Trend Analysis and Simulation of Human Vulnerability Based on Physical Factors of Riverbank Erosion Using RS and GIS

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Abstract

This study aims to analyze the pattern of bank erosion and simulate the physical aspects of vulnerability in the lower Meghna River, Bangladesh using remote sensing (RS) and geographic information systems (GIS). The physical factors of vulnerability were analyzed using GIS-based Structured Query Language (SQL). A questionnaire survey, GPS survey and field observation survey were conducted for collecting the primary data in the study area. The secondary data were mainly satellite image collected from the United States Geological Survey (USGS) website. Using time series Landsat images (MSS, TM and OLI-TIRS), this study analyzed 36 years of erosion and accretion process in the Mehendiganj Upazila region from 1980 to 2016. The result indicates that an enormous amount of land (4470.47 ha) was submerged by the river and average land loss rate was 124.18 ha/year. The study quantifies the number of vulnerable households beneath the present condition and how much it will be altered after a positive/negative change with the factors of vulnerability related to the households. Simulation data reveals that under the present physical condition, 43.88% of households were identified as severely vulnerable. The output of this study can be used in the classification of vulnerable households and for the improvement of the physical infrastructure development process near the erosion prone areas, also helps to mitigate environmental disaster in the developing countries.

Keywords Riverbank erosion · Vulnerability · Erosion · Accretion · Simulation · Riverine disaster

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1 Introduction

Bangladesh is the land of natural disasters. It is situated beside the world's largest rivers (the Brahmaputra, the Ganges, and the Meghna river) delta where erosion is a common phenomenon. Erosion is a very common morphological development in sedimentary plain rivers. Erosion of riverbank and shifting of river channel create many problems for Bangladesh in both socio-economic and environmental sectors (Klaassen et al. 2002). Riverbank erosion means the fragmentation or transferring away the sediments of the riverbank by itself which causes river channel bend (Fujita et al. 2000). In recent years, a number of researchers have investigated riverbank erosion and river channel shifting. (Phillip et al. 1989; Madej et al. 1994; Tangri 2000; Das and Saraf 2007; Das et al. 2007; Pati et al. 2008; Saleem et al. 2020). Water is the most common cause of soil erosion. Water is the main agent which causes the river basin degradation along with landforms and seashore changes. The massive rivers of Bangladesh viz., Jamuna, Padma, and Meghna have altered their

sequences suddenly causing riverbank erosion. Melting icecaps is generating huge amount of flowing water which leads to the increase in downward rivers flow.

The main three rivers (the Padma, the Meghna and the Jamuna) of Bangladesh have eroded around 1,59,000 ha of their floodplains since 1973. Around 1.6 million people of Bangladesh became homeless due to riverbank erosion. People who are living in the floodplains and char land have become helpless due to riverbank erosion (Aktar 2013a). The Meghna and Padma rivers both run from north to south, forming the Meghna estuary before entering the Bay of Bengal. In addition, the Meghna River is also morphologically a low-energy, multi-channel fluvial system, characterized by a system of linking channels and inter-channel region (Alam 1991). The maximum discharge of the Meghna river recorded 20,000 m³/s at the confluence point of the Padma–Meghna and 160,000 m³/s at the lower Meghna with the slope of 5 cm/km (Haskoning 1992). The magnitude of erosion and accretion within the Meghna estuary varies spatially. During the period 1973–2010, huge amount (98,079 ha) of land were eroded by the Lower Meghna river (CEGIS 2012). When riverbank erosion occurs, a large number of displaced individuals abandon their original homestead land and seek permanent or temporary refuge in the embankment or on neighboring land (Rahman 2010).

