Journal of Environmental Science 10 (3) (2023) 159-173

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University of Rajshahi

Journal of Environmental Science

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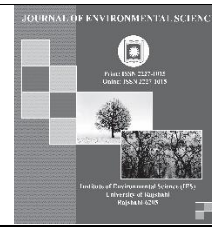

Erosion and Mitigation Measures in the Teesta River Bank of Bangladesh

Mst. Jebunnesa Islam*, Md. Ismail Firoz, Md. Zahurul Islam, Md. Moniruzzaman and Md. Latifur Rahman Sarker

Department of Geography and Environmental Studies, University of Rajshahi, Rajshahi 6205, Bangladesh.

A R T I C L E I N F O

Keywords:
Riverbank erosion
Mitigation
Respondents
Institutions
Teesta River
Bangladesh

A B S T R A C T

This paper explores the erosion conditions and mitigation practices of riverine communities at various levels (individual, community, NGO, and GO) along the River Teesta. To investigate these aspects, the study utilizes satellite data alongside primary observations. Selected satellite images from 1989, 1999, 2010, and 2022 were analyzed. The Modified Normalized Difference Water Index (MNDWI) was applied using Geographic Information System (GIS) and Remote Sensing (RS) techniques to identify bank lines for erosion analysis. A random sampling method was used to determine the sample size, selecting 426 households out of 955 from three unions—Bojra (site 1), Thetrai, and Daldalia (site 2)—to collect primary data through a questionnaire survey. The primary data were analyzed using descriptive and inferential statistics in SPSS. The results show that Bojra, Thetrai, and Daldalia have experienced significant erosion, with land losses of 86.63 hectares and 81.91 hectares between 2010 and 2022, respectively. Despite this, only traditional erosion control measures, such as bamboo piling *(Bandal)*, have been adopted at the individual and community levels to combat riverbank erosion. Meanwhile, the government has implemented both inadequate traditional measures (e.g., geo-bags, bamboo piling) and infrastructural interventions, such as boulder dumping and Cross/*I-badh*, to mitigate erosion. The findings of this study are expected to provide valuable guidelines for policymakers to ensure sustainable river management in northern Bangladesh.

1. Introduction

Bangladesh lies within the catchment area of the Ganges, Brahmaputra, and Meghna Rivers, which mainly drain through the country into the Bay of Bengal (Brammer, 2014). There are more than 220 rivers across Bangladesh, with a total length exceeding 24,000 km, covering approximately 7% of the national area (Rashed, 2008). The Teesta is a significant transboundary river in the northern region of Bangladesh (Mondal and Islam, 2017). Riverbank erosion is one of the major geomorphological challenges in the floodplains of alluvial rivers, occurring primarily during floods within the river channels (Bordoloi *et al.,* 2020). The Teesta River runs alongside this region and meets the Brahmaputra River. The Teesta basin is one of the most vulnerable river basins in the country due to its erosive nature and susceptibility to flash floods (Pal *et al.,* 2016).

It is a sandy, braided river that exhibits high seasonal flow variability, causing floodplain inundation during the monsoon season and low flow conditions during the dry season (Mullick *et al.,* 2010). During monsoons, heavy rainfall and upstream flows trigger floods and riverbank erosion, exacerbating the suffering of inhabitants through the massive loss of lives and property. Many people become homeless and landless due to riverbank erosion. To address the adverse environmental and socio-economic impacts of riverbank erosion, both individuals and the government

Corresponding author.
E-mail address: jebunnesa7@yahoo.com (Mst. Jebunnesa Islam)
Received 19 August 2023; Received in revised from 25 October 2023; Accepted 18 November 2023;
Available Online 03 December 2023
Published by Institute of Environmental Science, University of Rajshahi

have implemented various mitigation measures, which have slightly reduced the risk of bank erosion (Rumana *et al.,* 2023).

Mitigation refers to sustained actions taken to reduce or eliminate risks to people and property from hazards and their effects (Bullock *et al.,* 2013). Riverbank erosion mitigation measures are categorized into structural, non-structural, and biological protection measures (Islam, 2011). Structural measures commonly used include revetments, guide bunds, boulders, brick matressing, groynes, spurs, vanes, and submerged bendway weirs. On the other hand, examples of non-structural and biological protection measures include dredging, channelization, geo-bag dumping, bank vegetation, wooden/bamboo piling, willow posts, and bundling (Islam, 2011). In the late 1990s, sand-filled geotextile bag revetments were introduced in Bangladesh due to the inadequacy of traditional erosion protection measures. Initially used as an emergency preparedness strategy during the monsoon season, geotextile bags were filled with local sand to facilitate a rapid response to dynamic river changes (Oberhagemann and Hossain, 2011). Efforts to mitigate the impacts of riverbank erosion in Bangladesh have been largely structural and technological, often excluding non-structural measures that could help mitigate the effects of riverine hazards at the individual and community levels (Haque and Zaman, 1994).

In economic point of view, mitigating bank erosion has become an integral part of poverty reduction in Bangladesh (Islam, 2011). The Bangladesh Water Development Board (BWDB) is trying to protect the riverbank with its limited resources and budget to reduce the suffering of the people and minimize the national losses. Several low-cost structures like cross/*I-badh*, geo-bag dumping and *Bandal* were constructed along the left bank of the Teesta River by the BWDB. However, the government has issued a general policy on the distribution of relief materials to disaster victims that undermines equal opportunities for those affected by river erosion due to certain conditions attached to receiving the aid (Islam and Rashid, 2011). As a result, the riverbank erosion victims get only two types of assistance such as allotment (cash) for house building, and general relief (Food). NGOs like BRAC, ASHA, TMSS and RDRS are working with riverbank erosion displaces in certain areas of Teesta River. All the public representative including Member of Parliament, Upazilla chairman, Union chairman and members have adopted some mitigation measures like bamboo piling/*Bandal*, geo-bag/sandbag imputing and block-setting despite the lack of financial support. Traditional erosion control measures are practiced by local communities using natural resources such as bamboo and wood as well as tree plantation which has reduced massive losses and prevented bank erosion quickly and sustainably, in left bank of the Teesta River. However, there is no specific/effective policy or program for the riverbank eroded people either in government or in non-government sectors (Islam and Rashid, 2011).

Over the past few decades, numerous studies have been conducted on the Teesta River in Bangladesh. Research has primarily focused on various aspects of riverbank erosion mitigation, prevention, and preparedness (Bullock *et al.,* 2013; Rahman *et al.,* 2017; Haque, 1997). Several studies have emphasized sustainable mitigation measures for riverbank erosion (e.g., Islam, 2011; Oberhagemann and Hossain, 2011; Sarker *et al.,* 2011). These studies have systematically reviewed riverbank management techniques, including the use of geotextile bags, concrete blocks, boulders, and mattresses. Similarly, several studies have focused on traditional erosion control approaches for managing riverbank erosion and enhancing livelihood resilience in Bangladesh (Mamun *et al.,* 2022). Another study by Maurya *et al.,* (2020) examined the problems and remedial measures implemented in vulnerable areas using soft structural approaches. However, existing literature pays little attention to the mitigation measures adopted by individuals, communities, Government Organizations (GOs), and Non-Governmental Organizations (NGOs) to address Teesta Riverbank erosion in Bangladesh. To bridge this research gap, the present study investigates the various mitigation measures implemented at different levels. This research aims to assist policymakers in developing long-term mitigation strategies for vulnerable riparian areas.

