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Riverbank Erosion Along the Vidyadhari River, Gosaba, South 24 Parganas, West Bengal, India with Suitable Embankment Proposal: A Geospatial Investigation

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ABSTRACT

India is a country of rivers. Sundarban is the world's largest deltaic region, which is also part of the Ganga region. Highly populated this region is frequently faced intensive floods. The objective of this paper is to give a notion about the potential embankment zone along the Vidyadhari River. Changes in riverbanks since 1972 have been highlighted through GIS and Remote Sensing Applications. Through this paper, erosional and depositional zones along the Vidyadhari River are also spotted out. The potential embankment zone is measured by the vulnerability analysis based on river bank shifting. The proper embankment technology has also suggested a sustainable embankment along the river Vidyadhari river, which is guided by the Irrigation Department, Government of West Bengal.

Introduction

A stream that originates from a mountain, lake, spring, etc. reservoir and flows over the surface according to the slope of the land and joins a sea or a lake or any other watercourse is called a river. Depending on the slope and topography of the land, the flow of the river is divided into three categories, namely: The upper course, the middle course, and the lower course. As the velocity of the river is very low during this time and the river is very close to the mean sea level and became stagnant, the lower course of the river is observed in plain or delta regions. At this time, due to low velocity, the river cannot carry the silt, mud, sand, etc. which are carried along with the water. As a result, they accumulate on both sides of the river. Continuously in this natural process, silt accumulates on both banks of the river, and natural dams are formed. During this time the depth of the river decreases, as a result of which, occasionally during the rainy season, the excess water enters the river and cannot be drained through the riverbed. Then that excess water breaks or overtops the riverbank and causes a flood in the river valley. The silt, sand, mud, etc. carried with the flood water settles and accumulates in the lowlands of the basin area on both banks of the river. Thus floodplains and deltas are formed in the lower part of the river valley.

India is a country of rivers, which is comprised of seven major rivers and associated tributaries and distributaries making up the river network in India (Thakur et al., 2012; Das et al., 2014). Countless rivers, big or small, have profoundly influenced India's economy and the lifestyle of its people since the distant past. This is why India is called a riverine country. The rivers in India are recognized into four groups, viz. Himalayan rivers, Deccan plateau rivers, inland rivers, and coastal rivers. West Bengal is located in eastern India, stretched from the Himalayas in the north to the Bay of Bengal in the south. Mainly the two types of rivers are seen here – Coastal rivers and Rivers with an inland drainage basin. The river Ganges is the most influential in West Bengal. Every year, millions of people are affected by riverbank erosion and shift that causes the loss of croplands, farmland and settlement areas, destruction of artificial structures, etc. (Rahman & Gain, 2020). Recurring flood events in India cause severe damage to the land and other resources (Singh & Kumar, 2017). The Sundarbans region spans over India and Bangladesh and is the largest deltaic part of the Ganga – Brahmaputra and Meghna River system. About 4,267sq.km, Indian Sundarban is enveloped by water bodies (about 1,700sq.km) such as canals, creeks, and tidal rivers (width a few meters to kilometers). The rivers of the Sundarban region are associated with the tidally fed rivers. Each river is interconnected with the main river and its tributaries and distributaries. Every year monsoon floods are a frequent natural hazard in India. Two main river systems, namely, Ganga and Brahmaputra river systems, are highly affected by bank erosion activity (Sarma, 2013; Das et al., 2014; Mukherjee et al., 2017; Islam & Guchhait, 2019; Dekaraja & Mahanta, 2020; Das and Saha 2022). Vidyadhari River is the most effective river in this region. Due to some natural and anthropogenic activities such as diversion of the follow, velocity of the river, channel scouring, the cohesiveness of the texture of the banks, humidity of the soil, and different types of sediments, are responsible for this type of bank erosion. The processes of erosion of the rivers and the sea are quite similar in the active zones of Sundarban. Here, the responsible erosional processes are hydraulic action, abrasion or corrasion, Attrition, and Corrosion or Solution (Jayanta Gour 2012).

Regional tectonic activities, Quaternary, as well as Holocene sea-level fluctuation and sedimentation, affect the sedimentary structure of the Sundarban delta. Gosaba is one of the vulnerable blocks of Sundarban, which is located in the Canning Sub-division of the South 24 Parganas district, West Bengal, India. Geologically, the area is covered with Holocene newer sediments (Bandyopadhyay et al. 2014). Gosaba Block is located at 22°54’N to 22°08’N and 88°29’E to 88°49’E and it has an average elevation of 6 meters (20ft) from mean sea level. The said research work is employed to study the northeast segment of Gosaba, Sundarban. The longitudinal and latitudinal extension of the study area is 22°08’15” N to 22°11’41” N and 88°46’51” E to 88°49’32” E. The seven mouzas, viz.Manmathanagar, Chandipur, Gosaba, Arampur, Mazidbari, Birajnagar, and Dulki of Gosaba block are included in this study area. The study area is bounded on the northeast by Manmathanagar, northwest by Chandipur, west by Mazidbari, southwest by Birajnagar, south Dulki, southeast by Arampur, and east by Gosaba. Vidyadhari is the main river of the Gosaba block of Sundarban. The Vidyadhari River origins from Haringhata in Nadia district and streams through Deganga, Habra, and Barasat areas of North 24 Parganas and then meets to Raimangal River in the Sundarban of South 24 Parganas. An interconnected complex water system is developed in Sundarban. Vidyadhari River is also a similar river. Naturally, apart from being a major navigation route for earlier civilizations, this river was also projected as the major drainage system of the city of Kolkata. However, with the passage of time, the river has become narrower due to the collapse of its banks.