According to different studies perspective, vulnerability is the preliminary ground of disaster as well as the function of hazard susceptibility and coping capacity of the households to decrease risk at a particular point in time (Smit and Wandel 2006; Adger 2006; Emrich and Cutter 2011; Paul 2013; Akter and Mallick 2013; Blaikie et al. 2014; Hossain 2015; Bhuiyan et al. 2017; Hossain and Paul 2018). These studies focused on to determine the relationship between physical and socio-economic factors affecting a household and its vulnerability to peripheral force such as natural calamities. Respectively, vulnerability is described as an inner risk factor of a person or system exposed to a hazard that corresponds to the subject's or systems innate inclination to be impacted or vulnerable to damage (Paul 2013). Similarly, human vulnerability is the social, economic, and physical susceptibility or trend of a community to be damaged or altered by a natural or anthropogenic calamity. GIS is effective tools equipped with storing, organizing, analyzing, and presenting large spatial data (Salam et al. 2003; Taramelli et al. 2015). National and regional planning, emergency and disaster management, vulnerability simulation and reduction have all benefited from the use of GIS (Salam et al. 2003; Roche et al. 2013; Taramelli et al. 2015; Ali et al. 2019a). Simulation technique, on the other hand, is defined as the replication of the activity of a real-world sequence of operations across time (Sokolowski and Banks 2011; Srivastava 2015).

Riverbank erosion is a regular and widely destructible hazard in Bangladesh. Every year thousands of hectares of land get eroded by the mighty rivers of Bangladesh and make thousands of people homeless. Especially, the lower Meghna basin area is widely affected by riverbank erosion. There has been little scientific research work about simulation of human vulnerability based on physical factors of the riverbank erosion rather more concentration was given in deals with geomorphic phenomena and bank shifting. Most of the researchers focused on the overall erosion caused by a major river rather than to estimate the total erosion caused by different rivers (small/large) around a geographical area that are vulnerable to riverbank erosion (Madej et al. 1994; Thakur et al. 2011; Nath et al. 2013; Aktar 2013b; Bhuiyan et al. 2014; Saleem et al. 2020). On the other hand, this research work emphasized to assess total land loss of a geographical area (Mehendiganj Upazila) due to riverbank erosion. In case of riverbank erosion induced vulnerability assessment while other study mainly focused on the socio-economic factors (Haque and Hossain 1988; Bhuiyan et al. 2017; Debnath et al. 2016; Roy et al. 2017), this study focused on the physical factors and vulnerable household through GIS-based simulation.

Therefore, the primary goal of this research is to examine the trend of riverbank erosion and simulate the physical factors that contribute to human vulnerability using both primary and secondary data. Furthermore, this study tries to link up between the spatial patterns of riverbank erosion to human vulnerability.

2 Methodology

2.1 Location of the Study Area

Mehendiganj Upazila is positioned between the latitudes of 22.68° and 23.91° north, and the longitudes of 90.38° and 90.63° east (Fig. 1). The total area of Mehendiganj Upazila is about 418.98 sq km, and total population is 304,364 (BBS 2011). Mehendiganj is a confined geographical area surrounded by river in all the side. The Upazila is located on the lower Meghna floodplain, surrounded by different rivers such as Meghna, Arial Khan, Tetulia, Lata, Dharmaganj, Naya Bhangra, Chilmari, Azimpur, and Sultani (Banglapedia). Riverbank erosion is a severe and frequent phenomenon in Mehendiganj Upazila. Two erosion prone villages (Hasanpur and Asa) of Mehendiganj Upazila were selected for the study.

2.2 Data

The primary data were gathered through a questionnaire survey, GPS survey, direct field observation, and interviews

Fig. 1 Map of the study area

with the study's target group. The secondary data were collected from USGS. The collected imagery was pre-georeferenced and geometrically corrected Level-1 Landsat data. Other secondary data were collected from different government offices, e.g., Mehendiganj Upazila office, Upazila Agriculture office and Union Parishad office. To analyze 36 years of riverbank erosion, five Landsat satellite time series image (Table 1) were collected.

