Bulletin of Geography. Physical Geography Series, No. 23 (2022): 71–83
http://doi.org/10.12775/bgeo-2022-0011

Identification of prime factors of active river bank erosion in the lower course of Ganga-Bhagirathi River: a study

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Abstract. The present study aims to identify prime factors of active and continuous riverbank erosion. Field visits were conducted from 2015 to 2019. To fulfil the objective of the study, 21 study units prone to bank erosion were selected along the banks of Ganga-Bhagirathi at Jangipur sub-division. Remote sensing and geographic information system were used to measure the area under erosion and deposition from the 1985 to 2015 at five-year intervals. Bank height, bank angle, length of fracture from bank line, river velocity, and channel depth were measured for each study unit using different instruments like cup-type water current meter, clinometers, and measuring tape. Soil samples were collected for textural analysis. Factor analysis was performed to find out prime responsible factors for active riverbank erosion. The result of the study shows that bank height, bank angle, channel width, and fracture length together comprise the first component, which explains 29.48 percent of variance. Riverbank erosion happens due to physical and manmade factors in the lower plain area of the Ganga-Bhagirathi River.

Key words:
active riverbank erosion,
remote sensing and Geographic Information System,
instrument survey,
textural analysis,
factor analysis

Introduction

Riverbank erosion is a dynamic natural process. It involves the wash out of materials from the banks of a river. Bank erosion will generally happen when the magnitude of flowing water exceeds the strength of materials on the basal part of a riverbank (Ghosh and Sahu 2018, 2019a, b). The bank materials at the base of the riverbanks are eroded away by the running water, which leads to a new vacuum forming at the base of the riverbank. This mechanism also leads to form a steep wall above the bank that ultimately falls by hydraulic pressure, geotechnical events or the combined effect of both. Bank erosion is generally controlled by different factors like characteristics of bank materials, velocity of river, vegetation cover along riverbanks, and also by human activities (deforestation and built-up settlement along bank, etc.). Leopold et al. (1970) stated about the mechanism of bank erosion that erosion will occur when the force of river velocity crosses the resistance power of the bank material. Again, Leopold et al. (1970) commented, on the issue of erodibility, that it is influenced by different factors, namely the instability of rainfall, the infiltration capacity of the surface, and chemical and physical properties. According to Leopold et al. (1970), the chemical and physical properties of bank materials determine the cohesiveness of the soil. Meanwhile, vegetation directly acts as an important factor in maintaining the stability and infiltration capacity of soil. Hagerty and Ullrich (1981) opined about the erosional mechanism of the Ohio River.

They also focused on the internal erosion of bank materials by discharge flowing floods. River current has little impact on bank stability. Alterations in land use have an influential effect on slope stability and bank erosion. Augustowski and Kukulak (2021) showed how the frost processes influence retreat of riverbanks. Okagbue and Abam (1986) opined that the stratigraphy of most rivers of the Niger delta is a factor in erosion, being characterised by non-cohesive sands overlain by cohesive silt clays. Furthermore, a lower non-cohesive layer eroded at a much faster rate than an upper cohesive bank layer (Charlton 2008). This situation is responsible for the development of overhanging upper cohesive materials that will collapse by hydraulic action. Haque and Zaman (1989) stated that riverbank erosion in the major floodplain area of Bangladesh occurred due to sudden and rapid channel migration in almost every year. Leopold et al. (1970) stated that, since 1930, a number of studies have shown that permeability and relative aggregating or binding properties of soil materials are important factors in erodibility of soil. According to Smerdon and Beasley (1959), laboratory studies of the resistance to erosion of soils show that, with the increasing percentage of clay or aggregating materials, soil are less erodible. According to Knighton (1998), various factors are responsible for riverbank erosion. The important factors are channel flow characteristics (flow velocity, variability of stream discharge, etc.), characteristics of bank material composition (particle size, organic matter content in bank materials, etc.), climatic characteristics (intensity of rainfall, dry and wet climate, variation in temperature, etc.), channel geometry (depth, width, etc.), percentage of vegetation cover along riverbanks, and anthropogenic factors (settlement cover along the riverbanks, protection work, etc.). According to Charlton (2008), riverbank stability is determined by the balance between shear stress applied by the downslope element due to gravitational force and the shear strength of the riverbank materials. Riverbank erosion in a cohesive bank generally occurs across a failure plane. The nature of the failure plane is almost planar or curved. A cohesive bank is generally erosion-prone when the flood wave passes. Non-cohesive banks slide along shallow slip surfaces. Mixed banks characterised by fine cohesive material overlying non-cohesive sediments are more common. According to Leopold et al. (1970), the amount of erosion due to the splash of artificial rain starts to increase with the increasing percentage of sand and it starts to increase with the decreasing percentage of water-stable aggregates (clay). Again, Leopold et al. (1970) commented that mixing of clay-size particles with soil may markedly increase the cohesion of a given soil. The percentage of clay particles in soil plays a very important role in determining the erodibility of soil. Generally, clay and organic matter help to increase cohesion in soil. A high percentage of clay particles and organic matter in soil ensures more resistance to erosion. Research is very necessary to detect a satisfactory solution to riverbank erosion (Majumdar 1941). Bank erosion is a problem that should be of acute concern to administrators because it introduces different socio-economic problems whose impacts transform generation after generation. Haque et al. (1986) showed that, in the lower Brahamaputra flood plain of Bangladesh, people are displaced from their own land due to bank erosion. Rudra (1996) reported on the problem of erosion and population displacement in the downstream section of Farakka barrage. According to FPMP (2014), about 102 km of embankments of the Ganga / Padma River from Farakka to Jalangi are in a vulnerable condition due to Ganga riverbank erosion. And, at the same time, many villages are in a highly vulnerable situation due to riverbank erosion. Dabnath et al. (2017) studied the bank erosion problem of Khowai River in Tripura and reported on its consequences for land use / land cover along the riverbanks.

