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ORIGINAL ARTICLE

Assessment of relationship of braiding intensities with stream power and bank erosion rate through Plan Form Index (PFI) method: a study on selected reaches of the upstream of Ganga river near Malda district, West Bengal, India

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Abstract

River bank erosion is a hazardous and common phenomenon in diara region near Malda district of North East India during monsoon and post monsoon periods of every year. The left bank of Ganga river is texturally very weak along diara region of Malda district. The present work explores relations between stream power, braiding intensities and bank erosion in certain stretches of upstream of the Ganga river near Malda district of West Bengal in India. In the present study, we have tried to do a quantitative assessment of channel braiding process of the Ganga river by applying the Plan Form approach and equivalent measurement of stream power. A comparative study of discrete years has been done through braiding index to understand morphological behaviour of the channel. Beside its stream power of the selected stretches of the study area is estimated and compared with braiding intensity and bank erosion. This paper presents the dynamic behaviour of the channel pattern of the Ganga river system in Malda district over a time span of 40 years. This procedure addresses the selection of input parameters from digital satellite images comprising scenes for the years 1975, 1995 and 2015 with specific dates, from Rajmahal in Jharkhand district to Farakka barrage in Malda district. To obtain Plan Form Indices for the entire study area, required parameters were extracting through using GIS techniques. Stream power is measured through analyzing latest flood records and satellite images. The present study concluded that a wide spread and continuous braiding process has occurred in the study area due to aggradations of riverbed and temporal declination of stream power.

Keywords River plan form · Braiding indices · Bank erosion · Stream power · Plan Form Index (PFI) · Ganga river

Introduction

Lateral migration of channel refers to the positional change of a river channel in response to the varying fluid flow and sediment discharges volume which is always related with river bank erosion (Yang et al. 1999). Therefore, lateral migration is phenomenon that control catastrophic local or regional changes (Hickin and Nanson 1984). A review has been made on measurement of the river bank erosion and lateral channel changes. All types of satellite remote-sensing data are currently available, and their recent uses in studies of river systems have been highlighted (Muller et al. 1993). Gurnell et al. (1994) studied and measured channel plan form changes on the River Dee meanders. The changes were analyzed by the GIS-based methodology (Gurnell et al. 1994).

The lower Gangetic plain consist a major river systems in India. Gangetic plain covers a large extension of India. The River Ganga emerges from the Gangotri glacier, about 4500 m above mean sea level in the Uttarakhand Himalayas, and flows down to the Bay-of-Bengal covering a distance of 2525 km. The Ganga river carries large volume of sediment and deposited it in the plain areas. These transporting sediment loads are the source of major water resource in the river catchment. Besides that the deposition of sediment

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creates many hydro-geomorphological problems like the decrease of river depth due to heavy riverbed siltation. When the flow velocity becomes low, the river gives pressure on both river bed walls and as a result lateral erosion become start and flood and river bank erosion (Thakur et al. 2012).

Bank failure occurs when bank material becomes unstable and falls or slides at the base of the bank. There are several types of failure, and different failure mechanisms are observed for cohesive and non-cohesive bank materials. The moisture content of the bank is also significant, particularly for cohesive bank materials whose strength varies with the level of saturation. A certain amount of water is held in the pores, against the force of gravity, by metric suction forces. This occurs due to tension effects and a negative pore water pressure (less than atmospheric) develops when the soil is not completely saturated. It has also been suggested that desiccation can lead to a higher rates of bank retreat, because of the shrinking of clay particles causes cracking and shedding of loose material at the bank surface. Others important aspects of bank erosion process are bank heights, bank angle, and the effects of vegetation. The process of slaking occurs when banks are rapidly immersed by floodwaters and air becomes trapped and compressed within the pores. The resultant pressure causes material to become dislodged (Thome and Osman 1988). At high flows, banks may become saturated with water from the channel. Saturation also occurs when there is a rise in the water table or during prolonged rainfall. Under these conditions, a positive pore water pressure exists between the grains. This weakens the cohesive forces, acting as a lubricant and reducing intergranular friction. The stability of banks is determined by the balance between the shear stress exerted by the down-slope component of gravity (driving force) and shear strength of the bank material (resisting force). In cohesive banks, failure occurs across a failure plane**,** the surface within the bank across which shear stress exceeds shear strength.

Erosion occurs when current velocity and turbulence are more powerful than the weight of the soil particles and their cohesive strength. Therefore, cohesive soils (e.g., clay soils) are more resistant to erosion than non-cohesive soils (e.g., sandy soils). It should be noted that the raveling force is stronger when the direction of the current forms an angle with the soil surface. As said before that the erosive power-induced bank erosion depends on two factor, i.e. rate of material removal, and rate of material accumulation (the collapsed materials in the toe of the bank).

Due to its geo-location, Diara regions are rich in ground water; hence the ground water hydrology plays an important role in the occurrence of bank failure in those regions. During the lean season when the river water discharge of river water Ganga river water decrease the ground water of the adjacent flood plain area flows towards river course as sub-surface flow and supplies it water (the porous soil material of the left bank allows the free flow of ground water). This sub-surface flow carries the cementing material as well as sub-surface particles of the soil profile with it and weaken the soil binding and vacant the sub-surface layer of the soil water. As a result of this process, the surface layer along the bank side subsides inviting the river water intrusion in the inland area. This is not a direct process of bank erosion, but it is an important role in land loss in the study area.

The formation of bars and islands is so multifaceted that makes the fluvial landform pattern is more complex. The extremely braided nature of the Ganga river has lead many channels being active at a time. The process is closely related to the conclusions of Leopold and Wolman (1957), which imply that presence of coarse sand bars within the channel divert flow directions and increase the channel width. It develops numerous bars and converts the channel into braided pattern. Such kind of braided pattern is being formed in an alluvial stream like Ganga due to deposition of coarse material which cannot be removed through existing flow condition within the reach. These coarse materials act as a nucleus for a bar formation. The formation of the bar deflects the main stream towards the banks and may cause bank erosion. Therefore, it is very important to understand how the process of bank erosion controls through the variability of stream power and braiding intensities.

However, there is a lack of investigations on variability of stream power with braiding intensity and bank erosion for the Ganga river. In view of the above, the objectives of the present work are (1) to identify a rational braiding indicator to adequately represent braiding phenomenon in the upstream of Ganga river; (2) to predict the inconsistency of stream power in relation to braiding process and bank erosion and (3) to identify the river bank sites of the study area which display less susceptibility and played a role as control points for further detailed hydraulic investigations.

Study area and drawing out of channel form

Malda is a northern district of West Bengal. The district total area is about 3733 km^2 (Census of India 2001). The district consists of 15 sub-divisions, commonly known as blocks. South Western boundary of the district is drawn by the river Ganges. This study is focused on the left bank site of river Ganges which mainly located along the Diara regions of the district (Fig. 1). The geographic extent of the study area is from 24° 51′ N to 25° 14′ N and 87° 46′ E to 88° 60′ E, with area of 316.39 km^2. According to a report, 750 km^2 land area was lost within the last 30 years along the left bank of river Ganga near Malda district (Banerjee 1999).

Digital satellite images of Landsat OLI 8 sensor, consisting of scenes for the years 2015 are used for the present study. All the images are georeferenced under one geometric