2.3 Simulation Process

For the simulation of human vulnerability based on physical factors of riverbank erosion GIS-based SQL and mapping systems were used (Hossain and Paul 2017). The simulation was based on collected data sets (both primary and secondary) under the different changing scenarios. Different

Table 1 Description of Landsat images

Acquired date	Satellite	Sensor	Path/Row	Spatial resolution	Cloud coverage
4/12/1980	Landsat 3	MSS	147/44	60	0
19/02/1988	Landsat 5	TM	137/44	30	0
25/12/1996	Landsat 5	TM	137/44	30	0
21/12/2006	Landsat 5	TM	137/44	30	0
16/12/2016	Landsat 8	OLI-TIRS	137/44	30	0

Source: USGS

categories of risk factors (physical factors) and degree of judgment for simulation were established by field inspection and key informants' information.

2.4 Sample Design and Procedure

Simple random sampling techniques were used to decide the sample of households from the study areas. Considering 5% significance level, the projected sample size is 278 (Hasanpur Village 115 and Asa Village 163) out of a total of 917 households. By adopting Yamane formula (1967), the sample size was calculated (Eq. 1):

$$n = \frac{N}{1 + Ne^2} \quad (1)$$

2.5 Satellite Image Processing

The radiometric correction and atmospheric correction have been performed on all the images. Equation (2) was used for the DN value to radiance value conversion, and Eq. (3) was used to convert radiance values (L_λ) into atmospheric reflectance. From the USGS website, the E_{sun} value for both Landsat 3 and Landsat 5 were gathered. Landsat 8 image was converted using Eq. (4) from the Landsat 8 handbook. In case of atmospheric correction, Dark Object Subtraction (DOS) was accomplished by ENVI 5.1 software using band minimum method:

$$L_\lambda = \frac{L_{\text{max}\lambda} - L_{\text{min}\lambda}}{Q_{\text{calmax}} - Q_{\text{calmin}}} \times (Q_{\text{calmax}} - Q_{\text{calmin}}) + L_{\text{min}\lambda} \quad (2)$$

$$\rho = \frac{\pi L_\lambda d^2}{E_{\text{sun}} \cos \theta_s} \quad (3)$$

$$L_\lambda = MLQ_{\text{cal}} + A_L \quad (4)$$

2.6 Image Classification and Area Measurement

Using a density slicing method, the satellite images were first classified into binary images water and non-water classes (Wang et al. 2002). To find out the extent of water bodies, one single band (infrared band) has been classified.

The infrared band presents an improved illustration in the water-related attributes than the visible bands (Jain et al. 2005). Erdas Imagine 2014 software was used for images classification. The classified image has been converted into vector format using ArcGIS raster to vector tool. The land area of erosion and accretion were identified using superimposition method. The land areas of different stages were calculated by geometry and field calculator tools of ArcGIS attribute table.

3 Results and Discussion

3.1 Riverbank Erosion Trend in Mehendiganj Upazila

Table 2 illustrates 36 years of erosion and accretion scenarios from 1980 to 2016. Erosion rate was highest from 1988 to 1996 with 536.66 ha/year, 4293.26 ha land was eroded subsequent 8 years period during 1988–1996. Erosion rate was also higher between 2006 and 2016 with 516.10 ha/year (Fig. 2; Table 2). Total 5160.98 ha of land was eroded in the last 10 years period. In these 36 years, average erosion rate was calculated as 453.88 ha/year with the total erosion of 16,339.74 ha land (Table 2). Figure 2 represents the visual representation of the total accretion and erosion scenario of Mehendiganj Upazila.

The average accretion rate in Mehendiganj Upazila was 329.7 ha/year in Mehendiganj Upazila between 1980 and 2016 (Table 2). The highest accretion rate was observed in 1996–2006 and was 414.08 ha/year (Table 2; Fig. 2). The land area increased by 4140.84 ha in that period. During 2006–2016, the accretion rate was 228.27 ha/year which extended the land area by 2282.75 ha (Table 2).