So, from the forgoing discussion, it could be said that bank erosion happens due to various factors, both physical and manmade. To detect a satisfactory solution to riverbank erosion or any kind of hazards, the causes or main responsible factors should be identified first. The present study is about the identification of prime factors of active riverbank erosion. The present study is based on empirical observation. It was done from the year 2015 to 2019 by extensive field survey. This research is the first attempt to find the prime factors responsible for the occurrence of active riverbank failure using standardised mathematical techniques in developing countries like India. There are many studies concerned with riverbank failure, but most focus on the impacts of riverbank failure on various aspects. Some researches discussed the leading factors responsible for riverbank failure qualitatively without practical application. The present study has significance from the local to national and international level. This research exhibits real causes of bank erosion based on empirical study through statistical analysis. The adopted methodologies can be applied to other places to find out the prime factors responsible for the occurrence of related hazards. This study may help policymakers to better understand the prime causes of bank failure in order to take necessary action against the leading factors of riverbank erosion.

Objective of the study

The prime objective of the study is to identify leading factors responsible for active and continuous riverbank erosion through applying a standard mathematical model.

Methodology and data analysis

Study area

The study area was selected in the Jangipur sub-division of Murshidabad district, West Bengal, India (Fig. 1). The study area is situated in Murshidabad district, West Bengal, from 24˚13'14" to 24˚52'15" north latitude and 87˚48'00" to 88˚15'39" east longitude (Fig. 1). The main river of the study area is the Ganga River and its distributary river, the Bhagirathi. The total area of the sub-division is about 1,097.82 sq. km (Census of India 2011a). Physiographically, the Jangipur sub-division is more or less similar to the district Murshidabad. According to the report of the district Census handbook, Murshidabad (2011a), the Bhagirathi parts the Murshidabad district into two broad geographical regions. These two regions have almost equal area. But they are different in respect of geology. These two regions are the *Rarh* area and the *Bagri* area. As per the report of the district Census handbook, Murshidabad (2011b), the western tract or the *Rarh* area is located to the west of the river Bhagirathi. This area is also a continuation of the Sub-Vindhuyan region. This region is composed of lateritic clay. It is also characterised by nodular ghuting. The area is slightly undulating by nature. Generally, the soil of this area is greyish and reddish in colour and enriched with lime and iron-oxide (District Census handbook, Murshidabad 2011b). As per report of the district Census handbook, Murshidabad (2011a), the eastern tract or the *Bagri* area is on the eastern portion of the river Bhagirathi. This area is generally composed of Gangetic alluvial deposits. *Bagri* is situated between the Ganga, Bhagirathi and Jalangi rivers. *Bagri* was formed after the formation of the *Rarh* area (District Census handbook, Murshidabad 2011a). This area is generally low by nature and suffers from an annual inundation problem. The *Bagri* region is very fertile due to the accumulation of fresh silt almost every year (District Census handbook, Murshidabad, 2011a). As per the report of the Census of India (2011a), the total population of the district is about 7,103,807, of whom 5,703,115 people live in a rural area and 1,400,692 live in an urban area. O the district's total population, the total male population