In 2011, Md. B Hossain, T Sakai and Md. Z Hossain researched the river bank erosion of lower-coursed rivers of the plain regions in Bangladesh. In addition, they also examined the stability of the river embankment and the cause of its failure. The said research work is field-intensive and laboratory-based with the Japanese Industrial Standard (JIS). Soil permeability is the main variable to do the said study. Through their study, they suggest using geo-bags for slope protection of an embankment, which increases stability. In 2013, Subarna Chatterjee and Biswaranjan Mistri did research work on riverbank erosion of the Bhagirathi-Hooghly River near the Shantipur block of Nadia district, West Bengal. According to them, such kind of lateral erosion is influenced by the properties of flow, the composition of bank materials, climatic influence, the geometry of the channel, and vegetation cover. Subhamita Dhara and Biraj Kanti Mondal worked on the riverbank erosion due to changing and modification of the Saptamukhi River and Muriganga River at Namkhana, in 2018. Remote sensing and GIS techniques are being used to compute the riverbank shifting. Tanmoy Mondal and Biplab Tripathy, in July 2020 researched environmental degradation due to riverbank erosion. According to the said research paper, it has been evaluated that riverbank erosion is the prominent influencer of flood, landslide, and soil erosion along the river-associated zone. Suman Ghosh and Biswaranjan Mistri worked on the embankment breaching and its management in Gosaba, Sundarban, West Bengal in 2020. They figure out the embankment condition in Gosaba and measure, how they construct and their model.

The aforementioned research work is trying to assess the present condition of the river embankment and various GIS techniques are being used to examine the vulnerability status of the selected canvas of Gosaba, concerning river bank erosion, by the change detection study (Figure No. 3, 4, & 5). Remote sensing and geographic information system (GIS) are idyllic and seemingly tools for monitoring river erosion and its line transfer (Khatun et al., 2022). In the last two decades, the spatiotemporal confluence and off-take dynamics, sediment yield and channel bar dynamics have been analyzed by applying remote sensing and geographical technique (Ophra et al., 2018).

METHODS

Since the historical era, many authentic research works have been documented on channel migration and the mechanism of different types of channel avulsion on quaternary floodplain geological sites (Baki & Gan, 2012). Few research works have been done applying the given techniques (Lawler et al., 1997; Sarkar et al., 2012; Robinson 2013; Nath et al., 2013; Gogoi and Goswami, 2014) in riverbank shifting. With the help of research methodology, any kind of research problem can solve easily and in a systematic way. This research work consists of both primary and secondary data. The most important way to collect data or information is observation. Satellite imagery (Landsat) of the above-mentioned study area from the USGS Earth Explorer web portal (Table 1). Besides, other information is collected from the Irrigation Department web portal of the Government of West Bengal, journals, books, research reports, Govt. Project report, and PhD thesis.

Table 1. Source of Data

Type of Data	Source of Data	Year
GPS waypoint for Embankment Study	Primary Survey	Nov – Dec 2022
Satellite Data (Landsat)	(Secondary Data) USGS Earth Explorer	05-11-1972, 21-02-1980, 25-04-1992, 18-11-2003, 08-11-2011, 14-11-2022

TNT Mips (Version 2021), Arc GIS (Version 10.3.1), and Quantum GIS (Version 3.6.2) software are used to sketch all the maps and is being simulated riverbank in 2030. In addition, based on erosion and deposition rate vulnerability level is being delineated along the Vidyadhari River bank in Gosaba which also help to design the embankment potential zone. The hypothesis is tested in SPSS (IBM).

RESULTS AND DISCUSSION

Embankment Scenario along the Vidyadhari River in Study Area

The river embankment is the lifeline for the lower course of a river. The reclamation of immature land through the construction of embankments without proper planning has been increasing the vulnerability of embankment breaching due to various natural and anthropogenic causes (Ghoshand Mistri, 2020). The Sundarbans region spans over India and Bangladesh and is the largest deltaic part of the Ganga – Brahmaputra and Meghna River system. To understand the scenario of embankment breaching and its recent management strategy, an intensive field survey was conducted to comprehend the underlying reasons for embankment breaching and its management techniques at the ground level (Ghosh & Mistri, 2020). An embankment may refer to a levee or an artificial bank, mainly elevated from the surrounding parts of the land to prevent flooding by a river, lakes, or sea (Ghosh & Mistri, 2020). The total length of the embankment in Sundarban was 3638.18 km in 2010 (Sarkar et al., 2016). Embankments may be either made of earthen materials or bricks and concrete materials (Das, 2016). About 10.28 % of the riverbank is covered by the constructed embankment (Table 2). Various type of river embankment is found, viz. Brick pitching, block pitching, sand-bag, mud-bag, and timber-bamboo embankment (Figure 1 & 8).

