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Appraisal of Morphological Characteristics of the Bhagirathi River Channel in Murshidabad District, West Bengal

Anukul Chandra Mandal[1] and Gouri Sankar Bhunia[2]#

[1] Research Scholar, Department of Geography, Seacom Skill University, Birbhum, West Bengal

[2]Assistant Professor, Department of Geography, Seacom Skill University, Birbhum, West Bengal
 # Corresponding Author

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Abstract

Channel morphology of the Bhagirathi river in Murshidabad district has been analysed using multi-dated Landsat satellite data for 41 years (1977-2017) in terms of sinuosity index, tortuosity index, channel index, valley index, topographic Sinuosity Index, braided index. The "UNION" operation has been performed to identify the erosion and accretion zone for the two different succeeding years. The mean tortuosity index was calculated as 1.53, 1.44, 1.49, 1.43 and 1.44 for 1977, 1990, 2000, 2010 and 2017 respectively. The maximum percentage of channel width difference was recorded at CI (338.71%) with an annual rate of 138.87%. The highest value of BI (0.446) was recorded in Section-G and it was constantly changing year after year. The mean percentage of channel width was calculated as 12.28% for the entire study period. The fortitude of the channel girth was analysed to find that the vulnerability of the bank erosion is significant in the Sections- C, G and H. It may be attributed to the almanac flood in the lower course due to the avulsion of the Bhagirathi river channel in the non-cohesive sands. The information derived in this research may be used for formulating strategies of future mitigation and hazard awareness.

Introduction

River morphology has been a substance of prodigious experiment to researchers and engineers who make out that any exertion with reference to river engineering must be reliant upon an appropriate empathetic of morphological features and the responses to the executed vicissitudes (Chang, 2008). River improves numerous landforms through erosion, deposition and transportation. Landforms for instance channels, hill angle and floodplains form and their morphological components are connected by a pouring system of water flow and sediment through the morphological scheme (Biswaas and Das, 2016). River channels demonstrate changing physiognomies in both space and stage. It also replicates the collaboration of a series of scheming aspects, some of which may be controlled at the catchment scale. The degree of freedom of a river comprises of the depth, breadth, channel grade and bank inclination (Buffington, 2012).

Meandering rivers have drawn considerable attention from large group of researchers in various fields, ranging from fluvial geomorphology (Mallick, 2014), fluid morphodynamics (Dalbe and Juanes, 2018), river engineering (Elliot, 1984), petroleum engineering (Kleinhans, 2010), landscape ecology and river restoration (Singh, 2014). The formation path of drainage line relies upon the under-laying rock structure, climatic condition, vegetation, anthropogenic impact and the time taken in the development of the drainage system. Recently, numerous studies documented the channel morphology over multiple spatial and temporal scale, including controls of channel width, grain, size, bedforms, roughness, sediment transport etc (Chang, 2008; Panda, and Bandyopadhyay, 2011; Biswas and Das, 2016). Geoscientists also investigated the role of physical features, like vegetation and anthropogenic activities in affecting the geomorphic process and channel characteristics (Montgomery et al., 2003; Surian and Rinaldi, 2006). Moreover, river channel activities often prerequisite to be premeditated for its natural state and reactions to anthropological accomplishments.

Historical evidence suggests morphodynamic changes and meander evolution of the river Bhagirathi (Misra, 2018; Pal, 2015; Das et al., 2014; Panda and Bandyopadhyay, 2011). From the last 2-3 decades, geospatial technology has demonstrated itself as a valuable evidence maker for conducting river morphological investigations (Manjusree et al., 2014). Using multi-temporal satellite data, the latest configuration, shift in the river courses, formation of geomorphological features, bank erosion and deposition etc, have been mapped at various geomorphic scales (Lindenschmidt and Carr, 2018; Biswas and Das, 2016; Das et al., 2014; Panda, and Bandyopadhyay, 2011). Due to the dearth of enough evidence of floodplain structure, channel geometry, sediment depositional character of Bhagirathi River, it is very important to understand morphological characteristics and scientific explanation. This information can assist in investigating the morphological characteristics for the prevailing flood control programme and demarcation of susceptible stretches, scheduling embankment protection, and river management plan.

Study Area

The river Bhagirathi extends between 23°43'N to 24°52' N latitudes and 87°49'E to 88° 44'E longitudes of the Murshidabad district (Fig. 1). It is a branch of the river Ganges from Nurpur (i.e., 25 km below Farakka), and curving way to the south, it leaves the district just north of Plassey. After the establishment of Farakka barrage (in 1975), several cut-offs have been formed along its course and also increased the river discharge (Panda and Bandyopadhyay, 2011). However, the earlier study also denoted that significant changes in the river course have been observed in the middle course, near Berhampore town of Murshidabad district. The region is characterized by a tropical wet-and-dry climate, with a mean annual temperature of 27C. The average rainfall of the study area is about 1600mm. The district comprises two distinctive regions separated by the Bhagirathi river. The western part is the continuation of the Chotanagpur plateau, while the eastern part, the Bagri, is a fertile, low-lying alluvial tract. Rice, jute, legumes, oilseeds, wheat, barley, and mangoes are the chief crops in the study area.

Materials and Methods

Data Sources

Multi-dated Landsat data have been acquired from the USGS Earth Explorer community (https://earthexplorer.usgs.gov/) and used. The Landsat data (Path/Row 138/043) of the dry season have been employed to evade overestimation of the river stretch which is generally found during the high stage of flow. All data have been projected into the UTM system with WGS84 datum. All were then resampled into a 30m pixel size based on the nearest neighbour method. The geocoded images were then mosaiced using ENVI v4.0. Using the administrative boundary, the study area was subset through clipping method. The normalized difference water index (NDWI) was used to delineate the differences between land and water (Gao, 1996), as follows:

$$NDWI = \frac{SWIR - NIR}{SWIR + NIR}$$

The output derived from the NDWI image helps to identify the riverbank line. The shallow water channels have been reflected as a fragment of the river. Moreover, old and new sand accumulations at the riverbanks posted certain obscurity of the river. It has also been perceived that areas of recent soil deposits have a high moisture content compared to the areas contiguous to the riverbank (Sarkar et al., 2012).

Digitization of Satellite Data

The left and right banks of the river have been digitized using QGIS software. The bank lines of the Bhagirathi River for the years 1977, 1990, 2000, 2010, and 2017 were delimited with the visual elucidation along with the digital image processing techniques. The outlined bank lines were employed to create a channel midpoint streak (e.g., the line concerning the middle point in-between the two-channel margins) *via* on-screen digitization in QGIS Software v2.14.0 (Nicoll and Hickin, 2010).