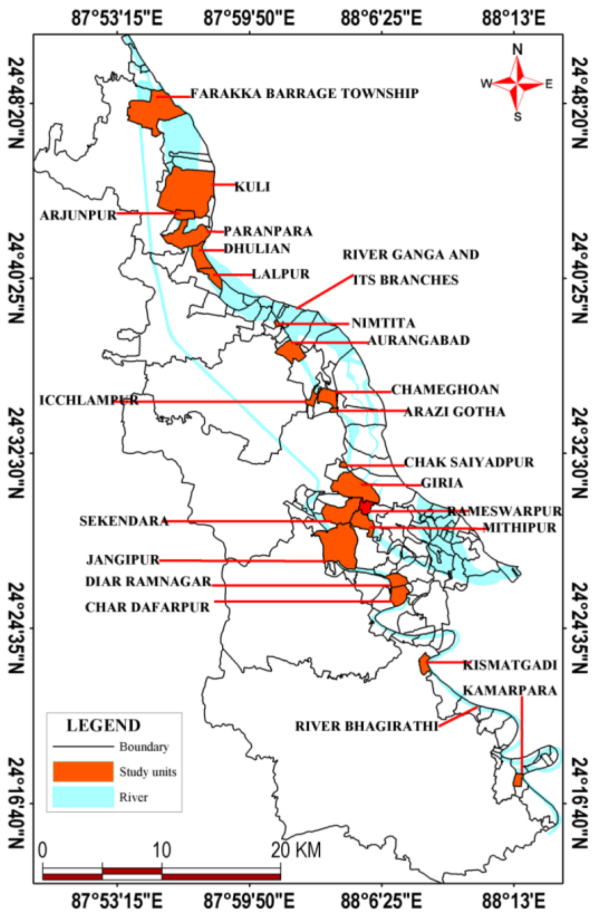

Fig. 1. Location of study area

is 3,627,564 and the female population is 3,476,243. Murshidabad district comprises 7.78 percent of the total population of the state of West Bengal. To serve the purpose of the study, 21 erosion-prone cadastral units along the banks of the Ganga-Bhagirathi were taken (Fig. 1) The study units with their jurisdiction list numbers (J. L No.) (Census of India 2011) are as follows: Farakka barrage township, Kuli (058), Arjunpur census town (CT), Paranpara CT, Dhulian municipality, Nimtita (108), Aurangabad CT, Chameghoan (70), Icchlampur CT, Arazi Gotha (074), Chak Saiyadpur (087), Jangipur municipality, Diar Ramnagar (144), Char Dafarpur (091), Giria CT, Mithipur CT, Sekendara (014), Kismat Gadi (042), and Kamarpara (183).

Data collection

Both primary and secondary data have been used to operate this study. Primary data like measurements of bank height, bank angle length of fracture from bank line, river velocity and channel depth were calculated from each selected study unit using different instruments like cup-type water current meter, clinometers and measuring tape (Table 1). Global positioning system (GPS) was used to take latitude and longitude of the study units. Secondary data like cadastral maps were collected from the district land and land reform officer, Murshidabad and from the website of district land and land reforms officer, Murshidabad (http://dllromsd.org/). Satellite images were collected from the official website of the United States Geological Survey (USGS) (Table 2).

Bank materials collection

Bank materials were collected from each study unit for laboratory testing purposes. Cohesion of bank materials is one of the important determinants of bank erosion (Charlton 2008). Cohesion of bank materials largely depends on percentage of clay and organic matter content in soil. Bank materials were collected from four points along the riverbank of each study unit. At the time of analysis, four samples of one study unit were mixed to get better results. Bank materials analysis was done at the Department of Agricultural Chemistry and Soil Science, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal.

Table 1. List of used instruments

Variables for measurement	Used instruments
Bank height, Fracture length from bank line, and Channel depth	Measuring tape
Bank angle	Clinometers
River velocity	Cup-type water current meter
Textural analysis of soil	Soil hydrometer, Mechanical shaker, and 1000ml Measuring cylinder, Hot water / steam bath, and Beaker

Table 2. Details of satellite images

Date of acquisition imageries	Path/Row	Dataset	Source
14.10.1985	138/044	TM	USGS
14.11.1990	138/044	TM (1984-1997)	USGS
17.10.1995	138/044	TM	USGS
17.11.2000	138/044	ETM+ (1999-2003)	USGS
14.10.2005	138/044	ETM+	USGS
28.10.2010	138/044	ETM+	USGS
11.11.2015	138/044	ETM+	USGS

Estimation of area under erosion and deposition

To find out the areas under erosion and deposition, bank lines of different years from the collected satellite images (Table 2) were digitised using GIS software, and the area under erosion and deposition was computed by superimposing the digitised bank lines of different years with the help of GIS software.

