Bengal, Census of India 2001 (https://censusindia.gov.in/) |
| Block map | Police station map along with villages | 1930 | – | – | 1 cm = 1 km | Administrative Atlas-West Bengal, Census of India 2001 (https://censusindia.gov.in/) |
| Remote sensing images | Landsat 5-TM | 24.12.1987 | 139 | 44 | 30 m | USGS (https://earthexplorer.usgs.gov/) |
| | Landsat 5-TM | 03.12.1997 | 139 | 44 | 30 m | |
| | Landsat 5-TM | 16.01.2008 | 139 | 44 | 30 m | |
| | Landsat 8-OLI | 13.12.2018 | 139 | 44 | 30 m | |

16.01.2008) and Landsat 8 Operational Land Imager (OLI) image of 2018 (acquired on 13.12.2018) with 30 m spatial resolution downloaded from EarthExplorer Interface (<https://earthexplorer.usgs.gov/>) developed by United States Geological Survey (USGS) (Table 14.1).

14.3.2 Methodology

14.3.2.1 Data Processing

The district administrative map has been used to extract the blocks of Bardhaman district and the river channel of 1930, and satellite images have been used to extract river channels of 1987, 1997, 2008 and 2018 to identify the bank line shiftings of the river Bhagirathi. The police station map is used to extract and mark the river adjacent villages, which have more possibility of being vulnerable to erosion during high river discharge. All the maps are transferred into raster format and properly geocoded (Universal Transverse Mercator projection, World Geodetic System 84 datum and zone 45 N) using the georeferencing tool of ArcGIS 10.3.1 software. Now all four images of different years are done Standard False Colour Composition (SFCC) in ArcGIS software to prepare the vector layers of riverbank lines.

14.3.2.2 Data Analysis

Sinuosity index is an important morphometric technique, which indicates the nature and behaviour of a river. It provides an understanding of the irregularity pattern of a river course in terms of channel bending (Charlton 2008; Huggett 2017; Leopold et al. 1995; Schumm 1963; Summerfield 2013) and it can be computed using the following formula (Schumm 1963):

$$\text{Sinuosity Index} = \frac{OL}{EL} \quad (14.1)$$

where 'OL' is the length of the observed path and 'EL' is the length of the expected straight path of a river. A value of less than 1.1 of the sinuosity index refers to the straight path of a river channel, while the value between 1.1 and 1.5 indicates sinuous. In contrast, a value of more than 1.5 is considered as meandering.

Now, the actual area of each C.D. block is measured by subtracting the river area from the total area of the concerned C.D. block. The total area of erosion and deposition within the Bardhaman district of the river Bhagirathi is also calculated. To do this, the vector layer of the river course of 1987 is superimposed on 1930 in ArcGIS software, and the total area of erosion and deposition is computed based on the difference

between vector layers of river courses. The same procedure is repeated from 1987 to 1997, 1997 to 2008 and 2008 to 2018. Ultimately, it gives results of erosion and deposition for a particular period. All the vector layers of riverbank lines of 5 different years are superimposed chronologically (the year 1930, 1987, 1997, 2008 and 2018) in ArcGIS software to generate a particular thematic map of change detection of the Bhagirathi River course. Based on the 88 years of digital database for change detection of the river, precise observation is made to identify those hotspots, which experienced more vulnerability in terms of lateral shifting of the channel in different periods in the entire studied river stretch. Therefore, a total number of 23 hotspots (most vulnerable riverbank areas to erosion) along the river are identified for cross-section considering the superimposed map (necessary ground truth verifications are also done) (Fig. 14.8). Based on these drawn cross-sections, the shifting of bank line of either side of the river is measured between two consecutive selected years e.g. 1930 to 1987, 1987 to 1997, 1997 to 2008 and 2008 to 2018 adopting a measuring tool in ArcGIS software. With the help of the measured data, the average erosion rate is calculated for each period.

Here an attempt has been made to estimate the future migration of the river Bhagirathi using statistical techniques. It will help to identify the areas, which might encounter the chance of being vulnerable due to river migration. The dataset of 1997, 2008 and 2018 are taken to predict the bank line shift for 2030 using the logarithmic regression method which has already been applied by many earlier researchers successfully (Das et al. 2012; Rusov et al. 2017). To validate the acceptability of future prediction, linear, logarithmic and polynomial regressions are performed to project the right bank shifting of the river along the cross-section for 2018 based on the right bank shifting database of the river from 1930–1987, 1987–1997 and 1997–2008. The derived results of logarithmic and linear regressions are found to be satisfactory than the polynomial regression when compared with actual bank line shifting data of 2018. Moreover, the logarithmic regression gives more reliable data

for 2018 than the linear regression (Table 14.2). Therefore, the future shifting of both the bank lines from 2018 to 2030 is projected by the logarithmic regression model based on the computed database of 23 hotspot cross-sections and their previous shifting of the riverbank lines from 1987–1997, 1997–2008 and 2008–2018. On the basis of projected riverbank shifting, the future vulnerable villages of the selected C.D. blocks of the Bardhaman district have been identified. The formulae of linear regression (formula 14.2) and logarithmic regression (Formula 14.3) are as follows:

$$Y = a + bX \quad (14.2)$$

where 'Y' is the estimated dependent variable, 'X' is the independent variable, 'a' and 'b' are constant and represent the Y intercept and the slope of the line, respectively.

$$Y = b \ln(X) + a \quad (14.3)$$

where 'Y' refers to the estimated dependent variable, 'X' means the independent variable and its value must be greater than '0', while 'ln' is the \log_e and is generally called as natural logarithm. The constants of a particular equation are 'a' and 'b'.

After the computation of projected riverbank line migration of the Bhagirathi for the year 2030, some of the hotspots of selected cross-sections, which are estimated to be more vulnerable out of total 23, are visited for ground truth verification and to understand the actual trend of bank line shifting at the present day (Fig. 14.15).

14.4 Results and Discussion

14.4.1 Changing Pattern of the Bhagirathi River from 1930 to 1987

The length of the river Bhagirathi was 123.53 km in 1930 and it was flowing along the extreme eastern margin of the Bardhaman district covering all the 7 C.D. blocks (Fig. 14.2). An area of 58.99 km² was computed as the total area of the Bhagirathi. The calculated sinuosity

Table 14.2 Actual and predicted right bank line shift of the Bhagirathi River

| Cross-section no | Actual right bank line shift in 2018 (m) | Right bank line shift in 2018 by linear regression (x = 31, i.e. no. of years since 1987) | Right bank line shift in 2018 by logarithmic regression (x = 32 nd year as 1987 is the 1 st year) |
|------------------|--|---|---|
| 1 | 4.40 | 23.93 | 1.66 |
| 2 | -13.74 | -139.98 | -71.66 |
| 3 | 25.77 | -234.25 | -117.54 |
| 4 | -31.17 | 131.84 | 61.18 |
| 5 | 12.07 | -42.59 | -16.95 |
| 6 | 54.88 | -699.76 | -207.79 |
| 7 | -11.40 | -385.56 | -173.86 |
| 8 | 224.16 | -182.90 | -58.79 |
| 9 | -1276.47 | 459.09 | 495.57 |
| 10 | 8.58 | 2375.53 | 871.75 |
| 11 | 145.47 | 2006.69 | 849.38 |
| 12 | 15.06 | 78.30 | 0.18 |
| 13 | -22.50 | -1331.09 | -710.58 |
| 14 | -42.57 | -562.00 | -238.45 |
| 15 | 57.88 | 692.70 | 235.82 |
| 16 | 109.82 | 2374.52 | 1136.82 |
| 17 | 21.67 | -1580.67 | -760.94 |
| 18 | 16.93 | -1491.38 | -557.04 |
| 19 | -21.26 | -1924.39 | -815.25 |
| 20 | 8.69 | 250.52 | 67.18 |
| 21 | 13.41 | 534.54 | 236.99 |
| 22 | -13.84 | -759.82 | -312.32 |
| 23 | 76.94 | 27.67 | 56.24 |

Note Negative values indicate erosion and positive values indicate accretion

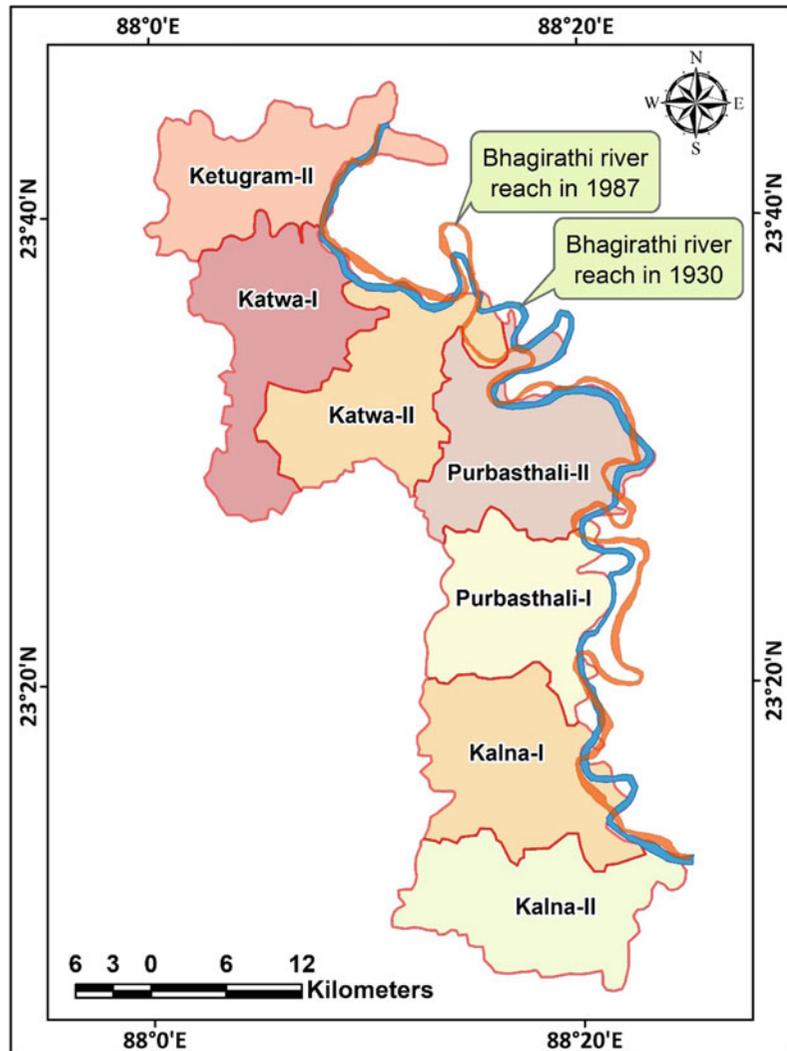
index of the river is 1.96, which indicates the meandering nature of the Bhagirathi (Fig. 14.6). On the contrary, the river experienced more lateral shifting in 1987 within a time frame of 57 years (from 1930 to 1987). The river almost shifted more eastward from Katwa-I, Purbasthali-I and Kalna-II C.D. blocks. The total length of the Bhagirathi was 133.47 km in 1987 with an increase of 34.94 km in length compared to 1930. Despite, an increase in the length of 9.94 km in 1987, the river lost an area of 11.63 km². This was due to the decrement in the width of the river from 1930 to 1987 (Fig. 14.10). During this period, a total area of all C.D. blocks increased, but Purbasthali-II experienced more

rise in the area compared to others C.D. blocks in 1987 (Fig. 14.7b). A value of 2.13 of the sinuosity index refers to more meander course of the Bhagirathi River in 1987 than in 1930 (Fig. 14.6).