2. Materials and Methods

2.1. Study area selection

The Teesta floodplains have been divided into three major units: the Upper, Middle, and Lower Teesta Basin. The Lower Teesta Basin extends from the Teesta-Sevoke Khola confluence zone to the Brahmaputra-Teesta confluence zone at Tistamukh Ghat in Bangladesh (Mitra and Mondal, 2022). This river runs through five northern districts of Bangladesh: Nilphamari, Lalmonirhat, Kurigram, Rangpur, and Gaibandha. The present study area, including Bojra, Thetrai, and Daldalia, is located on the left bank of the Teesta River.

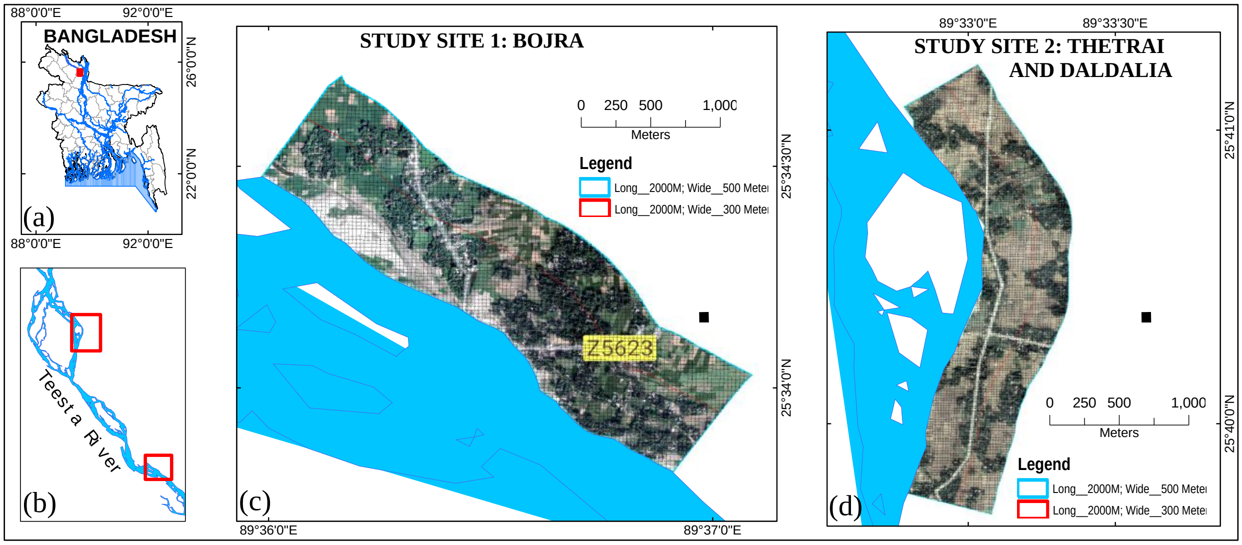

Fig. 1 Location of the study area: (a) Bangladesh (b) Teesta River (c) study site: Bojra (d) study site: Thetrai and Daldalia

The present study was conducted in three villages, namely Bojra (site 1), Thetrai, and Daldalia (site 2), located in Ulipur Upazila in Kurigram District (Fig. 1). Bojra village is situated on the left bank downstream of the Teesta River, lying between 25°34'0" to 25°34'30" north latitudes and 89°36'0" to 89°37'0" east longitudes. Thetrai and Daldalia villages are also located on the left bank downstream of the Teesta River, lying between 25°40'0" to 25°41'0" north latitudes and 89°32'30" to 89°33'30" east longitudes. To select the study areas, Landsat images from 1989, 1999, 2010, and 2022 were used. The MNDWI water index algorithm was applied to classify the images into land and water categories. To detect changes along the bank line, classified images were overlaid, and on-screen digitization of the bank line was undertaken to create bank line layers. Noticeable river shifting areas were identified by cross-sections while comparing the base year with the next immediate studied year (i.e., 1989 to 1999, 1989 to 2010, and 1989 to 2022). To estimate the most significant river shifting areas, all cross-section-based layers were superimposed, and common cross-section points were selected. Among them, two vulnerable sites were identified between 2010 and 2022. The image classification resulted in kappa indices of 0.83, 0.85, 0.87, and 0.96, with overall accuracies of 93%, 94%, 95%, and 96% for the images of 1989, 1999, 2010, and 2022, respectively.

2.2. Sampling and data collection

The identified river bank lines for the left (south) banks of the river were digitized from Google Earth. A 2 km bank line in Bojra village and a 2 km bank line along the riverbank in Thetrai and Daldalia villages were delineated. These bank lines were transferred in KML format and overlaid on ArcGIS software. The extracted bank lines were then converted into buffer zones extending 300 m and 500 m landward. Subsequently, the entire buffer zone was transferred via the 'layer to KML' function onto Google Earth images. The buffer zones were clipped using Google Earth images, and georeferencing was performed using ArcGIS software. Finally, the buffer zone was divided into 15×15 metre grids to calculate the total number of households in the study villages. It is important to note that each 15×15 metre grid was considered one household. Following a simple random sampling procedure, 426 households were selected out of 955 households (Table 1) from the villages at a 95% confidence level, ensuring proportional representation of both villages (Yamane, 1967).

Table 1. Study area and population size

District	Upazilla	Union	Total Household	Sample Household
Kurigram	Ulipur	Bojra	500	219
Kurigram	Ulipur	Thetrai and Daldalia	455	207
	Total		955	426

A structured questionnaire, consisting of both close-ended and open-ended questions, was used to collect data through face-to-face interviews in March 2023. Additionally, during field visits, a printed Google Earth image of the study area was utilized to visually identify the exact location, latitude, longitude, and type of the location under investigation. The questionnaire was divided into two parts: one for the respondents (close-ended questions) and another for the institutions (open-ended questions). In the first portion of the survey, respondents were asked about riverbank erosion mitigation at different levels. In the second part, we aimed to determine whether institutions such as the Bangladesh Water Development Board (BWDB), public representatives (MP, chairman, and members), and NGOs could effectively address river erosion problems through proper mitigation measures. Initially, both male and female household respondents were planned to be interviewed. However, after completing a few questionnaires, it was observed that male respondents were more knowledgeable about different types of mitigation measures, as they actively practiced these approaches. It is also noted that the respondents were divided into two clusters: Cluster 1 included those living within 0 to 300 meters, while Cluster 2 consisted of those residing between 300 and 500 meters.