Sectional Analysis

The whole river course of Bhagirathi in Murshidabad district (from Roshanpur to Barokulberia) has been alienated into 9 grids at an equal gap of 10km. These have been used for the planform parameters analysis. Each grid index features are assigned a sequential number starting with 'A" as the upper reach and 'J' as the lower reach of the Bhagirathi river in the Murshidabad district (Fig.1). All this information was assimilated into a GIS platform to compute the planform dynamics.

Identification of Morphometric Characteristics

The channel geometry instigates in its sinuous form. Sinuosity studies aid in recognizing the topographical and hydrological physiognomies of the drainage basin. Muller (1968) stated that sinuosity is the ratio between channel length and valley length. The Tortuosity index was calculated based on the valley length of the channel and channel air length. The tortuosity is demarcated as the proportion of the river length to the linear distance between its endpoints (Camporeale et al., 2005). The channel index of the study area has been demarcated as the ratio between channel length and valley index. Consequently, standard sinuosity index (SSI), hydraulic sinuosity index and topographic sinuosity index were calculated. Braiding index denotes to the number of active channels at base flow detached by the bars (Brice, 1964).

Demarcation of Erosion and Accretion Zones

The vectorized bank lines were shrouded for the chronological periods. The crisscrossing riverbanks are vectorized as polygons for erosion (e.g., river voyaged into new situation proportionate to the older channel) and accretion (e.g., polygon for preceding situation) in each section. The "UNION" operation has been performed to identify the erosion and accretion zone for the two different succeeding years. Finally, the erosion and accretion zone for the period of 1977 1990, 1990 2000, 2000 2010, 2010 2010 and 1977 2017. The average rate of erosion and deposition is governed by isolating the total erosion/accretion by the number of years intervened between two consecutive years (Yao et al., 2011).

Statistical Analysis

The descriptive statistics (mean, standard deviation, kurtosis, skewness) of the morphometric characteristics of the channel were analyzed using MS-Excel at 95% confidence level.

Results

Channel Patterns at different time intervals

The temporal and spatial changes of active channel pattern over the study period (1977-2017) has been shown in *Fig.2*. The section A represents the spatio-temporal changes of channel pattern in Suti-I and Raghunathganj-I block during the different study period (1977 - 2017) (*Fig.2a*). In 1977, 5.83 km^2 area was occupied by the main river course. However, the area of the active river channel shows progressively decreasing trend during the entire study period (*Table-1*). River islands are also observed in 1977, 2010 and 2017 and areas of wet sand were almost nil during the entire study period except in 1990. The Section-B lies between Raghunathganj-I and Sagardighi block. Here, the estimated area of active river channel recorded as 6.37 km^2, 6.04 km^2, 6.38 km^2, 6.33 km^2 and 6.17 km^2 in 1977, 1990, 2000, 2010, and 2017 respectively (*Fig.2b*). The river course was shifting towards the east in this zone. The areas of river islands were calculated in 1990 (0.17 km^2) and 2017 (0.22 km^2) only. Moreover, the wet sand was only documented in 2017.

The Section-C extends between Lalgola, Sagardighi and Bhgawangola-I block. Here, the active river channel gradually increased during the period between 1977 and 2017, except in 1990 (*Table -1*), although, the estimated area of river island was very less, except in 1977 (*Fig.2c*). The wet sand area was recorded as 2010 (0.42 km^2) and 2017 (0.21 km^2).

The section D is extended within the Murshidabad Jiaganj block of the Murshidabad district. In section-D, the area of active river course was decreasing in the entire study area, except in 2000 (*Fig.2d*). In section-E, the area occupied by the active river channel was almost constant, except in 1990 (*Fig.2e*). The main river course was almost constant in the entire study period. The Section-F lies between Murshidabad, Jiaganj and Behrampur block (*Fig.2f*). Here, the areas of main channel courses show increasing trend except in 1977. The lower portion of the river course was very much diverse. The maximum area of riverine island was recorded in 2010. The area of wet sand was almost nil in the entire study period. The Section-G extends between Behrampur and Beldanga I block in the Murshidabad district (*Fig.2g*). Here, the areal distribution of the main river course is diverse in nature. The lower and upper course in this section move towards the east and the middle portion move towards the west. Moreover, the island areas were gradually decreasing over the entire study period in this section. The maximum area of wet sand was recorded as 1.87 km^2 in 1990 and 1.13 km^2. Section - H in the study area is extended between Beldanga-I and Beldanga-II block (*Fig.2h*). In Section-H, the maximum area main river course was estimated in 2000 (5.19 km^2) and 2010 (5.04 km^2). The lowest area of the main river channel was recorded in 1990 (2.97 km^2). Thus, the areal distribution of river island shows increasing trend except in 1990 (*Table-1*). The Section-I lies within the BeldangaII block (*Fig.2i*). The spatial pattern of the channel was almost constant. The area of river course was recorded as 3.20 km^2, 4.85 km^2, 3.69 km^2, 3.41 km^2, 3.45 km^2, in 1977, 1990, 2000, 2010 and 2017 respectively. The island area was recorded as 0.39 km^2, 0.21 km^2, 0.15 km^2, and 0.28 km^2 in 1990, 2000, 2010 and 2017 respectively (*Table -1*).

Morphometric Patterns at different time intervals

River meandering is a natural geomorphic event as a result of continuing relocation of the river course and bank erosion (Ayman and Ahmed, 2009). Generally, the sinuosity of a stream refers to the aberration of a river course from its straight line between the source and mouth of the river channel (Chorley, 1968). The valley length (VL) and air length (AL) of the study area were calculated at different time periods at each section in the study site. The highest air length of the study area was measured at Section-B in 1977 whereas, the lowest value of AL was calculated as 6.64km at Section-I. The average value of the air length was calculated as 10.35km (S.D. ±1.55) in 1977. In 1990, the average value of AL was estimated at 10.60km with a standard deviation of ±1.82. Moreover, the estimated average value of AL in 2000 was calculated as 10.51km (S.D. ±1.71). In 2010 and 2017, the highest value of AL was calculated at Section-A. Conversely, the highest value of VL was recorded in Section-C in 1977 whereas, in 2017, Section-B was recorded the maximum value of VL. The average value of VL was calculated as 15.91km, 15.32km, 15.63km, 15.38km, 15.47 km in 1977, 1990, 2000, 2010 and 2017 respectively.

The channel index (CI) of the Bhagirathi river was calculated in a different section from 1977 to 2017 (*Table-2*). The channel index for Section-D and Section-E were mostly constant for the entire study period. The average value of CI was calculated as 1.26, 1.87, 2.00, 1.19, 1.02, 1.26, 1.46, 1.42 and 1.42 for Section A, Section B, Section C, Section D, Section E, Section F, Section G, Section H and Section I respectively. In section-G, the value of CI was highly variable, whereas, in Section-H, the value of CI was almost constant. The highest average value (1.48) of CI was recorded in 1977. However, the mean value of CI was uniform (1.42) for the year of 1990 and 2017. The lowest mean value of CI was calculated for the year of 2010 (1.41).