14.4.2 Changing Pattern of the Bhagirathi River from 1987 to 1997

In the case of 1997, the total length of the river was 117.31 km with a sinuosity index of 1.87, though the value depicts the meandering nature of the Bhagirathi River, it was much less than the

Fig. 14.2 Migration of the Bhagirathi River reach from 1930 to 1987

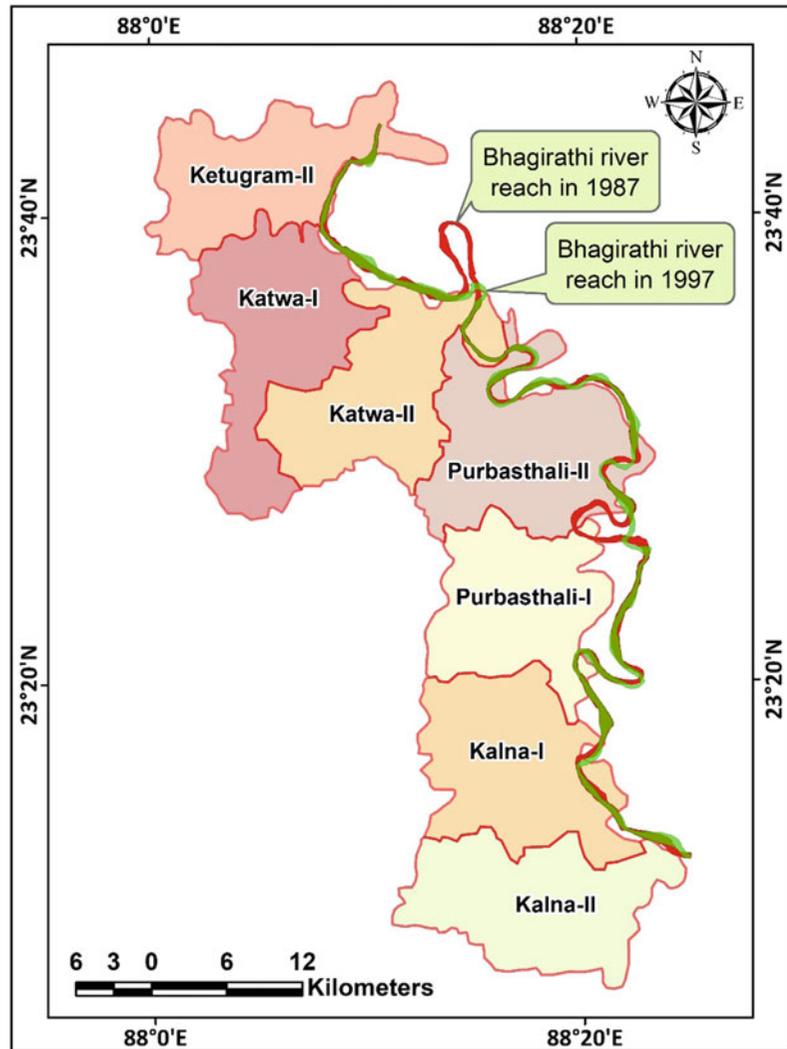


sinuosity value of 1987 (Fig. 14.6). The total area of the river was 49.32 km² and it got increased by 1.96 km² in 1997 compared to 1987. All the C.D. blocks underwent a minor transformation with respect to their administrative areas by the river erosion, though Katwa-II was more affected than the others (Fig. 14.7b). The river Bhagirathi took a straight course at Katwa-II and in between Purbasthali-II and Purbasthali-I, leaving behind two ox-bow lakes. The river shifted apart almost from the Katwa-I and Kalna- II C.D. blocks, but overall, the river maintained almost the same course of 1987 (Fig. 14.3).

14.4.3 Changing Pattern of the Bhagirathi River from 1997 to 2008

The length and sinuosity index of the Bhagirathi were 117.65 km and 1.88, respectively, in 2008 (Fig. 14.6), and these figures were almost the same in 1997. The river area was 48.45 km², which decreased by 0.87 km² from 1997. The course of the river was almost the same as in 1997, but there were some changes observed in the geometry of meanders. The river shifted more towards the eastern boundary of Kalna-II C.D. block (Fig. 14.4). The river Bhagirathi had not

Fig. 14.3 Migration of the Bhagirathi River reach from 1987 to 1997



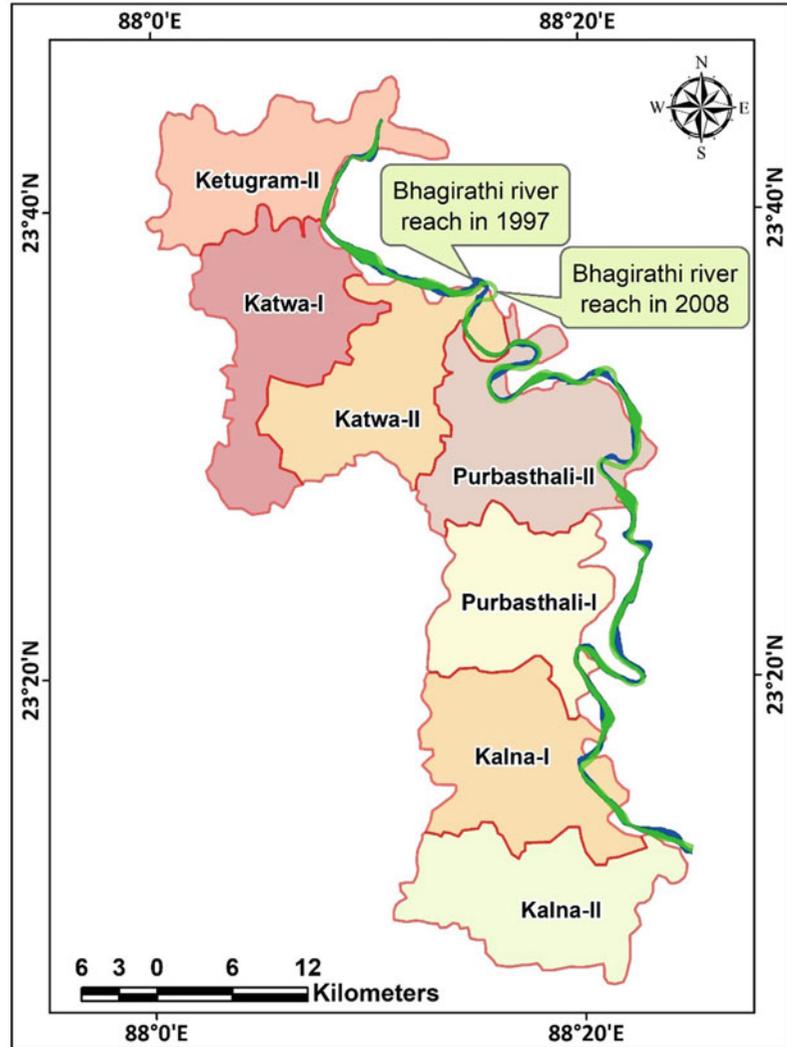
made any significant changes in areas of C.D. blocks; it made a small loss in terms of area of 6 C.D. blocks (Fig. 14.7b).

14.4.4 Changing Pattern of the Bhagirathi River from 2008 to 2018

The length of the river in 2018 was 114.66 km and it reduced by 2.99 km from 2008. The total area of

the river was calculated to be 49.32 km², which increased by 0.87 km² than the area in 2008. The meandering behaviour of the river was found from the calculated sinuosity index, i.e. 1.84 (Fig. 14.6). The Bhagirathi River changed its course at Katwa-II C.D. block developing an oxbow lake in 2018. The river maintained almost the same river course, as it was in 2008. Only some changes took place in river meander geometry (Fig. 14.5). The total areas of all the C.D. blocks remained almost the same in 2018 (Fig. 14.7b).

Fig. 14.4 Migration of the Bhagirathi River reach from 1997 to 2008



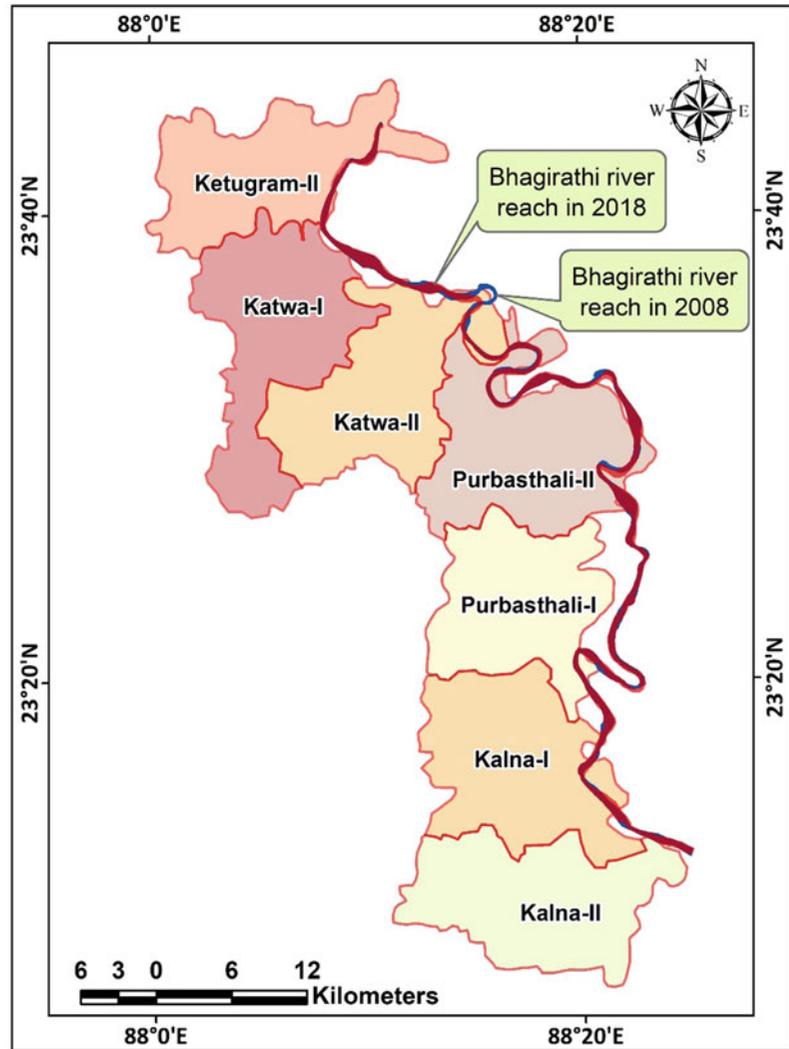
14.4.5 Bank Line Dynamics of the Bhagirathi River: Socio-economic Impacts

The dynamic nature of the fluvial processes never be stopped and it always tries to keep a balance between its flow conditions and sediment load, and that will give rise to changing the nature of floodplain architecture. This dynamicity of the fluvial processes can better be understood from W. M. Borlaug and E. W. Lane’s diagram, where it was explained that when sediment load is powerful than the power of streamflow, the deposition will take place and when the

discharge rate is high and powerful than sediment load erosion will take place (Gupta 2011). It is quite relevant in the case of our studied segment. From Tables 14.3 and 14.4, it is evident that in cross-sectional areas, both the processes of accretion and erosion are involved in the channel migration of the Bhagirathi.