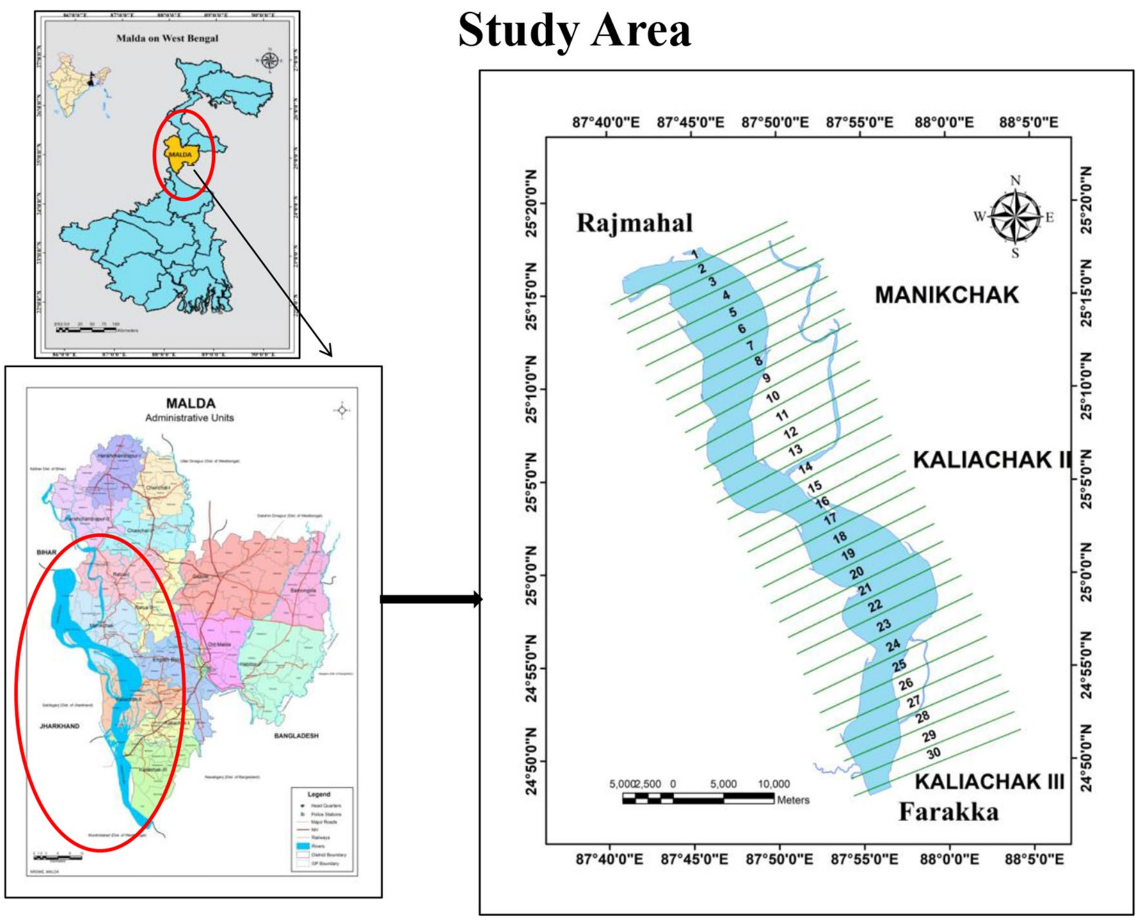


Fig. 1 Map of study area

co-ordinate system with respect to SOI Toposheet with 1:50,000 scale applying second order polynomial. Landsat TM images of the year of 1975, 1995 and 2015 are geometrically rectified with reference to the LANDSAT images of the same area. To do geo-referencing process, UTM projection system and WGS 84 datum have taken into consideration. Referencing process has been done with root mean square error of less than 1 value.

After that the left bank, line of the upstream of Ganga river is digitized using Arc GIS software from each set of imageries. The analyzing data for the present study have been presented in Table 1. Then, satellite images of the given years (1975, 1995 and 2015) were co-registered using an image-to-image registration technique.

The study area of around 185 km from Rajmahal in Sahibganj district, Jharkhand to upstream of Farakka barrage in Malda is considered.

Existing braiding indicators

Several past studies had presented discrimination between the straight, meandering, and braided streams on the basis of discharge and channel slope. Lane (1957) suggested the following criterion for the occurrence of braiding:

$$S > 0.004(Q_m) - 0.25, \quad (1)$$

where Q_m = mean annual discharge; and S = channel slope.

Table 1 Characteristics of the remote sensing data used

Data type	Details	Resolution (m)	Year/date	Source
Landsat TM 4–5	Path/row: 139/43	30	1995–11–08	USGS
Landsat TM 1–2	Path/row: 149/43	60	1975–11–22	USGS
Landsat OLI 8	Path/row: 139/43	30	2015–11–06	USGS
Google Earth Image	NA	NA	Nov, 2015	Google Earth

Using bank full discharge Q_b, Leopold and Wolman (1957) and Richards (1982) proposed the relationship for braiding to occur, which also predicts braids at higher slopes and discharges:

$$S > 0.013Q_b^{-0.44}, \tag{2}$$

where Q_b = bank full discharge.

Leopold and Wolman (1957) also indicated that braided and meandering streams can be separated by the relationship:

$$S = 0.06Q^{0.44}, \tag{3}$$

where S = channel; and Q = water discharge.

However, these indicators have been revisited by Schumm and Khan (1972) and they concluded that none of these recognizes the importance of sediment transport. These results imply a higher power expenditure rate in braided streams, a conclusion reinforced by flume experiments (Schumm and Khan 1972). Since bed material transport and bar formation are necessary in both meandering and braiding development processes, the threshold between the patterns should relate to the bed load.

Henderson (1961) re-analyzed Leopold and Wolman's data to derive an expression including.

*d*50, median grain size (mm):

$$S > 0.002d_{50}^{1.15}Q_b^{-0.46}, \tag{4}$$

where d_{50} = median grain size.

According to Eq. (4), a higher threshold slope is necessary for braiding to occur in coarse bed materials. Bank material resistance affects the rate of channel migration and should also influence the threshold, although its effect may be difficult to quantify and also be non-linear since greater stream power is required to erode clays and cobbles than sands.

Parker's (1976) stability analysis indirectly illustrates the effects of bank material resistance by defining the meander–braid threshold as:

$$S/\mathrm{Fr} = D/B, \tag{5}$$

where D = mean depth of the flow; B = width of the stream, and Fr = flow Froude number.

The depth, width and flow Froude number may be expressed in terms of discharge and bank silt–clay percentage, as suggested by Schumm (Richards 1982). Meandering occurs when $S/\mathrm{Fr} \le D/B$, braiding occurs when $S/\mathrm{Fr} \ge D/B$, and transition occurs for S/Fr is around equal to D/B.

Ferguson (1981) suggested the following condition for braiding to occur, which predicts steeper threshold slopes for braiding in channels with resistant silty banks:

$$S > 0.0028\left(Q_b\right)^{-0.34}B_c^{0.90}, \tag{6}$$

where B_c = percentage of silty clay content in the bank material.

Measures of the degree of braiding generally fall into two categories: (1) the mean number of active channels or braid bars per transect across the channel belt; and (2) the ratio of sum of channel lengths in a reach to a measure of reach-length (total sinuosity).Where sinuosity, P is defined as thalweg length/valley length.

Sharma (2004) developed Plan Form Index (PFI), Flow Geometry Index (FGI), and cross-slope ratio for identifying the degree of braiding of highly braided river. The PFI, FGI and

Cross-slope formulae have been given below:

$$\mathrm{PFI} = \{(T/B) \times 100\}/N, \tag{7}$$

$$\mathrm{FGI} = \{\sum di \cdot xi/(W \times D)\} \times N, \tag{8}$$

$$\text{Cross slope} = \left(B_L/2\right)/(\text{bank level} - \text{avg. bed level}), \tag{9}$$

where T = flow top width (m); B = overall width of the channel (m); B_L = transect length across river width; N = number of braided channel; *di* and *xi* are depth and top lateral distance of submerged sub-channel, respectively; and D = hydraulic mean depth.

Materials and methods

Domain and using data

In the present study, the river bank line has been extracted through applying proper GIS applications. Selected locations wise plan-form maps have been developed through analyzing satellite images for the discrete years, i.e. 1975, 1995 and 2015. Besides that the unit stream power is measured through the corresponding discharge data and computed width by average river bed gradients for the same period and the latest flood-period for selected sites.

Data geo referencing and image processing

One set of Survey of India topo-sheets (1965) and digital satellite images of IRS LISS-I and LISS-III and LANDSAT sensors, comprising scenes for the years 1975, 1995 and 2015 are used in the present study. The deriving maps (with pixel size of 30 m × 30 m) are georeferenced with RMS: < 1 value with taking nearest neighbours as resampling technique and digitized the river bank line for each discrete year. After that, supporting images like corresponding toposheets, etc. are also verified with the geo-referenced image using the image-to-image registration technique.

Delineation of river bank line

For convenience, the main river has been divided into 30 cross-sections with 3 reaches, and reference cross sections were drawn at the boundary of each strip. Each ten cross sections were grouped as a reach with numbering from Rajmahal upto Farakka Barrage of equal base length (Table 2). The derived data for each cross section from satellite images of years 1975, 1995 and 2015 were analyzed and the bank lines were also digitized for all the years (Fig. 2).

Intermediate channel widths, and total widths of channel at each predefined cross sections were measured using GIS software tools for computing Plan Form Indices for each cross sections for further analysis.

Table 2 Identification of reaches in respect of the location

Reach	Cross profile No	Location
Manikchak	1	Godai
	2	Chandipur mal
	3	Dergrama
	4	Chandipur Tofi
	5	Dakshin Chandipur
	6	Paschim Narayanpur
	7	Narayanpur
	8	Kamalpur
	9	Jot Bhabani
	10	Manikchack
Kaliachak II	11	Govindapur
	12	Dharampur
	13	Mirpur
	14	Rahimpur
	15	Gopalpur
	16	Uttar Lakshmipur
	17	Dharampur
	18	Kankribandha Jhaubona
	19	Kamaluddinpur
	20	Daridiar Jhaubona
Kaliachak III	21	Dharampur
	22	Panchanandapur
	23	Daskhatia
	24	Hamidpur
	25	Paranpur
	26	Dogacchi
	27	Nayagram
	28	Babla
	29	Purba Sripur
	30	Dakshin Debipur

The erosion depth in left and right banks of the river area during the study period was estimated by the GIS software tools through delineating the river bank lines.

Delineation of Plan Form Index (PFI)

To determine intensity of braiding of braided river, PFI was developed by Sharma (2004). The PFI formula has been given below:

$$\mathrm{PFI} = \{(T/B) \times 100\}/N, \tag{7}$$

where T = flow top width in metre; B = overall channel width in metre; N = number of braided channel (Sharma 2004).

PFI in Eq. 7 (description sketch has been shown in Fig. 3) indicates the fluvial landform disposition with respect water level; besides that lower values give indication of higher degree of braiding.

To explain braided phenomena, the following threshold values for PFI are forwarded by Sharma (2004):

PFI value less than 4: highly braided

PFI value ranges between 4 and 19: moderately braided

PFI value greater than 19; low braided.