Factors of active bank erosion

To find out the major factors of active bank erosion, an extensive field survey was conducted in the selected study units from 2015 to 2019. All selected parameters (Fig. 2) are described as follows:

1. Average bank height

This is the average value of measured bank heights of four points in a study unit. It was measured in

Fig. 2. Bank erosion prone vulnerable pockets in study area: a – vulnerable pocket at Giria; b – vulnerable pocket at Chak Saiyadpur; c – Measurements of bank angle by clinometers at Lalpur; d – measuring river velocity by current meter at Arjunpur; and e – Textural analysis of soil samples

metres in all selected study units using a measuring tape, basically from the month of March to May in a year because, during this period, the water level remains low in the river valley, ensuring a good result.

2. Average bank angle in degree

This is the average value of measured bank angles of four points in a study unit. It was measured using clinometers basically from the month of March to May in a year.

3. Length of fracture

This was measured in metres using a measuring tape in all selected study units. This is the horizontal length of fracture from the bank line. Only the highest length of fracture was taken into consideration in all study units.

4. Average velocity and average depth of channel

This is the average value of all readings across the drawn cross sections in all selected study units. A cup-type digital water current metre was used here to measure the river velocity (metres per second) in the selected areas under study (Fig. 2). This work was done from October to November, 2017, because it is very difficult to take velocities during monsoon months (June–September) in the study units. The formula for velocity is based on Garg (2002). The formula of velocity is (Eq. 1) as follows:

$$V=0.0011+0.6825R \quad (1)$$

where, V= velocity / second, and R= current meter reading.

5. Average channel width in kilometres

This is the average of measured channel widths of four points in every study unit. It was measured from a Google earth image from 2017, accessed through GIS software.

6. Area under vegetation and settlement in percentage

Forty-metre buffer areas were created on either side of the banks of the Ganga-Bhagirathi River to find out areas under vegetation and settlement with the help of GIS software. The buffers were created because the highest length of fracture from the bank line is observed in Giria CT at 36 metres and the lowest length of fracture is observed in Farakka barrage township at less than two metres. Areas covered by vegetation and settlement within the 40-metre buffer zones were digitised from Google earth image of 2017 with the help of GIS software for each selected study units.

The areas under vegetation and settlement (Eq. 2) were calculated using the following formula:

$$(V_t / V_a) \times 100\ \% \quad (2)$$

Where, V_t= Total area under vegetation or settlement, V_a= Total area of buffer zone.

7. Total clay plus silt in percentage

Particle-size distributions of the bank soils were determined following the Bouyoucos hydrometer method (Gee and Bauder, 1986) (Eq. 3). The percentage of dispersed material remaining in suspension (P) at any time is calculated by

$$P = \frac{(R_h - R_b \pm r)}{W} \times 100 \quad (3)$$

Where, R_h = hydrometer reading (R_{h1} and R_{h2}) of soil suspension, R_b = hydrometer reading of blank, r = temperature correction, and W = dry weight of soil sample.

8. Dispersible clay plus silt in percentage

To measure dispersible clay or silt or clay plus silt of the bank soils, the method given by Mbagwu and Auerswald (1999) was used. The method is the same as the Bouyoucos hydrometer method.

9. Oxidisable organic carbon

Oxidisable organic carbon (OC) (Eq. 4, 5) of the soil was determined following the method of Walkley and Black (1934). The formula of calculation is as follows:

$$Organic\ carbon\ (\%) = \left(\frac{B-T}{B}\right) \times 3 \quad (4)$$

Based on Mbagwu and Auerswald (1999).

Where, B = Blank reading, T = Titration value, and 3 = conversion factor considering solution strength and percentage.

$$Organic\ matter = Organic\ carbon\ \times 1.724 \quad (5)$$

Where, 1.724 = Vanbemelian factor, in general organic matter contains organic carbon 58%. So, the factor is 100/58=1.724.

Data Analysis

Principal Component Analysis (PCA) is a method of factor analysis. This method is developed primarily to synthesise a large number of variances into a smaller number of general components. The components have the maximum amount of descriptive ability (Mahmood 2008; Gaur et al. 2009). To find out the cause of Ganga-Bhagirathi active bank erosion in the Jangipur sub-division, factor analysis using PCA method (Eq. 6) was done by using SPSS software. The model of factor analysis is as follows:

Model

$$Z_j = a_{ji}P_1 + a_{j2}P_2 ---------- + a_{jn}P_n \quad (j = 1, 2, ..., n) \quad (6)$$

where, each of observed variables is considered as linear in terms of uncorrelated components, P1, P2..........................Pn (Islam 2016).

Pearson's correlation analysis was also performed among the selected variables to find out the correlation among them using SPSS software. Student's *t test* was performed with the help of SPSS software.