It was observed that channel morphology in different stretches of the Bhagirathi river shifted steadily. The upper and lower section of the Bhagirathi river in Murshidabad district show a lower value of SSI index (*Table-3*). The average value of SSI for 1977, 1990, 2000, 2010 and 2017 were calculated as 0.98, 1.00, 1.00, 1.02, and 0.99 respectively. The variability of SSI was mostly observed in Section-B, G, H and I. The lowest value of SSI (0.82) was recorded at Section-A in 1977. In Section-G, the lowest value (0.92) was calculated in 2000. The relative decrease of SSI coincides with the relative increase in the gradient of the stream. In 1990, a lower value of SSI was documented. This type of change in SSI value may be attributed to the influence of natural calamities and anthropogenic activities along the river course. Generally, the increasing value of SSI showed a decreasing tendency of the hydraulic gradient. The outcomes of the investigation varied year to year may be reliant on the exoneration and flow velocity of river course change because of the discrepancy in rainfall and anthropogenic activities.

The tortuosity is demarcated as the proportion of the river length to the linear distance between its endpoints (Camporeale et al., 2005). The mean value of tortuosity index was calculated as 1.53 (S.D. ±0.32), 1.44 (S.D. ±0.33), 1.49 (S.D. ±0.34), 1.43 (S.D. ±0.33) and 1.44 (S.D. ±0.32) for the year of 1977, 1990, 2000, 2010 and 2017 respectively. The highest coefficient of variation (C.V) was calculated in 2000 (23.15) and the minimum value of CV was recorded in 1977 (20.91) (Table-4). In Section-A, the maximum value of TI was estimated at 1.77 in 1977 and after that, it was decreasing in trend. Moreover, in Section-B, the value of TI was highly variable for the entire study period (1977 - 2017). The estimated TI value was 2.03 in 2000 in Section-C. However, the value of TI for Section-D was constant for the entire study period. In Section-F, the value of TI during the period 1977 and 2000 was decreasing in trend and after that, it was gradually increased. Moreover, in Section-G and H, the value of TI was increasing from 1977 to 2000 and then subsequently decreased.

The mean value of TSI was calculated as 32.80, 27.61, 30.45, 27.68 and 28.29 in 1977, 1990, 2000, 2010 and 2017 respectively. In Section-A, the maximum TSI value was calculated in 1977 and after that, the value was almost constant up to 2017 (*Table -5*). In *S*ection-B, D and E, the variability of TSI value is very less and almost nil. This may be attributed that the dominance of hydraulic action in this section was very low. In *S*ection-C, the inconsistency of the TSI value was observed for the entire study period. In *S*ection-F, the value of TSI was decreasing in trend from 1977 to 2000 (*Table-5*), representing a high topographic gradient and then it was increasing. In Section-G, the value of TSI was increased during the period between 1977 and 2010 (*Table-6*), indicated that the topographic gradient was low. Moreover, the higher value of TSI indicated the greater loophole of the preliminary surface. Consequently, in Section-H and I, the value of TSI was highly inconsistent for the entire study period that may be due to the recurrent flooding and siltation along the river course.

Variation of braiding index (BI) was observed of the equally defined 9 sections within the study area as shown in *Fig.6.* In Section-A, the value of BI varied between 0 and 0.07. In 1977, the value of BI was highest and gradually decreased to 0.003 in 2017, except for the year 2010. In Section-B, the value of BI calculated for the year of 1990 (0.023), 2010 (0.022) and 2017 (0.037). The variations of BI in Section-C were changing progressively and the highest value was recorded in 2010. However, the BI for the Section-D and E was almost nil for the entire study period. The highest value of BI was recorded in Section-G and it was constantly changing year after year. The highest value (0.446) was recorded in 1990 in this section. However, in Section H and I, the value of BI was gradually increased from 1977 to 2017.

Demarcation of Erosion and Accretion Zones

Lateral erosion by an alluvial river is noteworthy, mostly seen in the middle and lower courses and is a clue to the broadening of the river course. In this study, erosion and deposition area between two subsequent years was delineated during the 41 year period (1977-2017). The spatial distribution of erosion and deposition has been represented sectionwise for different time periods (*Fig.7*). During the period between 1977 and 1990, the total erosion was calculated as 12.12 km^2 (20.04%) whereas, the estimated deposition area was measured as 10.24 km^2 (16.93%) (*Table-6*). Most of the erosion and deposition zone were identified in Section-C, G, and H. In Section-D and E, the channel is almost straight and no erosion and deposition area were demarcated (*Fig.5.8a*).From1990 to 2000, the estimated area of erosion and deposition was calculated as 6.35 km^2 and 7.36 km^2 respectively. Erosion and deposition were insignificant in Section-A and Section-F. Most erosion and accretion zone were delineated in Section-C, G and H (*Fig.5.8b*). Between 2000 and 2010, major area under erosion was delineated in Section-G and I. Moreover, the deposition area was delimited in Section-F and H (*Fig. 5.8c*). The total estimated area of erosion was calculated as 3.97 km^2 whereas, the calculated area of deposition was recorded as 6.05 km^2 (10.92%). During the period between 2010 and 2017, the calculated are of erosion and deposition were 10.17% (5.58 km^2) and 6.24% (3.42 km^2) respectively (*Table -6*). The erosion area *has been* demarcated in the Section-F, Section-H and G during this period (*Fig.5.8d*). It specifies th*at th*e lateral erosion is extremely predominant in the Bhagirathi river. *Fig. 5.8e* portrays the overall pattern of erosion and deposition area of the Bhagirathi river course during the period between1977 and 2017. Overall, most of the erosion area was demarcated in Section-C, F (lower part only), G, H and I. Consequently, the deposition occurred in the middle course of Section-C, the lower course of Section-F, G, H and I. However, the estimated area of erosion and deposition was recorded as 17.43 km^2 (26.13%) and 16.47 km^2 (24.69%) respectively during this 41 years period (977-2017).

Discussion

Reconstruction of the chronology of channel movement by using historical maps and satellite images combined with geospatial technology has been widely used (Das et al., 2012, Thakur et al., 2012, Hazarika et al., 2015). During monsoon, due to over-flowing of water into the river course, the deep channels smack crossways and wear down the banks posturing risk of serious loss to prized property, transportation, and nearest towns and villages. The river Bhagirathi normally gets silted as the sediments tend to detrain the river bed because of the gravitational force and retained in interruptions as a result of upward currents during stormy flow overwhelming the gravity force.