The braiding indicator for PFI suggested by Sharma (2004) has been applied in the present study to predict the braiding intensity of the river. The whole study has been done to evaluate the temporal and spatial variation of braiding intensities along the whole given stretch of the river Ganga in Diara regions of Malda district in West Bengal.

Delineation of stream power (SP)

The hydraulic parameters of an open channel flow such as hydraulic mean depth, wetted perimeter, flow area, bed gradient, discharge and the physical properties, $\gamma(=\rho g)$ of the fluid are related to represent the unit stream power in respect to the direction of flow (Yang 1976; Chang 1979).

The unit stream power (N/m s) can be computed through the flowing equation;

$$'\Omega = (\gamma \times Q \times S), \tag{8}$$

where γ is the specific water weight and w is the channel width.

Results and discussion

Variation of braiding and bank erosion through Plan Form Index (PFI)

The PFI has calculated for each selected cross-section totaling 30 in numbers across the study sites are plotted against each cross-section number for discrete 3 years in Fig. 4.

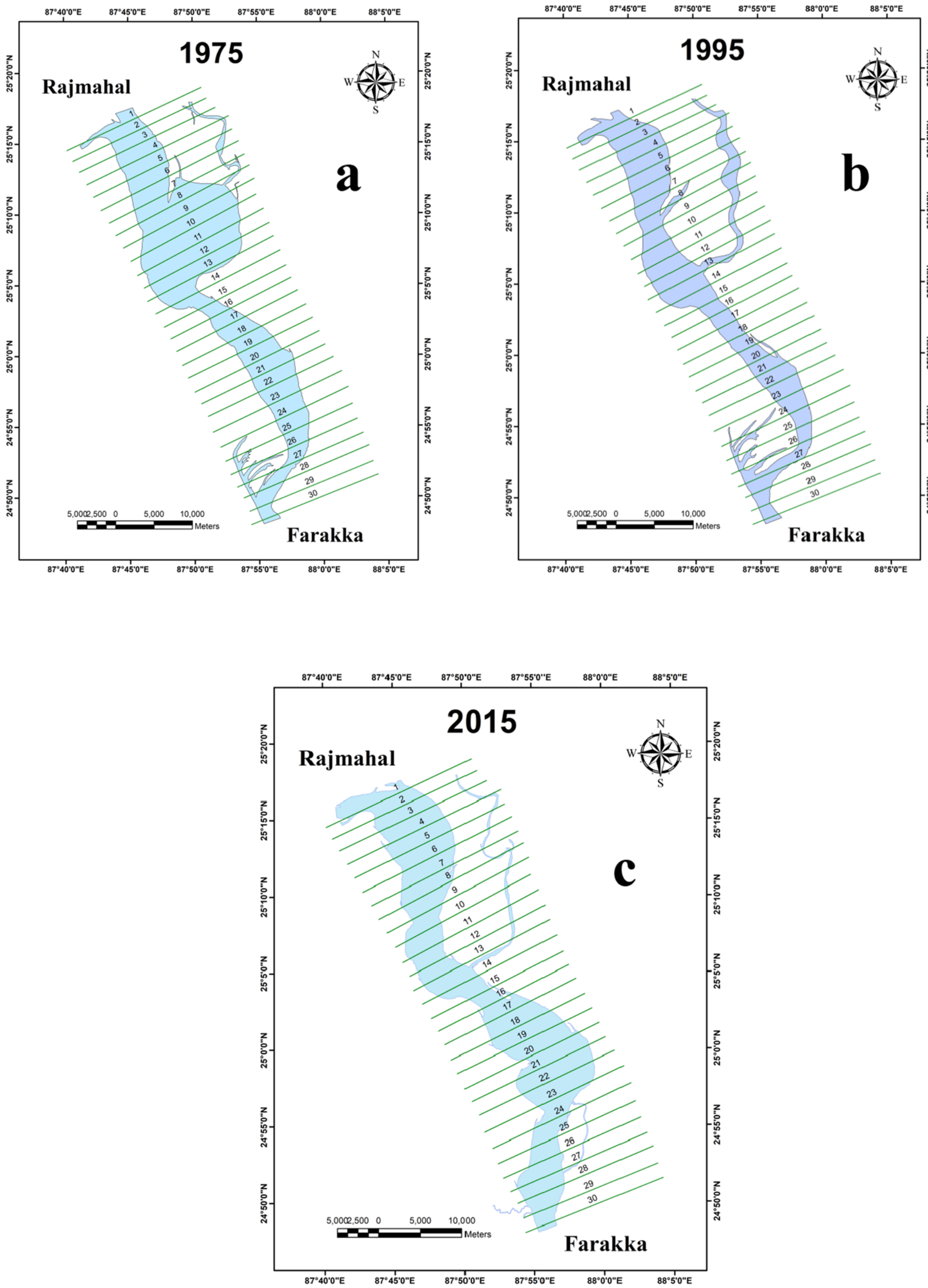


Fig. 2 Delineation of river bank line for the year **a** 1975, **b** 1995, **c** 2015

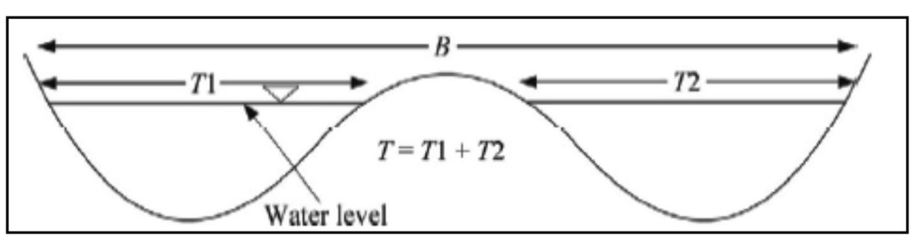


Fig. 3 Definition sketch of PFI

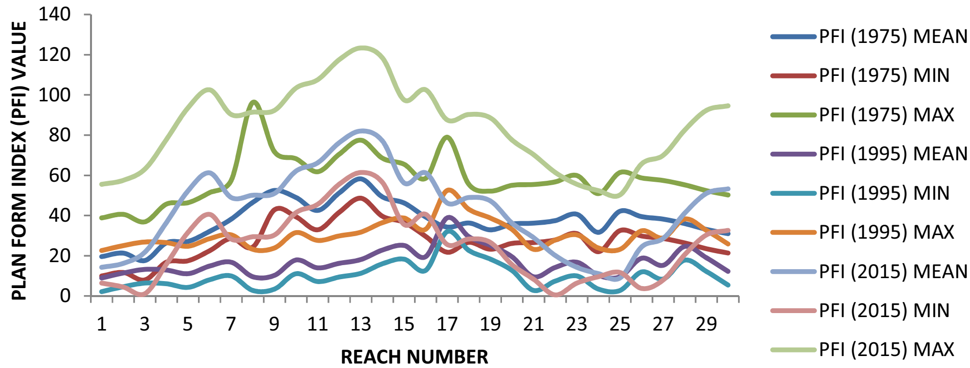


Fig. 4 Cross-section wise PFI values of the River in discrete years

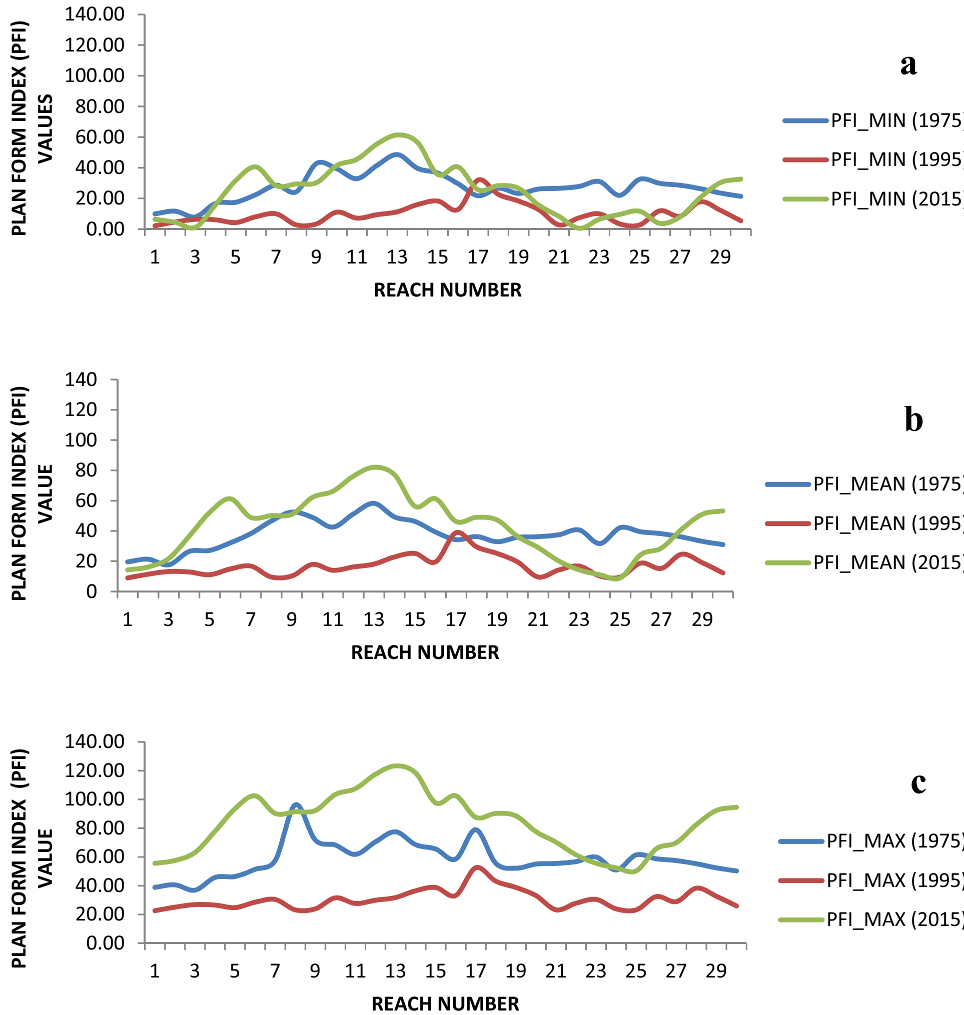
From the plot, it can be readily inferred that for the period 1975–2015, the PFI values decreased significantly indicating the increase in braiding intensities in majority of cross sections.