Data Constraint

The study area is located very near to the India–Bangladesh border area. There is tight restriction on surveying. Permission from the border security force (BSF) is required to access some places. There is no permission to access the opposite bank of the Ganga River in Bangladesh. The width of the Ganga varies from 1.5 km to 2.9 km in Jangipur sub-division. Boats are unavailable in some places. Taking the above-mentioned measurements in these areas is highly risky, and the India–Bangladesh border area is characterised by various antisocial activities.

Results and discussion

Shifting or migration of any alluvial channel is an inevitable phenomenon that removes bank materials from valley sides. Erosion and deposition go hand in hand. A balance between rate of erosion and rate of deposition denotes more or less the normal condition for the area under riverine track. According to Charlton (2008), continuous erosion means the rate of erosion exceeds rate of deposition. This situation indicates that the riverbanks are not free from further erosion. Various problems start to arise when the rate of erosion exceeds the rate of deposition, which means active and continuous riverbank erosion. Table 3 clearly shows that, in every year, the annual rate of removal of bank material from the basal part of the banks is faster than the annual rate of sediment accumulation at the basal part of the riverbank in Jangipur sub-division of Murshidabad district (Fig. 3). Therefore, there is a continuation of further bank erosion. Basically, the sizes of sand and silt particles are 2.0 to 0.0.05 mm and 0.05 to 0.002 mm respectively. The size of the clay particle is less than 0.002 mm. The cohesive

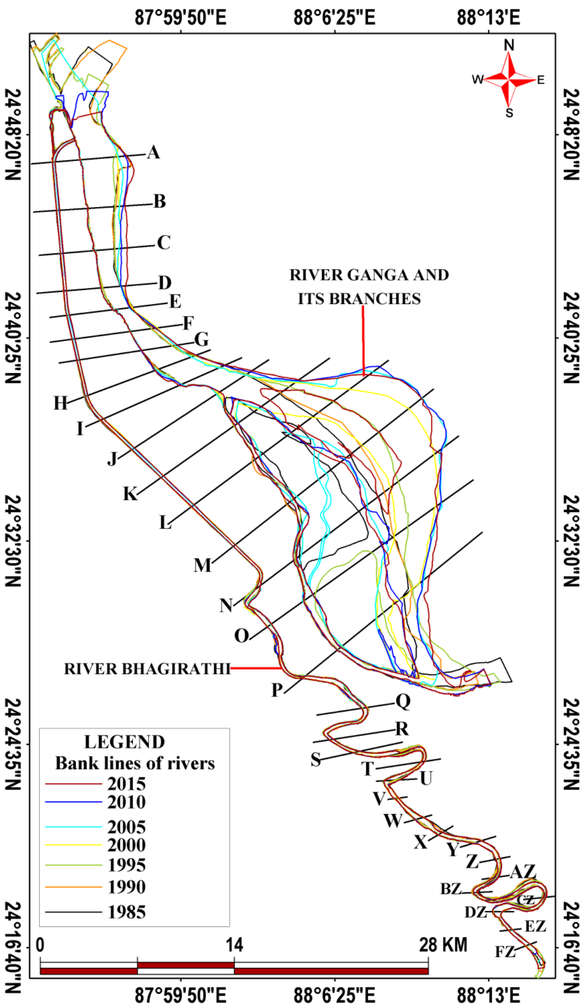

Fig. 3. Shifting of river Ganga-Bhagirathi over the cross sections in Jangipur sub-division. Based on satellite images mentioned in Table 2

Table 3. Erosion and deposition in Jangipur sub-division of Ganga-Bhagirathi River

Erosion and deposition in Jangipur sub-division (Km²)				
Years	Total erosion	Annual rate of erosion	Annual rate of deposition	Total deposition
1985-1990	8.174	1.634	0.597	2.987
1990-1995	7.319	1.463	1.286	6.433
1995-2000	7.535	1.507	1.118	5.593
2000-2005	8.826	1.765	0.428	2.144
2005-2010	6.283	1.256	0.79	3.954
2010-2015	4.801	0.96	0.636	3.181

forces between clay particles are greater, which creates resistance to erosion by running water, whereas sand particles are very easy to erode away (Charlton 2008). In this study, the result of analysis of bank materials clearly shows that the percentage of sand in soils along the riverbanks ranges from 38 to 87 percent (Table 4). In addition, study units like Kuli, Dhulian, Arjunpur, Giria, etc. (Table 4) have high percentages of sand particles in the soil along the riverbanks and, again, the percentage of clay particles is low, ranging from 8 to 11 percent (Table 4). Riverbanks with high percentages of clay and silt particles have more resistance to erosion (Charlton 2008). The average velocity of the river Ganga-Bhagirathi of the study units ranges from 0.2 to 0.701 metres per second. The result of the soil hydrometer analysis shows that the clay percentage in the selected soil samples is very much poorer