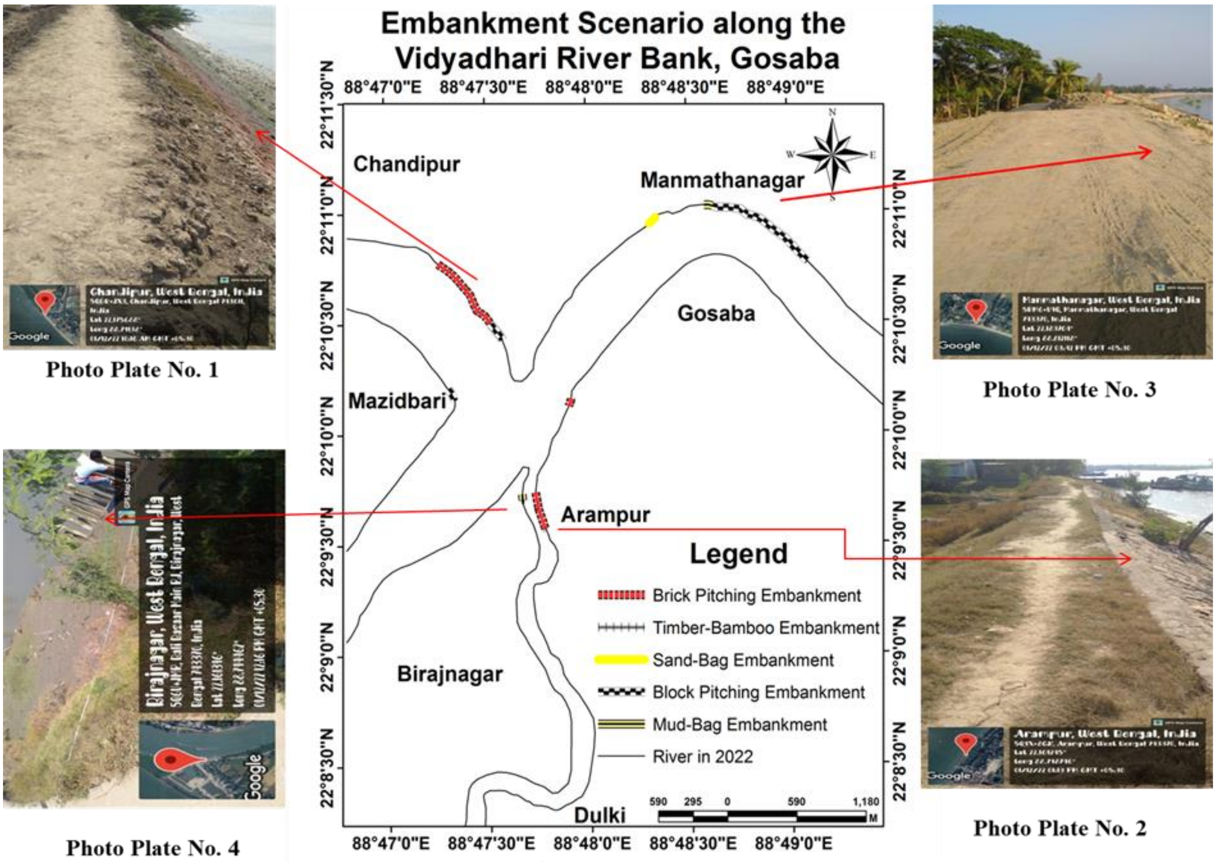


Figure No. 1

Brick Pitching Embankment

The Vidyadhari River and Gomar Khal follow a meandering path that increases in the outer bank at the northeastern portion of Gosaba. The brick pitching method for embankment construction quite helps to choke the bank erosion. The brick in the said part of Gosaba embanks about 4.33% riverbank. Maximum brick-pitched embankment constructed in Chandipur (687.81 meters on the left bank of Vidyadhari River) (Table 2, Figure 1 & Photo Plate No. 1). In addition, Arampur (323.12 meters on the left bank of Vidyadhari river) (Figure 1 & 8, Photo Plate No. 2) and Gosaba said the type of embankment constructed. Gosaba has the shortest embankment (66.39 meters on the left bank of the Vidyadhari River). The Brick Pitching embankments are found on the left bank of the Vidyadhari River. The brick embankment is configured at 30 meters in height and 7 meters in width (Table 2).

Table 2. Types of Embankment

Sl. No.	Mouza	Types of Embankment	Length	Height in feet	Width in feet	Bank	Total Bank Length in Meters (selected study area)
1	Chandipur	*Brick Pitching Embankment*	*687.81*	*31*	*6.3*	*Left*	*2587.34*
2		*Block Pitching Embankment*	*167.42*	*43*	*3.9*		
3	Manmathanagar	*Sand–Bag Embankment*	*71.15*	*24*	*6.5*	*Right*	*4109.86*
4		*Mud – Bag Embankment*	*75.44*	*-*	*-*	*Right*	
5		*Block Pitching Embankment*	*971.14*	*42*	*17*	*Right*	

6	Gosaba	*Brick Pitching Embankment*	*66.39*	*30*	*7*	*Left*	*5101.44*
7	Arampur	*Brick Pitching Embankment*	*323.12*	*25*	*7*	*Left*	*2793.63*
8	Birajnagar	*Mud–Bag Embankment*	*47.20*	-	-	*Right*	*6367.68*
9		*Timber-Bamboo Embankment*	*35.74*	*25*	*5.7*	*Right*	
10	Mazidbari	*Block Pitching Embankment*	*112.27*	-	-	*Right*	*2813.16*

Source: Primary Survey (2022) & Author's Computation

Block Pitching Embankment

The embankments, as public property act as a safeguard for private property (Sarkhel, 2013) in Gosaba. Cemented Blocks are pitched appropriately constructed with the 3:1 slope ratio of the riverside. This kind of costly and labor-intensive embankment is constructed about 5.33% riverbank of the study area. The block-pitched embankment is developed in Manmathanagar (971.14 meters on the right bank of the VidyadhariRiver) (Figure No. 1 & Photo plate No. 3), Chandipur (167.42 meters exists on the left bank), and Mazidbari (112.27 meters develops on the right bank of the Vidyadhari river). The height of the block-pitched embankment is 42 meters with 17 meters in width (Table 2).