The analysis has been further extended by calculating mean PFI and highest and lowest values are measured through maximum PFI (indicating least braiding within the reach) and minimum PFI (indicating highest braiding

Table 3 Comparison of Plan Form Index (PFI) for the year 1975, 1995 and 2015 for the Ganga River

Reach number	Location	PFI (1975)			PFI (1995)			PFI (2015)		
		MEAN	MIN	MAX	MEAN	MIN	MAX	MEAN	MIN	MAX
1	Godai	19.57	9.94	38.83	8.97	2.16	22.60	14.23	6.42	55.54
2	Chandipur mal	21.32	11.69	40.58	11.41	4.60	25.04	16.21	4.44	57.52
3	Dergrama	17.62	7.99	36.88	13.21	6.40	26.84	21.78	1.13	63.09
4	Chandipur Tofi	26.45	16.82	45.71	12.89	6.08	26.52	36.54	15.89	77.85
5	Dakshin Chandipur	27.14	17.51	46.40	11.1	4.29	24.73	52.33	31.68	93.64
6	Paschim Narayanpur	32.14	22.51	51.40	14.89	8.08	28.52	61.23	40.58	102.54
7	Narayanpur	38.26	28.63	57.52	16.77	9.96	30.40	48.95	28.30	90.26
8	Kamalpur	46.58	24.35	96.28	9.56	2.75	23.19	50.12	29.47	91.43
9	Jot Bhabani	52.47	42.84	71.73	10.25	3.44	23.88	50.98	30.33	92.29
10	Manikchack	48.98	39.35	68.24	17.89	11.08	31.52	62.14	41.49	103.45
11	Govindapur	42.54	32.91	61.80	13.99	7.18	27.62	66.23	45.58	107.54
12	Dharampur	51.26	41.63	70.52	16.25	9.44	29.88	76.25	55.60	117.56
13	Mirpur	58.24	48.61	77.50	18.11	11.30	31.74	82.05	61.40	123.36
14	Rahimpur	49.26	39.63	68.52	22.84	16.03	36.47	77.11	56.46	118.42
15	Gopalpur	46.25	36.62	65.51	25.13	18.32	38.76	56.23	35.58	97.54
16	Uttar Lakshmipur	39.27	29.64	58.53	19.56	12.75	33.19	61.25	40.60	102.56
17	Dharampur	34.25	21.76	78.96	38.87	32.06	52.50	46.23	25.58	87.54
18	Kankribandha Jhaubona	36.28	26.65	55.54	29.47	22.66	43.10	48.97	28.32	90.28
19	Kamaluddinpur	32.89	23.26	52.15	25.12	18.31	38.75	47.25	26.60	88.56
20	Daridiar Jhaubona	35.78	26.15	55.04	19.47	12.66	33.10	36.25	15.60	77.56
21	Dharampur	36.21	26.58	55.47	9.56	2.75	23.19	28.97	8.32	70.28
22	Panchanandapur	37.48	27.85	56.74	14.21	7.40	27.84	20.14	0.51	61.45
23	Daskhatia	40.65	31.02	59.91	16.78	9.97	30.41	14.25	6.40	55.56
24	Hamidpur	31.65	22.02	50.91	10.23	3.42	23.86	11.09	9.56	52.40
25	Paranpur	42.17	32.54	61.43	9.56	2.75	23.19	8.98	11.67	50.29
26	Dogacchi	39.45	29.82	58.71	18.77	11.96	32.40	24.39	3.74	65.70
27	Nayagram	38.21	28.58	57.47	15.26	8.45	28.89	28.65	8.00	69.96
28	Babla	35.99	26.36	55.25	24.65	17.84	38.28	41.25	20.60	82.56
29	Purba Sripur	33.12	23.49	52.38	18.99	12.18	32.62	51.02	30.37	92.33
30	Dakshin Debipur	30.98	21.35	50.24	12.23	5.42	25.86	53.28	32.63	94.59

Fig. 5 Variation in PFI with extreme values along the river (**a** PFI minimum, **b** PFI mean, **c** PFI maximum)



within the reach) for Reach 1 to Reach 3 comprising thirty cross-sections (Table 3). The subsequent plot for the mean, minimum and maximum PFI against cross-profile numbers are plotted and shown in Fig. 5 respectively. The mean PFI with maximum and minimum cross-sectional PFI indicates the magnitude of variation in braiding behaviour within a reach. It has been further elaborated for clarity in Fig. 6, respectively, through trend of PFI with time for the discrete years studied. It can be easily figured out that higher values are predominant in the year 2015, whereas in 1995 lower values are predominant from cross profile no. 1–20 which comprising Reach 1 and 2 but in case of last 10 cross sections in Reach 3 although lower values predominant in 1995 but higher values exist in 2015. It strongly suggests that irrespective of the time, the above-mentioned three discrete reaches show little changes in braiding intensity and pattern. It confirms the existence of the aforesaid four geological control points which hold the river, and in between there are intermittent fanning out of the river with time (Fig. 7).

As discussed, the graphical plots of PFI for the Ganga river shows a decreasing trend thereby registering an increasing level of braiding with time and space in view of the threshold limits, as described in existing braiding indicators section. These plots clearly reveal that PFI is a significant measure of braiding and closely be conventional to the actual physical condition of the occurrence of braiding intensity depicted in the deriving satellite images. In respect to threshold values of PFI, it can be concluded that the selected segments of river catchment have heavy plant form intensity with moderate and low braiding behaviour of river channel resulting a complex channel hydrodynamics.

Estimation of river bank line shifting and erosion area

Using the GIS software, vector layers of the bank line and river flow domain have been worked upon and results have been presented in Fig. 8, which accounts for the reach wise erosion area for periods 1975–1995 and 1995–2015.