The analytical results reveal that the river Bhagirathi has been changing its course from 1930 to 2018 without any specific trend and pattern. The shifting has no particular direction over the years; sometimes both the bank lines of the river have shifted in the same direction and sometimes one bank line has shifted in the

Fig. 14.5 Migration of the Bhagirathi River reach from 2008 to 2018



opposite direction to the other (Fig. 14.9). Thus, the width of the river has also changed (Fig. 14.10). This shifting has resulted in continuous devastation of agricultural lands and settlements due to erosion and also in the generation of new lands due to the aggradation process. The shifting pattern of the channel is more prominent between 1930 and 1987 (Fig. 14.2). The bank line shifting from 1987 to 2018 is not as prominent as 1930 to 1987 (Fig. 14.8). Thus, the river area of each C.D. block changed more from 1930 to 1987 as compared to 1987 to 2018 (Fig. 14.7a). It is also revealed that within the 57-year time span (from

1930 to 1987), the overall total eroded land area was 1054 ha affecting 29 mouzas (i.e. villages as per District Census Handbook, Bardhaman) of 6 C.D. blocks and the depositional area was 2777 ha within 43 mouzas of 7 C.D. blocks of Bardhaman district (Fig. 14.11). During 1987–1997, the total eroded area decreased to 294 ha affecting 18 mouzas of 6 C.D. blocks and deposited 274 ha of land within 19 mouzas of 6 C.D. blocks (Fig. 14.11). From 1997 to 2008 time period, the eroded area slightly increased to 362 ha affecting 19 mouzas and the depositional area increased to 282 ha influencing 16 mouzas of 5 C.D. blocks respectively (Fig. 14.11). In the

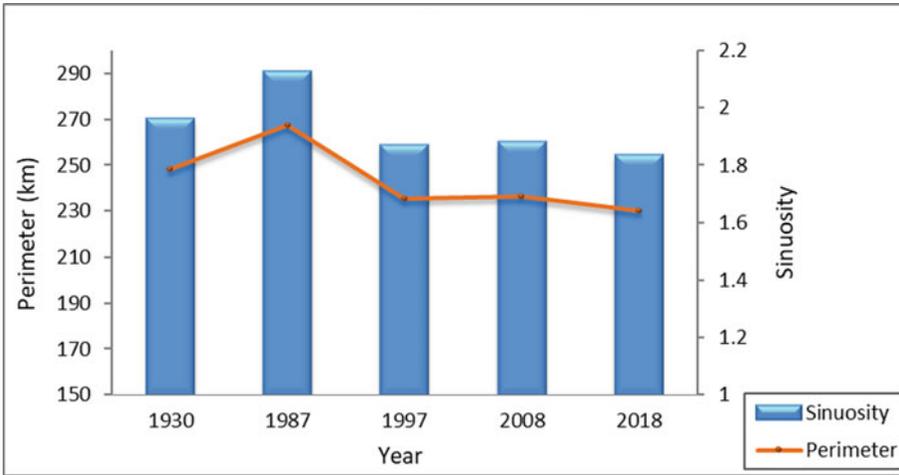


Fig. 14.6 Change in perimeter and sinuosity of the Bhagirathi River from 1930 to 2018

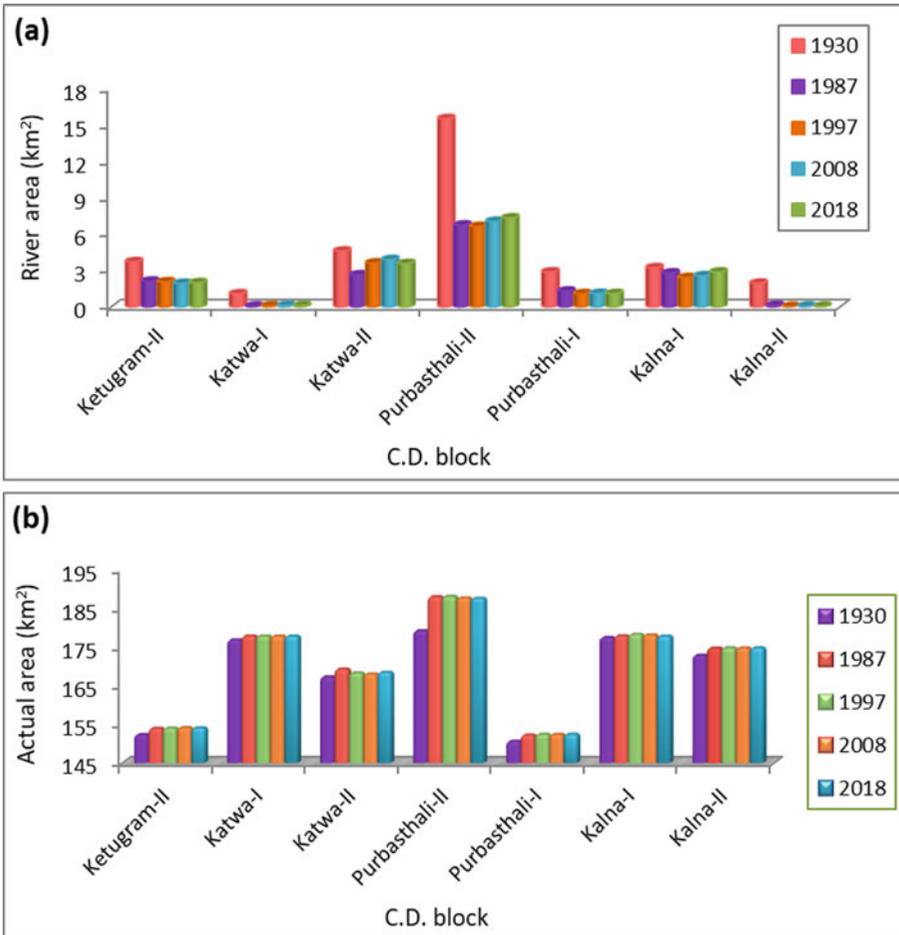
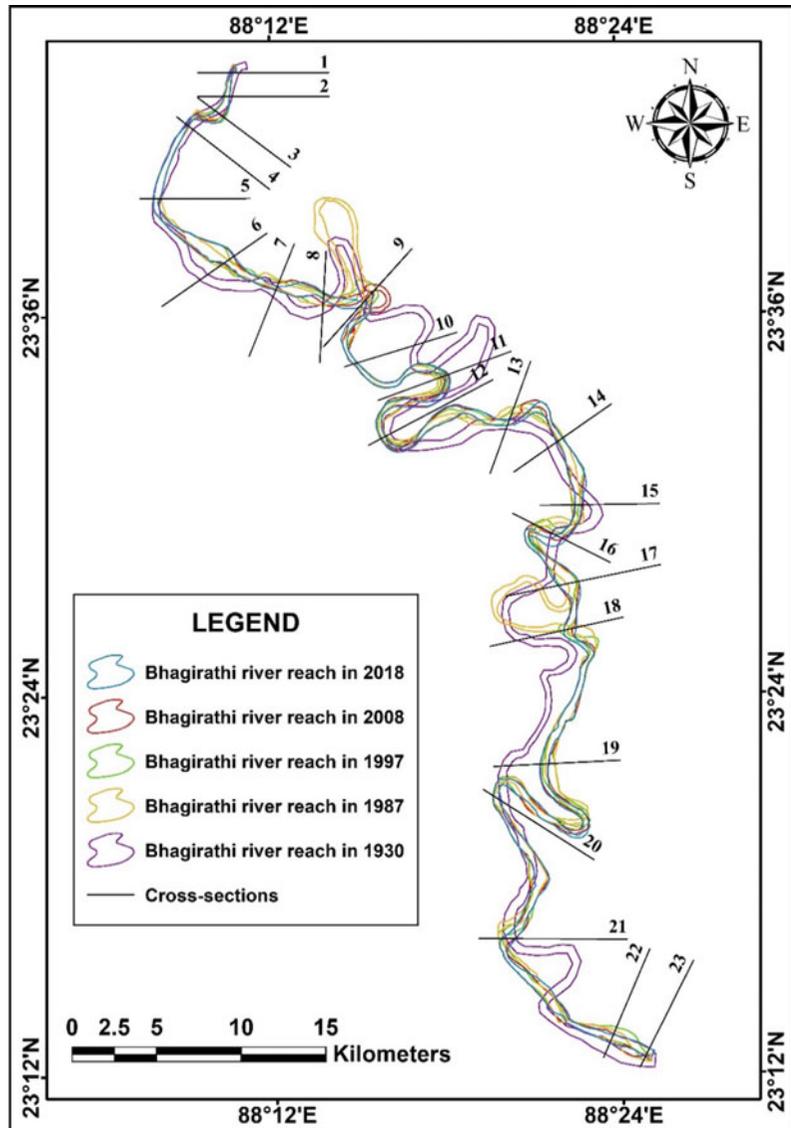


Fig. 14.7 Change in (a) river area and (b) Actual area within C.D. blocks due to channel shifting from 1930 to 2018

Fig. 14.8 Selected cross-sections across the bank lines of the Bhagirathi River reach



past decade of 2008–2018, the eroded area again reduced to 231 ha of land distributed within 17 mouzas of 5 C.D. blocks and the deposited area also reduced to 201 ha within 22 mouzas of 5 C. D. blocks (Fig. 14.11). Now, observing the overall trend and pattern of total erosion and deposition, the bank failure event may be perceived as insignificant with respect to its gravity and intensity. But the reality is something different from the overall average rate of erosion and accretion within this 114 km long linear stretch of the river Bhagirathi. Thus, the 23

drawn cross-sections (Fig. 14.8) based on identified bank erosion hotspots are assessed and evaluated to know the rate and pattern of bank line shifting for a better understanding of the reality and future trend. The cross-sections data unveils that within 1930–1987, the average rate of erosion due to the bank line shifting was 202 m/year affecting on an average 6 C.D. blocks. From 1987 to 1997, the average rate of erosion due to channel migration reduced to 167 m/year influencing 6 C.D. blocks. During 1997–2008, the average rate of river migration