Sand-bag Embankment

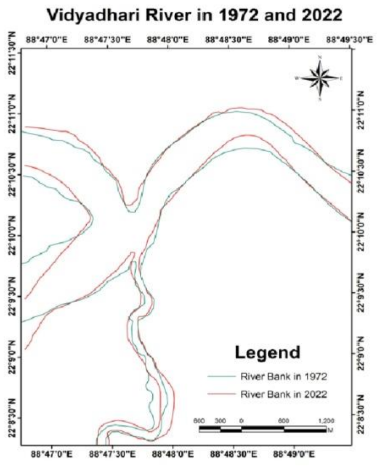
Sandbags are often used in the deltaic region to reduce the devastating effects of riverbank erosion (Ghosh & Mistri, 2020). About 0.29% river, the sandbag embanks the bank of the study area. The sandbag wall or barrier is arranged layer by layer to improve the stability of the riverbank (Ghosh & Mistri, 2020). The weight of the sandbag is 14 to 18 kg. Some bamboo piles are also used in front of sandbags to give the river bank more stability (Ghosh & Mistri, 2020). Some bamboo piles are also used in front of sandbags to stabilize the river. The sand-bag embankment is with 24meters in height and 6.5 meters in width. Sandbags are used as embankments in Manmathanagar (71.15 meters on the right bank of the river).

Mud-bag Embankment

About 0.49% riverbank is embanked by the mud-bag embankment (Table 2). Bamboo piles are used for stabilization. Mud-bag embankment is assisting only two mouzas Manmathanagar (75.44 meters on the right bank of the river Vidyadhari) and Birajnagar (47.20 meters on the right bank of the river). Mud-bag embankment is only located on the right side of the river (Figure 1 & 8).

Timber-Bamboo Embankment

Bamboo is an environment-friendly material to embank the riverbank. It helps to strengthen and stabilize the bank. The row of bamboo piles is firmly fixed with a rope or iron wire. Piling in wet soil of marshy land is very easy but required more strength (Ghosh & Mistri, 2020). About 0.14% riverbank is embanked by the timber-bamboo embankment and this type of embankment mechanism is used only in Birajnagar (35.74 meters on the right bank of the river) (Figure 1 & Photo Plate No 4). In some places, two parallel rows of piles are prepared, and the space between them is filled with boulders and pebbles to protect the embankment from toe erosion (Ghosh & Mistri, 2020). The height of the timber-bamboo embankment is 25 meters and the average width is 5.7 meters (Table 2, Figure 1 & Photo Plate No. 4). The primary survey clearly expresses that the Block Pitching Embankment method is used mostly in the areas of Sundarban. The embankment construction is much higher on the right bank rather than on the left bank of the Vidyadhari River. Birajnagar Mouza is experiencing the highest embankment construction in the study area.



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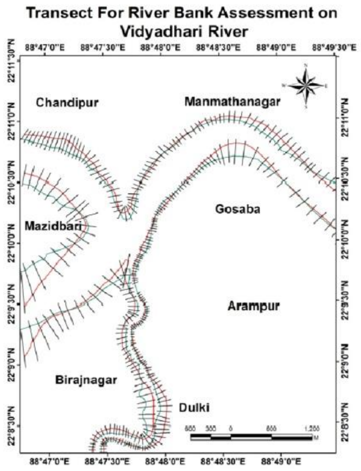

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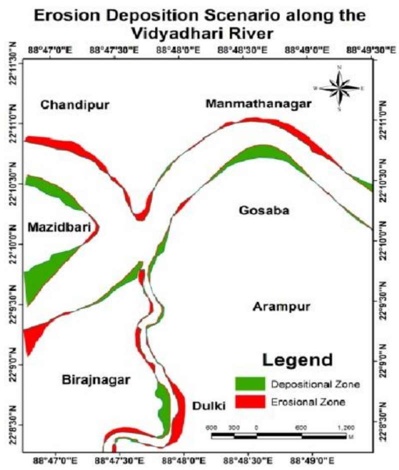


Figure No. 5

Figure (2) Vidyadhari River Bank in 1972 to 2022, (3) Transect, (4) Erosion and depositional scenario along the Vidyadhari River bank