2.3. Data analysis

To measure river bank line shifting in the study area, four Landsat images from 1989, 1999, 2010, and 2022 were used. The Modified Normalized Difference Water Index (MNDWI) was applied to delineate the bank lines for different years (as mentioned earlier). After extracting the bank lines from satellite images, they were analyzed to measure temporal bank line shifts, erosion, and accretion. The *Clip* and *Erase* functions of ArcGIS were used for these analyses. The major shifting areas were identified using cross-sections (Fig. 3). A measuring tape was then used to determine the maximum shifted area. On the other hand, to assess river erosion mitigation efforts at both individual and institutional levels, a mixed-method approach was used. This approach combined both qualitative and quantitative research. Quantitative research was conducted using a close-ended questionnaire to collect data from respondents. Meanwhile, open-ended questionnaires were analyzed through a qualitative approach to gather insights from various institutions. Data collected through the structured questionnaire were coded and analyzed using the Statistical Package for the Social Sciences (SPSS, version 25). During this process, all data were checked, verified, and edited to minimize errors. Descriptive and inferential statistical methods were used for data analysis. To examine the association and dependency between different variables, significance tests (e.g., Chi-square [χ^2], R^2), percentages, cross-tabulations, and other quantitative and qualitative techniques were applied. To analyze participants' opinions on various issues, descriptive statistics such as percentage and frequency were used to present the results.

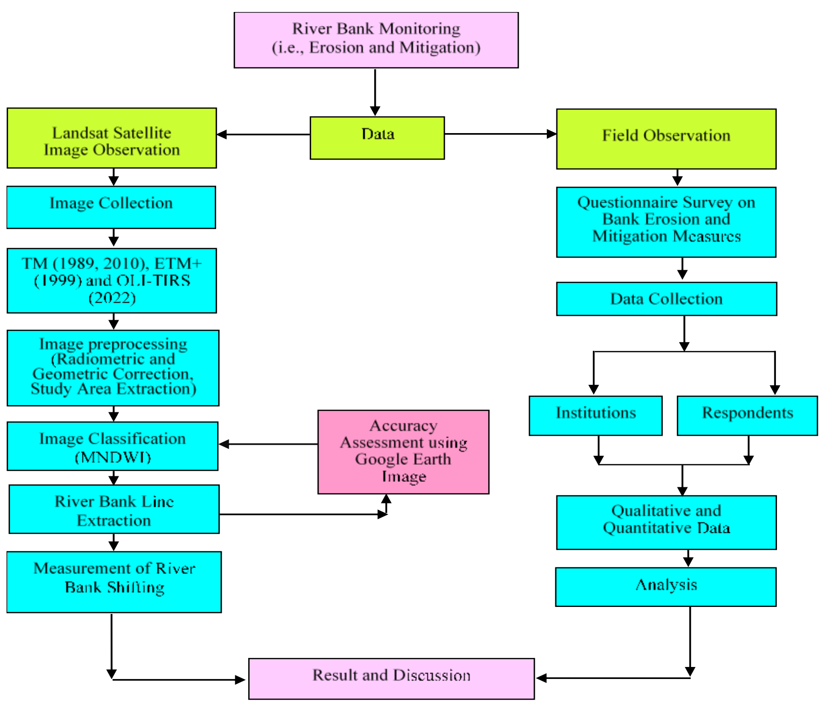

Fig. 2 Overall Methodology

Additionally, Geographic Information System (GIS)-based mapping techniques were used to delineate the service area. A methodological flowchart of the entire study has been illustrated in Fig. 2.

3. Results

The outcomes of the study are presented into two segments: the first segment focuses on riverbank erosion of the study area, while the second segment addresses measures to mitigate the impacts of natural disasters, including riverbank erosion, at the household, community, regional and national levels.

3.1. Riverbank Erosion of the Study Area

Riverbank erosion is a frequent natural hazard in Bangladesh, particularly in the floodplain regions. The Teesta River is one of the most erosion-prone rivers in Bangladesh, located in the northern part of the country. The most vulnerable zone of the Teesta River lies in Kurigram District. Ulipur Upazila (Kurigram) is part of the Teesta floodplain and is a newly formed floodplain in terms of topography. The soil in this region is fine, soft, and pliable. Moreover, the rise of the riverbed due to sedimentation reduces the river's water-holding capacity, leading to frequent flooding. As a result, erosion in this area is significant (Fig. 3).

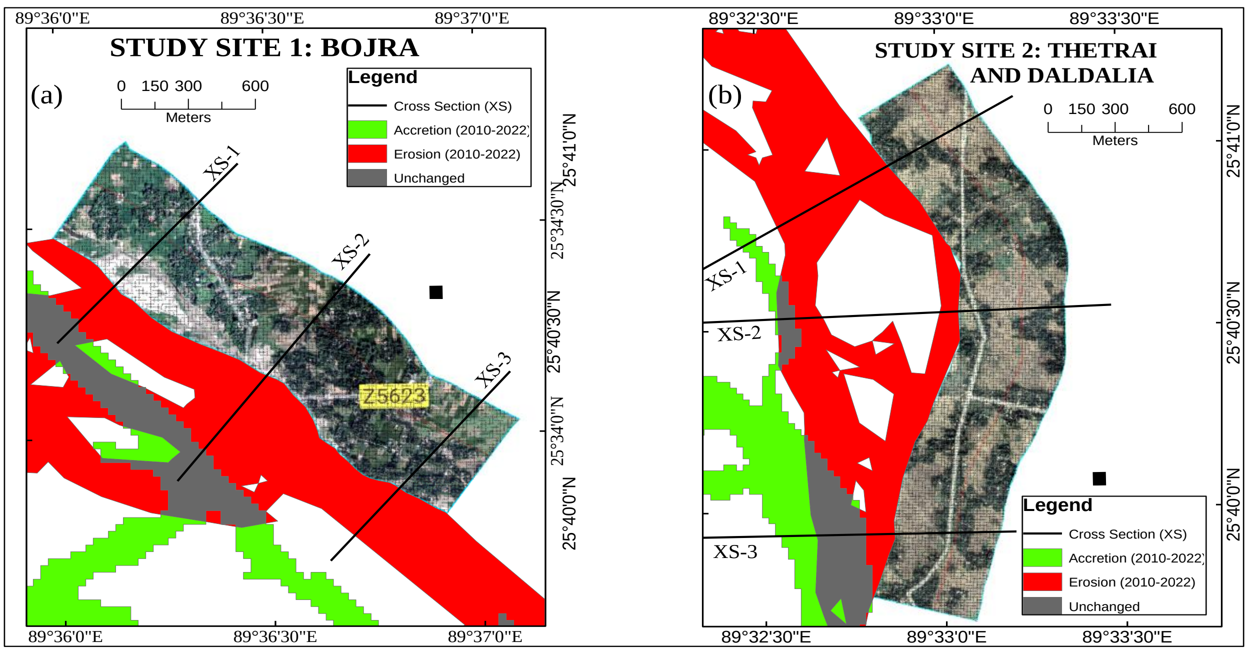

Fig. 3 Erosion of the study area. (a) and (b) represent the bank line shifting along the cross section between 2010 and 2022.

