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Multi-Criteria Analysis (MCA) for Identification of Vulnerable Areas Along Brahmaputra River in Assam and Their Field Assessment

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Abstract

The state govt is managing the flood control measures such as construction of embankments and anti-erosion measures in the Brahmaputra river basin in Assam. The existing cumulative length of embankments in Assam is 4,474 Kms, most of these embankments have been constructed before 1980. Floods cause considerable damage to flood management assets including embankments, spurs, studs, RCC porcupines, geo-textile fabric bags pitching, and bamboo piles as well as village households and standing crops. Hence, construction as well as regular monitoring of anti-erosion structures is essential. This study presents a prioritised list of 115 vulnerable areas, identified after analysis of 25 years of satellite imageries, GIS based multi-criteria analysis, vulnerability classes, and field assessment survey conducted by the author. These vulnerable areas where flood protection works are, of utmost importance are classified as very-highly sensitive, highly sensitive, moderate sensitive, and low sensitive, which are 18, 39, 36, and 22 respectively; then the state govt can prioritised vulnerable areas based on that classification. The eighteen very-highly sensitive areas are: 001-Upor Laupani, 010-Ting Khong Bhong Ali, 021-Churaipura, 025-Loliti Sopari, 041-Khurahola, 050-Kamolaiya, 062-Boga Mukh, 067-Mahmari Pathar, 079-Balatery, 080-Paharpur Katuli, 084-Tarakandi, 086-Mohanpur, 099-Baladmari Char, 100-Koriy, 108-Motichar, 110-Takimari, 112-Dakur Bhita, and 114-Patakata. A detailed observations, remarks, and recommendations with photographs of all vulnerable areas are also present in this paper.

Keywords

Multi-criteria Analysis, Vulnerable Areas, Field Assessment, Brahmaputra River, and RS/GIS

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1. Introduction

River floods are one of the most frequent and extensive natural disasters affecting many countries around the world [1]. These natural hazards have become the foremost geo-environmental issue in many regions worldwide, as infrequently a year pass by without any catastrophic event affecting both urban structure and human life [2]. Identification of these vulnerable areas using remote sensing and GIS aids us in estimating the precise location of sites where people, natural environment and/or property are at risk due to a potentially catastrophic event that could result in death, injury, pollution, or other destruction [3]. The identification of vulnerable population and places is necessary to enable local communities to acknowledge their vulnerability to natural disasters, improve their emergency management, and mitigate losses when a natural disaster occurs [4]. In the fields of geography and geo-hazard, a vulnerability index has been developed by combining various vulnerability indicators, to identify areas having a high vulnerability to natural disasters [5]. Multi-criteria models have been extensively applied in several studies by the decision makers [6]. GIS techniques have shown to provide additional and better information for these decision-making situations. GIS also allows the decision

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maker to identify a list meeting a predefined set of criteria with the overlay process [7].

The main objective of the present study is to identify the areas vulnerable to natural hazards along the Brahmaputra river in Assam using multi-criteria model, integrated with remote sensing and GIS data. To identify areas vulnerable to natural hazards, Author has generated eleven spatial criteria viz. settlement, public utilities, transportation network, embankments and spurs/studs, morphologically active river bankline reaches, erosional area, natural vegetation, population density, slope, soil texture and geology, along with 55 GIS data layers, stored in a geodatabase using ArcGIS 10.7 software [8]. Rank and weightage scheme is used to evaluate each criterion under consideration, in the order of the decision maker's preference [9]. Each criteria has a specific numeric value, which indicates its vulnerability to natural hazards. Multi-criteria model has been developed to identify the area vulnerable to these natural hazards [10]. The result obtained from this study has been verified by field assessment survey of 115 identified vulnerable areas.

2. About the Study Area

The Brahmaputra valley is a long and narrow valley in Assam, India. It is approximately 640 km long. The valley is bounded by high Himalayan mountain ranges in the north, the Patkai hill ranges in the east, the lower (Assam) hill ranges in the south and, in the west, it is contiguous with the plains of Bangladesh. The Brahmaputra river drains an area of around 580,000 km^2, distributed in four countries China (50.5%), India (33.6%), Bangladesh (8.1%) and Bhutan (7.8%). Originating from the great glacier mass of Chema-Yung-Dung in the Kailas range of southern Tibet at an elevation of 5,300 m above mean sea level (amsl), the Brahmaputra river travels a total distance of 2,880 Km (1,625 Km in China, 918 Km in India and 337 Km in Bangladesh) and is joined by the river Ganga (Ganges), before its outfall in the Bay of Bengal. As the river enters Arunachal Pradesh (India), it makes a very rapid descend from its original height in Tibet, and finally appears in the plains, where it is called Dihang. It flows for about 35 Km and is joined by two other major rivers: Dibang and Lohit. After this confluence, it becomes very wide and is called Brahmaputra river.

In Assam, the river is sometimes as wide as 10 Km or more. Between Dibrugarh and Lakhimpur districts, the river divides into two channels - the northern Kherkutia channel and the southern Brahmaputra channel. The two channels join again around 100 Km downstream, forming the Majuli island [11]. In Guwahati, near the ancient pilgrimage site of Hajo, the Brahmaputra River cuts through the rocks of the Shillong plateau and is ~1 km wide at its narrowest width [12]. The Brahmaputra river is one of the largest alluvial rivers in the world, which is characterized by frequent bank erosion due to changes in channel pattern and shifting of bank lines. As the flood cycle progresses, sediment transport in the Brahmaputra increases, and the thalweg and location of bars change position [13]. As the flood recedes, deposition takes place over the bed as bars and islands. In this way, the Brahmaputra river becomes intensely braided with innumerable sandbars, locally called chars. During high floods, most of the chars get submerged with only few remaining visible. Location map of the study area is shown in Figure 1.

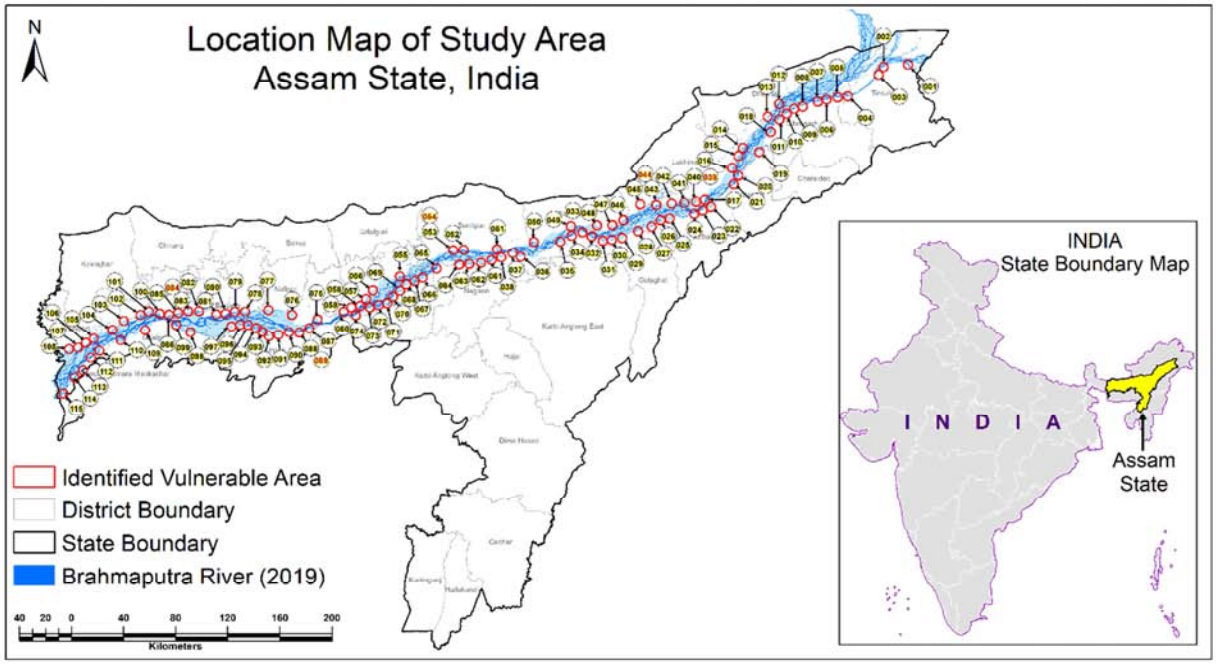


Figure 1. Location Map of Study Area, Assam (India).