Channel migration and erosion are multifaceted actions instigated by the interaction of numerous aspects comprising river emancipation, current of the river, the geology of the riverbank, geomorphology, geometrical characteristics of the channel along with man-made activities (Debnath et al., 2017). Lack of proper resolution makes the satellite imagery poor to appraise the base-channel morphology of the Bhagirathi river systems. Therefore, by assimilating of the cross-sectional data, remotely sensed images may be integrated for better results to demarcate the morpho-dynamics of the river parameters. The behaviour of the Bhagirathi river have been studied for 41 years from 1977 to 2017. The alluvial plains in and around the Bhagirathi rivers are sprinkled by several fluvial geomorphic features including paleochannels. Satellite-derived information was employed to identify the fluvio-geomorphological procedures and to map out the paleochannel and dry river courses. The wavelength is identical to double the linear space between the zero intersections of the curvature. On the other hand, the curvilinear pattern denotes the remoteness along the river (Allen, 1984). Most of the features are demarcated as meander scars demonstrating numerous periods of cutoffs. Some of the scars are now covered with natural vegetation and some are regularly cultivated. Several of the abandoned meander loops have been used for agricultural plantations.

River flooding is the key aspect disturbing the discrepancies in the amount of sediment deposition and erosion in any specific area (Anand, 2018). In Section-C, meanders are characterized by upstream orientation towards axial asymmetry. Meander progressions come about by an inclusive downstream lateral movement of both the limbs. Concurrent depositional sandbars are sub-parallel to the inner bank of the limbs. In certain instances, the evolution may occur in such a manner that the limbs of the meander become identical to each other, giving a gooseneck alignment. In Section-G and Section-H, multiple meanders with two developed summits pointing upstream and downstream correspondingly. Consequently, axial equilibrium is also bowed upstream and downstream. Centrifugally outward corrosion and aggradation occur around the two apices. The outcomes of the channel migration also represents that auxiliary evolution of this kinds of meandering through outward bank erosion eventually clues to neck cut-off.

It is found that most of the observation of BI were '0' indicated that river is much straighter in these section at that specific time period. The results also showed the dramatic changes of BI in Section-G and Section-H in the entire study period that may be attributed to influence of flooding in this zones that deposits the larger sediment along the river course. Tortuosity index helps us to understand the slope of the river and the tectonic changes leading to valley-slope changes (Yargholi and Goraji, 2014). Yemani et al., (2011) suggested that highly tortuous rives are adjacent to equipoise while the linear course of the river plugs to the youngness and neotectonic events of the area. Therefore, this is assumed that the Bhagirathi river courses are characterized by low SSI and they are in the stage of maturity.

Erosion along the Bhagirathi river course may be instigated by the emasculating of the upper bank constituents by channels (Panda and Bandyopadhyay, 2011). For the period of the high floods, an overhanging cantilevered block was formed that finally drops or by over-steepening of bar ingredients because of the relocation of the thalweg nearer to the bank in the deteriorating phases (Goswami, 2002). Earlier, it is reported that the bank erosion rate of the Bhagirathi river course is greater after the monsoon, when there is an increase in rainfall intensity (Bera, 2017). This may be attributed to the slump of water level affecting instability between the riverbank and water level and ensuing in the forfeiture of soil cohesive power that clues to the riverbank erosion. Moreover, sand (non-cohesive bank material) leads to higher erosion and finally indicates the broadening of the river course (Bhowmik et al., 2014). The analysis also suggested that the kinetic energy of the river water discharged from the Farakka Barrage bout the concave banks, particularly during monsoon and accordingly bank erosion succeeds in downstream in the entire sections. As the upper part of the Bhagirathi river is well shielded by numerous bank fortification revetments and flood guard embankments, the propensity of erosional events may be vital along the lower course which is unguarded.

Channel development is identified as an alteration in channel breadth that ensues when both banks are ebbing horizontally into the floodplain. Channel shrinkage arose when the channel thickness lessens over the period of dimension. This is caused when one bank ruins steady and the reverse bank experiences deposition, for instance, sand bar development or when both banks indenture because of deposition on the channel boundary. The progression of lateral erosion depends on the gradient and kind of the bank ingredients (Bhuiyan et al., 2014). Moreover, the vulnerability of the bank erosion is significant in the Section C, G and H. It may be attributed to the annual flood in the lower course because of the avulsion of the Bhagirathi river and comprised of non-cohesive sands.

Conclusion

The spatial variability of morphological variables of the Bhagirathi river was investigated and the result showed a significant change in Bhagirathi River during the period between 1977 and 2017. The analysis of cross-section along different reaches from 1977 to 2017 reveals that the endangered condition of the nearby land use and built-up areas due to the high risk of bank erosion. Outcomes of this study also revealed that both erosion and deposition has taken a plane in middle and lower sections due to natural as well as anthropogenic factors and influencing the river dynamics. Analyzing the morphometric variables providing the significant characteristics past and present behaviours of the Bhagirathi river. Therefore, the information derived in this research may be supportive of future mitigation and hazard awareness programmes by the planning authority.

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Table-1: Areal distribution of the Bhagirathi river course in Murshidabad district at different sectors, 1977-2017

O Area in km^2

Section	Features	1977	1990	2000	2010	2017
Section - A	River Course	5.83	3.94	4.30	4.27	3.96
	River Island	0.37	0.00	0.07	0.19	0.02
	Wet Sand	0	0.10	0	0.00	0.00
Section-B	River Course	6.37	6.04	6.38	6.33	6.17
	River Island	0.00	0.14	0.00	0.00	0.22
	Wet Sand	0.00	0.00	0.00	0.00	0.01
Section-C	River Course	6.69	6.42	6.74	6.79	6.75
	River Island	0.00	0.16	0.07	0.01	0.10
	Wet Sand	0.00	0.00	0.00	0.42	0.21
Section-D	River Course	2.47	2.41	2.50	2.35	2.44
	River Island	0.00	0.00	0.00	0.00	0.00
	Wet Sand	0.00	0.00	0.00	0.00	0.00
Section-E	River Course	2.85	2.68	2.80	2.79	2.92
	River Island	0.00	0.00	0.00	0.00	0.00
	Wet Sand	0.00	0.00	0.00	0.00	0.00
Section-F	River Course	4.11	3.63	3.84	4.09	4.02
	River Island	0.14	0.12	0.00	0.79	0.03
	Wet Sand	0.00	0.00	0.00	0.03	0.00
Section-G	River Course	4.13	5.25	5.63	5.01	4.86
	River Island	0.46	0.36	0.38	0.67	0.98
	Wet Sand	0.00	1.87	0.16	1.13	0.10
Section-H	River Course	3.85	2.97	5.19	5.04	4.62
	River Island	0.29	0.00	0.28	0.47	0.42
	Wet Sand	0.00	0.20	0.18	0.56	0.82
Section-I	River Course	3.20	4.85	3.69	3.41	3.45
	River Island	0.00	0.39	0.21	0.15	0.28
	Wet Sand	0.00	0.00	0.00	0.04	0.19