Table 14.3 Temporal shifting of bank lines of the Bhagirathi River along the cross-sections

| Cross-section no | 1930–1987 | | | | 1987–1997 | | | |
|------------------|--------------------------|-----------|---------------------------|-----------|--------------------------|-----------|---------------------------|-----------|
| | Left bank line shift (m) | Direction | Right bank line shift (m) | Direction | Left bank line shift (m) | Direction | Right bank line shift (m) | Direction |
| 1 | 395.46 | Right | -90.77 | Right | -4.54 | Left | -4.04 | Right |
| 2 | 133.82 | Right | 137.58 | Left | 14.40 | Right | -30.56 | Right |
| 3 | -287.51 | Left | 399.39 | Left | -114.04 | Left | -97.91 | Right |
| 4 | 280.46 | Right | -142.44 | Right | 19.96 | Right | 14.58 | Left |
| 5 | -53.12 | Left | 10.16 | Left | 201.40 | Right | 14.85 | Left |
| 6 | -1473.65 | Left | 1451.84 | Right | -95.93 | Left | 39.45 | Left |
| 7 | -393.87 | Left | 519.60 | Left | -8.12 | Left | -60.85 | Right |
| 8 | -349.94 | Left | 532.76 | Left | -187.16 | Left | -51.44 | Right |
| 9 | 250.31 | Right | -219.53 | Right | -602.38 | Left | 780.58 | Left |
| 10 | 4152.88 | Right | -3790.60 | Right | -61.01 | Left | -15.27 | Right |
| 11 | 2930.70 | Right | -2676.09 | Right | -304.75 | Left | 146.75 | Left |
| 12 | 362.35 | Right | -220.89 | Right | 66.92 | Right | -52.63 | Right |
| 13 | -790.29 | Left | 995.98 | Left | 108.47 | Right | -275.90 | Right |
| 14 | -519.59 | Left | 784.99 | Left | -27.63 | Left | -53.60 | Right |
| 15 | 1098.72 | Right | -859.45 | Right | 71.84 | Right | -135.90 | Right |
| 16 | 1378.04 | Right | -1019.48 | Right | 116.10 | Right | -128.10 | Right |
| 17 | -240.10 | Left | 2107.33 | Left | 50.67 | Right | -381.10 | Right |
| 18 | -3113.33 | Left | 2779.88 | Left | 935.80 | Right | -145.60 | Right |
| 19 | -2734.25 | Left | 2674.58 | Left | 17.05 | Right | -177.20 | Right |
| 20 | 676.50 | Right | -491.83 | Right | 23.70 | Right | -43.98 | Right |
| 21 | 761.06 | Right | -476.09 | Right | 59.90 | Right | -5.18 | Right |
| 22 | -746.56 | Left | 875.85 | Left | -211.30 | Left | 15.26 | Left |
| 23 | -86.76 | Left | 417.45 | Left | -44.36 | Left | -13.63 | Right |

Note Negative values indicate erosion and positive values indicate accretion

through bank erosion increased to 226 m/year affecting 5 C.D. blocks. Interestingly, again the rate of erosion within 2008–2018 reduced to 120 m/year on an average influencing 5 C.D. blocks. So, it could be found that the pattern of change in terms of erosion, where the high rate was replaced by a low rate of erosion and again the same trend was repeated. But the overall general trend shows the gradual decrement in erosion rate over the years (Fig. 14.13).

Based on the analyzed data, the rate, trend and pattern of the channel migration within this reach, it can be said that the river Bhagirathi is going to attain its decaying stage, but now

resuscitated by the Feeder canal of the Farakka barrage system. It is a quite normal process of degeneration of the distributary system of the Ganga–Brahmaputra Delta (GBD), where the off-take points of the distributaries were getting defunct. The establishment of the Farakka barrage in Murshidabad in 1975 had affected river hydraulics (Basu and Sen 1997; Pal et al. 2016) and changed the dynamicity of the river. There was a significant change in the Bhagirathi River seen over the long period of 57 years, i.e. in between the courses of 1930 and 1987 (Fig. 14.2). The diverted water from the Ganga into the Bhagirathi increased the

Table 14.4 Temporal shifting of bank lines of the Bhagirathi River along the cross-sections

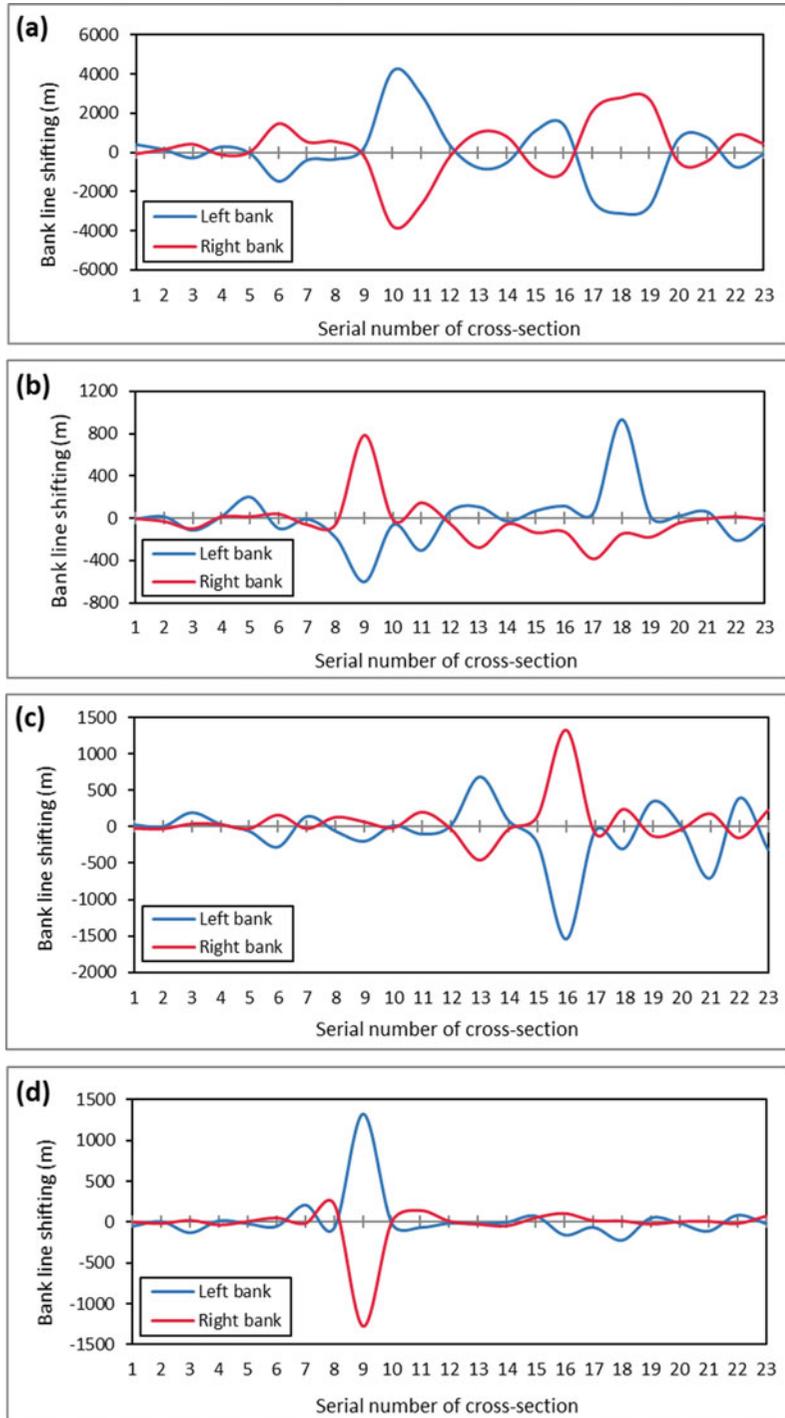
| Cross-section no | 1997–2008 | | | | 2008–2018 | | | |
|------------------|--------------------------|-----------|---------------------------|-----------|--------------------------|-----------|---------------------------|-----------|
| | Left bank line shift (m) | Direction | Right bank line shift (m) | Direction | Left bank line shift (m) | Direction | Right bank line shift (m) | Direction |
| 1 | 25.78 | Right | -24.35 | Right | -46.80 | Left | 4.40 | Left |
| 2 | -2.38 | Left | -32.62 | Right | 9.78 | Right | -13.74 | Right |
| 3 | 190.64 | Right | 36.57 | Left | -125.96 | Left | 25.77 | Left |
| 4 | 33.74 | Right | 27.82 | Left | 19.76 | Right | -31.17 | Right |
| 5 | -63.12 | Left | -30.50 | Right | -16.04 | Left | 12.07 | Left |
| 6 | -280.66 | Left | 157.20 | Left | -48.13 | Left | 54.88 | Left |
| 7 | 137.65 | Right | -28.16 | Right | 211.27 | Right | -11.40 | Right |
| 8 | -64.21 | Left | 128.10 | Left | -66.61 | Left | 224.16 | Left |
| 9 | -202.84 | Left | 63.04 | Left | 1321.40 | Right | -1276.50 | Right |
| 10 | 12.77 | Right | -18.64 | Right | -12.17 | Left | 8.58 | Left |
| 11 | -103.60 | Left | 198.55 | Left | -62.03 | Left | 145.47 | Left |
| 12 | 15.86 | Right | -34.48 | Right | -11.08 | Left | 15.06 | Left |
| 13 | 683.58 | Right | -462.23 | Right | -16.98 | Left | -22.50 | Right |
| 14 | 79.95 | Right | -35.87 | Right | 2.04 | Right | -42.57 | Right |
| 15 | -232.33 | Left | 141.47 | Left | 77.80 | Right | 57.88 | Left |
| 16 | -1546.60 | Left | 1325.80 | Left | -154.08 | Left | 109.82 | Left |
| 17 | -63.99 | Left | -96.50 | Right | -60.40 | Left | 21.67 | Left |
| 18 | -303.63 | Left | 237.40 | Left | -218.76 | Left | 16.93 | Left |
| 19 | 344.55 | Right | -130.66 | Right | 53.23 | Right | -21.26 | Right |
| 20 | -4.25 | Left | -36.19 | Right | -9.66 | Left | 8.69 | Left |
| 21 | -708.03 | Left | 175.68 | Left | -107.62 | Left | 13.41 | Left |
| 22 | 389.50 | Right | -156.69 | Right | 86.91 | Right | -13.84 | Right |
| 23 | -317.40 | Left | 222.64 | Left | -13.69 | Left | 76.94 | Left |