3. Data Used, Their Sources and Methodology

In this study, various basic thematic layers were created from different source including map, field study, satellite imageries and secondary data. Using ArcGIS 10.7 software tools, several maps were prepared including rural and urban settlement; public utilities; transportation network; embankments, and spurs/studs; morphologically active river bankline reaches; erosional area; natural vegetation; population density; slope; soil texture; and geology. Data used, and their sources are given in Table 1.

Table 1. Data used, its Sources and Methodology.

S. No.	Data Layer / Maps	Data Sources and Methodology
1.	Survey of India (SoI) Toposheet at 1:50,000 Scale	Total number toposheets = 65 (area within 10 Km both side buffer from current Brahmaputra river bankline) Source: http://soinakshe.uk.gov.in/Home.aspx [14]
2.	Landsat Series Satellite Imageries from 1996 to 2020	Satellite remote sensing data was collected from USGS. Landsat satellite imageries from 1996 to 2020 were downloaded from Earth Explorer, USGS. 1) Landsat-5 TM satellite imageries: 1996, 1997, 1998, 1999, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011. 2) Landsat-7 ETM+ satellite Imageries: 2000, 2001, 2002, 2003, 2012, 2013. 3) Landsat-8 OLI satellite imageries: 2014, 2015, 2016, 2017, 2018, 2019, 2020. Total number of satellite scenes = 275 (covered whole Assam state) Spatial resolution: 30 m Source: https://earthexplorer.usgs.gov [15]
3.	Elevation Data	Shuttle Radar Topography Mission (SRTM) DEM data of whole Brahmaputra basin (outlet at Assam-Bangladesh border) with 30 m spatial resolution has been downloaded from NASA & USGS EROS Data Centre. Area covered: 503,855.63 Km^2 Source: http://glcfapp.glcf.umd.edu:8080/esdi [16]
4.	Rural and Urban Settlement	Land use and land cover map with settlement and forest cover area was prepared using Landsat-8 OLI satellite imagery with 30 m spatial resolution of year 2020. These data layers were updated with best available Google Earth satellite imagery. These data layers are also verified through limited field check.
5.	Public Utilities	Public utilities such as educational institute (university / college / school), Government offices, medical facilities (clinic / hospital), religious places, and industries were captured by using Survey of India toposheet at 1:50,000 scale, Google Earth, and Google Map.
6.	Transportation Network	Transportation system like roads, railway lines, bridges, airports, ferry services locations were digitized by using Survey of India toposheet at 1:50,000 scale, Google Earth, and Google Map.
7.	Embankments, and Spurs / Studs	River training structures / bank protection structures such as locations and physical attributes of bridges, embankments, spurs, studs, geo-bags, and porcupines were digitized on Google Earth satellite imagery / ArcGIS online satellite imagery. Some of spurs, studs, geo-bags, and porcupine structures were also verified in the field. Embankments structures were cross verified with Survey of India toposheet at 1:50,000 scale.
8.	Morphologically Active River Bankline Reaches	River banklines of Brahmaputra River were digitized in ArcGIS 10.7 software by using multi-spectral, multi-spatial, and multi-temporal Landsat satellite imageries from 1996 to 2020. All banklines were superimposed in one window to find the morphologically active river bankline reaches.
9.	Erosional Area	Common erosional areas over the years (1996 to 2020) along both of the banks of the river (left and right) were estimated and extracted using Landsat satellite imageries from 1996 to 2020.
10.	Natural Vegetation	Natural Vegetation i.e. reserved forest, protected forest, wildlife sanctuary, and national parks were digitized using Landsat-8 OLI satellite imagery with 30 m spatial resolution of year 2020. These data layers were also updated with best available Google Earth satellite imagery. These layers were verified by limited field check.
11.	Population Density	CD Block wise maps of Assam state were downloaded from Census of India website. These maps were geo-referenced in ArcGIS 10.7 software and the CD block boundary was digitized. CD block wise population distribution data of year 2011 was collected from Census of India and was joined with the CD block. These datasets were used for generation of population density map. Source: https://censusindia.gov.in/2011census/dchb/Assam.html [17]
12.	Slope Map	Slope map has been created using Spatial Analyst Extension in ArcGIS 10.7 and Shuttle Radar Topography Mission (SRTM) DEM data with 30m spatial resolution. NASA & USGS EROS Data Centre: http://glcfapp.glcf.umd.edu:8080/esdi [16]
13.	Soil Texture	Soil map has been downloaded from National Atlas of India, National Soil Survey, and National Atlas and Thematic Mapping Organization (NATMO), 1981. This map was geo-referenced and digitized and prepared a soil texture map. This map was also updated using Landsat-8 OLI and PAN sharpened satellite imagery and were verified by limited field check. Source: http://asmenvis.nic.in/Database/Land_Resources_834.aspx [18]
14.	Geology	Geological quadrangle maps were downloaded from Geological Survey of India (GSI) website and were updated using Landsat-8 OLI and PAN sharpened satellite imagery, and Survey of India (SoI) Toposheets at 1:50,000 scale with limited field check. Source: http://www.portal.gsi.gov.in [19]

4. Result and Discussion

4.1. Identification of Vulnerable Areas

The author has analysed the multi-temporal satellite imageries from 1996 to 2020 (25 years dataset), and prepared various GIS datasets such as frequency of riverbank line shifting, and erosion-deposition pattern over the years, for identification of the vulnerable areas. Total 115 erosion vulnerable areas were identified by this process.

4.2. Multi-Criteria Analysis (MCA) for Classification of Vulnerable Areas

There are variety of methods that can be used to integrate the different criteria for the identification of vulnerable areas into a tool. Here, author has used a multi-criteria model integrated with remote sensing and GIS data to identify the areas vulnerable to natural hazards. Author has generated several spatial criteria viz. (i) settlements - rural & urban; (ii) public utilities - educational institutes (university / college / school), government offices, medical & healthcare facilities (clinics / hospital), religious places (temple, church, gurudwara, masjid and others), and industries; (iii) transportation system - roadways, railway lines, bridges, airports, ferry services locations; (iv) bank protection structures - embankments and spurs/studs; (v) morphologically active river bankline reaches; (vi) common erosional areas over the years (1996 to 2020); (vii) natural vegetation - reserved forest, protected forest, wildlife sanctuary, and national parks; (viii) population density; (ix) slope; (x) soil textures; and (xi) geology (lithology). The information to generate these datasets was acquired through various sources and was stored in a GIS-enable geodatabase.