Erosion Deposition along the Vidyadhari River in Study Area

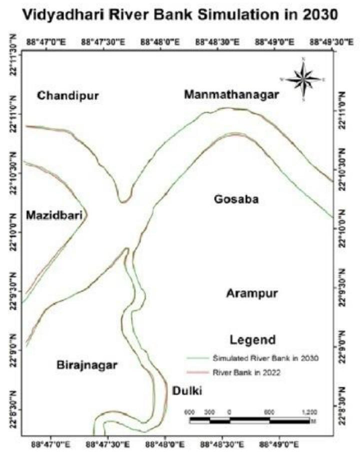
Riverbank erosion is a dynamic natural process (Ghosh, 2022). Bank erosion will generally happen when the magnitude of flowing water exceeds the strength of materials on the basal part of a riverbank (Ghosh & Sahu 2018, 2019a, b). The riverbank distortion towards land is the tether of the erosional zone and shifting towards the river is demarcated as the depositional zone. The efficiency of embankment management and its mechanism of breaching depend on various factors such as river hydraulics and the estuarine process (Das & Maity, 2012). Land reclamation program has been carried out many times in this area but the importance of these tidal creeks or channels are neglected every time. The entire Gosaba is pronounced by the tidal activity of the river. Helical flow is the prominent mechanism to govern the riverbank erosion in Gosaba. The rate and intensity of riverbank erosion also depend on various other factors like the amount and frequency of water supply, sediment supply, geology, soil characteristics, vegetation cover, and surface land-use system (Ghosh & Mistri, 2020). Remote sensing and GIS applications in bank erosion studies have a great role in management studies (Das & Saraf, 2007; Das et al., 2012a; Ophra et al., 2018). In recent years, various research studies have been conducted by applying geospatial techniques to evaluate channel course modifications, degree of anthropogenic stress, cost-benefit analysis, and quantification of river bank erosion (Bera et al., 2019b). Cross-sectional interventions (Figure No. 4) on river channels alter the channel morphology by modifying the discharge volume (Islam & Guchhait, 2020).

Table 3. Erosion – Deposition Scenario Due to River bank erosion in Study Area

Mouza	Total Eroded Area since 1972 (in m^2)	Total Deposited Area since 1972 (in m^2)	Balance
Chandipur	188788.39	0.0	-188788.39
Manmathanagar	132059.95	57047.51	-75012.44
Gosaba	15982.82	176780.31	+160797.49
Arampur	4233.62	58424.51	+54190.89
Dulki	125143.08	8643.15	-116499.93
Birajnagar	186621.09	172404.08	-14217.01
Mazidpur	18235.69	343223.50	+324987.81

Source: Primary Survey (2022) & Author's Computation

The river becomes an interesting case study when it undergoes several morphological changes longitudinally and transversally, related to various types of hydraulic works, weirs, and embankments over long periods (Geria et al., 2018). River morphology describes the concept of geographic form, the river channel classification, the edges of the river, and geomorphic analysis (Momin et al., 2020). However, bank erosion is mainly regulated by the nature of bank materials and river discharge (Youdeowei 1997; Gosh & Bera, 2022). Secondly, the nature of channel flow and velocity also has a great influence on the bank erosion process (Majumdar & Das (Pan) 2014). The augmentation of riverbank accretion and deterioration process is assorted at the different segments of the study area. Prediction of the location and the extent of riverbank erosion (Figure No. 4, 5 & Table 3) continue to be difficult despite the testing of a range of approaches and methods (Sandra and David, 2000; Bandyopadhyay et al., 2014).



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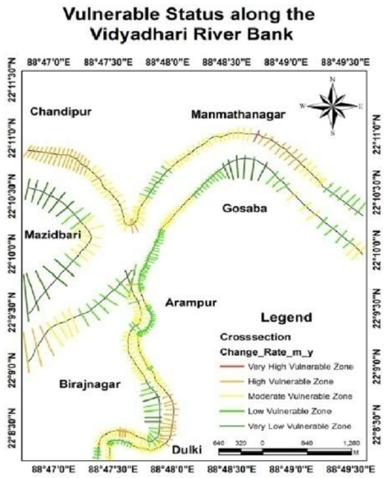

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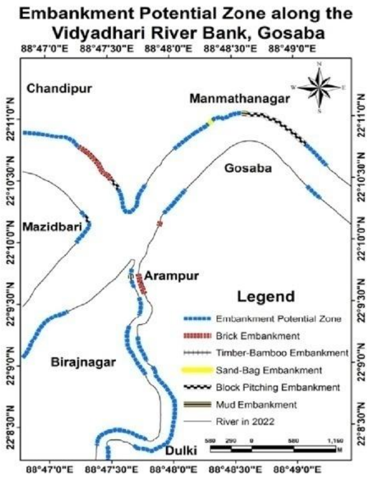

Figure No. 8

Figure (5) Vidyadhari River Bank simulation in 2030, (6) Vulnerability Status of River bank, (7) Embankment potential zone along the Vidyadhari River bank

The total eroded areas of Sundarbans are as follows Chandipur (188788.39 m^2), Manmathanahar (132059.95 m^2), Gosaba (15982.82 m^2), Arampur (4233.62 m^2), Birajnagar (186621.09m^2), and Mazidpur (18235.69 m^2). The total deposited areas of Sundarban are as follows Chandipur (0.0 m^2), Manmathanagar (57047.51m^2), Gosaba (176780.31m^2), Arampur (58424.51m^2), Dulki (8643.15m^2), Birajnagar (172404.08m^2), Mazidpur (343223.50 m^2). The erosional land is highest in Chandipur (188788.39 m^2) and lowest in Arampur (4233.62m^2). The primary survey also assesses that Gosaba has the highest depositional areas (176780.31m^2) and the lowest in Chandipur (0.0m^2). From the above research work and computation, it has been revealed that Chandipur (-188788.39 m^2), Dulki (-116499.93 m^2), Manmathanagar (-75012.44 m^2), and Birajnagar (-14217.01 m^2) are more prone to intensive erosion in comparison to Mazidpur (+324987.81 m^2), Gosaba (+160797.49 m^2) and Arampur (+54190.89 m^2) (Table 3; Figure No. 2, 3, 4). The high velocity with turbulence during monsoon month erodes the non-cohesive bank materials and enhances the bank erosion and lateral shifting of the channel (Guchhait et al., 2016). However, selective entrainment of non-cohesive bank materials during high flow weakens the overall structure, which leads to bank failure (Gosh & Bera, 2022). Combined processes of aggradations and degradation within river channels bring channel instability which ultimately leads to channel migration (Ahmed and Das 2018; Ahmed et al,. 2018).