The spatial pattern of erosion was quantified at the sites of Bojra, Thetrai, and Daldalia over the period from 2010 to 2022 (Table 2). During this time, Bojra, Thetrai, and Daldalia experienced 86.63 ha and 81.91 ha of erosion, respectively. The erosion pattern also indicated that both sites experienced significant annual erosion, highlighting the instability of the left bank (Fig. 3). On the other hand, the change analysis revealed that the banks in the study areas gained 21.73 ha and 108.60 ha over the entire study period (2010–2022).

Table 2. Erosion and accretion

Study site (LB)	Erosion (2010-2022) in hectare	Accretion (2010-2022) in hectare
Bojra	86.63 (7.22 ha y^{-1})	21.73 (1.81 ha y^{-1})
Thetrai and Daldalia	81.91 (6.83 ha y^{-1})	108.60 (9.05 ha y^{-1})

3.2. Bankline shifting in study area

Table 3 represents the bank line shifting towards the floodplain over the last 12 years (2010 to 2022) at both study sites. From this table, it can be observed that the highest shifting occurred along the left riverbank at XS-2 in both study sites, with 418 m in study site 1 (Bojra) and 758 m in study site 2 (Thetrai and Daldalia). Between these two sites, it is evident that site 2 has been significantly affected by riverbank erosion at XS-1 and XS-2. Along these cross-sections, the bank line has shifted more than 600 m towards the floodplain in the last 12 years. Similarly, at site 1, the bank line has shifted more than 400 m at XS-2 and more than 200 m at XS-1 and XS-3. Overall, it can be concluded that both study sites have experienced significant bank line shifting due to extensive riverbank erosion.

Table 3. Eroded Area of study locations

Study Site 1 (Bojra)		**Study Site 2 (Thetrai and Daldalia)**	
Cross Section	**Riverbank shifting (Meter)**	**Cross Section**	**Riverbank shifting (Meter)**
XS-1	217	XS-1	616
XS-2	418	XS-2	758
XS-3	270	XS-3	124

3.3. Reasons of riverbank erosion of the study areas

Excessive monsoon rainfall may be the primary cause of increased riverbank erosion, as it generates strong waves and river currents, leading to the loss of land and homestead areas. According to Table 4, 61.75% of respondents stated that riverbanks erode every year due to strong currents caused by floods. Additionally, 23.75% of respondents believe that the formation of sandbars *(char)* in the middle of the river is one of the reasons for riverbank erosion. Climate change has contributed to the rapid siltation of the river in recent years, which has intensified bank erosion during the monsoon season (Islam *et al.*, 2019). Furthermore, different soil types, particularly sandy soil, also contribute to erosion (Table 2). As a result, bank erosion creates a vulnerable situation almost every year, affecting the study villages. Increased sedimentation and erosion rates, irregular rainfall patterns, channel shifting, and the lack of proper management are additional causes of riverbank erosion.

Table 4. Main reasons of riverbank erosion

Reasons of riverbank erosion	**Study Site 1 (Bojra)**		**Study Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
Strong current	137	62.6	126	60.9
Creation of bar	49	22.4	52	25.1
Soil type	30	13.7	26	12.6
Lack of proper management	2	.9	2	1.0
Others	1	.5	1	.5
Total	219	100	207	100

Source: Field Survey, 2023

Table 5(A). Mitigation measures taken by individual level

Site 1 (Bojra)			**Site 2 (Thetrai and Daldalia)**		
Mitigation measure (0-300 metre)	(f)	(%)	**Mitigation measure (0-300 metre)**	(f)	(%)
No	44	33.1	No	84	68.9
Yes	89	66.9	Yes	38	31.1
Total	133	100.0	Total	122	100
Pearson chi-square=32.566, df=1 P=.000					

Measures they have taken (0-300 metre)	**Site 1 (Bojra)**		**Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
No measure	44	33.1	84	68.9
Geo-bag/sandbag	13	9.8	12	9.8
Transfer of house wall and shed	10	7.5	8	6.5
Bamboo piling/*Bandal*	66	49.6	18	14.7
Total	133	100	122	100

Table 5(B). Mitigation measure taken by individual level

Site 1 (Bojra)			Site 2 (Thetrai and Daldalia)		
Mitigation measure (300-500 metre)	(f)	(%)	**Mitigation measure (300-500 metre)**	(f)	(%)
No	80	93.0	No	23	27.1
Yes	06	7.0	Yes	62	72.9
Total	86	100	Total	85	100
Pearson chi-square=77.652, df=1 P=.000					

Measures they have taken (300-500 metre)	**Site 1 (Bojra)**		**Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
No measure	80	93.0	23	27.1
Geo-bag/sandbag	0	0.0	20	23.5
Transfer of house wall and shed	2	2.3	5	5.8
Bamboo piling/*Bandal*	4	4.6	37	43.5
Total	86	100	85	100

Source: Field survey, 2023

3.4. Mitigation measure to combat riverbank erosion at individual level

As mentioned earlier, the severity of erosion in the study area is very high, making the mitigation of riverbank erosion a critical issue. Since, erosion occurs over large areas, it is not possible to mitigate it effectively at the individual level. However, traditional mitigation methods, such as bamboo piling *(Bandal)*, can be implemented at the individual level as temporary solutions. As shown in Table 5(A), people living between 0 and 300 meters from the riverbank have taken some measures to prevent erosion. Among the 255 respondents in this range, most have adopted traditional methods to mitigate river erosion. Specifically, 49.6% and 14.7% of respondents have constructed bamboo piling *(Bandal)* as a mitigation measure. Additionally, a portion of respondents have used geo-bags/sandbags or relocated house walls and corrugated iron sheets to reduce the impact of erosion. In contrast, respondents living between 300 and 500 meters from the riverbank (Table 5B) are less likely to participate in erosion mitigation activities. From the above discussion, it can be concluded that people living closer to the riverbanks are more vulnerable than those residing farther away (Field Observation). The Chi-square test findings confirm a significant association between the study villages and mitigation measures at the individual level.

Table 6. Relationship between protection measure at individual level and respondent's gender, age, education, income, occupation and distance.