Author has examined several individual criteria, assigned them relative levels of importance, and used a mathematical resultant model to identify the areas most vulnerable to natural hazards. By adopting this method, it is possible to systematically identify the dominant criteria, clearly document the relative importance of one criterion over another, analyse the net outcome using a GIS, and then possibly revisit the mathematical relationships in this decision model. By revising the relative importance to identified criteria based upon the specific thematic databases under consideration, it is possible to generate the vulnerable areas map to natural hazards [20].

To achieve this, all the criteria are assigned "rank" denoting their relative levels of importance within the vulnerability study. These ranks were assigned as numeric values ranging from 1 to 10, with 1 reflecting a low level of vulnerability and 10 reflecting a high level of vulnerability. For example, within the criteria of embankments, spurs / studs had a different level of influence on the vulnerability, as compared with other river training structures. Further, the distance of the channel from each of these features further modifies the relative vulnerability, like here based on the proximity to a specific river training structure. To properly include this geographic inconsistency across the vulnerability extents, a similar scale of 1 to 10 has been used to assign individual "weights" based on the proximal relationship to each specific feature type within a specific criterion, which has been used in the decision model [21]. Collectively, the weights, multiplied by the rank, provide a vulnerability score that cumulatively has been used to identify the area's most vulnerable to natural hazards. The details of ranks and weights for each criteria and their proximity analysis is given in Table 2, and shown in Figure 2.

Table 2. Vulnerability Score for Classification of Vulnerable Areas.

No.	Criteria	Proximity analysis	Rank (R_i)	Weights (W_i)	Score (S_i)	Remarks
1	Active channel near to settlement (S_{ET})	S_{ET}+0 m to 400 m	10	10	100	Settlements and nearby areas are vulnerable with exposed property, people, economy and environmental and social environment. So, for proximity analysis the high numeric numbers are assigned to settlements and nearby area.
		400 m to 800 m		9	90	
		800 m to 1200 m		7	70	
		1200 m to 1600 m		5	50	
		1600 m to 2000 m		3	30	
		More than 2000 m		1	10	
2	Active channel near to public utilities (U_{TL})	U_{TL}+0 m to 400 m	9	10	90	Public utilities i.e. educational institute (university / college / school), government offices, medical facilities (clinic / hospital), religious places, and industries are vulnerable with exposed public utilities / facilities, property, and social activities. Accordingly, for proximity analysis high numeric numbers are assigned to public utilities.
		400 m to 800 m		8	72	
		800 m to 1200 m		7	63	
		1200 m to 1600 m		6	54	
		1600 m to 2000 m		4	36	
		More than 2000 m		2	18	
3	Active channel near to transportations (T_{RA})	T_{RA}+0 m to 200 m	9	10	90	Transportations i.e. roads, railway lines, bridges, airports, ferry services locations are usually used for peregrination. The areas near the transportations are vulnerable. Therefore, high numeric numbers have assigned to areas near transportation, and lower number beyond the transportations.
		200 m to 400 m		9	81	
		400 m to 600 m		8	72	
		600 m to 800 m		4	36	
		800 m to 1000 m		2	18	
		More than 1000 m		1	9	
4	Active channel near to embankments, and spurs / studs (E_{SS})	E_{SS}+0 m to 200 m	8	9	72	An embankment is an artificial barrier / ridge that typically is used to hold back water, flood control and to prevent water from passing beyond desirable limits. Embankment is also protecting the settlement as well as highly valuable assets. Area nearby the embankment is vulnerable, because if embankment breach, it will affect the settlement and assets.
		200 m to 400 m		8	64	
		400 m to 600 m		6	48	
		600 m to 800 m		5	40	
		800 m to 1000 m		3	24	
		More than 1000 m		2	16	
5	Morphologically active river bankline reaches	M_{AR}+0 m to 200 m	7	10	70	Brahmaputra River is braided morpho-dynamic and continuously change its position, shape and other characteristics with variations in discharge and time.
		200 m to 400 m		8	56	
		400 m to 600 m		7	49	

No.	Criteria	Proximity analysis	Rank (R_i)	Weights (W_i)	Score (S_i)	Remarks
	(M_{AR})	600 m to 800 m		5	35	Morphologically active river bankline reaches are highly prone to erosion and vulnerable.
		800 m to 1000 m		3	21	
		More than 1000 m		1	7	
6	Erosional area (E_{RA})	E_{RA}+0 m to 200 m	6	9	54	Common erosional areas over the years (1996 to 2019) along both river banklines i.e. left / right bankline are also highly prone to erosion / vulnerable, because these river portions are not stable due to highly erodible bank material, variability of cohesive soil in bank material composition, and slope.
		200 m to 400 m		8	48	
		400 m to 600 m		7	42	
		600 m to 800 m		5	30	
		800 m to 1000 m		3	18	
		More than 1000 m		2	12	
7	Natural vegetation (N_{AT})	N_{AT} +0 m to 400 m	5	8	40	Natural vegetation i.e. reserved forest, protected forest, wildlife sanctuary, and national parks are vulnerable. High numeric numbers were assigned to nearby areas of natural vegetations, and lower number beyond the natural vegetations.
		400 m to 800 m		7	35	
		800 m to 1200 m		5	25	
		1200 m to 1600 m		4	20	
		1600 m to 2000 m		2	10	
		More than 2000 m		1	5	
8	Population density (P_{OP})	Less than 200 p/km^2	4	1	4	High dense areas are vulnerable because many people are living in a confined area. High numeric numbers have assigned to dense areas. Block wise population density has been used for this analysis.
		200 to 400 p/km^2		3	12	
		400 to 600 p/km^2		5	20	
		600 to 800 p/km^2		7	28	
		800 to 1000 p/km^2		9	36	
		More than 1000 p/km^2		10	40	
9	Slope (S_{LP})	> 5°	3	2	6	Steeper slopes (<25°) are vulnerable to erosion, while slope below 10° has low vulnerability.
		5° - 10°		4	12	
		10° - 15°		6	18	
		15° - 20°		8	24	
		20° - 25°		9	27	
		< 25°		10	30	
10	Soil texture (S_{OL})	Sand	2	10	20	Sandy soil is vulnerable due to lose material, more porosity, and highly erosional properties, and clay soil only little vulnerable because of compact material.
		Sandy loam		9	18	
		Loam		7	14	
		Silt loam		6	12	
		Silt		5	10	
		Clay loam		3	6	
		Clay		1	2	
11	Geology (G_{EO})	Un-stabilized sand, silt and clay	1	10	10	Un-stabilized and feebly oxidized sand, silt and clay are vulnerable due to lose material, and for proximity analysis, the high numeric numbers were assigned to these lithologies. The lithology like Mica (Biotite) Gneiss, and Migmatite / Banded Gneiss are the metamorphic rock, and compact in formation, subsequently the low numeric numbers were assigned to these lithologies.
		Feebly oxidized sand, silt and clay		8	8	
		White to greyish sand, silt, pebble and clay.		5	6	
		Silt, sand & clay sequence with carbonized wood		3	4	
		Mica (Biotite) gneiss		2	2	
		Migmatite / banded gneiss		1	1	

4.3. Development of Multi-Criteria Model

A multi-criteria model has been developed (Eq.1), and the ranks and weights were assigned to each criterion [8]. The detail of the model is shown in Equation (1).

$$VA = S_{ET} + U_{TL} + T_{RA} + E_{SS} + M_{AR} + E_{RA} + N_{AT} + P_{OP} + S_{LP} + S_{OL} + G_{EO} \quad (1)$$

Where, VA = Sum of ratings of all causative criteria for vulnerable areas, S_{ET} = settlements, U_{TL} = public utilities places, T_{RA} = transportations, E_{SS} = embankments, spurs / studs, M_{AR} = morphologically active river bankline reaches, ERA = common erosional areas over the years (1996 to 2020), NAT = natural vegetation, P_{OP} = population density, S_{LP} = slope, S_{OL} = soil textures, and G_{EO} = geology.