Source: Computed by theauthors

Table-2: Channel Index (CI) of Bhagirathi river during the period 1977 and 2017

Section	1977	1990	2000	2010	2017
	(Length in km)				
A	1.46	1.20	1.22	1.21	1.21
B	1.90	1.85	1.88	1.90	1.83
C	1.98	2.00	2.06	1.98	1.99
D	1.19	1.19	1.22	1.19	1.19
E	1.02	1.02	1.02	1.02	1.02
F	1.45	1.18	1.20	1.21	1.25
G	1.38	1.44	1.56	1.43	1.50
H	1.44	1.44	1.44	1.38	1.38
I	1.55	1.42	1.40	1.33	1.41

Table-3: Standard Sinuosity Index (SSI) of Bhagirathi river between 1977 and 2017

Section	1977	1990	2000	2010	2017
	(Length in km)				
A	0.82	1.00	1.00	1.00	1.00
B	1.00	0.99	0.98	0.98	0.98
C	1.00	1.00	1.01	1.01	1.00
D	1.00	1.00	1.00	1.00	1.00
E	1.00	1.00	1.00	1.00	1.00
F	1.00	0.99	1.00	1.00	0.99
G	0.99	0.99	0.98	0.92	0.97
H	0.99	0.93	0.95	0.99	0.97
I	0.99	0.98	0.86	0.95	0.95

Table-4: Tortuosity Index (TI) of Bhagirathi river between 1977 and 2017

Section	1977	1990	2000	2010	2017
	(Length in km)				
A	1.77	1.21	1.23	1.21	1.22
B	1.91	1.87	1.92	1.93	1.86
C	1.98	2.00	2.03	1.96	1.99
D	1.19	1.19	1.22	1.19	1.18
E	1.02	1.02	1.02	1.02	1.02
F	1.45	1.19	1.21	1.21	1.26
G	1.39	1.44	1.60	1.56	1.55
H	1.45	1.55	1.52	1.40	1.42
I	1.57	1.45	1.62	1.40	1.48

Table-5: Topographic Sinuosity Index (TSI) of Bhagirathi river between 1977 and 2017

Section	1977	1990	2000	2010	2017
	(Length in km)				
A	53.07	17.24	18.68	17.58	17.95
B	47.75	46.93	48.69	49.08	47.07
C	49.22	50.21	50.24	48.57	49.57
D	15.70	15.81	18.07	16.11	15.48
E	1.64	2.21	2.25	2.30	2.44
F	31.16	16.03	17.27	17.46	20.77
G	28.67	30.84	38.14	39.01	36.90
H	31.21	37.80	36.18	28.74	30.63
I	36.80	31.45	44.49	30.24	33.77

Table- 6: Erosion and Deposition area along the Bhagirathi river course

Year	1977 - 1990		1990 - 2000		2000 - 2010		2010 - 2017		1977 - 2017	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Erosion	12.12	20.04	6.35	11.40	3.97	7.17	5.58	10.17	17.43	26.13
Deposition	10.24	16.93	7.36	13.21	6.05	10.92	3.42	6.24	16.47	24.69
River Course	38.11	63.02	41.99	75.39	45.38	81.91	45.85	83.59	32.81	49.18