Prediction of the River Bank

The erosion zone has been identified through the superimposition of vectorized (Figure 3, 4 & 5) multi-temporal satellite images (Ghosh and Mukhopadhyay, 2016). The principal purpose of this said research work is sketching of embankment and riverbank breaching. The riverbank is simulated in 2030 based on 50 years of data (1972 to 2022). The regional or micro scale landscape modifications, shape, and form of floodplain alterations exist due to lateral river channel migration (Thakur et al., 2012).

Table 4. Vulnerable River Bank in Gosaba (selected zone)

River Bank Change Rate (in meters/year)	Vulnerability	Mouza
Below -1.72	*Very High Vulnerable Zone*	*Manmathanagar*
(-1.72) to (-1.44)	*High Vulnerable Zone*	*Chandipur, Manmathanagar, Arampur, Dulki, Birajnagar*
(-1.44) to 0.11	*Moderate Vulnerable Zone*	*Chandipur, Manmathanagar, Gosaba, Arampur, Dulki, Birajnagar, Mazidbari*
0.11 to 2.27	*Low Vulnerable Zone*	*Manmathanagar, Gosaba, Arampur, Dulki, Birajnagar, Mazidbari*
2.27 to 10.73	*Very Low Vulnerable Zone*	*Gosaba, Birajnagar, Mazidbari*

Source: Primary Survey (2022) & Author's Computation

With the help of the riverbank simulation method (Figure 6), it can easily be said that there are five types of vulnerability zone along the banks of the Vidyadhari River. Manmathanagar exists in Very high vulnerable zone (Below -1.72 m/year), whereas Chandupur, Dulki, Arampur, Birajnagar are in High Vulnerable zone (-1.72 to -1.44 m/year), Manmarhanagar, Gosaba, Arampur, Dulki, Birajnagar, Mazidbari are in Moderate Vulnerable Zone (-1.44 to -0.11 m/year), Gosaba, Arampur, Dulki, Birajnagar, Manmathanagar are in Low Vulnerable Zone (0.11 - 2.27 m/year) and Gosaba, Birajnagar, Mazidbari are in Very Low Vulnerable Zone (2.27 - 10.73 m/year) (Table 4 & Figure 5 & 7). From this analysis, it has been observed that Chandipur and Manmathanagar will be experienced more erosional work in the future. In addition, the north-western segment of Birajnagar will be faced river bank retreatment (Figure 5).

Vulnerability Analysis

The riverbank of the deltaic plain is dynamic. The geomorphological structure depends on the various processes of the riverbank. Satellite imageries using Arc GIS (Figure 4 & 7) and necessary field surveys are used to measure the vulnerable zone of the embankment by Gram Panchayat (Ghosh & Mistri, 2020). The riverbank of the selected study area is breached due to natural and anthropogenic causes.

Natural Causes

1. Unscientific embankment construction along the Vidyadhari River increases the rate of siltation at the riverbed.
2. Longitudinal embankment construction on tidal creeks choked the natural flow and pronounce to hydraulic pressure for riverbank erosion.
3. Old earthen embankments of the study area are constructed during the British colonial period. These are technically very weak in the present circumstance.
4. The frequency and intensity of cyclone occurrence over the Sundarban region are rapidly increasing due to climate change. This creates tremendous pressure on the riverbank.
5. The mangrove forest in Sundarban acts as a natural barrier. Deforestation of it brings Sundarban under threat.

Anthropogenic Causes

1. Since last century, the population pressure has increased in the Gosaba region. Thus, due to the mutation of land-use and land-cover patterns, is harming rivers.
2. Chanel's width of the tidal creek becomes narrower due to embankment construction on both sides that reduce the water carrying capacity. It also causes riverbank breaching.
3. At the mouth of tidal creeks, several lock gates have been constructed to drain out excess water from inland. Several lock gates have been constructed at the mouth of the tidal creeks, to drain out excess water from inland. The huge pressure of water during climatic extremes (cyclones) suddenly breaks down the system of sluice gates and causes large-scale embankment breaches in the delta (Ghosh & Mistri, 2020).
4. Riverbanks are the natural levee of the flood plain or deltaic region and they are marked as the dry point. Consequently, people use banks

as communication pathways. The said things also influence bank erosion.

5. Shrimp catching along the bank is also pronounced to erode the bank's soil. Based on the change of riverbank, vulnerability is being measured along the Vidyadhari River in the selected part of Gosaba. About 24.88 km length riverbank of the selected study area of Gosaba, Sundarban is isolated into five zones, viz. very high vulnerable zone, high vulnerable zone, moderate vulnerable zone, low vulnerable zone, and very low vulnerable zone. The maximum vulnerable riverbank is Chandipur (1117.73 meters). Birajnagar has the highest length of moderate vulnerability riverbank (2744.78 meters) and Mazidbari has the highest length of low vulnerability riverbank (1747.14 meters).