After collection of data from available sources, initial data maps (Figure 2) were re-classified according to the score given in Table 2. Based on VA value, vulnerable areas map to natural hazards has been classified in five categories as given in Table 3. The most suitable method for the application of multi-criteria analysis in a case is highly dependent on the main objectives and needs of the study (e.g. flexible, widely applicable, efficient, and accurate) and on the quality, availability, and reliability of the data. The success of identification of areas vulnerable to natural hazards depends strongly on criteria used. By using the eleven spatial criteria, Author has generated a classified vulnerable area map and

shown in Figure 3. Classification scheme wise vulnerable areas is given in Table 3.

Table 3. Classification of Vulnerable Areas.

S. No.	Vulnerability Classes	Total Score wise Classification Scheme	Number of Vulnerable Areas	Vulnerable Site Number
1	Very-Highly Sensitive	More than 400	18	001, 010, 021, 025, 041, 050, 062, 067, 079, 080, 084, 086, 099, 100, 108, 110, 112, and 114.
2	Highly Sensitive	400 to 300	39	002, 004, 006, 007, 008, 009, 017, 018, 024, 026, 029, 030, 031, 037, 040, 043, 044, 049, 054, 057, 058, 061, 066, 068, 069, 076, 077, 078, 082, 087, 089, 090, 091, 092, 105, 106, 107, 111, and 113.
3	Moderate Sensitive	300 to 200	36	005, 011, 012, 013 014, 015, 016, 019, 022, 027, 028, 032, 033, 038, 039, 042, 045, 046, 053, 055, 056, 063, 070, 072, 081, 085, 088, 093, 094, 095, 096, 101, 103, 104, 109, and 115.
4	Low Sensitive	200 to 100	22	003, 020, 023, 034, 035, 036, 047, 048, 051, 052, 059, 060, 064, 065, 071, 073, 074, 075, 083, 097, 098, and 102.
		Total	115	

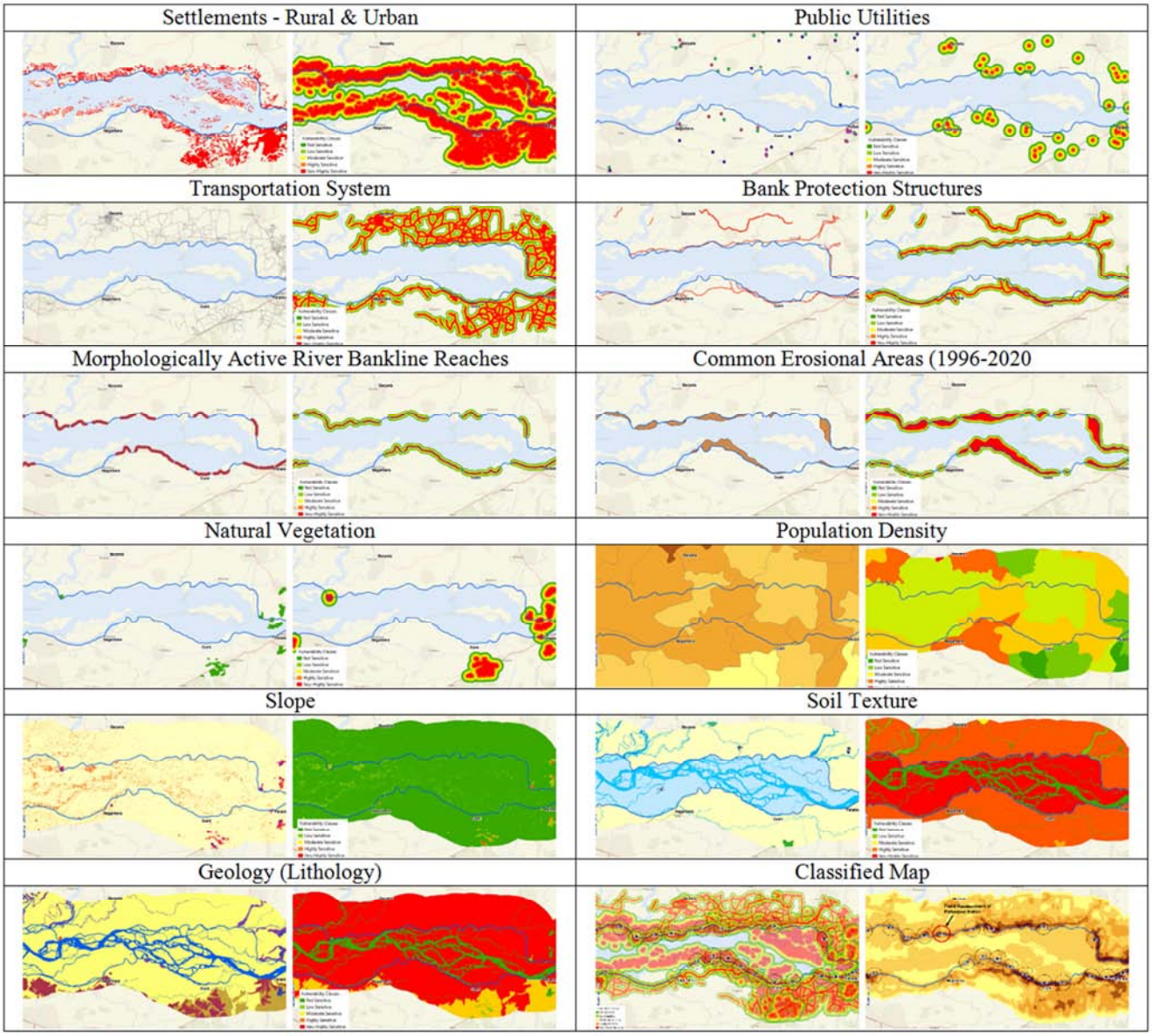


Figure 2. Spatial Criteria with Proximity Analysis, and Classified Map.