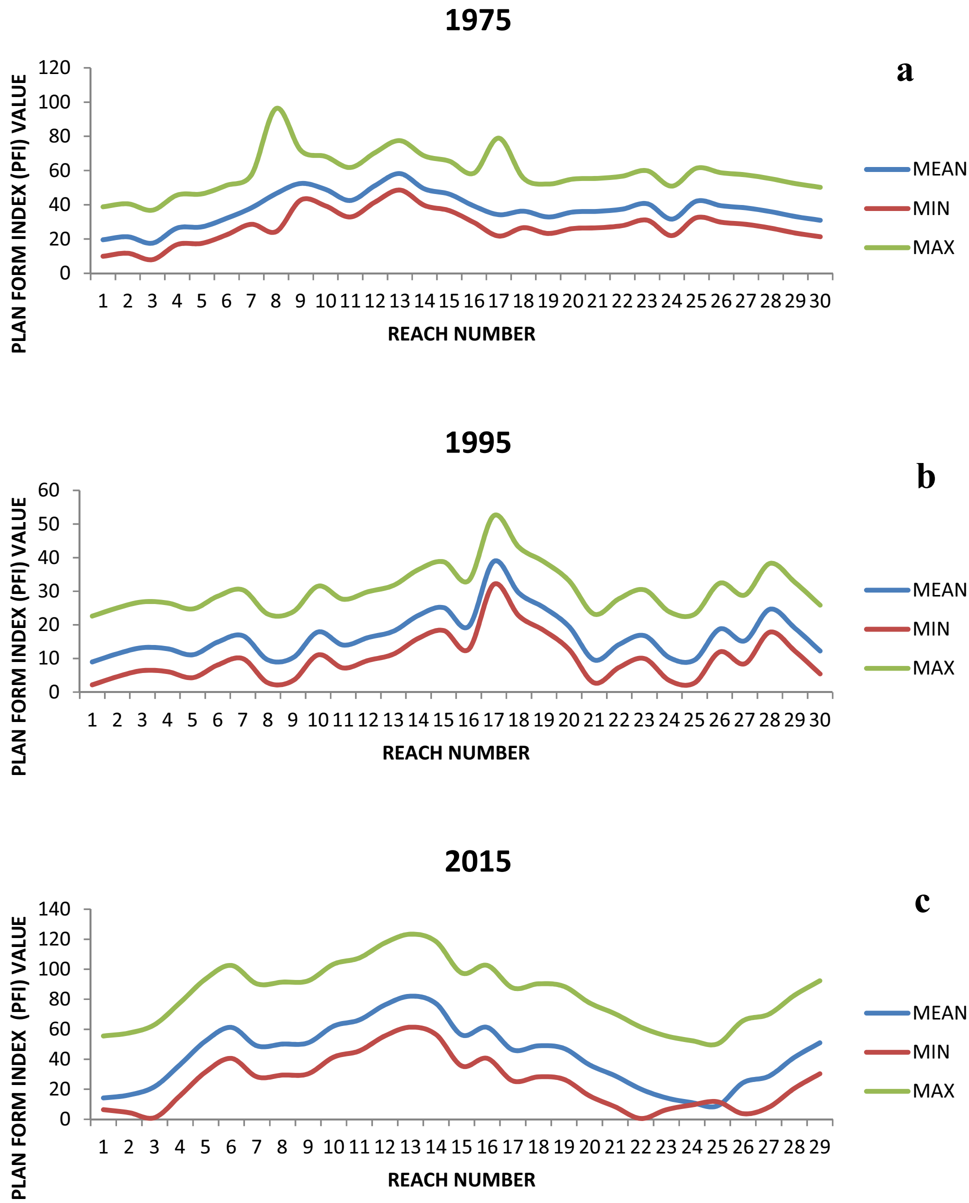


Fig. 6 Variation in PFI values along the river in discrete years (**a** year-1975, **b** year-1995, **c** year-2015)

Erosion volume along the reaches has been calculated based on the river bank line shifting for the given discrete years. Similarly, erosion area along selected reaches is calculated through area estimation using GIS software tools.

Figure 8 depicts the area eroded in left and right banks of the study cross profile number 1–30 of the Ganga river. Along the cross-sections, distance between the left banks of 3 consecutive years has been calculated and reported on this paper. In the time period between 1975 to 1995, left bank line was shifted in right direction in case of upper segments of the study area which is basically under the Manikchak block (Reach 1). After this segment, some portion of the river, left bank shifted towards the left side, then again channel was shifted right hand whole channel shifted towards same direction upto the Farakka barrage. So in this given time period, the tendency of left bank line shifting is more variable. On the other hand in case of right bank line shifting between 1975 and 1995 was less variable because major portion of the river shifted towards the right. As a result, both bank lines were shifted in opposite direction from each other along the cross-section line from 11 to 13 and 17 to 21 where left bank line and right bank shifted towards their own direction respectively and eroded gradually, as a result river catchment become wide. Besides that, along the cross-section line 15, left bank line and right bank line shifted their reverse directions, respectively, which indicate width of river channel in this segment becomes narrow from its existing condition. On the remaining portion of the river catchment, both bank lines were shifted in similar direction, so width of the river become invariable in this segment.

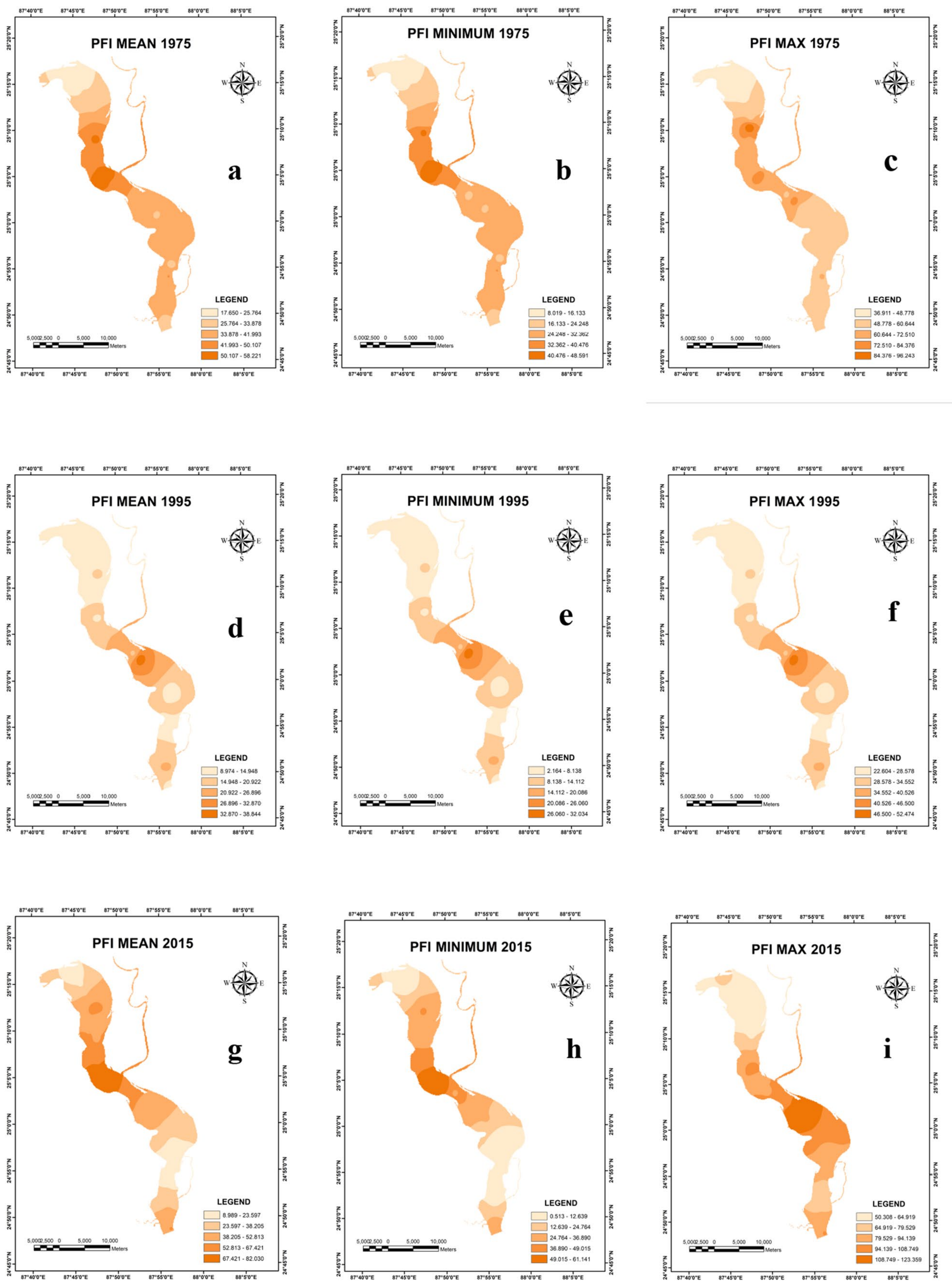


Fig. 7 Mapping of Plan Form Index (PFI), **a**–**c** PFI 1975, **d**–**f** PFI 1995, **g**–**i** PFI 2015

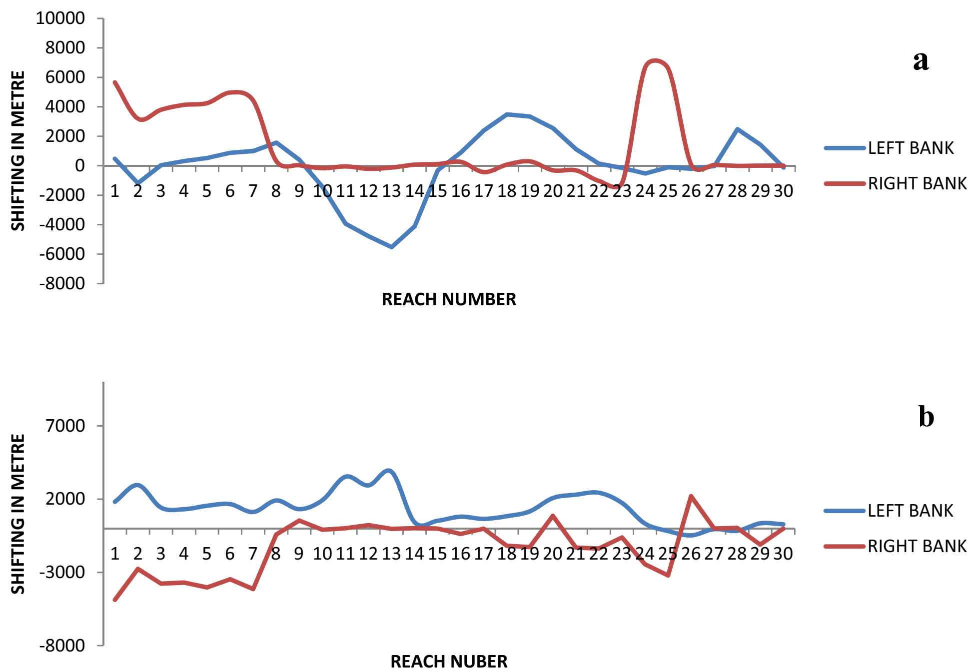


Fig. 8 Bank line shifting through erosion along the river in discrete years (**a** 1975–1995, **b** 1995–2015)

In the second case, bank line shifting of Ganga was totally changed after 1995 upto 2015. Shifting nature of left bank lines was variable, because in this period, bank line was shifted partially in left direction and partially in right ward in upper reaches. After that again channel shifted towards left and then again towards the right. At last, channel was again shifted towards the left adjacent to the barrage. Besides that, right bank line was shifted leftward at the upper reach and towards right ward from medium segments followed through lower segment upto barrage. As result cross-sectional line 7–13, left bank line shifted towards right and right bank shifted towards left and channel length becomes narrow in nature. Besides that along the cross-sectional line 17–23, left bank line and right bank line were shifted opposite direction from one each other, as a result river channel become widening from its previous condition in this section.