Table 4. Textural analysis of the soil in the selected study units

Study units	Textural analysis			Organic matter in percentage
	Percentage of clay	Percentage of silt	Percentage of sand	
Farakka barrage township	10.64	50.4	38.96	0.424
Kuli	10.48	10.0	79.52	0.212
Arjunpur	10.64	30.4	58.96	0.106
Paranpara	14.64	28.4	56.96	0.132
Dhulian	10.64	28.4	60.96	0.159
Lalpur	10.64	30.4	58.96	0.133
Nimtita	10.48	38.0	51.52	0.344
Aurangabad	16.64	32.4	50.96	0.398
Chameghoan	10.64	16.4	72.96	0.344
Icchlampur	12.64	16.4	70.96	0.371
Arazi Gotha	12.48	18.0	69.52	0.133
ChakSaiyadpur	10.64	2.4	86.96	0.106
Jangipur	9.04	16.0	74.96	0.159
DiarRamnagar	10.64	32.4	56.96	0.238
Char Dafarpur	8.64	30.4	60.96	0.186
Giria	10.48	18.0	71.52	0.110
Mithipur	12.48	20.0	67.52	0.133
Sekandara	8.64	24.4	66.96	0.292
Rameswarpur	8.64	18.4	72.96	0.190
KismatGadi	8.64	48.4	42.96	0.292
Kamarpara	10.64	48.4	40.96	0.451

than the silt and sand percentage. The percentage of sand particles is higher than the percentage of silt and clay in the selected soil samples (Table 4). Cohesion is determined by the percentage of clay and organic matter present in soil. It is one of the important determinants of erosion. The percentage of silt is also more than clay in the selected study units. The percentage of organic matter in the soil ranges from 0.1 to 0.45 in almost all cases, which ensures very low organic matter present in the soil (Table 4). Therefore, the soil samples are less cohesive in nature. A less cohesive bank is more subject to washing away by the flow velocity of the channel. Many other factors may be responsible for active riverbank erosion. An attempt has been made here to identify the leading factors of active riverbank failure. To satisfy this goal, factor analysis was performed by Principal Component Analysis (PCA). PCA is a method of data processing in which some synthetic variables are called Principal Components. They are extracted from a large number of variables (Constantin, 2014). At first, before beginning the PCA, testing is essential in order to decide whether the data or sample is suitable for PCA or not. The 'Kaiser–Meyer–Olikin (KMO) measure of sample adequacy' and 'Bartlett's Test of Sphericity' were done using SPSS software. The index value of KMO ranges from zero to one. A KMO value equal to or more than 0.50 means the sample is fit for PCA (Constantin 2014). 'Bartlett's Test of Sphericity' is also significant, and the P value should be less than 0.05 (Williams et al. 2010; Constantin 2014). In the present analysis, the KMO measure of sample adequacy is equal to 0.5 and Bartlett's Test of Sphericity is 0.000 (Table 5). So, the sample is fit for PCA. Table 5 shows the PCA result on the causes of active riverbank erosion. The loading of each variable for the retained Principal Components is given in Table 5, where the heaviest loadings are highlighted. The four components have been extracted from PCA (Table 5). These are as follows:

First Component: Bank height, bank angle, channel width and fracture length together comprise the first component. The first component explains 29.48 percent of variance.

Table 5. Textural analysis of the soil in the selected study units

Kaiser–Meyer–Olkin measure of sampling adequacy		Values	**Input variables**	**Components**			
				1	2	3	4
Kaiser–Meyer–Olkin measure of sampling adequacy		**0.5**	Average Velocity (metre/second)	0.535	0.733	0.078	-0.205
			Average Bank height in metres	**0.849**	-0.010	-0.206	0.164
			Average Bank angle in degrees	**0.732**	0.249	-0.068	-0.495
			Average Channel width in kilometres	**0.817**	-0.231	0.015	0.239
Bartlett's test of sphericity	Approx. Chi-square	98.224	Settlement cover %	-0.103	**0.833**	-0.145	0.167
			Vegetation cover %	-0.391	0.090	**0.545**	0.310
			Dispersible clay + silt %	0.119	.205	0.089	**0.904**
	Degree of freedom	55	Total clay + silt %	0.087	-0.021	0.558	**0.665**
			Organic matter %	0.006	-0.064	**0.924**	0.068
	Significance	0	Average Fracture length in metres	**0.506**	-0.252	-0.574	-0.072
			Average Channel depth in metres	-0.186	**0.822**	0.184	0.094
			Per cent Variance explained Total=77.333%	29.480	20.530	17.715	9.627

Extraction method: Principal Component Analysis
Rotation Method: Varimax with Kaiser Normalisation a. Rotation converged in 8 iterations

Second Component: Average velocity (metre / second), percentage of settlement cover and average channel depth in metres together comprised the second component, explaining 20.53 percent of the variance in the dataset.
Third Component: Percentage of vegetation cover and percentage of organic matter comprised the third component and explained 17.715 percent of variance.
Fourth Component: Dispersible clay plus silt in percentage and total clay plus silt in percentage comprised the fourth component and explained 9.627 percent of the variance.