Note Negative values indicate erosion and positive values indicate accretion

hydraulic dynamicity and channel oscillation of the river Bhagirathi (mainly for the first two decades after the establishment of Farakka Barrage) to accommodate itself into the altered hydraulic condition (Rudra 2018). The river Bhagirathi with new hydraulic dynamicity developed two ox-bow lakes on the floodplain beheading the meanders. The first one was developed in 1989 upstream of Nabadwip, which was triggered by huge flood water of the same year (Basu et al. 2005; Islam and Guchhait 2017; Rudra 2018), and another one was developed near Shantipur in 1994 (Rudra 2018). The hotspots of the bank erosion remain

active in high discharge conditions during the Monsoon period and also aggravates by the local anthropogenic activities in the form of sediment mining from the channel or ferry service operations (Fig. 14.12a, b). On the other hand, the tributary system contributes a lot and plays a vital role in maintaining the Bhagirathi River system. Two major right-hand tributaries, namely: Mayurakshi and Ajay meet the river Bhagirathi near Kalyanpur of Murshidabad district and near Katwa of Bardhaman district, more south to Kalyanpur, respectively (Pal et al. 2016; Rudra 2008). Mayurakshi and Ajay discharge a huge volume

Fig. 14.9 Bank line shifting of the Bhagirathi River due to erosion (negative values) or accretion (positive values) from (a) 1930 to 1987, (b) 1987 to 1997, (c) 1997 to 2008, (d) 2008 to 2018



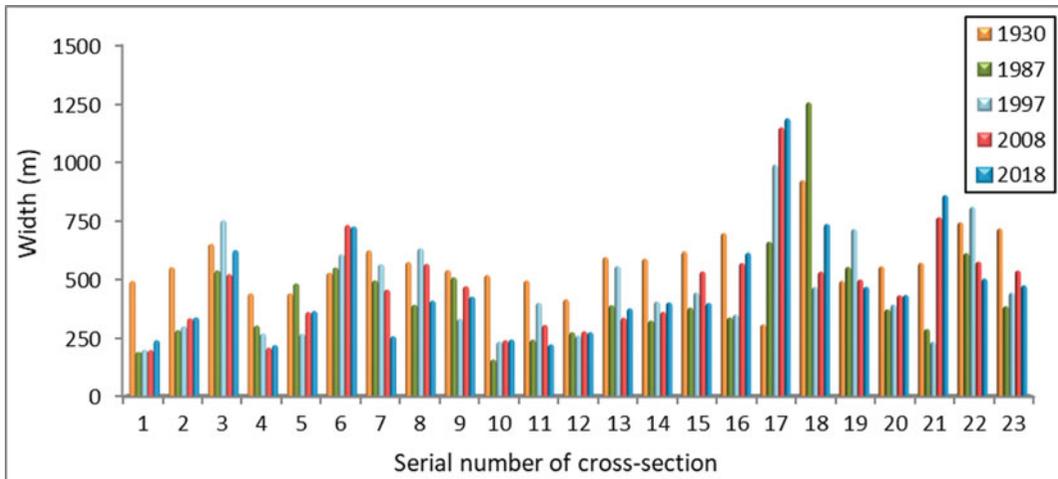


Fig. 14.10 Change in width of the Bhagirathi River along the cross-sections from 1930 to 2018

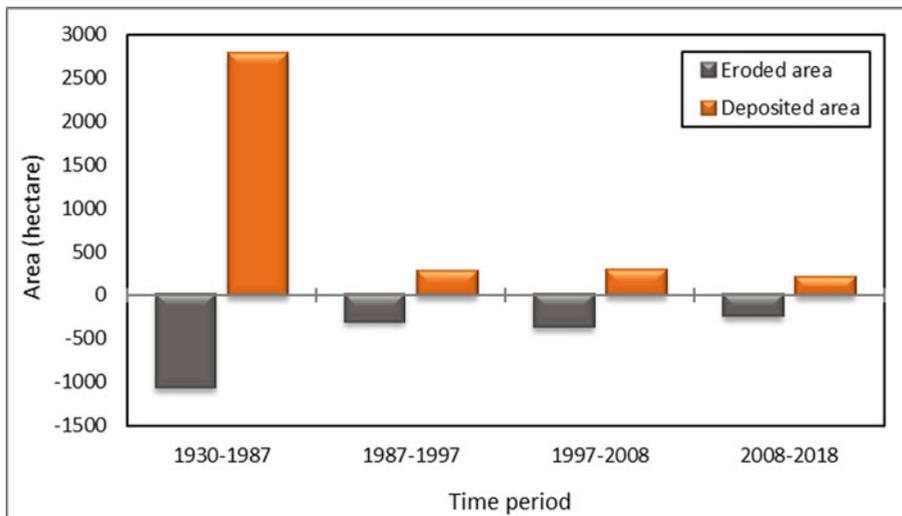


Fig. 14.11 Total eroded and deposited area within Bardhaman district due to lateral migration of the Bhagirathi River in different periods

of water along with sediments to the Bhagirathi during the rainy season, and ultimately this brings significant changes in meander geometry and associated features (Rudra 2018). It is evident from the Google Earth Pro images (images of Landsat/Copernicus satellite) of 1984, 1990, 2000, 2010 and 2018 (all the images are of December month) that a significant variation in alluvial bars in terms of number is observed during this period in the

study area. There were 17 alluvial bars of different sizes found in the river channel in 1984 and it got increased over time, such as 20 in 1990, 22 in 2000, 31 in 2010 and 43 in 2018. It simply refers to the dynamicity of the river Bhagirathi.

On the contrary, the process of erosion also gets accelerated due to anthropogenic activities. In the entire stretch of the study area, there are plenty of numbers of brickkiln industries on

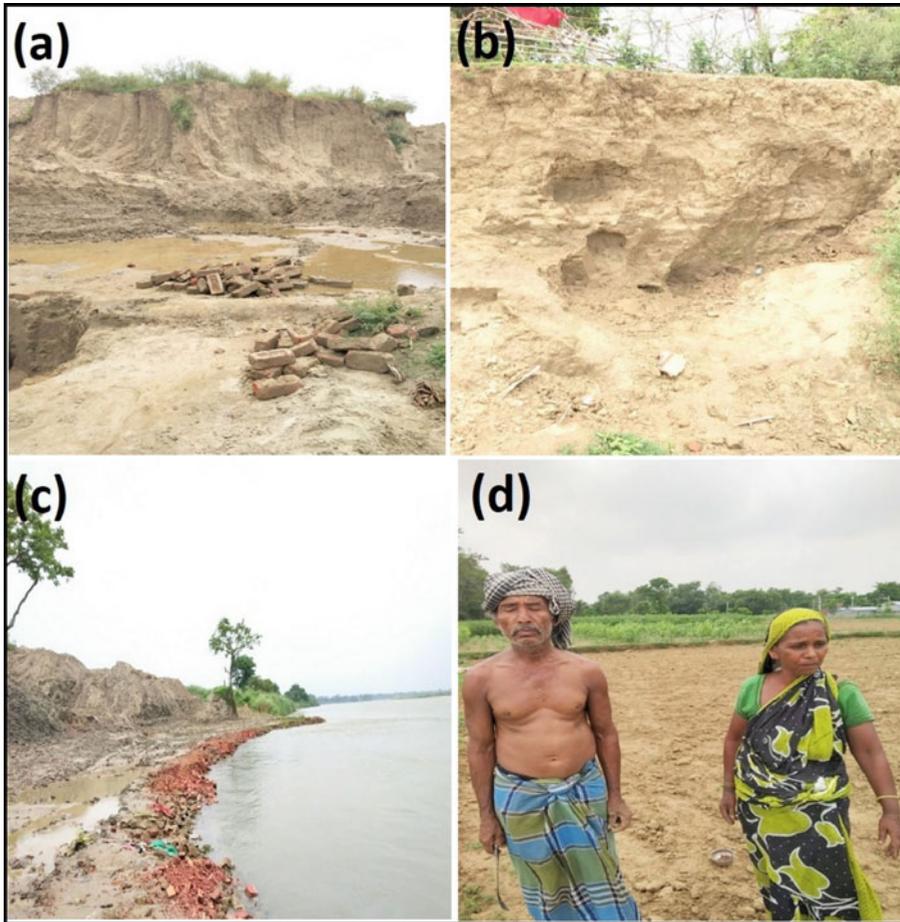


Fig. 14.12 Illegal sediment mining sites for **a** brickkiln industry and **b** pottery industry. **c** Dumping of waste materials of brickkiln industries along the Bhagirathi River as an effort to prevent erosion by the local residents. **d** The lady in this picture has lost her in-laws house along

with agricultural land and became agricultural labourer, and the man beside the lady has already lost some of his land and the agricultural land on which he standing is also eroding

either side of the river. Many people are engaged in illegal and unscientific sediment mining to supply the same to the brickkiln industry, pottery industry and other works (Fig. 14.12a, b, c). These works suddenly enhance the process of bank erosion modifying the local flow pattern and enhancing the toe erosion. The bank materials along the river are mainly composed of loose soil particles of non-cohesive sand with more pore spaces. During the Monsoon period, the heavy downpour causes abrupt bank erosion, which may incur a bank slump (Bag et al. 2019; Panda and Bandyopadhyay 2011). A sudden

high discharge event encourages the chance of bank failure. The fast rates of bank retreat usually seen in the meander apex are also explained by high shear stress generated at the bend by higher flow velocity. Apart from direct entraining materials from the bank face, the flow also scours its base that leads to over steepening and failure. Entrainment of bank materials is also possible by oscillation created by the boats and launches. With the shifting of the Bhagirathi, in most segments, lands continuously get eroded at one bank and accrete on the other. Allotment of the newly emerged land (alluvial bars or *chars*)

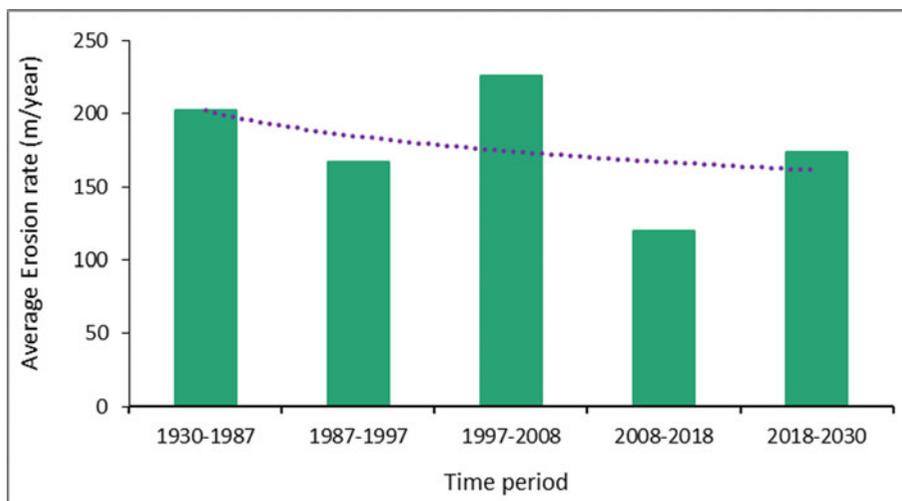


Fig. 14.13 Average rate of erosion of bank lines of the Bhagirathi River in different periods with an overall trend of average erosion rate

among the farmers becomes a major issue in the region when it becomes mature enough for cultivation. The overall economic status is low with low per capita income and below the standard of living because a few numbers of people are landlords. Mental stress and anxiety, arising from the continuous threat of land erosion, are a constant companion for the residents of the riparian settlements (Fig. 14.12d). On the other hand, depositional activity became aggravated because of different engineering structure construction as bank protection measures, like bank paving, spur construction, etc. and communication linkages, like bridge construction. Riverbank protection measures of the river Bhagirathi show encouraging results, and the local administrations are also eager to take necessary steps for bank protection measures. The study of bank erosion helps to bring out relative magnitudes of diverse issues related to bank erosion by the river Bhagirathi from the standpoint of the affected people.