The satellite image based an estimation of area eroded in the Ganga river during periods 1975–1995 and 1995–2015 is presented in Table 4, which shows the eroding tendency along the river banks of the Ganga river in the entire study area. For the period of 40 years, the total land loss per year excluding forest area is found out to be 7,856,247.871 m^2/year or 7.856247871 km^2/year. Table 4 shows amount of erosion become relatively high in case of left bank compare to the right bank during this period. During this period, in the upstream of the Narayanpur, river practically changed its dominant path. For more recent period of 1995–2015, the total land loss per year (excluding avulsion) is found out to be 7,596,921.88 m^2/year or 7. 59,692,188 km^2/year, registering sharp decrease in land lost due to reducing river erosion in recent years.

Moreover, the vulnerability of the stream bank erosion is significant in case of left bank line which has been seen from Table 4. Here, about 180.38 km of both left and right bank side of the river has potential erosion tendency. The plot of potential bank line shifting versus cross profiles (Fig. 8) also shows that upstream of Kamalpur (profile number 8) and between Daskhatia and Nayagram (from profile number 23 to profile number 27), erosion tendency is considerably high in the left bank line in between 1975 and 1995. Besides that in between 1995 and 2015 erosion tendency of both bank line become considerably stable. On the other hand in case of right bank from Manikchak to Gopalpur (from profile number 10 to profile number 15), amount of erosion is considerably high. The erosion pattern of the left and right banks of the Ganga river during the study period is depicted in Fig. 8. The extent of bank erosion in different location can be qualitatively assessed from the recent map, with the bank-line extracted for discrete years through Arc GIS tools.

Variation of unit stream power and sediment flow rate

It is emphasized that a perfect combination of these parameters would help to derive requisite stream power (SP) to erode the riverbed and produce incised channels. The magnitude of unit stream power is one of the deterministic parameters of erosion of bed and banks of a stream. It has been found relevant to correlate the temporal changes in effective width of the Ganga river along different cross-sections and estimate unit stream power to interpret the braiding processes. In general, channel plan forms, floodplain segments

Table 4 Land lost in Main Ganga River during the study period

Reach no	Left bank			Right bank		
	Total erosion length in m	Land loss in m^2 (1975–1995)	Land loss in m^2 (1995–2015)	Total erosion length in m	Land loss in m^2 (1975–1995)	Land loss in m^2 (1995–2015)
1	2287.829	11,929,163.27	7,988,079.538	10,524.281	809,020.81	0
2	4147.16	6,673,182.395	4,307,607.051	5952.18	519,051.69	0
3	1458.574	18,815,290.57	16,985,776.19	7573.305	856,662.19	0
4	1628.774	3,440,935.99	1,927,789.888	7827.268	0	0
5	2073.054	873,997.8867	728,584.6103	8273.672	2,915,043.5	0
6	2541.036	5,737,620.098	3,662,340.904	8436.219	3,112,928.5	954,917.94
7	2118.569	1,165,296.53	116,242.5511	8555.21	2,288,096.5	850,329
8	3481.938	3,667,303.326	3,262,408.088	719.048	692,810.38	360,713.34
9	1709.028	1,384,376.121	382,951.107	571.713	12,916,452	18,408,974
10	3364.616	3,079,173.849	3,118,131.601	252.588	0	1,108,874.9
11	7465.496	1,486,840.269	761,159.4124	61.893	0	549,896.63
12	7729.236	221,985.9034	15,637,877.76	434.615	4,061,292	10,323,005
13	9398.892	2,010,579.969	2,245,727.396	157.262	0	734,894.88
14	4544.623	4,854,715.979	4,527,090.597	89.591	1,415,864.9	72,298.34
15	832.094	5,005,865.604	3,557,404.328	109.19	3,896,380.8	0
16	1696.841	1,732,829.136	1,731,040.615	640.671	3,779,377	553,830.31
17	3050.598	7,071,173.46	7,477,702.2	447.012	2,081,695.1	1,429,529.1
18	4320.23	2,584,322.934	2,584,322.934	1256.39	2,694,750	7,808,632.5
19	4511.708	1,138,207.239	1,138,207.239	1562.34	0	0
20	4620.217	2,862,286.148	2,862,286.148	1176.908	0	0
21	3423.938	3,719,286.224	3,713,554.201	1620.057	0	0
22	2571.909	851,362.137	851,362.137	2407.387	0	0
23	1894.932	1,692,446.127	1,349,031.524	1752.859	0	0
24	858.51	6,706,434.146	2,295,883.681	9132.555	0	0
25	276.007	11,259,955.56	5,360,200.341	9779.153	0	0
26	679.729	46,602.78207	0.000257	2248.014	0	0
27	72.184	439,263.0127	1,111,939.177	63.515	0	0
28	2640.961	3,690,984.986	5,394,469.322	47.615	0	0
29	1770.443	3,119,949.299	692,750.1938	1110.436	0	0
30	409.176	3,010,620.93	3,010,620.93	20.561	0	0
Total	87,578.302	120,272,051.9	108,782,541.7	92,803.508	42,039,425.37	43,155,895.94

separated by the latter and alluvial channel bed-forms (Alekseevskiy et al. 2008).

To appreciate the relation of stream power with braiding, certain analyses are vital. Assessment of braiding index essentially considered on the corresponding stages of the river at selected locations. Care has been taken to assess this parameter at low flow periods to passably represent the evolved channels of the river in a particular instance of time; however, it is essential to correlate stage-discharge of the river with corresponding measured braiding parameter to accomplish meaningful and rational analysis of the fluvial channel process. The satellite data-based study detailed in the previous section becomes of much impact and fetched very significant and meaningful outcomes when it is correlated to hydraulic and hydrological parameters such as water velocity and sediment transport rates for the given time periods.

In this study, whole river segment has subdivided into three patches, these are Godai to Manikchak, Govindapur to Daridiar Jhaubona and Dharampur to Dakshin Debipur which all patches are showed that bank erosion rate became high in Godai to Manikchak patch during 1975–1995, but in recent times, river dynamicity and erosion intensity increases towards downstream segment near Farakka barrage along the Dharampur to Dakshin Debipur patch. Each selected patch comprises ten cross-sections. The sediment flow rate has been shown in Figs. 9 and 10 along all patches in discrete years. It is observed that sediment flow become increasing from the month of April to September, basically in monsoon months along all three selected three patches.

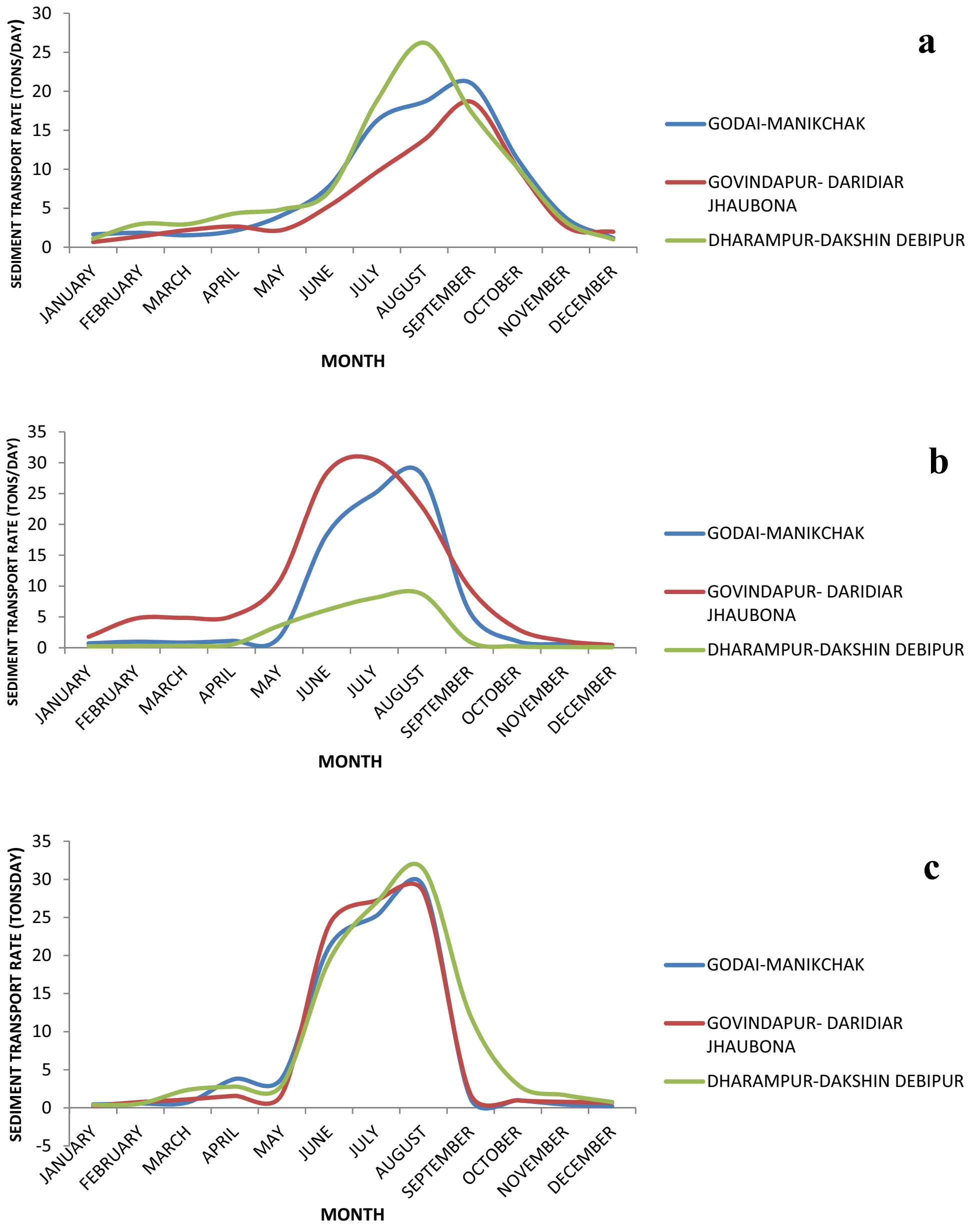


Fig. 9 Temporal variation of sediment inflow in selected reaches (**a** 1975, **b** 1995, **c** 2015)