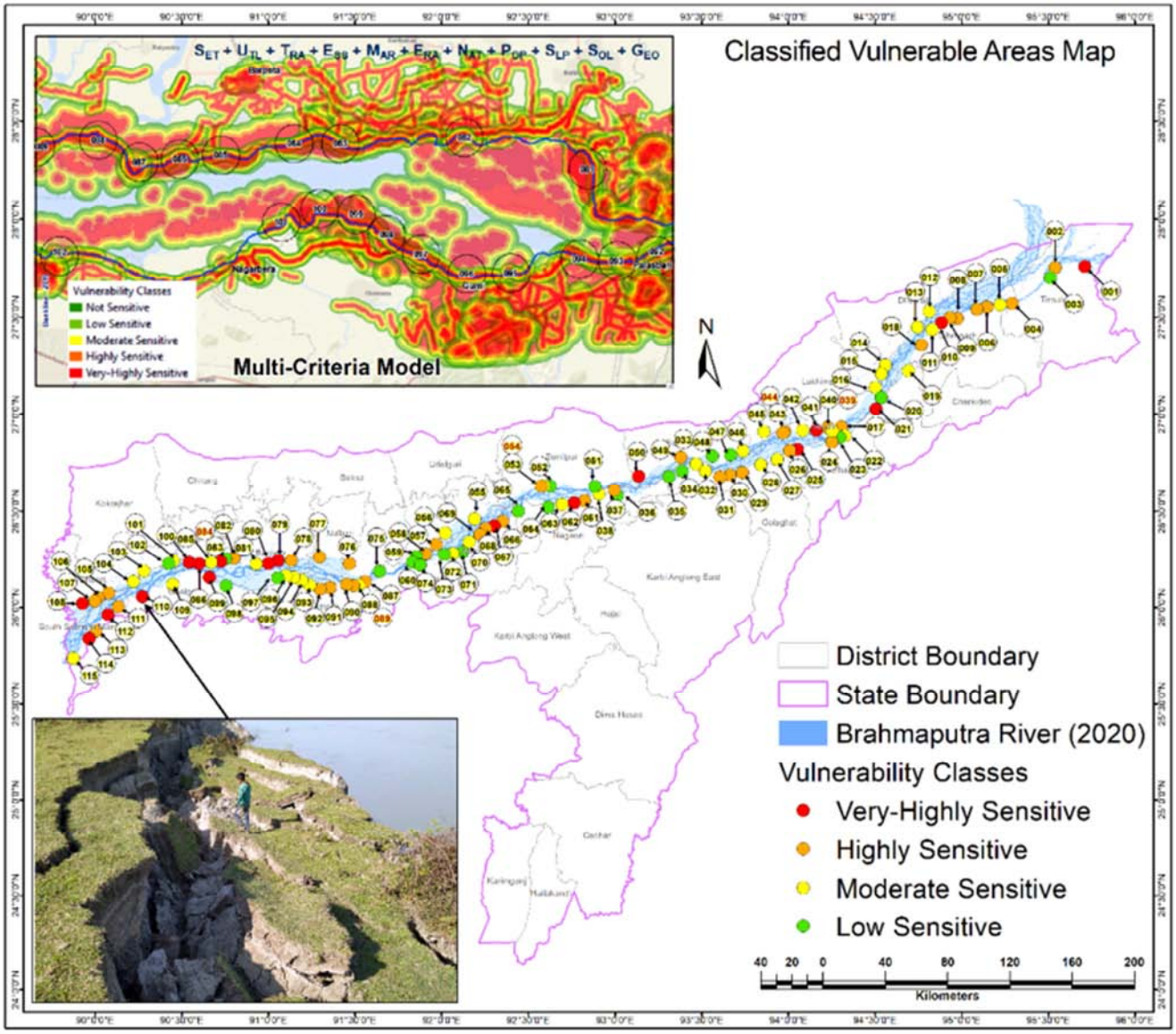


Figure 3. Classified Vulnerable Area Map of Assam.

4.4. Field Assessment

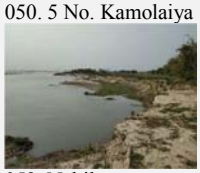
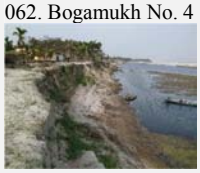
There are thirteen major aspect in the field assessment form for which the details were recorded in the field. These aspects are: general information; vulnerable area situated at river reaches; lithological, slope and soil information; physical attributes of riverbank; physical attributes of channel; geomorphic features; land use / land cover (within 100 m of vulnerable area); any infrastructure (nearby the vulnerable area); major impacts from vulnerable area; evidence of recent management; flood related information of the village nearby the vulnerable area; flood management activities; and significant observations. Because of these are huge database of vulnerable areas, here is only present (Table 4) the significant observations and remarks of all 115 vulnerable areas.

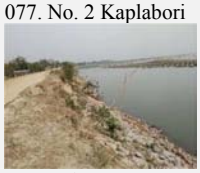
Table 4. Significant Observations, Remarks and Recommendation of all Vulnerable Areas.

Sites and Photos	Observation and Remarks	Sites and Photos	Observation and Remarks
001. Upor Laupani 	1) Erosion process is very high. 2) The embankment is installed that may get affected in future due to heavy erosion. 3) Geo-textile fabric bags pitching at u/s and d/s of the village to control the erosion.	002. Na Bormura Chariaali 	1) Heavy erosion at the d/s of the village is observed. 2) Proper Geo-textile fabric bags pitching is required.
003. Laina Gaon	1) 4 villagers washed-out at the d/s of the village in 2004. 2) In the existing situation, the erosion is low.	004. Runga Gaon	1) At this site, there is a tea plantation and tea estate where heavy erosion is observed.

Sites and Photos	Observation and Remarks	Sites and Photos	Observation and Remarks
 005. Mullu Gaon	3) Bank line is required to control the erosion.	 006. Bhogari Tolaiya	2) Tea Estate can be washed-out in any point of time due to heavy erosion.
 007. Romoria	1) RCC porcupines were installed in 2018 but could not control the flow due to which the erosion is still heavy. 2) More porcupines are stored on-site.	 008. Maijan Mathalatee	1) At this site, the erosion rate is quite high. 2) Geo-bags pitching has been done some stretch in 2017. 3) RCC porcupines were installed in 2012 but these are under water.
 009. Maijan Natun	1) Installation of new embankment at the u/s of the village. 2) Increase in height of existing embankment by 6 feet.	 010. Ting Khong Bhong Ali	1) Increase in height of the embankment by 5 feet is required. 2) Boulder riprap or geo-textile fabric bags pitching of the complete bank line is must require.
 011. Aitheng Singamari Habi	1) An embankment of 15 feet height is installed. 2) Boulder or geo-textile fabric bags pitching is required to control the erosion.	 012. Panbari Sivanagar	1) Erosion process is very high. 2) This village is located at very dangerous place as the erosion is very heavy. 3) RCC porcupines are almost deteriorated or covered by sand.
 013. Amguri Bali	1) Erosion process is high. 2-3 Km of land eroded in last 4 years. 2) Flood related issues are more due to construction of Bogibeel bridge.	 014. Bahir Kapsan	1) Erosion rate is high. 2) 100 m of land has been washed-out in 2019 only. 3) A tributary of Brahmaputra river causes flood in this village. Bogibeel bridge is located at the d/s of village
 015. Khamon Birina	1) Embankment breach had been recorded in 1988 and 2007. 2) Due to Bogibeel bridge, flood frequency has increased.	 016. Tekeliphuta	1) Embankment breach had been recorded in 2007 since then there is no flooding. 2) An embankment with Geo-textile fabric bags pitching and a spur structure was constructed in 2018.
 017. Salmora	1) Moderate erosion is observed. 2) The area is well protected by embankment (15 feet height and 20 feet width).	 018. Dalani Gaon	1) Erosion process is very high. 2) The area is well protected by embankment (15 feet height and 20 feet width). 3) Embankment with slope protection using geo-mattress / geo-textile fabric.
 019. Burgaon	1) Erosion is moderate in this region due to protection works. 2) At this site, a series of spur structures with 1 Km length has been installed in d/s of that village in 2015.	 020. Daboli Chapori	1) Moderate erosion is observed. 2) Bogibeel bridge is located at the u/s of that village. 3) The village has an embankment of 15 feet height so there is no record of flood.
 021. Churaipura	1) Moderate erosion has been observed. 2) An embankment of 15 feet height is damaged.	 022. Beajor Chigar	1) Heavy erosion is observed, and 500 m of land has been washed-out in 2019. 2) Village is situated between a tributary and the Brahmaputra river.
 023. No.1 Neemati	1) Riverbank failure (slumping) and very heavy erosion has been observed. 2) In last one year, 500-600 m of land has been eroded. 3) Villagers themselves take steps to protect the embankment breach. 1) Heavy erosion is observed. 2) Geo-textiles fabrics bags or boulder pitching on the bank and spur structures at the u/s and d/s must be constructed to protect	 024. Neemati Ghat	1) Heavy erosion is observed. 2) About 200 m of land has been washed-out in 2019. 3) Embankment breach noted in 2010 and got repaired in 2011. 1) Heavy erosion in the u/s and d/s of ferry ghat. 2) Bankline need to be protected by geo-textiles fabrics bags pitching.