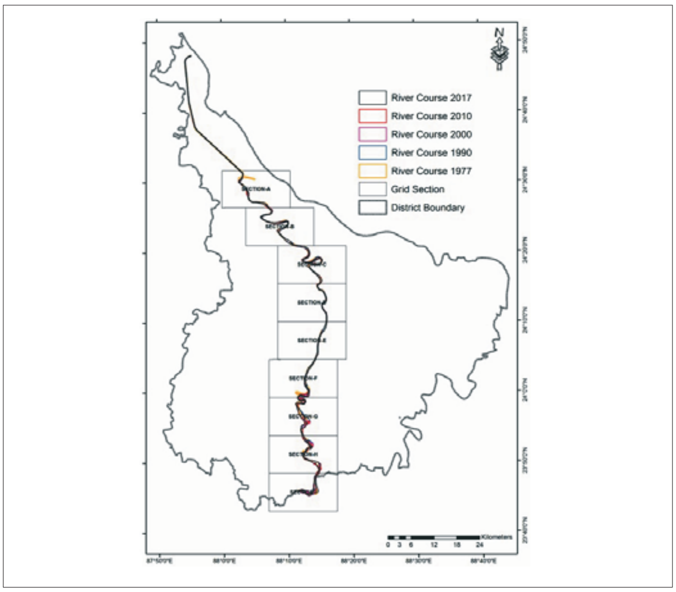

Fig.1: Sections at 10km interval along the Bhagirathi river

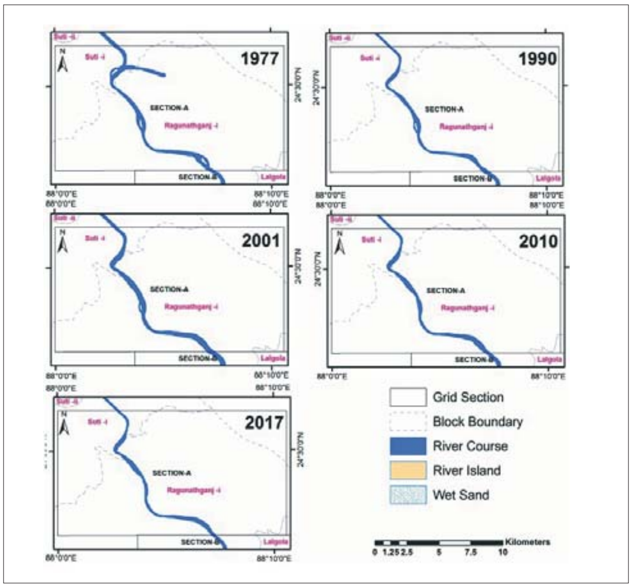

Fig.2a: Spatio-temporal changes of Bhagirathi river in Section-A, 1977 2017

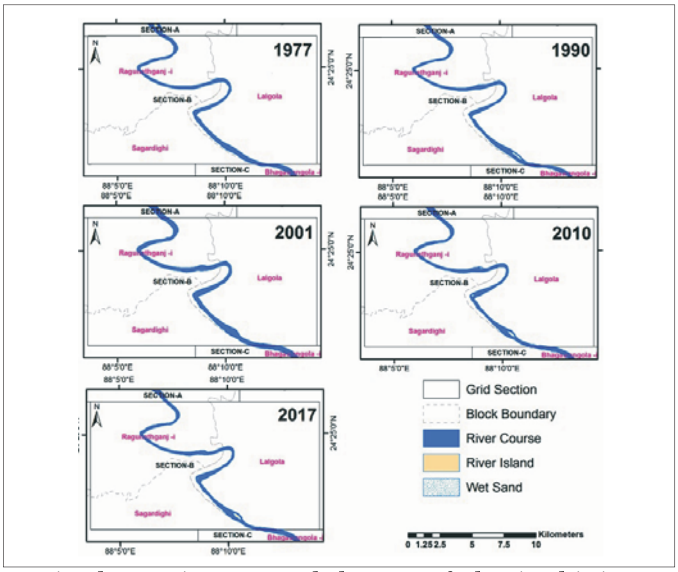

Fig.2b: Spatio-temporal changes of Bhagirathi river in Section-B, 1977 2017

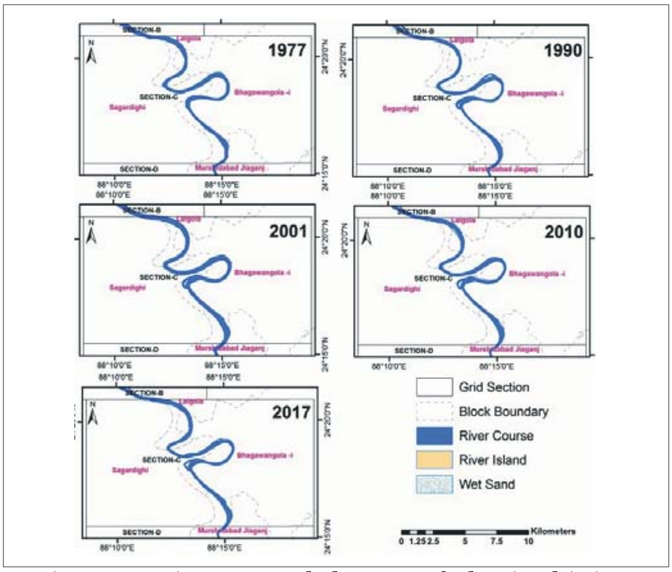

Fig.2c: Spatio-temporal changes of Bhagirathi river in Section-C, 1977 2017

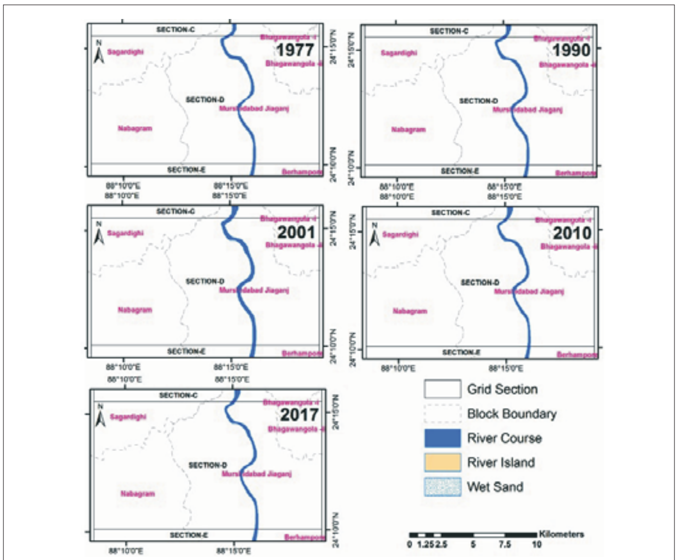

Fig.2d: Spatio-temporal changes of Bhagirathi river in Section-D, 1977 2017

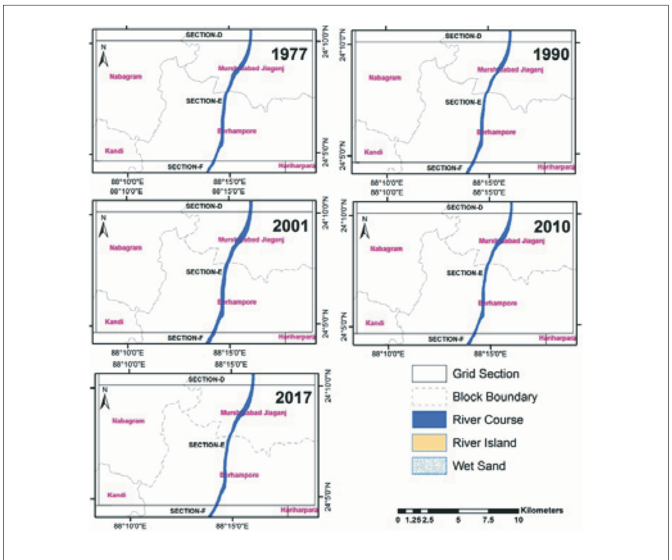

Fig.2e: Spatio-temporal changes of Bhagirathi river in Section-E, 1977 2017