Similar trend has been shown during all selected discrete years. Besides that along the Godai to Manikchak patch, Rate of sediment flow within river catchment become rapidly increasing from 1975 to 1995 but since 1995–2015 time period, increasement of sediment flow rate become quite balance except post monsoon and winter months. Second, along the Govindapur to Daridar Jhaubona, rate of sediment flow is increasing from 1975 to 2015 at very low rate in winter and summer season due to lack of flow velocity, after that in the monsoon months, sediment flow rate rapidly increased from 1975 to 1995 and slowly increased from 1995 to 2015 at balancing rate, lastly in the post-monsoon month sediment flow rate rapidly decreased from 1975 to 1995 and after that low rating increasement has happened after 1995 upto 2015. Third, similar kind of scenario has been shown along Dharampur to Dakshin Debipur patch. Therefore, all over scenario clearly indicates that sediment flow rate and sedimentation process become highly active during monsoon months and its effect is formation of numerous charlands within the river catchment at late monsoon period in every year.

Changeability of stream power at flood or high flow and low flow periods presented for selected river reaches namely Godai–Manikchak, Govindapur–Daridiar Jhaubona and Dharampur–Dakshin Debipur (Fig. 11) suggest that the magnitude of stream power becomes low here which representing less amount of potential energy exaggerated within per unit mass of water. Deriving maps

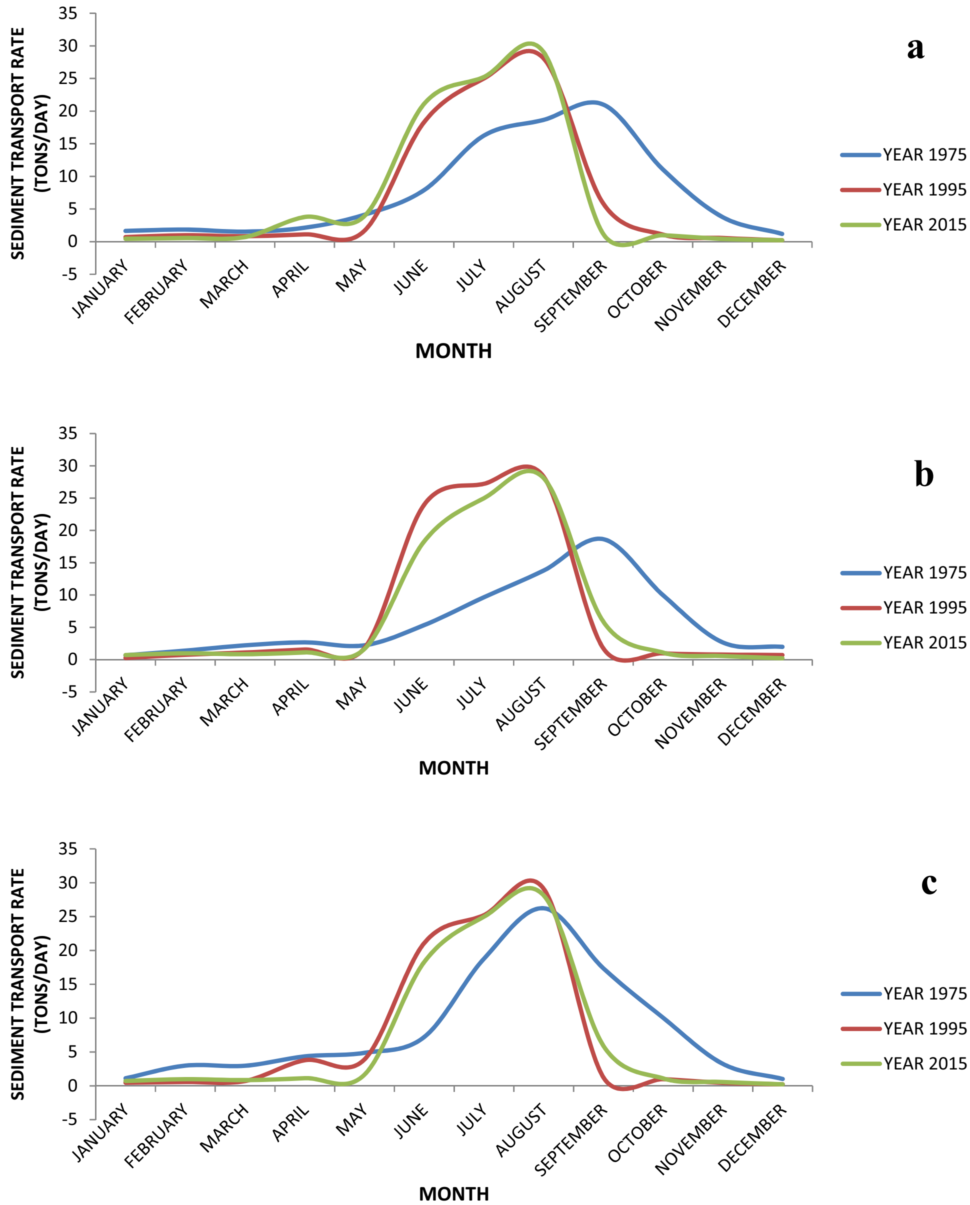


Fig. 10 Reach-wise sediment flow in discrete years (**a** Godai–Manikchak, **b** Govindapur–Daridiar Jhaubona, **c** Dharampur–Dakshin Debipur)

depict that in case of 1975 after construction of Farakka barrage Stream power intensity become low in upstream portion of the river catchment near to the Rajmahal and it becomes increasing into downstream portion of Manikchak (Reach no. 1) during flood period and again becomes decreasing near to the Farakka barrage. Besides that in case of low flood period the whole scenario became changes. Stream power intensity became gradually lowering down with decreasing amount of water discharge. Very small extent of stream power was found in downstream portion of the catchment nearer to the barrage due to water current of dam. After that since 1995, stream power become high in upper catchment of river and its rapid intensity continued upto middle portion of the catchment during high flow period and suddenly decreasing towards downstream nearer to the dam. But in case of this period, totally reverse condition has been found in low flow period of the river, stream power intensity become low in upper portion of the river and power become exaggerated into the downstream portion of the catchment. Lastly in 2015, stream power become relatively high in downstream portion of the river catchment nearer to the Farakka barrage in both high flow and low flow period of the river. The cause behind of this phenomenon is that due to existence of Farakka barrage over the river catchment, numerous char land has grown up within the river channel through the process of siltation, as a result stream flow path become dissected and narrowing down which intensified velocity of flow as well as stream power of river.