Sites and Photos	Observation and Remarks	Sites and Photos	Observation and Remarks
 025. Loliti Sopari	Jhanghimukh, Nimati Gaon and Jorhat town.	 026. Naul Gaon	3) Increase in height of existing embankment by 4 feet.
 027. Chakial Chapori Gaon	The old embankment was washed-out in 1998. In 1999, a new embankment was installed 3 Km away from the old embankment.	 028. Bakoli Chapori No. 2	1) Embankment of 15 feet height was installed in this village in 1950. 2) RCC porcupines are installed in good number at this site.
 029. Bonkwal	1) Erosion process is very high, 500 m of land has been washed-out in 2019. 2) Embankment breach was recorded in 2017 and repaired in the same year.	 030. Chohala	1) Erosion process is high, and 500 m of land has been eroded in 2019. 2) Increase the height of old embankment by 5 feet to stop the flood water entering the village.
 031. Badbari Missing Gaon	1) Erosion process is high. 2) There is an embankment to save the village, but during the flood the water passes through the embankment.	 032. Kaziranga National Park-1	1) Moderate erosion is observed. 2) The installation of geo-textile fabric bags with proper mechanism is under process.
 033. Kaziranga National Park-2	1) Heavy erosion has been observed at this site, but bank protection work is under process. 2) In last 2 years, 200 houses were lost due to heavy flooding.	 034. Kaziranga National Park-3	1) Forest Ranger has informed us that approx. 22 Sq. Km of rich forest has been eroded is last 10 years. 2) Riverbank should be protected by boulder or geo-textile fabric bags pitching.
 035. Kaziranga National Park-4	1) Forest Ranger has informed us that approx. 22 Sq. Km of rich forest has been washed-out is last 10 years. 2) Boulder or geo-textile fabric bags pitching is required to protect the bank.	 036. Bhagjan (Sugunbari)	1) Forest Ranger has informed us that approx. 22 Sq. Km of rich forest has been washed-out is last 10 years. 2) Riverbank should be protected by boulder or geo-textile fabric bags pitching.
 037. Hathimara	1) Forest Ranger has informed us that approx. 22 Sq. Km of rich forest has been washed-out is last 10 years. 2) Boulder or geo-textile fabric bags pitching is required to protect the bank.	 038. Gakhirkhait	1) Embankment with 15 feet height is installed in that area. 2) Embankment got breached in 2017 which causes flooding in the village. 3) The repair of embankment had been done in 2018.
 039. Dakhim Kamar Gaon	1) On side channel modification or re-section is under construction. 2) After the hilly area, channel digging, and channel modification by boulder pitching is also under construction.	 040. Sumoimari	1) It is at the confluence of two branches of the Brahmaputra river which causes heavy erosion. Village named Gagalmari which was washed-out in 2014. 2) Spur structure repair is under process.
 041. Khurahola	Erosion is a major concern because they lose 20-30 m of their agriculture land every year, and this process is continuous going-on.	 042. Bokat Chopari	1) In last 20 years, more than 10 villages have been washed-out. 2) RCC porcupines have been installed at this site.
 043. Baghgaon	1) Erosion process is very high, around 2 Km of land across the river has been eroded in last one year. 2) In last 10 years, 400 houses have been washed-out due to heavy flooding. 1) Due to heavy erosion, 2 Km of land has been eroded in last 5 years. 2) Channel modification with geo-textile fabric	 044. Missamora	1) Heavy erosion has been observed at site and about 300 m of land has been washed-out in 2019. 2) Bank pitching work with geo-textile fabric bags is under construction. 1) The village is located at the confluence of Subansiri and Brahmaputra river.

Sites and Photos	Observation and Remarks	Sites and Photos	Observation and Remarks
 045. Majgaon	bags pitching is under construction.	 046. Lohimukh	2) Approx. 2 Km of land has been eroded in last 25 years, the erosion is now controlled in recent years.
 047. Ranamukh	1) 3 feet of water level has been observed in the village during flood. 2) Embankment breach was recorded in 1999.	 048. Tultuli	1) Embankment breach occurred in 2011 as 2 Km of its reach washed-out. 2) Heavy erosion is observed, 2 Km of land has been eroded in last 6-7 years.
 049. Kosakota (Nepaliwari)	1) Heavy erosion has been observed at this site and 40 feet of land has been eroded in 2019. 2) Most of the houses are elevated around 6 feet from the ground.	 050. 5 No. Kamolaiya	A new branch of braided river has been formed by the brick kiln owners and it has impacted the village, it has become the reason behind flooding in the village.
 051. 4 No. Sherwani	1) One major thing that has been observed at this site is the river is moving away from the village in last 40 years (around 4-5 Km). 2) This village has been flooded in 1990, after that no flood recorded here.	 052. Nabil	1) In 2019, 2 Km of embankment has been washed-out and also 300-400 m of land has washed-out. 2) Heavy erosion has been observed and 500 houses have been washed-out in last 5 years.
 053. Sunjari	1) The village gets flooded every year because there has no bank protection installed. 2) The existing embankment was breached in 2012 which needs to be repaired.	 054. Teliagaon	1) Embankment breach was recorded in the u/s of this site in 2000. 2) Heavy erosion is major concern in this village.
 055. 2 No. Magurmari	1) Riverbank is well protected by geo-textile fabric bags from Sunjari to Tailagaon. 2) People of this village shifts to school or relief camp in case there is flooding.	 056. Chereng	1) Land is progressively eroding; 2 Km of land and 1500 houses has been washed-out in last 10 years. 2) Embankment breach in 2012 has been recoded.
 057. Dhuriya Keheti	1) Mix of vertical and composite erosion were observed at site. 2) Set-back embankment of 10 feet height was breached in 2019. People are living between river / embankment, face flood every year.	 058. Kirakara	1) Moderate erosion has been observed at site. 600 houses have been washed-out in last 5 years. 2) An embankment was installed in 2015 which got washed-out in 2019.
 059. Dhanbari Fukratuli	1) The erosion process is very heavy. The water level of 20 feet has been recorded in the village in 2019. 2) The agriculture land is only get affected by flood.	 060. Kurua	1) This village gets flooded every year; 5 to 6 feet of water level was recorded in in the village in 2019.
 061. Bhurbandha No. 4	1) In last 10-12 years, 500 m of land has been eroded due to heavy erosion. 2) Heavy erosion is observed. 300-400 houses were lost in last 5 years.	 062. Bogamukh No. 4	1) An embankment near by the village has been breached in 2000 and Village has got flooded. 2) Every year low-lying areas of gets submerged with water.
 063. Burachopari (WL Sanctuary)	1) Heavy erosion has been observed and nearly 5 Km long embankment has been washed-out in last 2 to 3 years. 2) 1000 houses were lost in last 5 years. 1) In 2019, 1 Km of land as well as two villages have been washed-out due to heavy erosion. 2) Approx. 200 houses have been washed out in 2019.	 064. Chitalmari	1) Heavy erosion is observed, and the village is under danger of being washed-out. 2) In 2019, 1 Km of land has been washed-out. 3) Embankment breach was recorded at the u/s of the village. 1) There are 6 villages are located between this village and current active channel. 2) The total population of these area is approx. 20,000.