Mitigation measure at individual level (Site 1)							Mitigation measure at individual level (Site 2)						
Gender	No		Yes		Total		**Gender**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
Male	87	54.4	73	45.6	160	100	Male	94	53.1	83	46.9	177	100
Female	37	62.7	22	37.3	59	100	Female	13	43.3	17	56.7	30	100
Total	124	56.6	95	43.4	219	100	Total	107	51.7	100	48.3	207	100
Pearson chi-square=1.220 df=1 p=.269							Pearson chi-square=.981 df=1 p=.322						
Age	No		Yes		Total		**Age**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
20-35	41	56.2	32	43.8	73	100	20-35	27	54.0	23	46.0	50	100
36-50	52	54.2	44	45.8	96	100	36-50	40	47.1	45	52.9	45	100
51-65	27	65.9	14	34.1	41	100	51-65	32	55.2	26	44.8	85	100
66-80	4	44.4	5	55.6	9	100	66-80	8	57.1	6	42.9	58	100
Total	124	56.6	95	43.4	219	100	Total	107	51.7	100	48.3	14	100
Pearson chi-square=2.208 df=3 p=.530							Pearson chi-square=1.285 df=3 p=.733						
Education	No		Yes		Total		**Education**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
Illiterate	55	61.1	35	38.9	90	100	Illiterate	47	56.0	37	44.0	84	100
Primary	33	64.7	18	35.3	51	100	Primary	30	50.0	30	50.0	60	100
Secondary	23	53.5	20	46.5	43	100	Secondary	19	51.4	18	48.6	37	100
Higher secondary	10	50.0	10	50.0	20	100	Higher secondary	7	58.3	5	41.7	12	100
Honours	3	20.0	12	80.0	15	100	Honours	4	28.6	10	71.4	14	100
Total	124	56.6	95	43.4	219	100	Total	107	51.7	100	48.3	207	100
Pearson chi-square=10.185 df=4 p=.029							Pearson chi-square=3.890 df=4 p=.421						
Monthly income	No		Yes		Total		**Monthly income**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)

Below 5000 taka	32	62.7	19	37.3	51	100	Below 5000 taka	50	51.7	31	38.3	81	100
5000 to10000	63	57.3	47	42.7	110	100	5000 to10000	37	52.1	34	47.9	71	100
10000 to 15000	24	61.5	15	38.5	39	100	10000 to 15000	11	36.7	19	63.3	30	100
15000 to 20000	3	33.3	6	66.7	9	100	15000 to 20000	5	31.2	11	68.8	16	100
Upto 20000	2	20.0	8	80.0	10	100	Upto 20000	4	44.4	5	55.6	9	100
Total	124	56.6	95	43.4	219	100	Total	107	51.7	100	48.3	207	100
Pearson chi-square=8.629 df=4 p=.071							Pearson chi-square=8.851 df=4 p=.065						
Occupation	No		Yes		Total		**Occupation**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
Agriculture	50	56.8	38	43.2	88	100	Agriculture	49	62.0	30	48.0	79	100
Business	12	44.4	15	55.6	27	100	Business	21	63.6	12	36.4	33	100
Service	2	13.3	13	86.7	15	100	Service	7	36.8	12	63.2	19	100
Day labour	11	73.3	4	26.7	15	100	Day labour	6	21.4	22	78.6	28	100
Housewife	33	61.1	21	38.9	54	100	Housewife	12	41.4	17	58.6	29	100
Others	16	80.0	4	20.0	20	100	Others	12	63.2	7	36.8	19	100
Total	124	56.6	95	43.4	219	100	Total	107	51.7	100	48.3	207	100
Pearson chi-square=19.675 df=5 p=.001							Pearson chi-square=19.446 df=5 p=.002						
Distance from the river	No		Yes		Total		**Distance from the river**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
0 to 100 metre	38	39.6	58	60.4	96	100	0 to 100 metre	58	65.9	30	34.1	88	100
100 to 200 metre	1	4.0	24	96.0	25	100	100 to 200 metre	18	72.0	7	28.0	25	100
200 to 300 metre	5	41.7	7	58.3	12	100	200 to 300 metre	8	88.9	1	11.1	9	100
300 to 400 metre	49	92.5	4	7.5	53	100	300 to 400 metre	13	33.3	26	66.7	39	100
400 to 500 metre	31	93.9	2	6.1	33	100	400 to 500 metre	10	21.7	36	78.3	46	100
Total	124	56.6	95	43.4	219	100	Total	107	51.7	100	48.3	207	100
Pearson chi-square=87.038 df=4 p=.000							Pearson chi-square=38.029 df=4 p=.000						
R=.217 R²=.047 AdjustedR²=.030 p=.012													

Source: Field survey, 2023

3.5. Association between mitigation measures and respondent's demographic variables (Individual)

Table 4 presents the relationship between protection measures at the individual level and several independent variables, including respondents' gender, age, education, income, occupation, and house distance from the riverbank. Among these variables, respondents' education level, occupation, and house distance showed a significant relationship with riverbank erosion mitigation measures at the individual level. This implies that educated individuals and those whose houses are vulnerable to bank erosion are more concerned about taking erosion control measures, which may contribute to resilience in their livelihoods (Mamun *et al.*, 2022). In contrast, other variables, such as gender, age, and monthly income, showed an insignificant relationship (Table 6). However, from the overall analysis, it can be concluded that despite the significant relationship between bank erosion protection measures and individual-level responsibilities, effective mitigation of river erosion remains uncertain. Based on the regression model ($R = .217$, $R^2 = .047$, Adjusted $R^2 = .030$, $p = .012$), this study finds that gender, age, education level, income, occupation, and house distance from the riverbank are all significant factors influencing mitigation measures at the individual level.

Table 7(A). Mitigation measures taken by community level

	Site 1 (Bojra)		**Site 2 (Thetrai and Daldalia)**	
Mitigation measure (0-300 metre)	(f)	(%)	(f)	(%)
No	29	21.8	42	34.4
Yes	104	78.2	80	65.6
Total	133	100	122	100
Pearson chi-square=5.046, df=1 P=.025				
Measures they have taken (0-300 metre)	**Site 1 (Bojra)**		**Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
No measure	29	21.8	42	34.4
Geo-bag/sandbag	17	12.7	31	25.4
Transfer of house wall and shed	1	0.7	1	0.8
Bamboo piling/*Bandal*	78	58.6	41	33.6
Working as a group	6	4.5	6	4.9
Others	1	0.7	1	0.8
Total	133	100	122	100

Table 7(B). Mitigation measures taken by community level

	Site 1 (Bojra)		Site 2 (Thetrai and Daldalia)	
Mitigation measure (300-500metre)	(f)	(%)	(f)	(%)
No	53	61.6	8	9.4
Yes	33	38.4	77	90.6
Total	86	100	85	100
Pearson chi-square=50.793, df=1 P=.000				
Measures they have taken (0-300 metre)	**Site 1 (Bojra)**		**Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
No measure	53	61.6	8	9.4
Geo-bag/sandbag	14	16.2	19	22.3
Bamboo piling/*Bandal*	15	17.4	58	70.7
Working as a group	2	2.3	0	0.0
Total	86	100	85	100

Source: Field survey, 2023

3.6. Mitigation measures to combat riverbank erosion at community level

The study reveals that out of 255 respondents (from both sites) living between 0 and 300 meters from the riverbank, approximately 71.9% reported taking measures at the community level to prevent riverbank erosion (Table 7A). Among them, the majority have adopted bamboo piling *(Bandal)* as a mitigation method. According to local resident Sohel Miah (42), *"We often collect subscriptions or bamboo and construct bamboo piling/Bandal at the community level."* In contrast, fewer respondents living between 300 and 500 meters from the riverbank have taken steps to mitigate erosion, which is significantly lower than those living closer to the river (Table 7B). Overall, community participation in bank erosion mitigation requires all available resources to ensure sustainability. The Chi-square test findings reveal a significant association between study villages and mitigation measures at the community level.