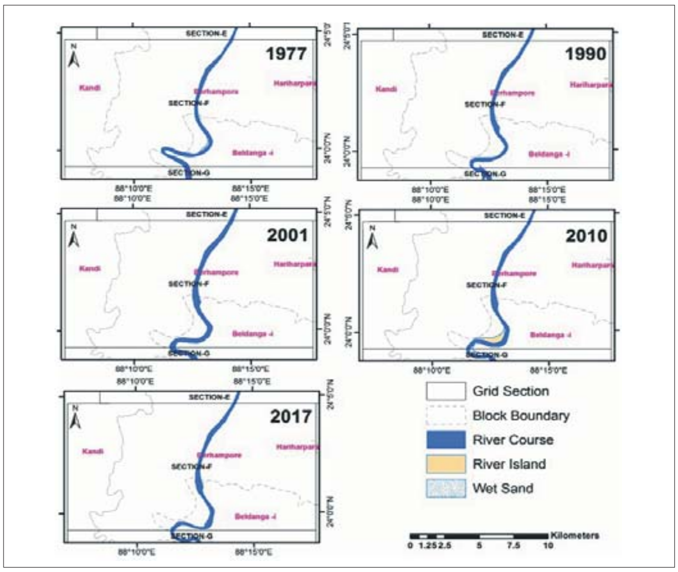

Fig.2f: Spatio-temporal changes of Bhagirathi river in Section-F, 1977 2017

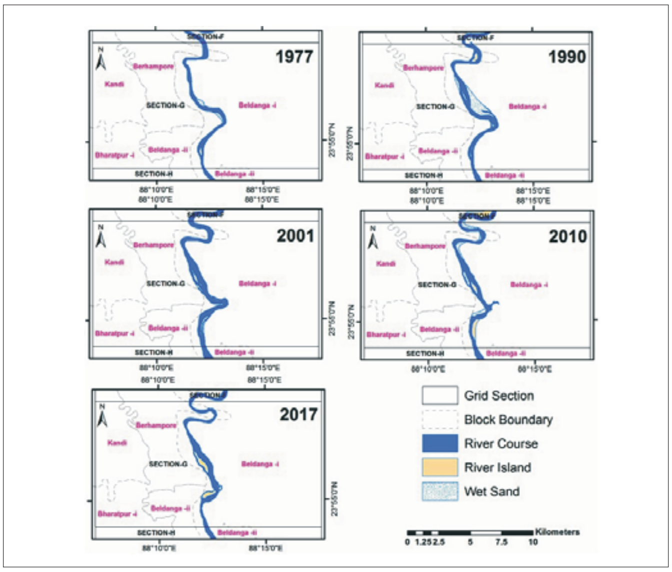

Fig.2g: Spatio-temporal changes of Bhagirathi river in Section-G, 1977 2017

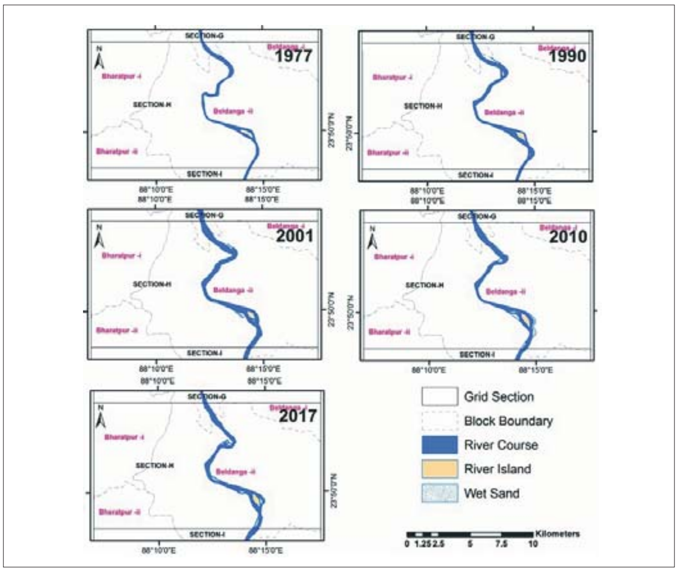

Fig.2h: Spatio-temporal changes of Bhagirathi river in Section-H, 1977 2017

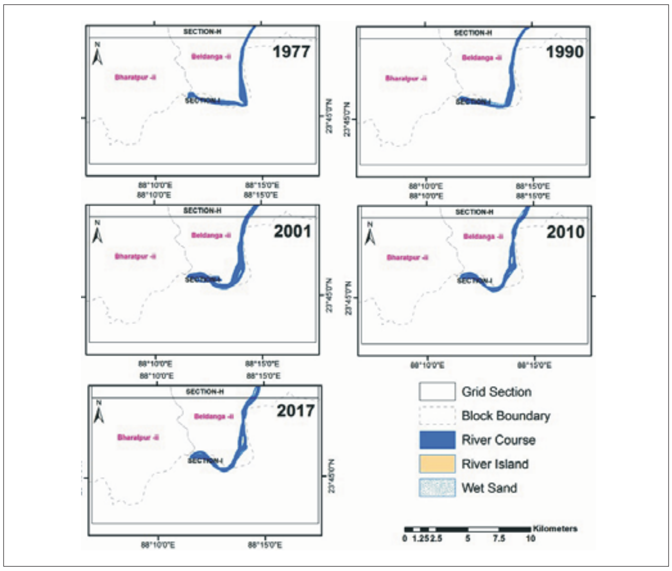

Fig.2i: Spatio-temporal changes of Bhagirathi river in Section-I, 1977 2017

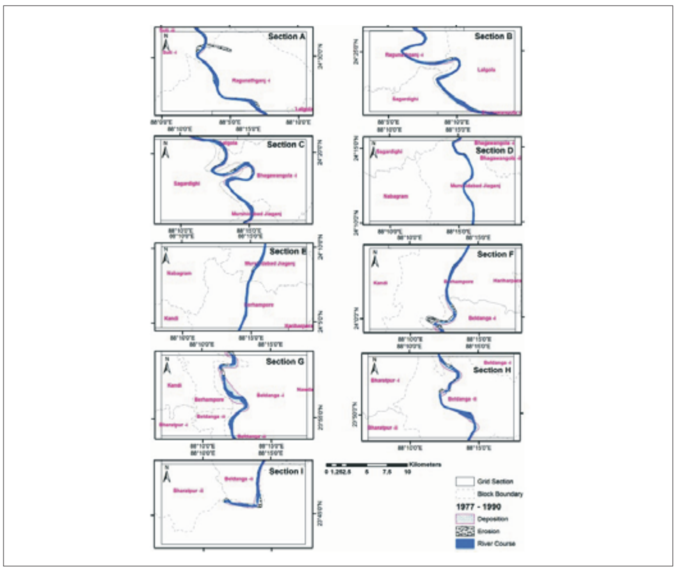

Fig.3a: Identification of Erosion and Deposition zones, 1977 and 1990

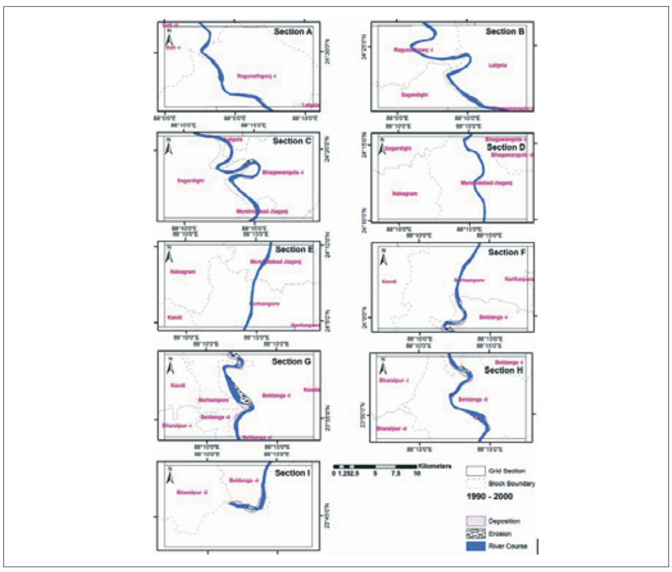

Fig.3b: Identification of Erosion and Deposition zones, 1990 and 2000