Sites and Photos	Observation and Remarks	Sites and Photos	Observation and Remarks
 065. Muwamari (Balbiri)		 066. Solmari	
 067. Mahmari Pathar	1) Embankment breach has been recorded in d/s of village at two different locations with length of 1 Km each. 2) RCC porcupines have been installed here.	 068. Balidunga	1) an embankment was breached in 2019. 2) The shift of 5 km has been recorded in last few years. 3) RCC porcupines were installed here.
 069. Borduba	1) The 2 Km land from the river has been eroded in 2019. 2) This site is vulnerable as the erosion is still active and about 70 m of land has been washed-out in last 2 months.	 070. Baralimari	1) This site is situated on a tributary of the Brahmaputra river which flows during the monsoon and low erosion is observed.
 071. Burgaon	1) Heavy erosion is observed on this site as the 5 km of land has been washed out in last 5 years including 80 houses. 2) 5 km of embankment has been washed-out.	 072. Garubandha	1) Heavy erosion is observed and lot of RCC porcupines has been installed which are in the middle of active river. 2) 400 to 500 houses have been washed-out in last 5 years.
 073. Hiloikhunda No. 2	1) Heavy erosion is observed. 2) Embankment breach at Boramari village causes flooding in this village.	 074. Barchapuri	Heavy erosion is observed and embankment breach at three places has been recorded in 2019. A village Katagorhi washed-out.
 075. Amin Gaon	1) Vertical erosion has been observed at this site. 2) Villagers have been shifted to the elevated region during flood.	 076. Gendhiletri	1) Large sand deposition is there at the d/s of village. 2) Villagers have requested for the availability of drinking water or handpump.
 077. No. 2 Kaplabori	1) Mining is going on as the deposited sand has been collected by the contractors. 2) Water do not cross the highway as per villagers.	 078. Bahari Koltali	1) In last one year, 500 m of land has been washed-out during flood. 2) Nearly 200 houses have been washed-out in last 5 years.
 079. Balatery	1) An embankment at certain location gets breached every year and villagers with the help of government bodies construct the bund to stop the water entering the village.	 080. Paharpur Katuli	1) The village is well protected with an embankment which is in good condition. 2) There is large part of land between the embankment and river which gets eroded by flood every year.
 081. Kanara Gaon	1) There is large part of land between the embankment and river which gets eroded by flood every year. 2) 500 m of land has been washed-out in 2019.	 082. Chikni Rejab	1) It is extremely vulnerable area; 2 Km of land has been washed-out in last 2 months. 2) The erosion is active, and 500 feet of land is eroding every day.
 083. Paschim Moinbari	3) Heavy erosion has been observed at this site. 4) 250 to 300 houses have been washed-out in last 5 years. RCC porcupines (more than 10,000), and stud structures (more than 200) have been installed in large numbers.	 084. Tarakandi	1) Heavy erosion is observed at this site. Erosion is still active at this site, and large blocks of land are falling vertically into the river. 2) 100 houses have been washed-out in last 2-3 years. Heavy and active vertical erosion is observed, 500 m of land has been washed-out in 2019. 250-300 houses have been washed out in last 5 years.

Sites and Photos	Observation and Remarks	Sites and Photos	Observation and Remarks
 085. 6 No. Char		 086. Mohanpur Part-1	
 087. Majirgaon (Sedilapur)	A channel of braided river is dynamically moving left-to-right-to-left, and this process is continuous and repeating itself again-and-again over the last 20 years.	 088. Dokala Colony (Palasbari)	1) Heavy erosion has been observed at this site. 2) Although many (more than 10,000) RCC porcupines were installed from 2015 to 2017.
 089. Purana Karipara	1) Heavy bank erosion has been seen. 2) The water level of 4 to 5 feet has been recorded in the village in 2019 during flood.	 090. Futuri (Mukurdhuj)	1) An embankment named Dakola Colony road is installed. Boulder pitching work on embankment is under construction. 2) Embankment maintenance work is under progress.
 091. Gumi / Ambari	1) The major concern on this site is dredging can be seen for the brick kiln which can be harmful in future. 2) Extraction of mud from the existing embankment has been observed.	 092. Zaharpur	1) The river is embanked which is under construction from last two years with concrete blocks pitching. 2) 3 mini spurs have been installed.
 093. Khuliya Mari Thukrawari	1) RCC porcupines were installed due to which heavy deposition has been seen and now these porcupines are under the sand deposition. 2) Existing embankment got breached in 2010.	 094. Bordianaya Para	1) The bank is protected by geo-textile fabric bags. 2) A spur structure has been installed with boulder pitching. 3) Rural area and agriculture fields are there near the river.
 095. Panikheti	1) Heavy erosion in the d/s of the river has been observed. 2) RCC porcupines has been installed. 3) 50-60 houses are lost every year.	 096. Chintamuni	1) Channel modification or channel re-section work at a channel of braided river is under construction. 2) They have also casing the geo-bags with iron wire.
 097. Kachumara	1) River bankline is well protected with geo-textile fabric bags and RCC porcupines. 2) Several RCC porcupines have been installed.	 098. Mornoi Singimari Char	1) RCC porcupines and bamboo piles have been seen, most-of-which are inside the river. 2) About 50 to 60 houses have been washed-out in last 5 years.
 099. Baladari Char	1) Village gets flooded every year. There has no bank protection works. 2) 75 to 80 houses have been washed-out in last 5 years.	 100. Koriya Part-2	1) Significant erosion has been observed. 2) The water level of 3-4 feet has been recorded every year during flood. 3) 10 houses have been washed-out in last 5 years.
 101. Sawar Singal Pal	1) There has a lot RCC porcupines has been installed, but most of them has been damaged by flood. 2) 200 to 300 houses have been washed -out in last 5 years.	 102. Halalwara	1) In 2019, 100-150 feet of land has been washed-out, and village is in danger due to high erosion process. 2) The entire village remains submerged with water throughout the flood season.
 103. Suapata Part-3	1) Water level of 4-5 feet has been recorded in 2019 and water remains in the village for 2-3 months. 2) 2000 houses have been washed-out in Bonigaon village in last few years. 1) Heavy erosion has been observed at the u/s of river. 2) 2-3 houses have been washed-out every year.	 104. Baghmara	1) One complete village has been washed-out in 2017. 2) Erosion process is still pro-active, and land is eroding. 3) 2000 houses were lost in last 5 years. 1) In 2013, an embankment has been washed-out and at present erosion process is very high. 2) 50 houses have been washed-out in

Sites and Photos	Observation and Remarks	Sites and Photos	Observation and Remarks
 105. Katlamari River Block-3	1) Heavy erosion is observed. 2) According to the villagers, the river has shifted approximately 500 feet towards the village. 3) There has no approach road to reach this site.	 106. Majherchar	last 5 years. 1) Several RCC porcupines has been installed at this site. 2) The water level of 3-4 feet has been recorded every year during flood. 3) The agriculture land is mainly affected due to flood.
 107. Kuntrichar Part-2	1) RCC porcupines and bamboo piles are installed, but at present these are under water. 2) 200 houses have been washed-out in last 5 years.	 108. Motichar (Kalanchipara)	In 2009, this village was located at left side of the braided channel, but the river has been eroded the land at high-rate, and now village is located at approx. 2 Km of right side of braided channel.
 109. Ramhari Part-3	1) Heavy erosion has been observed. 2) 100 houses have been located on the riverbank, which immediately gets affected by flood.	 110. Takimari	1) An embankment, which was constructed in 1998 has been washed-out and in 2019. 2) A part of embankment got damaged; 20 to 30 houses have been washed-out in 2019.
 111. Fulerchar (Tikona)	1) Moderate to heavy erosion is observed. 2) The water level of 10 feet to 3 feet was recorded from village to road in 2019.	 112. Dakur Bhita	1) Erosion process is high. 2) In 2019, a road has been washed-out. 3) The village is under threat of being washed-out soon.
 113. Khulaktek	1) The village is located at Assam-Meghalaya border and during flood they shift to Meghalaya for their survival. 2) Embankment breach was recorded in 2019.	 114. Patakata	1) This village is in danger situation due to heavy erosion 2) A ferry ghat is located at the u/s of the village.
 115. Fulerchar Part-4	1) A ferry ghat is located here. 2) This ferry ghat has been used for transportation between South Salmara Mankachar and Dhubri. 3) No river training work is required.		