14.4.6 Chances of Vulnerability of the Areas Adjacent to the Bhagirathi River

It has also been computed to know the future trend of lateral migration based on the

logarithmic regression model and found that the bank lines will undergo an average rate of erosion of 174 m/year from 2018 to 2030 (Table 14.5 and Fig. 14.13). It reveals that the pattern of erosion of riverbanks constantly changes over each period. Based on the predicted bank line shifting of 2030, the villages belonging adjacent to either side of the river channel within the jurisdiction of Bardhaman district are identified. There may 17 villages be affected by the lateral migration of the river due to the process of erosion in the future, of which 3 villages (namely: Kalyanpur, Bishnupur and Sankhai) are from Ketugram-II C.D. block, 3 villages (namely: Char Brajanathpur, Kalikapur and Gazipur) belong to Katwa-II C.D. block, 6 villages (namely: Sarisha, Jhaudanga, Dampal, Majida, Mertala and Gopipur) come under Purbasthali-II C.D. block, 2 villages (namely: Jaluidanga and Jalahati) are from Purbasthali-I C. D. block, 2 villages (namely: Gramkalna and Krishnadebpur) are located at Kalna-I C.D. block and 1 village (namely: Hanspukur) is from Kalna-II C.D. block (Figs. 14.14 and 14.15). It is estimated that more than 16,000 households with a population of around 65,000 may find themselves vulnerable to those 17 villages. There is a chance of more or less 14,000 households of Kalna-I, Purbasthali-II, Katwa-II and

Table 14.5 Future shifting trend in right and left bank lines of the Bhagirathi River

| Cross-section no | Right bank line shift in 2030 (m) by logarithmic regression ($x = 34$ th year as 1997 is the 1st year) | Associated process on river bank | Left bank line shift in 2030 (m) by logarithmic regression ($x = 34$ th year as 1997 is the 1st year) | Associated process on river bank |
|------------------|---|----------------------------------|--|----------------------------------|
| 1 | -8.72 | Erosion | -18.77 | Erosion |
| 2 | -19.60 | Erosion | 2.23 | Accretion |
| 3 | 61.70 | Accretion | 38.29 | Accretion |
| 4 | -11.20 | Erosion | 27.09 | Accretion |
| 5 | -11.09 | Erosion | -94.04 | Erosion |
| 6 | 112.68 | Accretion | -159.21 | Erosion |
| 7 | -8.17 | Erosion | 226.01 | Accretion |
| 8 | 240.79 | Accretion | -35.89 | Erosion |
| 9 | -1071.82 | Erosion | 986.71 | Accretion |
| 10 | 0.04 | Accretion | 12.93 | Accretion |
| 11 | 173.18 | Accretion | -24.68 | Erosion |
| 12 | 5.45 | Accretion | -15.93 | Erosion |
| 13 | -192.75 | Erosion | 322.25 | Accretion |
| 14 | -36.34 | Erosion | 50.43 | Accretion |
| 15 | 149.36 | Accretion | -84.48 | Erosion |
| 16 | 809.93 | Accretion | -955.25 | Erosion |
| 17 | 57.67 | Accretion | -89.42 | Erosion |
| 18 | 173.08 | Accretion | -545.53 | Erosion |
| 19 | -40.93 | Erosion | 215.88 | Accretion |
| 20 | -2.13 | Erosion | -14.94 | Erosion |
| 21 | 103.63 | Accretion | -465.54 | Erosion |
| 22 | -96.36 | Erosion | 319.56 | Accretion |
| 23 | 176.00 | Accretion | -166.53 | Erosion |

Note Negative values indicate erosion and positive values indicate accretion

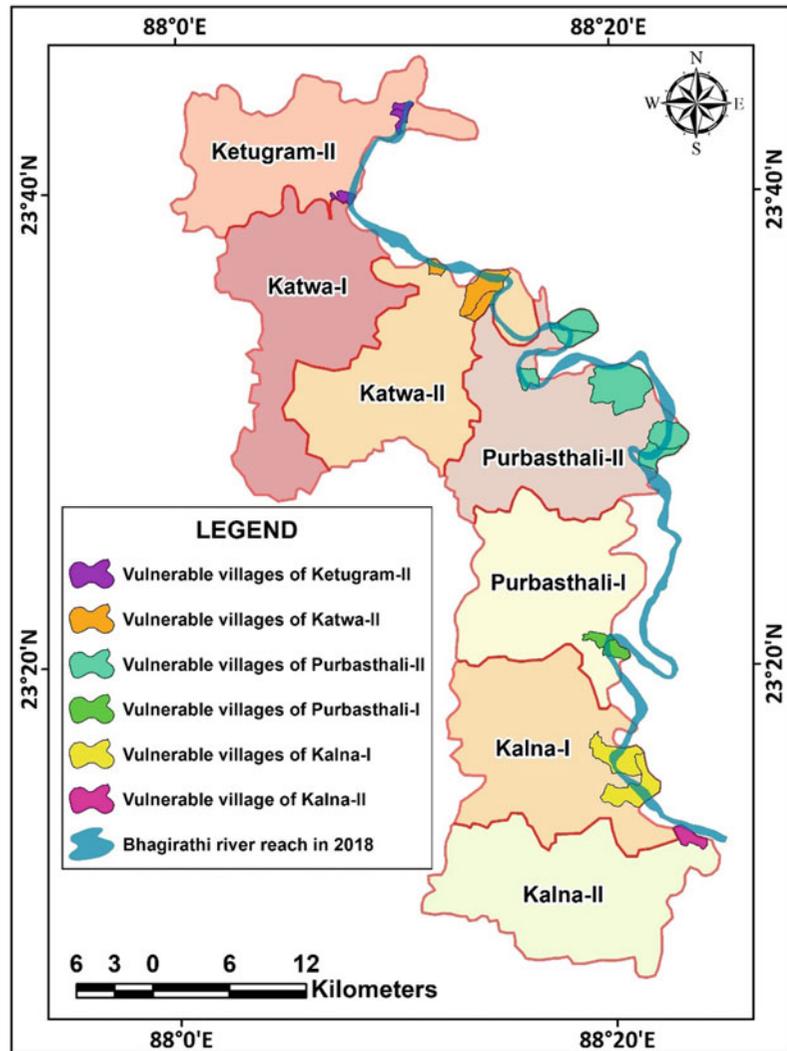
Purbasthali-I C.D. blocks to be affected badly by future channel migration (Census of India 2011). Since the river Bhagirathi stays apart from the Katwa-I C.D. block, thus no village of the C.D. block might not face any vulnerability related to the lateral migration of the channel from 2018 to 2030 (Fig. 14.14).

14.5 Data Validation

The common remotely sensed data validation technique includes the formulation of an error matrix using the field data or published data of other reliable sources. However, the digital

dataset, such as ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and SRTM (Shuttle Radar Topography Mission) can also be used as an alternative way for the comparison and validation of satellite image derived data (Hamid et al. 2017). In the present study, the field data cannot be generated as the selected time periods are of the past, and the published data of other sources also cannot be used because of the discrepancy in the absolute location of the drawn cross-sections. Therefore, the only available SRTM data, which was acquired in the year 2000 is used after proper geocoding (Universal Transverse Mercator projection, World Geodetic System 84 datum and

Fig. 14.14 Predicted vulnerable villages of the study area due to channel migration of the Bhagirathi River from 2018 to 2030



zone 45 N) in the ArcGIS environment to validate the satellite image derived Bhagirathi River reach of 1997, as there will be minimal difference between the river reach of 1997 and 2000. Based on the SRTM data, profile graphs are generated one by one along the 23 cross-sections by using the Stack Profile (3D Analyst) tool in ArcGIS. The distance and elevation data of each profile are exported from the attribute table of Stack Profile to MS Excel to generate a profile line graph. The elevation of the intersection points of each cross-section and river bank lines of 1997

are extracted from SRTM, and the distance of these points along each cross-section are measured by adopting a measuring tool in ArcGIS. These points are overlaid on the profile line graph of the respective cross-section with the help of distance and elevation data in MS Excel, which denote the position of the river banks on the profile line graph. Figure 14.16a, b represent the location of the river banks in 1997 that fall almost accurately on the profile line graph generated from SRTM data along the cross-section numbers 11 and 19, respectively.