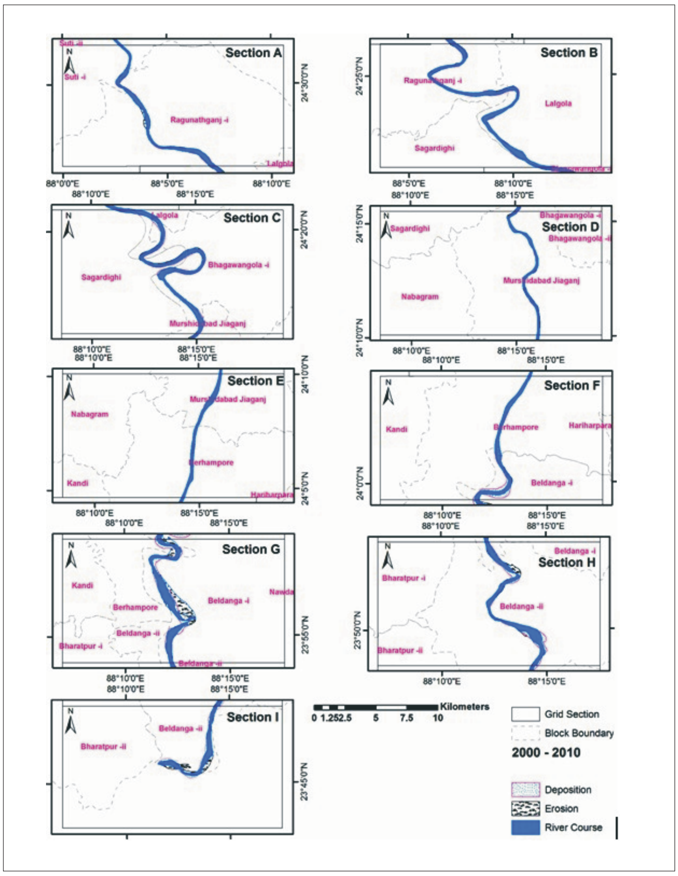

Fig.3c: Identification of Erosion and Deposition zones, 2000 and 2010

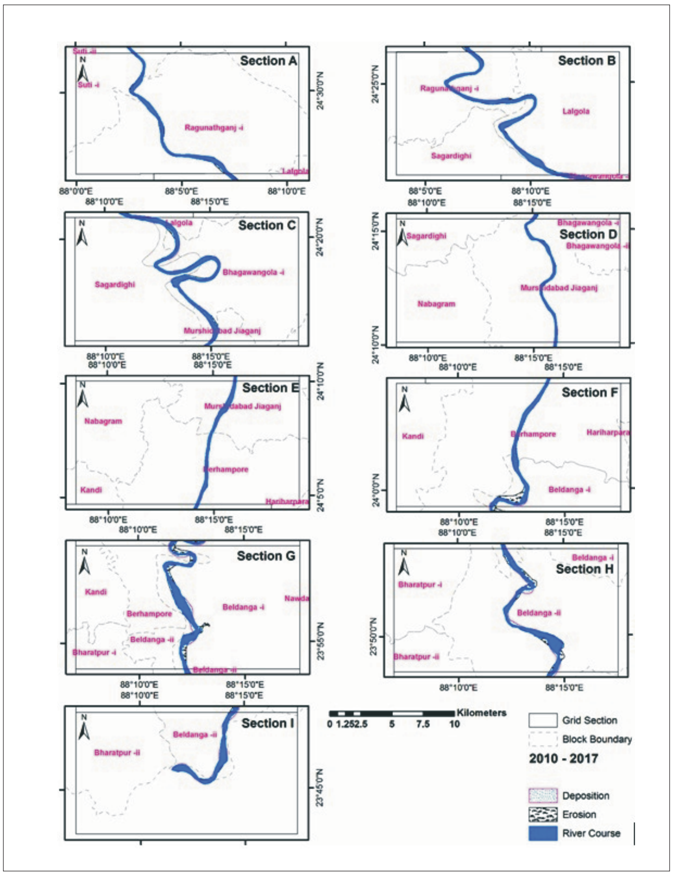

Fig.3c: Identification of Erosion and Deposition zones, 2010 and 2017

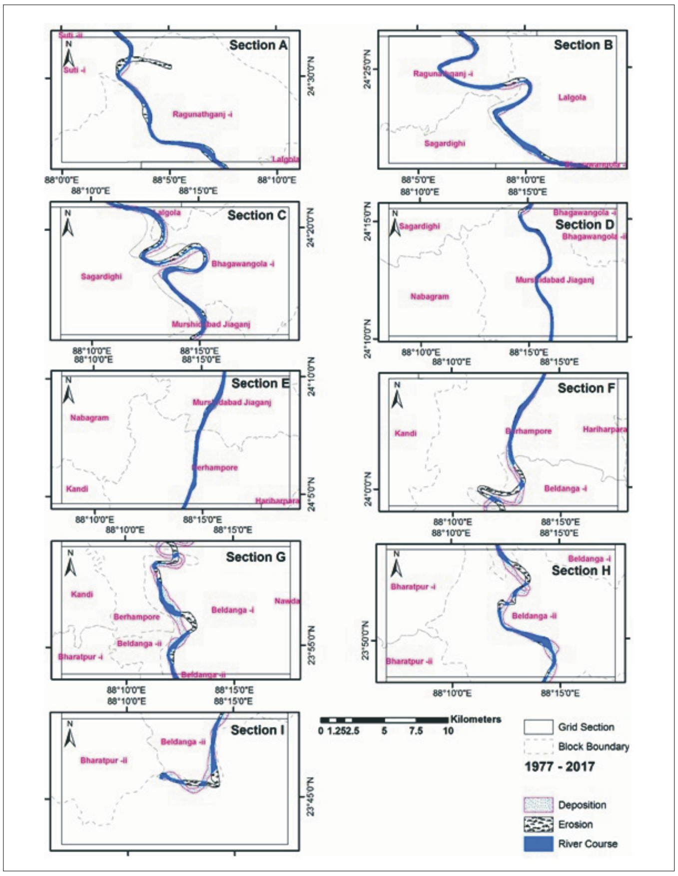

Fig.3b: Identification of Erosion and Deposition zones, 1977 and 2017

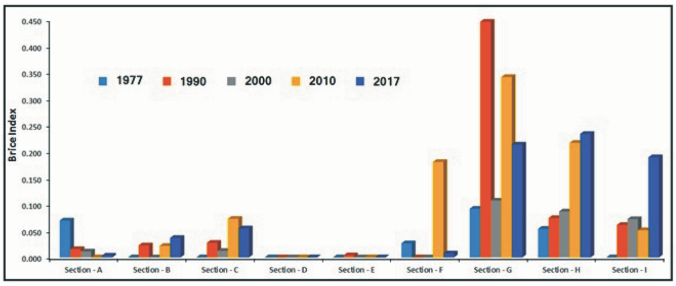

Fig.4: Brice Index of the river Bhagirathi,1977 and 2017

Anukul Chandra Mandal
Research Scholar: Department of Geography,
Seacom Skill University, West Bengal
Email: mandalanukul1983@gmail.com

Dr. Gouri Sankar Bhunia
Assistant Professor: Department of Geography,
Seacom Skill University, West Bengal
Email: rsgis6gouri@gmail.com