3.7. Association between mitigation measures and respondent's demographic variables (Community)

This section (Table 8) examines the association between various variables gender, age, education, income, occupation, and distance and community-level mitigation measures for river erosion. The variable income shows a significant relationship ($p = .003$ and $p = .014$) with mitigation approaches, indicating that individuals with sufficient financial resources are more likely to take steps to mitigate erosion. The respondents' occupation is another important factor influencing the adoption of mitigation measures. A significant relationship exists between occupation and riverbank erosion mitigation, as occupation enhances people's capacity for work and ensures a secure livelihood, enabling them to take action to prevent erosion. Distance demonstrates a highly significant association with the dependent variable ($p = .000$), meaning that people living along the riverbank are more likely to implement mitigation measures to protect their homes and agricultural land. In the study area (site 1), education has a strong association with riverbank erosion mitigation measures ($p = .047$). Educated individuals are more aware of different mitigation strategies; however, most respondents in the study village (Bojra) were illiterate. Among the independent variables, gender and age do not show a significant relationship with community-level mitigation measures (Table 8). Based on the regression model ($R = .201$, $R^2 = .041$, Adjusted $R^2 = .023$, $p = .030$), this study finds that gender, age, education level, income, occupation, and house distance from the river are all significant factors influencing mitigation measures at the community level.

Table 8. Relationship between protection measure at community level and respondent's gender, age, education, income, occupation and distance.

Protection measure at community level (Site 1)							Protection measure at community level (Site 2)						
Gender	No		Yes		Total		**Gender**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
Male	57	35.6	103	64.4	160	100	Male	46	26.0	131	74.0	177	100
Female	25	42.4	34	57.6	59	100	Female	4	13.3	26	86.7	30	100
Total	82	37.4	137	62.6	219	100	Total	50	24.2	157	75.8	207	100
Pearson chi-square=.838 df=1 p=.360							Pearson chi-square=2.243 df=1 p=.134						

Age	No		Yes		Total		**Age**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
20-35	29	39.7	44	60.3	73	100	20-35	10	20.0	40	80.0	50	100
36-50	38	39.6	58	60.4	96	100	36-50	16	18.8	69	81.2	85	100
51-65	13	31.7	28	68.3	41	100	51-65	20	34.5	38	65.5	58	100
66-80	2	22.2	7	77.8	9	100	66-80	4	28.6	10	71.4	14	100
Total	82	37.4	137	62.6	219	100	Total	50	24.2	157	75.8	207	100
Pearson chi-square=1.816 df=3 p=.611							Pearson chi-square=5.316 df=3 p=.150						
Education	No		Yes		Total		**Education**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
Illiterate	35	38.9	55	61.1	90	100	Illiterate	23	27.4	61	72.6	84	100
Primary	23	45.1	28	54.9	51	100	Primary	14	23.3	46	76.7	60	100
Secondary	17	39.5	26	60.5	43	100	Secondary	9	24.3	28	75.7	37	100
Higher secondary	6	30.0	14	70.0	20	100	Higher secondary	3	25.0	9	75.0	12	100
Honours	1	6.7	14	93.3	15	100	Honours	1	7.1	13	92.9	14	100
Total	82	37.4	137	62.6	219	100	Total	50	24.2	157	75.8	207	100
Likelihood ratio=9.647 df=4 p=.047							Pearson chi-square=2.716 df=4 p=.606						
Monthly income	No		Yes		Total		**Monthly income**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
Below 5000 taka	22	43.1	29	56.9	51	100	Below 5000 taka	30	37.0	51	63.0	81	100
5000 to10000	48	43.6	62	56.4	110	100	5000 to10000	10	14.1	61	85.9	71	100
10000 to 15000	11	28.2	28	71.8	39	100	10000 to 15000	5	16.7	5	83.3	30	100
15000 to 20000	0	0.0	9	100.0	9	100	15000 to 20000	3	18.8	13	81.2	16	100
Upto 20000	1	10.0	9	90.0	10	100	Upto 20000	2	22.2	7	77.8	9	100
Total	82	37.4	137	62.6	219	100	Total	50	24.2	157	75.8	207	100
Likelihood ratio=16.291 df=4 p=.003							Pearson chi-square=12.459 df=4 p=.014						
Occupation	No		Yes		Total		**Occupation**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
Agriculture	29	33.0	59	67.0	88	100	Agriculture	27	34.2	52	65.8	79	100
Business	10	37.0	17	63.0	27	100	Business	4	12.1	29	87.9	33	100
Service	1	6.7	14	93.3	15	100	Service	5	26.3	14	73.7	19	100
Day labour	9	60.0	6	40.0	15	100	Day labour	5	17.9	23	82.1	28	100
Housewife	23	42.6	31	57.4	54	100	Housewife	3	10.3	26	89.7	29	100
Others	10	50.0	10	50.0	20	100	Others	6	31.6	13	68.4	19	100
Total	82	37.4	137	62.6	219	100	Total	50	24.2	157	75.8	207	100
Likelihood ratio=13.549 df=5 p=.019							Pearson chi-square=11.185 df=5 p=.048						
Distance from the river	No		Yes		Total		**Distance from the river**	No		Yes		Total	
	(f)	(%)	(f)	(%)	(f)	(%)		(f)	(%)	(f)	(%)	(f)	(%)
0 to 100 metre	24	25.0	72	75.0	96	100	0 to 100 metre	33	37.5	55	62.5	88	100
100 to 200 metre	3	12.0	22	88.0	25	100	100 to 200 metre	4	16.0	21	84.0	25	100
200 to 300 metre	2	16.7	10	83.3	12	100	200 to 300 metre	5	55.6	4	44.4	9	100
300 to 400 metre	30	56.6	23	43.4	53	100	300 to 400 metre	4	10.3	35	89.7	39	100
400 to 500 metre	23	69.7	10	30.3	33	100	400 to 500 metre	4	8.7	42	91.3	46	100
Total	82	37.4	137	62.6	219	100	Total	50	24.2	157	75.8	207	100
Likelihood ratio=39.477 df=4 p=.000							Pearson chi-square=24.419 df=4 p=.000						
$R=.201$ $R^2=.041$ Adjusted $R^2=.023$ $p=.030$													