5. Conclusion

5.1. District Wise Distribution of Vulnerable Areas

The district boundary map was overlaid on the vulnerable areas layer to obtain district wise distribution of the vulnerable areas. The district with maximum number of vulnerable areas is Kamrup, Barpeta, and Morigaon with 11, 10, and 9 vulnerable areas in each district, respectively. Out of 115 vulnerable areas along Brahmaputra river in Assam, 66 vulnerable areas are situated on the left (south) bank and 49 vulnerable areas are situated on the right (north) bank. District wise distribution of vulnerable areas is given in Table 5.

5.2. Soil Type vs Bankline Migration Rate in Vulnerable Areas

The field assessment survey of the left and right banks of Brahmaputra river revealed that the soils of the riverbanks mainly comprise of fine clay, heavy clay and sandy clay, heavy clay, sandy clay, sandy clay and silt, and sandy clay and sand, out of which sandy clay and sand are non-cohesive, loose and is more common. Size of the soil particles (sand size or smaller) and the percentages of sand, silt and clay in the soil are influenced by the bank erosion, and it was found that the percentage of sand is greater in the areas of significant riverbank erosion. Lateral migration is a common feature of a braided channel and therefore, it also becomes an important determinant to ascertain the nature of migration of the river bankline. Among the identified vulnerable sites, the lateral migration is highest at Site No. 70 ‘Baralimari, and lowest at

Site No. 89 'Purana Karipara'. Statistical analysis of the average annual channel migration rate of each vulnerable site (1996 to 2020) was carried-out and was compared to riverbank soil types. The results are given in Table 6.

Table 5. District wise Distribution of Vulnerable Areas.

S. No.	District Name	No. of Vulnerable Areas	S. No.	District Name	No. of Vulnerable Areas
1	Tinsukiya	4	12	Morigaon	9
2	Dibrugarh	8	13	Darrang	5
3	Dhemaji	2	14	Dispur	1
4	Lakhimpur	6	15	Kamrup	11
5	Majuli	8	16	Nalbari	1
6	Siva Sagar	2	17	Barpeta	10
7	Jorhat	3	18	Bongaigaon	4
8	Golaghat	8	19	Goalpara	4
9	Bishawnath	5	20	Dhubri	6
10	Sonitpur	5	21	S. Salmara Mankachar	5
11	Nagaon	8		Total	115

Table 6. Average Annual Channel Migration Rate (from 1996 to 2020) vs. Soil Type.

S. No.	Soil Type	Soil Type wise Average Annual Channel Migration Rate (m / year)
1	Fine clay	055.63
2	Heavy clay and sandy clay	079.62
3	Heavy clay	088.33
4	Sandy clay	089.74
5	Sandy clay and silt	104.89
6	Sandy clay and sandy	121.69

The Brahmaputra river has frequently changed its course over the last 25 years, with vast erosion of the riverbank, especially after the 1998 floods[1] [22]. Referring to Table 6, the channel migration rate is very high in (i) sandy clay and sandy, (ii) sandy clay and silt, and (iii) sandy clay (in decreasing order), while channel migration rate is lower in (iv) fine clay and (v) heavy clay. The bankline of the Brahmaputra river is very unstable and bank failure is rampant in many vulnerable areas along the river during the monsoon season. These failures are a function of hydraulic character of flow and engineering properties of bank materials. Riverbank failure (slumping) is caused by undercutting of the upper bank materials and by the field assessment it is revealed that it is the most widespread erosional process responsible for riverbank failure.

5.3. Soil Type vs Land Erosion in Vulnerable Areas

Riverbank erosion and deposition is a mechanism of sediment (bank material) transportation by a river that affects the river channel courses [23]. Fluvial geomorphic processes are highly active in most of the rivers in north and north-east India. River erosion is commonly observed in the Brahmaputra river and its tributaries as well. Multi-temporal Landsat satellite remote sensing data from 1996 to 2020 were used for this analysis. Banklines of pre-monsoon from 1996 to 2020 have been digitized. The two resultant shapefiles were superimposed in-order-to demarcate union wise erosion and deposition areas. The high erosion and high bar deposition areas were identified, which were verified during the field assessment. The total area of erosion and deposition from all the unions were calculated from 1996 to 2020 using ArcGIS 10.7 software. Based on the last 25 years (from 1996 to 2020) Landsat satellite imagery analysis, the average annual erosion rate (in km^2) is calculated. The average annual erosion rate is highest at Site No. 70 'Baralimari, which is 1.885 km^2/year, and lowest at Site No. 89 'Purana Karipara', which is 0.087 km^2/year. Statistical analysis of average annual erosion rate in each vulnerable site (1996 to 2020) was carried out and was compared with the riverbank soil types. The results are given in Table 7.

Table 7. Average Annual Erosion Rate (1996 to 2020) vs. Soil Type.

S. No.	Soil Type	Soil Type wise Average Annual Erosion Rate (Km^2 / year)
1	Fine clay	0.3996
2	Heavy clay and sandy clay	0.4939
3	Heavy clay	0.4939
4	Sandy clay	0.5021
5	Sandy clay and silt	0.5960
6	Sandy clay and sandy	0.6812

Referring to Table 7, the average annual erosion rate is very high in (i) sandy clay and sandy soil, (ii) sandy clay and silt soil, and (iii) sandy clay soil (in order of decreasing rate), while average annual erosion rate is lower in (iv) fine clay soil, and (v) heavy clay soil. The particle size analysis clearly indicates that the clay content plays vital role in resisting erosion in the Brahmaputra valley. In areas less prone to erosion, the percentage of clay is quite high as compared to the areas prone to erosion. Silty and sandy soils are most prone to erosion by water, and is erosion is observed higher in the areas with high rainfall and gentle slopes. The areas highly vulnerable to erosion commonly have shallow channels or rills.

5.4. Recommendation

Many vulnerable areas along the Brahmaputra river, visited by

1 Water Resources Department, Govt. of Assam. https://waterresources.assam.gov.in

the author, need an urgent attention for flood and erosion control as those areas are not equipped with proper embankments and other river training structures. Erosion is also intensive in these areas and human lives and livestock as well as land and properties are at risk. Urgent attention is also required towards the rampant channel migration of Brahmaputra river. So far, the measures taken to protect the area from flood and erosion are not adequate. Some of the important embankments were constructed long time back and needs maintenance, and thus, pose a huge risk to life and property. Embankments, spurs, RCC porcupines, bamboo piles, geo-textile fabric bags filled by riverbank material, etc. are constructed / installed at various vulnerable location, but many of these are eroded away or damaged by the flood water. Additional protection works are required to protect the actively eroding riverbank line and to strengthen the existing embankments. State Govt. or other stakeholders can use this classification scheme for vulnerable areas and can make plans and strategies for regular monitoring and management of the critical reaches in order of their vulnerability.

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