It is showed that the percentage of changes in land area due to erosion and deposition process and from 1980 to 1988 accretion rate was exalted than erosion rate, and the opposite phenomenon occurred within the year 1988–1996 where land area decreased by 2090.57 ha (Table 2). Among the four periods, the most devastating period was 2006–2016, where 2878.23 ha land was vanished in this period (Fig. 2).

Table 2 Erosion and deposition scenario of Mehendiganj Upazila from 1980 to 2016

Period	Total erosion (ha)	Erosion rate (ha/year)	Average erosion rate (ha/year)	Total accretion (ha)	Accretion rate (ha/year)	Average accretion rate (ha/year)	Land area change (ha)	% change
1980–1988	2978.14	372.27	453.88	3242.99	405.37	329.70	264.86	0.82
1988–1996	4293.26	536.66		2202.70	275.34		– 2090.57	– 6.40
1996–2006	3907.36	390.74		4140.84	414.08		233.48	0.76
2006–2016	5160.98	516.10		2282.75	228.27		– 2878.23	– 9.34
Total	16,339.74	N/A		11,869.28	N/A		– 4470.47	– 13.79

The bold text is used for better visual and emphasize the values

Fig. 2 Riverbank erosion and accretion of Mehendiganj Upazila

Throughout this study period (36 years), total land loss was estimated 4470.47 ha with a rate of 124.18 ha/year (Table 2).

3.2 Simulation of Factors of Human Vulnerability

The physical aspects of human vulnerability to riverbank erosion were simulated. The simulation was run in a variety of scenarios and with a variety of judgmental criteria. The factors' values were either satisfactorily (positively) or unfavorably (negatively). The study reveals the present scenario of vulnerability in the household level, contrariwise

conditional scenarios under the projected change of current conditions of vulnerability.

3.2.1 Simulation of Physical Factors

Two physical factors were taken consideration which may affect human vulnerability to riverbank erosion. Elevation of house from MSL and the remoteness of the river from the residence were two physical factors used in the simulation (Table 3). Progress and degradation of the current condition under favorable (positive) and unfavorable (negative)

Table 3 Physical factors of simulation process

Vulnerability factors	Degree of evaluation of present status	Modifications of simulation	
		Positive alteration	Negative alteration
1. Distance from river to the house (in meter)	Moderate near (less than 400 m)	100 m addition to the current distance	100 m reduction to current distance
2. Elevation of house (in feet from MSL)	Moderate (less than 30 feet)	5 ft addition to the current elevation	5 ft reduction to the current elevation

scenarios were taken into account for the simulation of collected data. The households in this study were given a standard altitude of 30 feet to investigate their current vulnerability status (Table 3). 5 feet elevation was, respectively, increased and decreased with present status to visualize the changes (positive and negative). House which was situated 400 m from the river was taken as standard. On the other hand, 100 m remoteness was, respectively, increased and lessened with current values of all household's distance (Table 3).

In the study period based on existing physical structure of households, 43.88% were identified as severely vulnerable households (Fig. 3). In contrast, for the changing of physical

environment, the quantity of most vulnerable households was changed. Sahana and Sajjad (2019) conducted a study in the Sundarbans nearly half of the villages are highly vulnerable and have limited capacity in the case of a natural disaster. The most vulnerable villages situated in the lower elevation, whereas higher elevation showed low vulnerability. Ali et al. (2019b) worked on a vulnerability mapping due to flood and estimate the vulnerable area using GIS-based AHP approaches. The findings revealed that distance from the river, differences in rainfall, and land use land cover all play a significant role in flooding, and that a GIS-based model can help identify vulnerable areas and assess potential risk areas. Table 4 indicates that when physical factors

Fig. 3 Most vulnerable households based on physical factors

Table 4 Result of the simulation of the physical factors

Assessment scenario	Hasanpur		Asa		Total	
	HH	%	HH	%	HH	%
Existing vulnerability	50	43.48	72	44.17	122	43.88
After positive change	84	73.04	118	72.39	202	72.66
After negative change	21	18.26	21	12.88	42	15.11

Source: result of simulation

changed in a positive way, the number of vulnerable households climbed up to 72.66% (Table 4; Fig. 4). In contrast, after a negative change in physical factors of human vulnerability, the number of vulnerable households declined by 15.11% (Table 4; Fig. 5).