Table 5. Vulnerability Zone of Embankments

Sl. No.	Mouza	Vulnerability Status	Length of Vulnerable River Bank (Meters)	Length of Vulnerable River Bank (in %)	Total Length (Meters)
1	Chandipur	High Vulnerable	1117.73	43.19	2587.34
2		Moderately Vulnerable	1469.61	46.81	
3	Manmathanagar	Very High Vulnerable	111.72	02.72	4109.86
4		High Vulnerable	793.37	19.30	
5		Moderately Vulnerable	1837.08	44.70	
6		Low Vulnerable	1367.69	33.28	
7	Gosaba	Moderately Vulnerable	1577.70	30.93	5101.44
8		Low Vulnerable	2758.69	54.08	
9		Very Low Vulnerable	765.05	14.99	
10	Arampur	High Vulnerable	864.93	30.96	2793.63
11		Moderately Vulnerable	1242.94	44.49	
12		Low Vulnerable	685.76	24.55	
13	Dulki	Moderately Vulnerable	694.66	62.79	1106.26
14		Low Vulnerable	411.60	37.21	
15	Birajnagar	High Vulnerable	873.22	13.71	6367.68
16		Moderately Vulnerable	2744.78	43.11	
17		Low Vulnerable	2301.87	36.15	
18		Very Low Vulnerable	447.81	07.30	
19	Mazidbari	Moderately Vulnerable	634.12	22.54	2813.16
20		Low Vulnerable	431.90	15.35	
21		Very Low Vulnerable	1747.14	62.11	

Source: Primary Survey (2022) & Author's Computation

From the above computation and observation, it has been revealed that the maximum bank length of Mazidbari (about 62.11% of the total length of the riverbank in Mazidbari, the selected study area) comes under the very low vulnerable zone. Gosaba (54.08%) is reported maximum low vulnerable zone of the total riverbank length. Dulki (62.79%) experienced a maximum moderate vulnerable zone of the total bank length of this mouza. Chandipur (43.19) mouza is accompanied by a highly vulnerable riverbank zone among the all mouzas of the study area. A very highly vulnerable riverbank is in Manmathanagar (2.72%) only (Table 4, 5; Figure 6).

Embankment Potential Zone Assessment

The embankment potential zone traced and demarcated the particular riverbank that experienced the river devastating work. The bank retreatment rate per year is the main indicator to assess the potential zone in the study area of Gosaba.

Table 6. Embankment Potential Zone in Gosaba (selected zone)

Mouza	Length of Embankment Potential Zone in Meters	Length of Total Embankment (Meters)	Total Bank Length (Meters)
Chandipur	*1733.73*	*855.23*	*2587.34*
Manmathanagar	*1486.05*	*1117.73*	*4109.86*
Gosaba	*915.55*	*66.39*	*5101.44*
Arampur	*2655.72*	*323.12*	*2793.63*
Dulki	*487.28*	*00.00*	*1106.26*
Birajnagar	*3141.99*	*82.94*	*6367.68*
Mazidpur	*453.57*	*112.27*	*2813.16*

Source: Primary Survey (2022) & Author's Computation

The length of potential embankments in the study is as follows, Chandipur 1733.73 meters, Manmathanagar 1486.05 meters, Gosaba 915.55 meters, Arampur 2655.72 meters, Dulki 487.28 meters, Birajnagar 3141.99 meters, and Mazidpur 453.57 meters. From the above computation, it has been traced that Birajnagar (3141.99 meters) accompanied the maximum embankment potential zone out of all mouza of the selected study area of Gosaba and the low embankment potential zone assess in Mazidpur (453.57 meters) (Table 6; Figure 8).