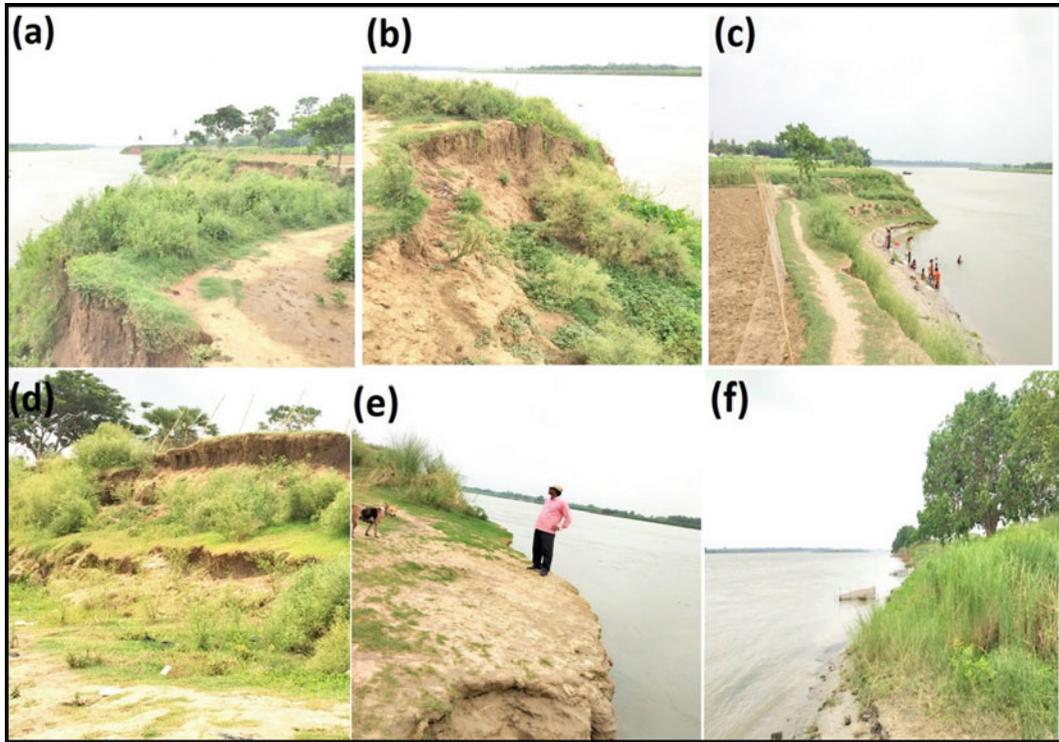


Fig. 14.15 Erosion prone spots at the bank of the Bhagirathi River creating vulnerability to the local residents in terms of houses, agricultural land and

adjacent pack-track of the villages of (a) Ketugram-II, (b) Katwa-II, (c) Purbasthali-II, (d) Purbasthali-I, (e) Kalna-I and (f) Kalna-II C. D. blocks

14.6 Conclusion

The present study unveils that the channel of river Bhagirathi in the studied reach is dynamic. From 1930 to 2018, the average rate of bank line erosion within the studied reach was 192 m/year and it has been observed along with gradual changes in its meander geometry. Due to the process of accretion, many point bars have been evolving and some of them are used in the form of new land for human habitation and agricultural practices. It has come to see that a point bar converted into a village, namely: Char Brajanathpur on the right bank of the river, near the Katwa-II C.D. block, after 1995 (Census of India 2001). The river Bhagirathi flows along the eastern margin of 7 populous C.D. blocks and increasing population density exerts tremendous pressure on land for habitation and food on either side of the river.

Therefore, any kind of change in the position of the bank line automatically affects a huge number of riparian inhabitants and making the issue popular to society. The future prediction of channel migration in the form of bank line shifting of 2030 estimates that more or less 65,000 people of 17 riverine villages (Census of India 2011) of Bardhaman district may be vulnerable to erosion in the future. This gradual process of bank line shifting leads to damages and losses of agricultural lands and settlements due to the process of erosion and also creates new hope of lights generating new land by the process of accretion. But the proper planning well in advance with the appropriate management strategy may be a checkmate to combat the future vulnerability of the study area. This study also opens new avenues of researches for researchers to understand the variable factors associated with determining the dynamicity of the present river

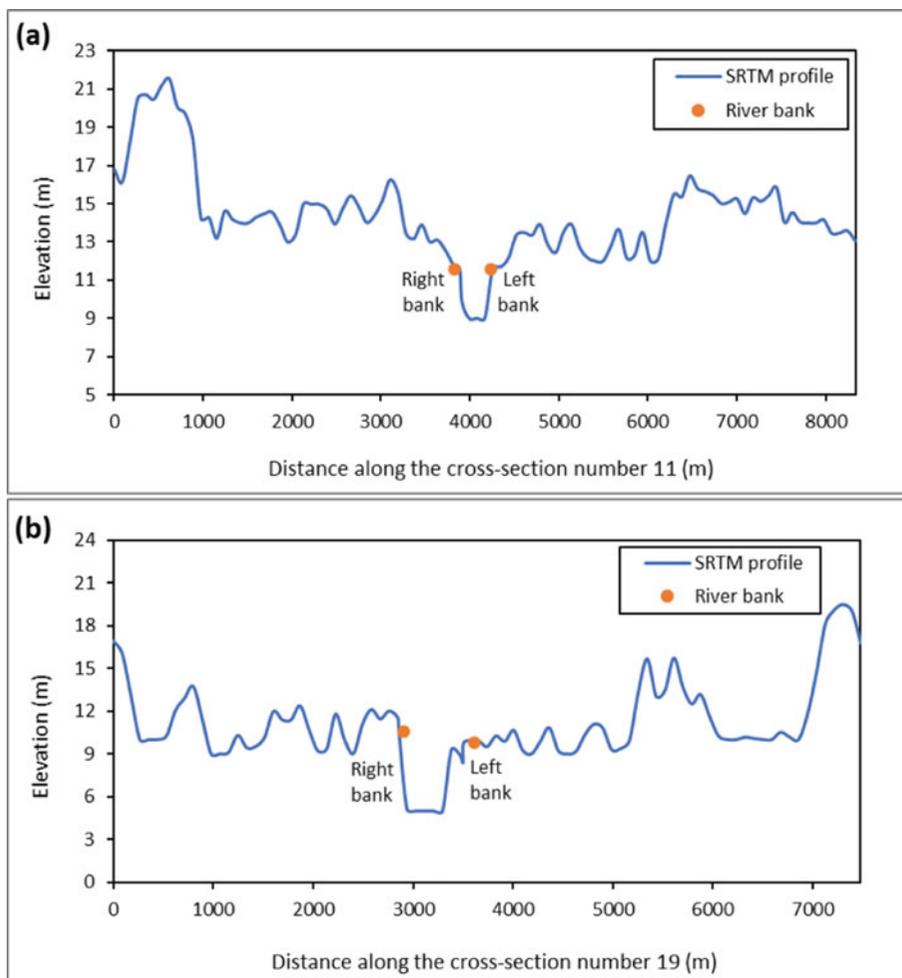


Fig. 14.16 Validation of the river reach generated from satellite image

reach. The long-term assessment of rate, trend and pattern of bank erosion and its digital database generation will help to formulate proper planning and rehabilitation of people up to C.D. block level, mouza level and even up to plot-level monitoring. It will also be able to find out the future vulnerable pockets of bank erosion and to formulate its proper way of mitigation. The plot-level distribution of land to erosion victims and rehabilitation can be made easier if the digital data can be linked with the land record system through e-governance, and ultimately sustainable development plan can be formulated updating the

whole system involving digital database and its management plan from time to time.

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References

- Aher SP, Bairagi SI, Deshmukh PP, Gaikwad RD (2012) River change detection and bank erosion identification using topographical and remote sensing data. *Int J Appl Inf Syst* 2(3):1–7
- Ahmed I, Das N, Debnath J, Bhowmik M (2018) Erosion induced channel migration and its impact on dwellers in the lower Gumti river, Tripura India. *Spat Inf Res* 26(5):537–549. <https://doi.org/10.1007/s41324-018-0196-9>
- Alexeevsky NI, Chalov RS, Berkovich KM, Chalov SR (2013) Channel changes in largest Russian rivers: natural and anthropogenic effects. *Int J River Basin Manag* 11(2):175–191. <https://doi.org/10.1080/15715124.2013.814660>
- Bag R, Mondal I, Bandyopadhyay J (2019) Assessing the oscillation of channel geometry and meander migration cardinality of Bhagirathi river, West Bengal India. *J Geograp Sci* 29(4):613–634. <https://doi.org/10.1007/s11442-019-1618-z>
- Basu SR (2001) Impact of the Farakka barrage on the Bhagirathi-Hugli and the port of Calcutta. In: Basu SR (ed) *Impact of on man on environment: some cases of concern: professor R. N. Dubey memorial lectures*. Professor R.N. Dubey Foundation, Allahabad, pp 39–71
- Basu SR, Ghosh A, De SK (2005) Meandering and cut-off of the river Bhagirathi. In: Kalwar SC (ed) *Geomorphology and environmental sustainability*. Concept Publishing Company, New Delhi, pp 20–37
- Basu SR, Sen A (1997) A study on the recent changes (1978–1992) in the morphology of River Hooghly Indian. *J Geomorphol* 2(1):39–49
- Basu SR, Sen A, Ghosh A (1996) Some consideration on the decay of deltaic drainage system of Bengal with special reference to the river Bhagirathi-Hugli. In: Tiwari RC (ed) *Proceedings, 6th conference of Indian Institute of Geomorphologists*. Allahabad Geographical Society, Allahabad, pp 57–68
- Beechie TJ, Liermann M, Pollock MM, Baker S, Davies J (2006) Channel pattern and river-floodplain dynamics in forested mountain river systems. *Geomorphology* 78(1–2):124–141. <https://doi.org/10.1016/j.geomorph.2006.01.030>
- Bhunia GS, Shit PK, Pal DK (2016) Channel dynamics associated with land use/cover change in Ganges river, India, 1989–2010. *Spat Inf Res* 24(4):437–449. <https://doi.org/10.1007/s41324-016-0045-7>
- Bisson M, Piccinini S, Zanchetta G (2011) A multidisciplinary GIS-based approach for mapping paleoriver migration: a case study of the Serchio river (Lucca alluvial plain, Tuscany). *Gisci Remote Sens* 48(4):566–582. <https://doi.org/10.2747/1548-1603.48.4.566>
- Census of India (2001) *Administrative Atlas-West Bengal 2001*. Directorate of Census Operations, West Bengal, India
- Census of India (2011) *District census handbook-Barddhaman 2011*. Directorate of Census Operations, West Bengal, India
- Chakraborty S, Mukhopadhyay S (2015) An assessment on the nature of channel migration of river Diana of the sub-Himalayan West Bengal using field and GIS techniques. *Arab J Geosci* 8(8):5649–5661. <https://doi.org/10.1007/s12517-014-1594-5>
- Charlton R (2008) *Fundamentals of fluvial geomorphology*. Routledge, New York
- Church M (1992) *Channel morphology and topology*. In: Calow P, Petts GE (eds) *The rivers handbook: hydrological and ecological principles*. Blackwell, Oxford, pp 126–143
- Das B, Mondal M, Das A (2012) Monitoring of bankline erosion of river Ganga, Malda district and West Bengal: using RS and GIS compiled with statistical techniques. *Int J Geomat Geosci* 3(1):239–248
- Das JD, Dutta T, Saraf AK (2007) Remote sensing and GIS application in change detection of the Barak river channel, N.E. India. *J Indian Soc Remote Sens* 35(4):301–312. <https://doi.org/10.1007/BF02990786>
- Debnath J, Das (Pan) N, Ahmed I, Bhowmik M (2017) Channel migration and its impact on land use/land cover using RS and GIS: a study on Khowai river of Tripura, North-East India. *Egypt J Remote Sens Space Sci* 20(2):197–210. <https://doi.org/10.1016/j.ejrs.2017.01.009>
- Dey S, Mandal S (2019) Assessing channel migration dynamics and vulnerability (1977–2018) of the Torsa river in the Duars and Tal region of eastern Himalayan foothills, West Bengal India. *Spat Inf Res* 27(1):75–86. <https://doi.org/10.1007/s41324-018-0213-z>
- Duran R, Beevers L, Crosato A, Wright N (2011) *Bank retreat study of a meandering river reach: case study: river Irwell*. 7th international symposium on ecohydraulics 2009. Curran Associates Inc., New York, pp 1002–1012
- Dury GH (1977) *Underfit streams: retrospect and prospect*. In: Gregory KJ (ed) *River channel changes*. Wiley Interscience, Chichester, pp 281–293
- Gain AK, Giupponi C (2014) Impact of the Farakka dam on thresholds of the hydrologic flow regime in the lower Ganges river basin (Bangladesh). *Water* 6(8):2501–2518. <https://doi.org/10.3390/w6082501>
- Ghosh D (2007) *Environmental appraisal of bank erosion of the Ganga in Malda and Murshidabad districts, West Bengal*. Unpublished thesis, The University of Burdwan
- Ghosh D, Sahu AS (2018) Problem of river bank failure and the condition of the erosion victims: a case study in Dhulian, West Bengal, India. *Reg Sci Inq X* (2):205–214