3.2.2 Simulation Based on Previous Riverbank Erosion Impacts

Different factors of previous riverbank erosion impacts were simulated in the vulnerability template (Table 5). Selected characteristics was the number of HH experience riverbank erosion, amount of land loss, monthly income decrease by the household and overall damage caused by riverbank erosion. For the simulation of data, progress and degradation of present condition were taken into consideration, respectively, under the favorable (positive) and non-favorable (negative) situations. For the assessment of existing scenario of vulnerability, 1 time was considered as the standard for household-experienced riverbank erosion, 1 time reduction and 1 time addition with the present value to visualize the positive and negative change. In case of land loss,

100 decimals were taken as standard and 50 decimals are decreased and increased to find the positive and negative scenarios.

Similarly, to simulate the present condition, Tk. 2000 is considered as the standard amount of monthly income decreased by the household and 1000 reduction and addition to simulate both favorable and unfavorable shift, respectively. Finally, the existing value of damage of household factor was defined risk degree 2 (High) and 1 degree down and up for visualizing the positive and negative change scenario (Table 5).

In the current situation, 15.11% of households were recognized as severely vulnerable (Table 6; Fig. 6). Conversely, due to transform of the previous situation the numbers of most vulnerable households were changed. If the positive change or considered less severe previous impact, then the quantity of vulnerable households will be reduced by 3.95% of total households (Table 6; Fig. 7). Conversely, the numbers were increased by 18.71% after a negative change of previous impact of human vulnerability (Fig. 8). Hossain and Paul (2017) investigated cyclones and storm surges vulnerability based on socio-economic and physical factors

Fig. 4 Simulated vulnerable households based on positive alterations of physical factors

Fig. 5 Simulated vulnerable households based on negative alterations of physical factors

Table 5 Previous riverbank erosion impact factors simulation process

Vulnerability factors	Degree of evaluation of present status	Modifications of simulation	
		Positive alteration	Negative alteration
1. The times household-experienced riverbank erosion	1/more than 1	1 time reduction from present value	1 time addition from present value
2. Land loss of the household (decimal)	100 decimals (moderate)	50 decimal reductions from present value	50 addition reduction from present value
3. Income decrease of the household (TK per month)	High risky (more than 2000 TK)	1000 TK reduction from the present value	1000 TK addition with the present value
4. Damages of the household	High	Moderate	Very high

Table 6 Results of the simulation using the previous riverbank erosion impact

Assessment scenario	Hasanpur		Asa		Total	
	HH	%	HH	%	HH	%
Existing vulnerability	14	12.17	28	17.18	42	15.11
After positive change	4	3.48	7	4.29	11	3.95
After negative change	26	22.61	26	15.95	52	18.71

Source: result of simulation

Fig. 6 Most vulnerable households based on previous impact factors

using GIS. Their findings indicate that for human vulnerability assessment, socio-economic and physical elements play a crucial role in determining a household's level of vulnerability. Findings also suggest the extent of household's vulnerability is changed concerning physical and socio-economic condition.

3.2.3 Simulation of Coping Capacity Factors

From the literature and local inhabitant's perspective of the study area, several coping capacity factors were taken into consideration. The coping capacity factor includes landholdings, financial help source and savings of the household. For the simulation of data, progress and degradation of the present condition were taken into consideration, respectively under the favorable (positive) and non-favorable (negative) situations. To detect the current status of vulnerability 25 decimal was taken as standard land area owned by the households. To visualize the positive and negative change, 10 decimal lands was either increased or decreased with present status. In case of financial help

source, risk level 2 m was taken as standard (Table 7). Level 1 was lessened with present values of all household's condition in positive change, no option for negative change in this case. In case of savings of the household factor, the households have no savings considered as the standard value. The answer yes (have savings) was taken as positive change and in this case, there is no negative change scenario (Table 7).