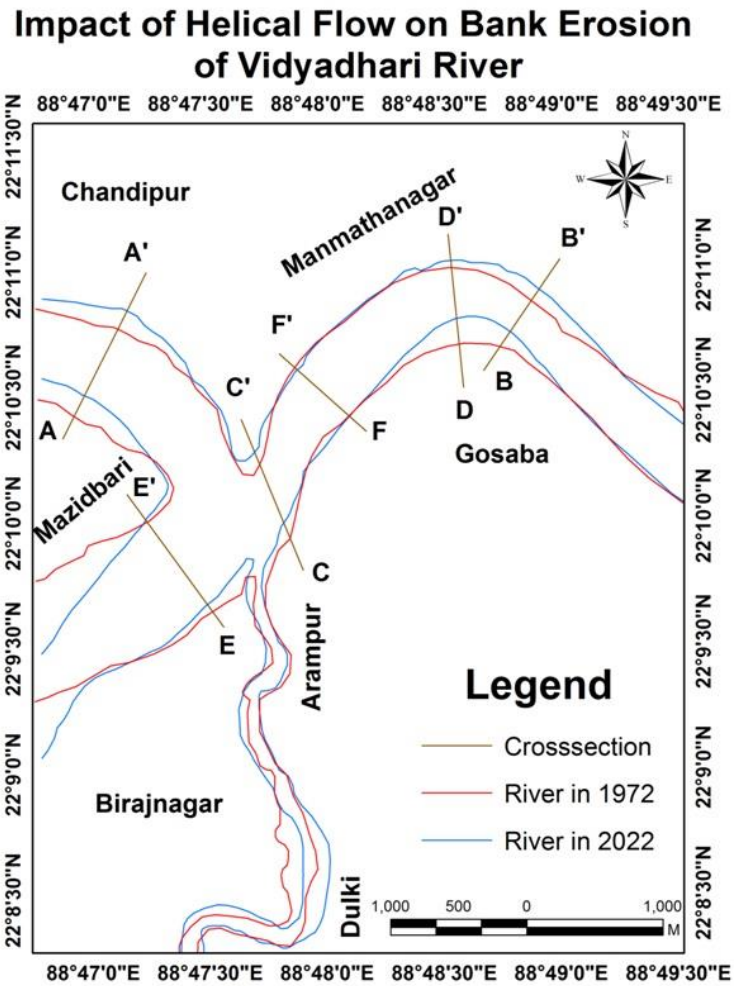

Figure 8. Impact of Helical Flow on Riverbank Shifting

Hypothesis Testing

Descriptive Statistics on river degradation and accretion along the cross-sections are summarized (Figure 8). The said computation is for the analysis of the river's hydrological mechanism behind the distortion of the riverbank. In the initial stage, it has been assumed that the riverbank erosion and accretion in selected parts of Gosaba follow the helical mechanism.

Table 7. Descriptive Statistics for Helical Flow (Hypothesis Testing)

Cross-section	Variable	Mean	Std Deviation	Std Error Mean	*t* Test	Sig. (2-tailed)
AA’	Positive Change of River Bank in Meter	152.5462200	22.37884059	10.00812176	7.648*	0.002
	Negative Change of River Bank in Meter	-99.01443200	58.31485579	26.07919633		
BB’	Positive Change of River Bank in Meter	81.08478800	34.50404967	15.43068011	5.283*	0.006
	Negative Change of River Bank in Meter	-56.57652200	36.78941728	16.45272758		
CC’	Positive Change of River Bank in Meter	103.7387560	15.66335473	7.004865188	13.809*	0.000
	Negative Change of River Bank in Meter	-84.53859200	34.99411971	15.64984610		
DD’	Positive Change of River Bank in Meter	164.9916040	38.34970060	17.15050749	8.184*	0.001
	Negative Change of River Bank in Meter	-28.14892880	17.91665702	8.012572605		
EE’	Positive Change of River Bank in Meter	43.37887860	24.15127915	10.80078038	7.865*	0.001
	Negative Change of River Bank in Meter	-44.67965600	16.93419340	7.573201518		
FF’	Positive Change of River Bank in Meter	23.29403800	14.96406616	6.692133832	3.563**	0.024
	Negative Change of River Bank in Meter	-23.14346080	24.09302403	10.77472790		

Note: * Statistically Significant at 0.01 level, **Statistically Significant at 0.05 level

Source: Primary Survey (2022) & Author’s Computation

The above table shows the results. The estimated parameters have significant values and also have some expected symptoms. From this above computation, it has been measured that the said hypothesis is accepted at the 1% level (Table 7). From this research work, the embankment potential zone has been assessed based riverbank erosion rate. Through hypothesis testing, it is proved that the helical flow mechanism is active in riverbank erosion. It has been observed that the helical flow facing the erosional riverbank is steeper (Ratio 1(V): 2.5 (H)). Thus, as per the guidelines on riverbank protection (Memo No. 501 – IFC/ IW/O/IFC/4M-30/2014; Dated, 10th December 2019) by the Department of Irrigation & Waterways, Government of West Bengal (2019), Type 5C-II embankment is recommended for the selected study area of Gosaba.

CONCLUSION

The Indian Sundarban belongs to the part of the Ganga Delta (Dhara & Mondal, July 2018). Floods and riverbank erosion are the most frequent natural hazards in India, specifically in the deltaic regions (Das & Samanta, 2022). Riverbank erosion is a growing problem in the world (Mondal & Tripathy, 2021). It causes damage to structures and land loss adjacent to the river channel, leading to various alterations to the riverbed and floodplain (Henshaw et al., 2013; Marteau et al., 2017). River Bank erosion has emerged to be one of the most annoying environmental hazards these days (Chatterjee & Mistri, September 2013). The word erosion, derived from the Latin word "erodere", means to gnaw. It is a complex process that incorporates actions of several complex processes and cannot be attributed to any single process (Chatterjee & Mistri, September 2013). The Spatio-temporal vulnerability of embankment breaching depends on both natural and anthropogenic factors (Ghosh & Mistri, 2020). In the last three or four decades, the physical landscape has been completely modified due to unscientific land use practices (Chamling & Bera, 2020a).

The current study employed the satellite remote sensing data-derived GIS layers to assess the river morphology (Khatun et al., 2022) in the Vidyadhari River in parts of Gosaba Sundarban, India. From this research work, it has been addressed that the study area is in an alarming condition concerning riverbank erosion. The modern engineering method of the embankment is efficient enough to protect the riverbank from erosion but it is challenging to construct in such a hydro-geomorphologically diversified land (Ghosh & Mistri, 2020). Therefore, the allocation and management of the river bank are very complex issues. To protect the alarming vulnerable sites of Gosaba, Sundarban region, modern engineering methods, and equipment are desiderated for the construction of embankment in a sustainable manner.

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