Source: Field survey, 2023

Table 9. Riverbank erosion mitigation measures

The role of NGOs in mitigating riverbank erosion	Site 1 (Bojra)		Site 2 (Thetrai and Daldalia)	
	(f)	(%)	(f)	(%)
No	217	99.1	196	94.7
Yes	2	.9	11	5.3
Total	219	100	207	100
Pearson chi-square=6.966, df=1 P=.008				
Measures taken by NGOs	**Site 1 (Bojra)**		**Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
Cross *badh*	101	46.1	78	37.7
Bamboo piling/*Bandal*	32	14.6	31	15.0
Block dumping	24	11.0	17	8.2
Geo-bag/sandbag	36	16.4	65	31.4
Tree plantation	19	8.7	14	6.8
Others	7	3.2	2	1.0
Total	219	100	207	100

Source: Field survey, 2023

3.8. Role of NGOs in riverbank erosion Mitigation (Respondent's view)

Most NGOs perceive that infrastructural or engineered erosion control measures to prevent and mitigate riverbank erosion are the responsibility of the government due to the necessity of financial and technological input (Luna, 2001). Table 9 indicates that according to 96.9% of respondents in the study villages NGOs have no role in mitigating riverbank erosion. However, a few respondents stated that NGOs participated, but their involvement was limited to distributing relief and rehabilitating displaced individuals in certain areas after bank erosion. The data also reveal that about 41.9% of respondents believe that NGOs can provide cross dams to mitigate erosion. Different proportions of respondents (Table 9) mentioned that NGOs could implement traditional measures such as constructing bamboo piling/*Bandal*, dumping geo-bags and blocks, and undertaking tree plantation programs in coordination with locals to mitigate river erosion. Since infrastructural approaches are very expensive, NGOs can coordinate with the government to build permanent structures such as dams and block settings. Above all, the people of Bojra, Thetrai, and Daldalia mentioned that NGOs could take emergency preparedness measures to prevent riverbank erosion by forming groups with villagers during such events. The Chi-square test results also indicate that the mitigation measures taken by NGOs are statistically significant in both study locations.

3.8.1 Role of NGOs in riverbank erosion Mitigation (NGOs opinion)

BRAC, ASHA, TMSS, RDRS, Mahidev, and other NGOs continue their programs in the study area (Bojra, Thetrai, and Daldalia). During the post-erosion period, they carry out various activities, including lending money, providing food, and offering other services. NGOs are also active in emergency evacuation and assisting people in reaching shelters. However, when it comes to bank erosion mitigation, NGOs do not play a significant role. They do not participate in any permanent or temporary programs to mitigate erosion. However, if an adequate budget is allocated to this sector, they are willing to adopt traditional mitigation methods such as tree plantation, bamboo piling/*Bandal*, and the use of geo-bags or sandbags. Some NGOs have emphasized awareness-building and training programs to help people protect themselves temporarily from erosion. Moreover, they have also expressed interest in informing their higher authorities about the need for riverbank erosion mitigation.

Table 10. Types of mitigation measures

Measures taken by public representatives	Site 1 (Bojra)		Site 2 (Thetrai and Daldalia)	
	(f)	(%)	(f)	(%)
No	157	71.7	129	62.3
Yes	62	28.3	78	37.7
Total	219	100	207	100
Pearson chi-square=4.235, df=1 P=.040				
Measures they have taken (300-500 metre)	**Site 1 (Bojra)**		**Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
No measure	157	71.7	129	62.3
Geo-bag/sandbag	47	21.4	69	33.3
cross/*I-badh*	4	1.8	1	0.5
Inform higher authorities	9	4.1	8	3.8
Bamboo piling	2	0.9	0	0.0
Total	219	100	207	100

Source: Field survey, 2023

3.9. The role of public representatives to combat riverbank erosion (Respondent's view)

The role of public representatives is crucial in the development of any area. About one third (32.8%) of the respondents mentioned that public representatives have adopted measures to mitigate riverbank erosion. Table 10 shows that one of the measures taken by public representatives is the dumping of sandbags or geo-bags; however, this effort is insufficient compared to the actual requirement. For example, according to local people, only 20 geo-bags are dumped every 150 meters, which is inadequate for mitigating riverbank erosion. The Chi-square test also reveals that the mitigation measures taken by public representatives are statistically significant at a 95% confidence level across all study areas.

3.9.1 The role of public representatives to combat riverbank erosion (Upazilla/Union chairman and members opinion)

The local government (chairman and members) has taken various measures to temporarily mitigate riverbank erosion. Among the measures adopted by the local government, the most notable are dumping geo-bags/sandbags and bamboo piling/*Bandal*. These measures are generally implemented based on the overall vulnerability of the area. Additionally, the local government seeks public opinion to address imminent river erosion. The Upazila chairman also reported that he has practiced similar traditional measures, such as bamboo piling/*Bandal* and geo-bag/sandbag dumping. According to the Upazila chairman, these traditional measures have helped protect bankside schools, madrasas, business establishments, and even large areas of Thetrai and Daldalia unions.

Table 11. Types of mitigation measures

Measures taken by government officials	**Site 1 (Bojra)**		**Site 2 (Thetrai and Daldalia)**	
	(f)	(%)	(f)	(%)
No	40	18.3	44	21.3
Yes	179	81.7	163	78.7
Total	219	100.0	207	100.0
Pearson chi-square=244.727, df=1 P=.000				
Types of measures	(f)	(%)	(f)	(%)
Traditional	95	53.1	150	92.0
Structural	19	10.6	2	1.2
Both	65	36.3	11	6.7
Total	179	100.0	163	100.0
Traditional	(f)	(%)	(f)	(%)
Geo-bag/sandbag dumping	139	86.9	145	90.1
Bamboo piling/*Bandal*	20	12.5	16	9.9
Tree plantation	1	.6	0	0.0
Total	160	100.0	161	100.0
Structural	(f)	(%)	(f)	(%)
Block setting	58	69.0	12	92.3
Permanent dam	1	1.2	0	0
Spur	1	1.2	0	0
Cross/*I badh*	24	28.6	1	7.7
Total	84	100.0	13	100.0

Source: Field survey, 2023

3.10. The role of GOs to combat riverbank erosion (Respondent's view)

The disaster management concept of the Government of Bangladesh is to reduce the risk faced by the people, especially the poor and the marginalized (Salehin *et al.*, 2020). There is no alternative to government action for a permanent solution to a major problem like riverbank erosion. In the surveyed areas (Bojra, Thetrai, and Daldalia), about 80.2% of respondents (Table 11) agreed that the government has implemented both traditional and infrastructural approaches to mitigate riverbank erosion. Various traditional measures, such as bamboo piling/*Bandal*, geo-bags/sandbags, and tree plantation, have been applied (Table 11). On the other hand, respondents mentioned structural approaches like block setting and cross/*I-badh*. It is important to note that while traditional methods can provide temporary mitigation of riverbank erosion, infrastructural approaches must be adopted for a sustainable protective solution. In this situation, people affected by riverbank erosion believe that the government should take appropriate measures to address the issue effectively. The Chi-square test results also reveal that the mitigation measures taken by government organizations are statistically significant at a 95% confidence level across both study locations.