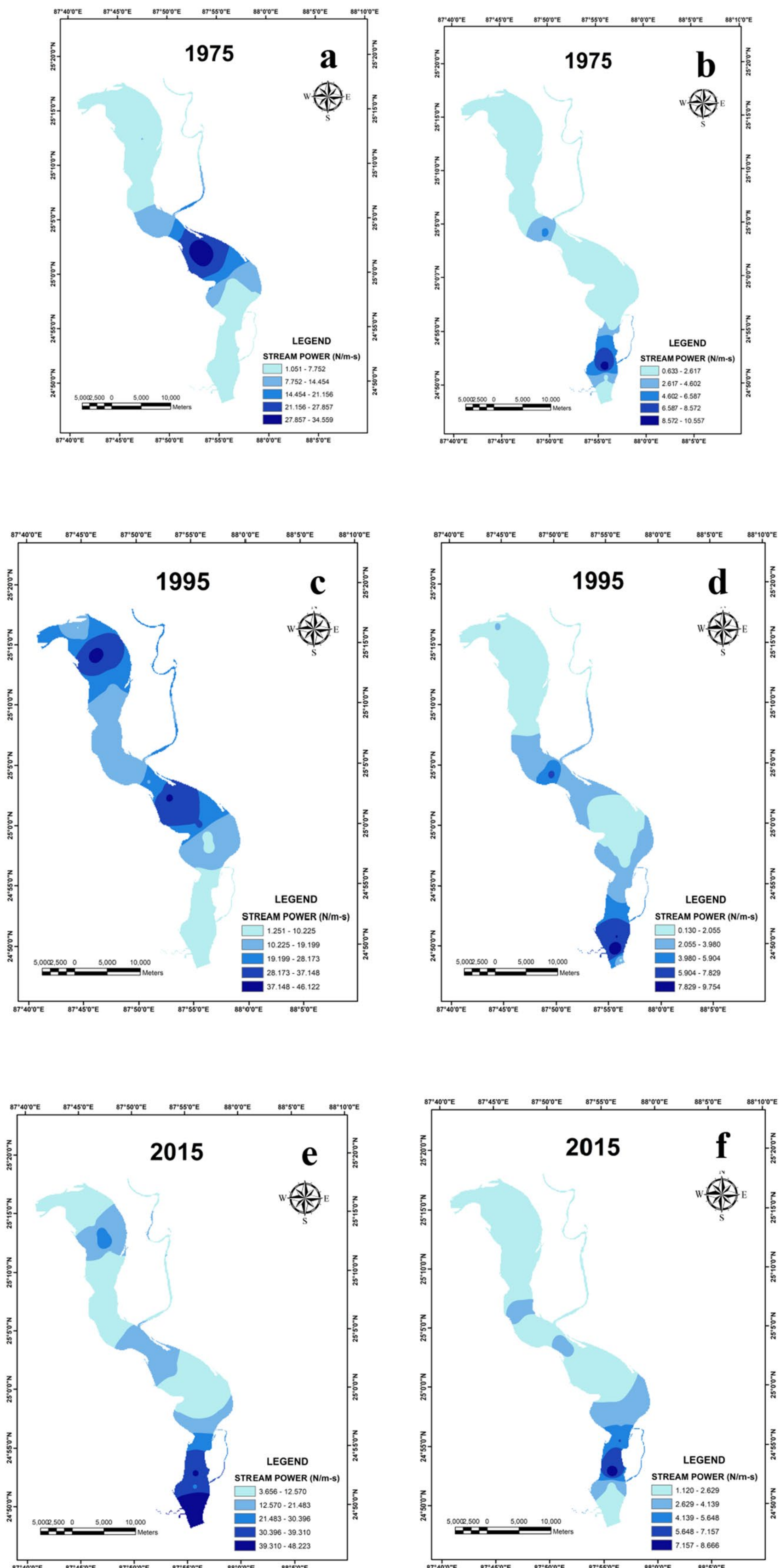


Fig. 11 Variation of stream power during **a**, **c**, **e** flood period, **b**, **d**, **f** low flow period

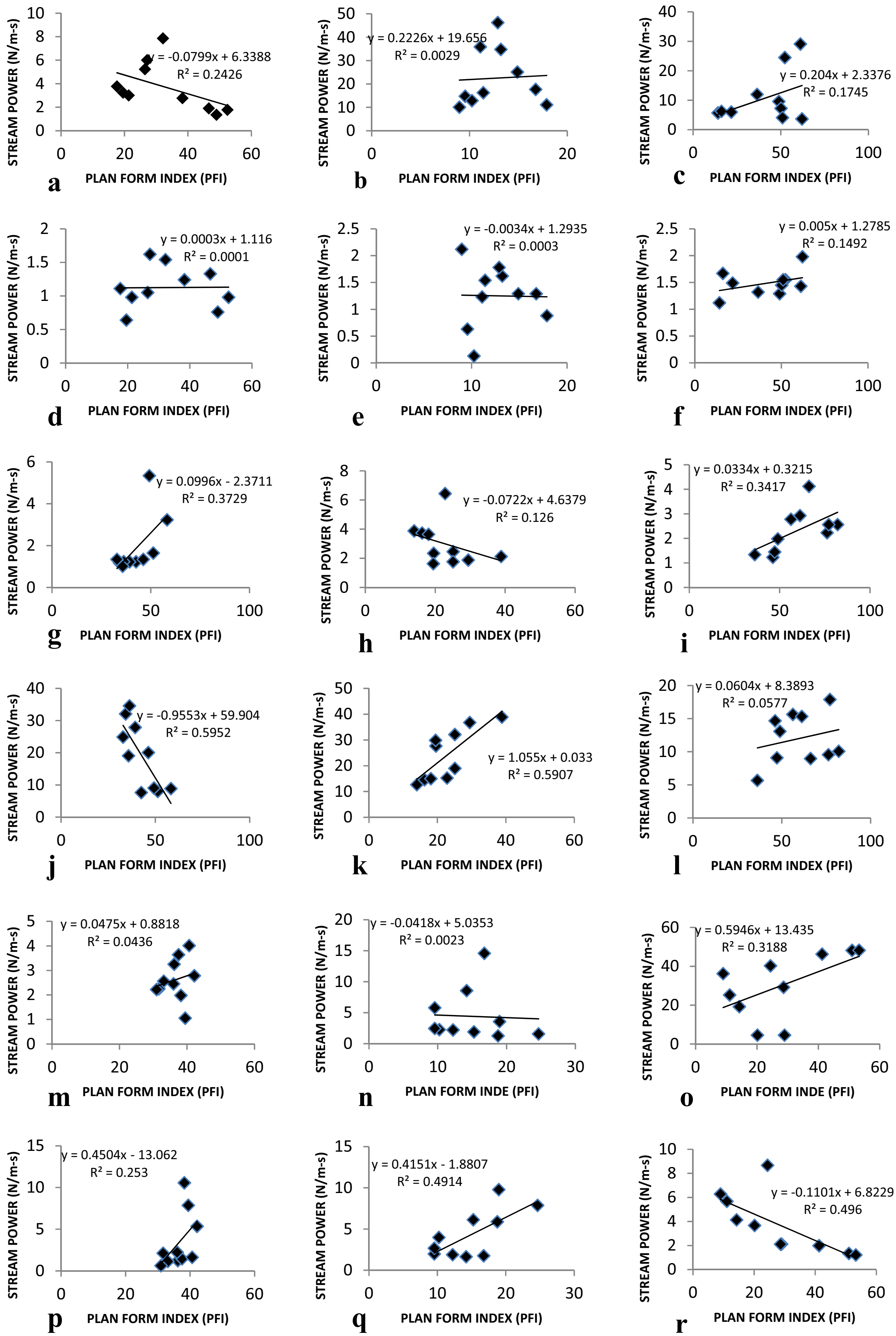


Fig. 12 Variability of stream power with PFI index value at flood and low flow period for **a**–**f** Manikchak, **g**–**l** Kaliachak II, **m**–**r** Kaliachak III

Relationship between stream power, braiding behaviour and bank erosion

Variability of stream power at high flow and low flow periods with estimated braiding index values presented through linear regression for selected river reaches namely Godai–Manikchak, Govindapur–Daridiar Jhaubona and Dharampur–Dakshin Debipur (Fig. 12) suggest that wherever PFI goes up, the corresponding stream power becomes lowered indicating lesser potential energy expenditure per unit mass of water. Figure 12 depicts that along the Manikchak reaches (from Godai to Manikchak), PFI values are negatively correlate with stream power, after that during 1995, the relationship become stagnant and with forwarding time extension the pattern of trend line indicates a positive relationship between them in high flow period. Besides that in low flood maintain a neutral relationship between PFI values and unit stream power because here coefficient determination values for all discrete years become 0 or nearer to the value 0. Therefore, it can be concluded that with growing up of PFI values, stream power is not significantly changed. After that along the Kaliachak II reaches (from Govindapur to Daridiar Jhaubona), there is a strong positive relationship has been shown between PFI values and stream power during both high and low flood periods. Therefore, it means with increasing braidingness of the river, stream power of the catchment also become increasing with extending time periods from 1975 to 2015. Lastly along the Kaliachak III reach (from Dharampur- Dakshin Debipur), similar relationship between PFI values and stream power can be found. Basically, this reach located nearer to the Farakka Barrage. As a result at the time of high discharge period, with increasing braiding index value unit stream power value also increased during all discrete years. But in case of low flow period of the river from 1975 to 2015, unit stream power become lowering down with increasing braiding index values. Because here due to presence of dam, a local base level has been formed which absorb potential energy of the river and lowering down the stream power in this segment with extending time periods.

Conclusions

The geological control point as discussed earlier, within the middle stretches of river from Govindapur to Daridiar Jhaubona is relatively well-drained flatland formed by the alluvial deposition of newer alluvium where the tendency of the river on the remaining upper and lower stretches are highly dynamic. This study identifies the major geological control points present in Ganga rivers from Rajmahal upto Farakka barrage. These control points are located in the vicinity of Manikchak, Kaliachak II and Kaliachak III region in Malda district. These channel control points usually have well-defined and stable hydrographical profiles. Beside that presence of Farakka barrage also plays a major role to control complex behaviour of river channel. Theses behaviour is being temporally severed in the geological time scale. The variability of stream power with bank erosion and braiding processes is observed along the selected stretches of the river Ganga besides the Diara region in Malda district and a specific behavioural pattern of channel is being observed within these processes. For example, braiding intensities of channel become increasing along upper and lower stretches which containing a low stream power except during flood period, which indicate a higher possibility of bank erosion. Also opposite situation has been shown middle stretches where probability of bank erosion may be less in nature.

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