Each component has an eigen value greater than one and these four components together explained 77 percent of the variance in the dataset (Table 5). Therefore, it can be stated that nature of riverbank (bank height, bank angle, etc.) and nature of river channel (channel depth and channel width) play more important roles in bank erosion. Average velocity of river, percentage of settlement cover and average channel depth have more influence on riverbank erosion than percentage of vegetation cover and percentage of organic matter in soil. Again, dispersible clay plus silt in percentage and total clay plus silt in percentage have less influence on riverbank erosion than percentage of vegetation cover and percentage of organic matter in soil. All the selected variables are important in the occurrence of active riverbank erosion. In fact, all these are responsible factors of riverbank erosion. At first, the first component (bank height, bank angle, channel width and fracture length) is totally determined by the nature of bank materials or composition of bank materials. If the riverbank is more cohesive, then it is less subjected to erosion. Cohesion is determined by the percentage of clay and organic matter contained in the soil. Organic matter is determined by the present of vegetation cover along the riverbank. Here, riverbank cohesiveness is a dominant factor of erosion. The flow velocity of the channel will be more effective if the bank is less cohesive. So, riverbank cohesiveness is one of the major factors in determining the erodibility of riverbank materials. The result of Pearson's correlation analysis (Table 6) shows that bank angle and bank height are positively correlated (r=0.50) with each other and correlation is significant at 95 percent level of confidence. Length of fracture is positively correlated with bank angle and bank height, and correlation values are 0.440 and 0.475, respectively. The correlations are significant at 95 percent level of confidence. Vegetation cover is negatively correlated with bank angle and fracture length and the correlations values are (r) -0.489 and -0.462 respectively, whereas correlations are significant at 95 percent level of confidence. Again, the correlation between vegetation cover and organic matter stands positive (0.476) and the correlations are significant at 95 percent level of confidence. Correlations between total clay plus silt and organic matter stands positive (r=0.539) and the correlations are significant at 95 percent level of confidence. So, an increase in percentage of vegetation cover along the riverbank ensures more percentage of organic matter and clay in soil, which denotes improvement in soil cohesion. Again, velocity and bank angle are positively correlated (r=0.577) with each other and correlation is significant at 99 percent level of confidence. The correlation between settlement cover (%) and depth of channel is positive and significant (Table 6) because many study units are situated along the bank of the Bhagirathi. The depth of the river channel is well maintained in the Bhagirathi to ensure the navigability of Kolkata port. Along the bank of the Bhagirathi, a considerable percentage of settlement cover is observed. Depth of river channel and velocity of river are positively correlated with each other. Again, channel width and bank height are positively and significantly correlated with each other (r=0.685) (Table 6). In erosion-prone areas, the angle of the riverbank is high and therefore the slope is steep. The high angle ensures that the riverbank is under the threat of riverbank erosion. Generally, velocity of river becomes more active where the bank is less cohesive and creates a vacuum at the base of the bank, which in turn incurs bank erosion. Therefore, it can be said that the main factors of bank erosion are less cohesion in soil (determined by clay and organic matter percentage in the soil), low percentage of vegetation cover along the banks, the presence of more settlement cover along the riverbank and low depth in the river channel.

Conclusion

It can be concluded that active and continuous riverbank erosion means that the rate of annual erosion exceeds annual rate riverbank deposition.