- Gregory KJ (1977) The context of river channel changes. In: Gregory KJ (ed) River channel changes. Wiley Interscience, Chichester, pp 1–12
- Gregory KJ (1979) Fluvial geomorphology. *Progress in Physical Geography: Earth and Environment* 3 (2):274–282. <https://doi.org/10.1177/030913337900300207>
- Gregory KJ (1983) Fluvial geomorphology. *Prog Phys Geograp Earth Environ* 7(3):385–396. <https://doi.org/10.1177/030913338300700305>
- Guite LT, Bora A (2016) Impact of river bank erosion on land cover in lower Subansiri river flood plain. *Int J Sci Res Publ* 6(5):480–486
- Gupta A (2011) Tropical geomorphology. Cambridge University Press, Cambridge
- Hamid M, Ashraf M, Hamid Q, Sarwar SM, Saqib ZA (2017) Geospatial techniques for assessment of bank erosion and accretion in the Marala Alexandria reach of the river Chenab, Pakistan. *Sains Malays* 46 (3):413–420. <https://doi.org/10.17576/jsm-2017-4603-08>
- Hickin EJ, Nanson GC (1975) The character of channel migration on the Beatton river, northeast British Columbia. *Can Geolog Surv Am Bull* 86:487–494. [https://doi.org/10.1130/0016-7606\(1975\)86<487:TCOCMO>2.0.CO;2](https://doi.org/10.1130/0016-7606(1975)86<487:TCOCMO>2.0.CO;2)
- Huggett RJ (2017) Fundamentals of geomorphology, 4th edn. Routledge, New York
- Islam A, Guchhait SK (2017) Analysing the influence of Farakka barrage project on channel dynamics and meander geometry of Bhagirathi river of West Bengal India. *Arab J Geosci* 10(11):245. <https://doi.org/10.1007/s12517-017-3004-2>
- Knight MJ (1975) Recent crevassing of the Erap river New Guinea. *Aust Geograp Stud* 13(1):77–82. <https://doi.org/10.1111/j.1467-8470.1975.tb00068.x>
- Kotoky P, Bezbaruah D, Baruah J, Sarma JN (2005) Nature of bank erosion along the Brahmaputra river channel, Assam India. *Curr Sci* 88(4):634–639
- Kumar A, Jayappa KS, Deepika B (2010) Application of remote sensing and geographic information system in change detection of the Netravati and Gurpur river channels, Karnataka India. *Geocarto Int* 25(5):397–425. <https://doi.org/10.1080/10106049.2010.496004>
- Laha C (2015) Oscillation of meandering Bhagirathi on the alluvial flood plain of Bengal basin, India; as controlled by the palaeo-geomorphic architecture. *Int J Geomat Geosci* 5(4):564–572
- Laha C, Bandyapadhyay S (2013) Analysis of the changing morphometry of river Ganga, shift monitoring and vulnerability analysis using space-borne techniques: a statistical approach. *Int J Sci Res Publ* 3(7):1–10
- Leopold LB, Wolman MG, Miller JP (1995) Fluvial processes in geomorphology, 2nd edn. Dover publications, INC, New York
- Lewin J, Hughes D (1976) Assessing channel change in Welsh rivers. *Cambria* 3:1–10
- Majumder MK (2004) Bangladesh: Ganga under Threat. Dispute over the Ganga: a look in the potential water-related conflicts of the south Asia. Panose Institute South Asia, Kathmandu, pp 22–53
- Mandal AC, Patra P, Majumder R, Ghosh DK, Bhunia GS (2017) Evaluating meander shifting dynamics (1977–2017) of the Bhagirathi river course in Murshidabad District, West Bengal India. *Spat Inf Res* 26(1):33–45. <https://doi.org/10.1007/s41324-017-0153-z>
- Millar R (2000) Influence of bank vegetation on alluvial channel patterns. *Water Resour* 36(4):1109–1118. <https://doi.org/10.1029/1999WR900346>
- Mondal J, Mandal S (2018) Monitoring changing course of the river Ganga and land-use dynamicity in Manikchak Diara of Malda district, West Bengal, India, using geospatial tools. *Spat Inf Res* 26(6):691–704. <https://doi.org/10.1007/s41324-018-0210-2>
- Mukherjee R, Bilas R, Biswas SS, Pal R (2016) Bank erosion and accretion dynamics explored by GIS techniques in lower Ramganga river, Western Uttar Pradesh India. *Spat Inf Res* 25(1):23–38. <https://doi.org/10.1007/s41324-016-0074-2>
- Ophra SJ, Begum S, Islam R, Islam MN (2018) Assessment of bank erosion and channel shifting of Padma River in Bangladesh using RS and GIS techniques. *Spat Inf Res* 26(6):599–605. [10.1007/s41324-018-0202-2](https://doi.org/10.1007/s41324-018-0202-2)
- Pal R, Biswas SS, Pramanik MK, Mondal B (2016) Bank vulnerability and avulsion modeling of the Bhagirathi-Hugli river between Ajay and Jalangi confluences in lower Ganga plain India. *Model Earth Syst Environ* 2 (2):65. [10.1007/s40808-016-0125-7](https://doi.org/10.1007/s40808-016-0125-7)
- Panda S, Bandyopadhyay J (2011) Morphodynamic changes of Bhagirathi river at Murshidabad district using geoinformatics. *J GeograpInf Syst* 3:85–97. [10.4366/jgis.2011.31006](https://doi.org/10.4366/jgis.2011.31006)
- Philip G, Gupta RP, Bhattacharya A (1989) Channel migration studies in the middle Ganga basin, India, using remote sensing data. *Int J Remote Sens* 10 (6):1141–1149. <https://doi.org/10.1080/01431168908903953>
- Ranjan P, Ramanathan A (2018) Hooghly river. In: Singh DS (ed) *The Indian rivers: scientific and socio-economic aspects*. Springer Nature, Singapore, pp 251–257
- Rudra K (1996) The Farakka barrage- an interruption to fluvial regime. *Indian J Landsc Syst Ecol Stud* 19 (2):105–110
- Rudra K (2008) *Banglar nadikatha* (in Bengali). Sahitya Samsad, Kolkata
- Rudra K (2012) Atlas of the changing river courses in West Bengal. Sea Explorers Institute, Kolkata
- Rudra K (2014) Changing river courses in the western part of the Ganga-Brahmaputra delta. *Geomorphology* 227:87–100. <https://doi.org/10.1016/j.geomorph.2014.05.013>
- Rudra K (2018) Rivers of the Ganga-Brahmaputra-Meghna delta: a fluvial account of Bengal. Springer International Publishing AG, Switzerland
- Rusov J, Misita M, Milanovic DD, Milanovic DL (2017) Applying regression models to predict business results. *FME Trans* 45:198–202

- Saleem A, Dewan A, Rahman MM, Nawfee SM, Karim R, Lu XX (2020) Spatial and temporal variations of erosion and accretion: a case of a large tropical river. *Earth Syst Environ* 4(1):167–181. <https://doi.org/10.1007/s41748-019-00143-8>
- Sarkar MH (2004) Impact of upstream human interventions on the morphology of the Ganges-Garai system. In: Mirza MMQ (ed) *The Ganges water diversion: environmental effects and implications*. Kluwer Academic Pub, Dordrecht, pp 49–80
- Sarkar SK, Bhattacharya A, Bhattacharya B (2003) The river Ganga of northern India: an appraisal of its geomorphic and ecological changes. *Water Sci Technol* 48(7):121–128
- Schumm SA (1963) Sinuosity of alluvial rivers on the great plains. *Geol Soc Am Bull* 74:1089–1099
- Summerfield MA (2013) *Global geomorphology: an introduction to study of landforms*, 2nd edn. Routledge, New York
- Thakur PK, Laha C, Aggarwal SP (2012) River bank erosion hazard study of river Ganga, upstream of Farakka barrage using remote sensing and GIS. *Nat Hazards* 61:967–987. <https://doi.org/10.1007/s11069-011-9944-z>
- Thorne CR (1982) Processes and mechanisms of river bank erosion. In: Hey RD, Bathurst JC, Thorne CR (eds) *Gravel bed rivers*. Wiley, Chichester, pp 227–259
- Thorne CR (1992) Bend scour and bank erosion on the meandering Red River, Louisiana. In: Carling MA, Petts GE (eds) *Lowland floodplain rivers: geomorphological perspectives*. Wiley, Chichester, pp 95–116
- Thorne CR (2002) Geomorphic analysis of large alluvial rivers. *Geomorphology* 44(3–4):203–219. [https://doi.org/10.1016/S0169-555X\(01\)00175-1](https://doi.org/10.1016/S0169-555X(01)00175-1)
- Újvári G, Mentés G, Bányai L, Kraft J, Gyimóthy A, Kovács J (2009) Evolution of a bank failure along the river Danube at Dunaszekcső Hungary. *Geomorphology* 109(3–4):197–209. <https://doi.org/10.1016/j.geomorph.2009.03.002>
- Yang X, Damen MCJ, Zuidam RAV (1999) Satellite remote sensing and GIS for the analysis of channel migration changes in the active Yellow river delta, China. *Int J Appl Earth Obs Geoinf* 1(2):146–157. [https://doi.org/10.1016/S0303-2434\(99\)85007-7](https://doi.org/10.1016/S0303-2434(99)85007-7)
- Yunus AP, Jie D, Armugha K, Sravanthi N, Rao LAK, Hao C (2019) Channel migration characteristics of the Yamuna river from 1954 to 2015 in the vicinity of Agra, India: a case study using remote sensing and GIS. *Int J River Basin Manag* 17(3):367–375. <https://doi.org/10.1080/15715124.2019.1566238>