3.10.1 The role of GO institutions to combat riverbank erosion (BWDB opinion)

According to BWDB, the department has practiced infrastructural measures to prevent riverbank erosion in the study area. Among these, cross/*I-badh* and block setting are significant (Fig. 4). Cross/*I-badh* is a type of flood protection barriers. Undertaking such activities an area of about 1.50 km has been protected from riverbank erosion (West Bojra). Besides, every year Teesta basin experiences bank erosion during the monsoon season. The immediate action at this time is to identify the most erosive areas and mitigate the riverbank from erosion by dumping sandbags or geo-bags.

From the above discussions, it is found that though the various types of mitigation measures have adopted by different institutions in the study villages but most of them are not adequate and sustainable. Government documents and the NGO literature indicate that there is a wide recognition that effective disaster response at the local level is not possible by government agencies alone and that the cost of management needs to be shared by all stakeholder.

Fig. 4 Concrete block (Bojra) adopted by GO

4. Discussion

The findings indicate that the majority of households adopt various types of mitigation measures. The study identifies that respondents practice bamboo piling/*Bandal* to mitigate riverbank erosion at both the individual and community levels (Fig. 5a). This is because the material used in this traditional approach (bamboo) is very cheap, readily available, and well-known to the local people. Newport and Jawahar (2003) mentioned that an effective mitigation measure cannot be implemented without the participation of the vulnerable community and the public in general. Although households adopt this measure as an emergency preparedness strategy during the rainy season, they believe it would be more effective if implemented during the dry season. The analysis reveals that vulnerability is higher among households in nearby and scattered settlements due to sudden riverbank erosion and inadequate land. Mamun *et al.,* (2022) found that most households living along the riverbank have directly experienced erosion impacts on their socio-economic conditions and livelihoods. A significant difference is observed among the various factors influencing erosion control approaches that contribute to livelihood resilience. Education, income, occupation, and distance from the river all positively increase the likelihood of adopting erosion control measures at both the individual and community levels. Education is considered one of the most important factors in riverbank erosion mitigation, as it promotes both survival and an improved quality of life (Hutton and Haque, 2004). However, gender and age have no significant effect on erosion control approaches. Nevertheless, older homestead families tend to have more information due to their life experiences. This study provided useful recommendations to increase the mitigating capacity of riparian people.

Although temporary mitigation is possible at the individual and community levels, infrastructural approaches must be adopted for a sustainable protective measure. Engineering-based erosion control approaches are time-consuming and expensive, and local households are not involved in these measures (Mamun *et al.,* 2022). People expect direct support from the government to implement a sufficient number of geo-bags and structural mitigation measures in their areas, which can be carried out by local government institutions. This paper reveals that despite a lack of financial support, Government Organizations (GOs) and public representatives attempt to mitigate riverbank erosion through boulder placement, geo-bag dumping, and the construction of cross/*I-badh* (Fig. 5b). For example, the Bangladesh Water Development Board (BWDB) requests funding for river erosion mitigation before the monsoon season and hires contractors even before the budget is allocated. Currently, the Water Development Board oversees the planning and management of riverine hazards in Bangladesh, focusing primarily on engineering and structural responses (Haque and Mutton, 2004).

Further initiatives are needed to integrate the efforts of different organizations and to strengthen institutional mechanisms through decentralization and grassroot-level disaster mitigation planning. From a disaster-management

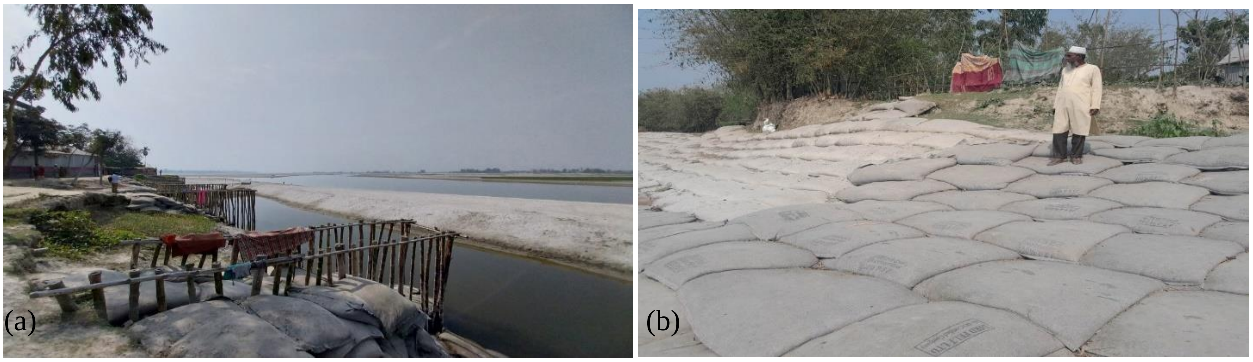

Fig. 5 Bamboo piling/*Bandal* (Daldalia) (a) and Geo-bag/Sandbag (Thetrai) (b).

perspective, it is essential to ensure that vulnerable populations are not excluded from planning and decision-making processes. Disaster management must be an inclusive and democratic process, aimed not only at mitigating and preventing natural hazards but also at promoting human development (Haque and Mutton, 2004). Incorporating respondents' opinions and involvement will be beneficial for decision-makers in formulating well-organized mitigation measures for sustainable transboundary river management.

5. Conclusion

In terms of discharge, Teesta is the fourth largest river in Bangladesh which falls into the Brahmaputra/Jamuna River. Numerous *chars*/bars can be seen in this river and the weak alluvial soil of the banks of the Teesta is a dominant factor for erosion after each successive flood. Besides various bank protection works, riverbank erosion remains a constant threat to the riparian inhabitants and the land-scarce country. This paper used geospatial techniques to measure channel characteristics in two study areas as well as collect data from respondents through questionnaire surveys to know about river erosion mitigation measures at different levels. The findings show that traditional erosion control measures such as bamboo piling/*Bandal* at individual and community levels and structural/engineered erosion control methods at public representative and GO levels have been adopted to mitigate riverbank erosion. The structural/engineered erosion control approach should be part of development planning, and it can be effective when they involve all stakeholders' government, local communities, NGOs, media, the private sector, academia, neighboring countries, and donor communities. However, this study provided useful recommendations for enhancing the mitigation capacity of riparian people. Government should take more effective measures to reduce the impact of river erosion. Apart from taking preventive and protective measures, there should also be some rehabilitation and livelihood-based measures, which will help vulnerable people to find their way back into the mainstream society. Proper rehabilitation and evacuation process should be developed for them on priority basis to deal with river erosion. This study helps to better understand the impact of river erosion on such residents, which will assist the government in formulating policies to improve the livelihood of the affected. Furthermore, such findings from this study will be helpful to examine the effectiveness of vulnerability mitigation measures for other natural disasters such as floods and droughts in other regions of Bangladesh.

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