Table 6. Correlations among the different selected variables

		Average bank height	Bank erosion	Average bank angle	Average velocity	Vegetation cover %	Total clay plus silt %	Organic matter %	Average fracture length	Channel width	Settlement cover %	Channel Depth
Average bank height	Pearson Correlation	1	0.525(*)	0.50(*)	0.418	-0.233	-0.058	-0.190	0.475(*)	0.685(**)	-0.069	-0.203
	Sig. (2-tailed)		0.015	0.026	0.060	0.310	0.803	0.409	0.030	0.001	0.765	0.378
	N	21	21	21	21	21	21	21	21	21	21	21
Bank erosion	Pearson Correlation	0.525(*)	1	0.639(**)	0.327	-0.254	-0.303	-0.092	0.290	0.536(*)	-0.146	-0.162
	Sig. (2-tailed)	0.015		0.002	0.148	0.267	0.181	0.691	0.202	0.012	0.528	0.482
	N	21	21	21	21	21	21	21	21	21	21	21
Average bank angle	Pearson Correlation	0.50(*)	0.639(**)	1	0.577(**)	-0.489(*)	-0.247	-0.062	0.440(*)	0.346	0.148	-0.052
	Sig. (2-tailed)	0.026	0.002		0.006	0.025	0.281	0.788	0.046	0.125	0.521	0.822
	N	21	21	21	21	21	21	21	21	21	21	21
Average velocity	Pearson Correlation	0.418	0.327	0.577(**)	1	-0.113	-0.128	-0.022	0.033	0.228	0.403	0.499(*)
	Sig. (2-tailed)	0.060	0.148	0.006		0.626	0.579	0.924	0.888	0.321	0.070	0.021
	N	21	21	21	21	21	21	21	21	21	21	21
Vegetation cover %	Pearson Correlation	-0.233	-0.254	-0.489(*)	-.113	1	0.246	0.476(*)	-0.462(*)	-0.259	0.043	0.260
	Sig. (2-tailed)	0.310	0.267	0.025	0.626		0.282	0.029	0.035	0.257	0.855	0.256
	N	21	21	21	21	21	21	21	21	21	21	21
Total clay plus silt %	Pearson Correlation	-0.058	-0.303	-0.247	-0.128	0.246	1	0.539(*)	-0.313	0.250	0.032	0.191
	Sig. (2-tailed)	0.803	0.181	0.281	0.579	0.282		0.012	0.167	0.275	0.890	0.407
	N	21	21	21	21	21	21	21	21	21	21	21
Organic matter %	Pearson Correlation	-.190	-0.092	-0.062	-0.022	0.476(*)	0.539(*)	1	-0.389	-0.057	-0.097	0.067
	Sig. (2-tailed)	0.409	0.691	0.788	0.924	0.029	0.012		0.081	0.807	0.677	0.773
	N	21	21	21	21	21	21	21	21	21	21	21
Average fracture length	Pearson Correlation	0.475(*)	0.290	0.440(*)	0.033	-0.462(*)	-0.313	-0.389	1	0.311	-0.212	-0.334
	Sig. (2-tailed)	0.030	0.202	0.046	0.888	0.035	0.167	0.081		0.170	0.355	0.139
	N	21	21	21	21	21	21	21	21	21	21	21
Channel width	Pearson Correlation	0.685(**)	0.536(*)	0.346	0.228	-0.259	0.250	-0.057	0.311	1	-0.237	-0.266
	Sig. (2-tailed)	0.001	0.012	0.125	0.321	0.257	0.275	0.807	0.170		0.301	0.245
	N	21	21	21	21	21	21	21	21	21	21	21
Settlement cover %	Pearson Correlation	-0.069	-0.146	0.148	0.403	0.043	0.032	-0.097	-0.212	-0.237	1	0.519(*)
	Sig. (2-tailed)	0.765	0.528	0.521	0.070	0.855	0.890	0.677	0.355	0.301		0.016
	N	21	21	21	21	21	21	21	21	21	21	21
Channel Depth	Pearson Correlation	-0.203	-0.162	-0.052	0.499(*)	0.260	0.191	0.067	-0.334	-0.266	0.519(*)	1
	Sig. (2-tailed)	0.378	0.482	0.822	0.021	0.256	0.407	0.773	0.139	0.245	0.016	
	N	21	21	21	21	21	21	21	21	21	21	21

** *Correlation is significant at the 0.01 level (2-tailed).*
* *Correlation is significant at the 0.05 level (2-tailed).*

Riverbank erosion is caused by physical and manmade factors. The main causes of active bank erosion are: less cohesion in soil (bank material), low percentage of vegetation cover along the bank, the presentce of more settlement cover along the riverbank, and low depth in river channel, which can also be observed also in Jangipur sub-division. After analyszing the collected bank materials of each selected study unit, it is observed that all the study units have high susceptibility to erosion because the critical level of soil organic matter index (St) is less than five percent. The aArea characterizised by active and continuous bank erosion is subjected to implement measurement strategies being implemented by the concerned authorities.

Acknowledgement

Author is greatly thankful to Dr. Abhay Sankar Sahu, Associate Professor, Department of Geography, University of Kalyani, for his guidance during this research. I am also thankful to Dr. Prasanta Kumar Bandyopadhyay, Professor, the Department of Agricultural Chemistry and Soil Science, BCKV, Mohanpur, Nadia, for his worthy cooperation during this research.'

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Received 17 February 2022
Accepted 04 December 2022