Under the obtainable coping capacity situation of households, 32.37% were identified as severely vulnerable households (Table 8; Fig. 9). Alternatively, due to modification in coping capacity, the numbers of the most vulnerable households have changed. If coping capacity improves, the number of vulnerable household's falls by 5.04% of total households (Table 8; Fig. 10). Conversely, the number has been increased by 29.50% after a negative change of coping capacity factors of human vulnerability (Table 8; Fig. 11). It has been observed that modifying the coping capacity factors can vary the degree of vulnerability of a household under study.

Fig. 7 Simulated vulnerable households based on the positive alterations of previous impact factors

4 Conclusions

The study demonstrated the trend of riverbank erosion and simulates the people's vulnerability due to riverbank erosion. However, according to the findings of this study, riverbank erosion eroded approximately one-seventh of the land in Mehendiganj Upazila during the study period. The simulation's results show that physical elements play an important role in determining vulnerable households, and that the extent of a household's vulnerability varies depending on the physical aspects. Household's location and elevation, the remoteness of households was recognized as the main factors affecting the human vulnerability to the riverbank erosion scenario. Spatio-temporal

information about the trend of river erosion patterns with a combination of simulation helps to identify the most vulnerable households in the erosion prone area of any countries. The study provides useful tools for the future to build knowledge and data networks about vulnerable households, which can be used to enhance economic resilience and coping capacity of households near the riverside area. The output of this study will be helpful for government and related authorities to realize the promulgation of policy related to riverbank erosion and take proper actions for the displaced people due to riverine disaster. This research work also helps the decision makers to take the initiatives for the implementation of modern technologies to control riverbank erosion which will ultimately reduce environmental vulnerability.

Fig. 8 Simulated vulnerable households based on the negative alterations of previous impact factors

Table 7 Coping capacity factors of simulation process

Vulnerability factors	Degree of evaluation of present status	Modifications of simulation	
		Positive alteration	Negative alteration
1. Land owned by the household (decimal)	Less than 25 decimals	10 decimal additions with the present value	10 reduction addition with the present value
2. Financial help source	Risk level 2 (NGO/Village Mahajan)	Risk level 1 (relatives/neighbors)	*No option for negative change
3. Savings of the household	No (High risk)	Yes	*No option for negative change

*Emphasize that there is no option for negative change for that particular factor

Table 8 Results of the simulation of the coping capacity factors

Assessment scenario	Hasanpur		Asa		Total	
	HH	%	HH	%	HH	%
Existing vulnerability	42	36.52	48	29.45	90	32.37
After positive change	7	6.09	7	4.29	14	5.04
After negative change	41	35.65	41	25.15	82	29.50

Source: result of simulation

Fig. 9 Most vulnerable households based on coping capacity factors

Fig. 10 Simulated vulnerable households based on the positive alterations of coping capacity factors

Fig. 11 Simulated vulnerable households based on the negative alterations of coping capacity factors

Author Contributions TRC initiated and contributed to the preliminary concept of the study under the supervision of ZA and SI. Afterward, TRC collected the primary data from the study area and completed the analysis. Then after collecting the secondary data, statistical, spatial data analysis, and all of the embedded maps were done by TRC under the supervision of ZA and SI. SA assists TRC while drafting the initial version. Meanwhile, SA and ZA have completed all necessary revisions and editing in the manuscript. HK provides suggestions and guidelines. Subsequently, ZA completed the final draft and revised it critically. Finally, all the authors approved this final version.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval Although this study does not have any direct or indirect risks to participants, we received informed consent from the respondents. This manuscript does not contain any studies with animals performed by any of the authors.

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