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Braided River Morphodynamics and Trend Analysis of Brahmaputra River Bankline Between Pandu and Goalpara, Assam

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Abstract

Braiding is a fluvial pattern characterized by a complex dynamic where different channels merge and divide continuously, and it is most dynamic earth-surface processes. In this type of study, the remote sensing and geographic information system techniques are playing a vital role for analyzing of braided river morpho-dynamics and trend analysis of river bankline. Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI satellite remote sensing data between 1996 and 2021 (26 years in total) during the dry season (March-April-May) have been used for this study of Brahmaputra river bankline between Pandu and Goalpara, Assam. World biggest river width variation has been observed in this reach, while the average river width of Brahmaputra river in Assan is 9.33 Km. The minimum and maximum river width variation is 1.49 Km at Saraighat bridge to 18.83 Km (just 37 Km downstream of Saraighat bridge). The average number of braided bars and braided bar areas in Brahmaputra river reach between Pandu and Goalpara is 184, and 390.29 Km^2 respectively. The entire river reach is highly dynamic, the major bed level changes (-0.33 m) were observed at Paharpur Katuli village of Barpeta district. It is situated at very danger node and need urgent treat. The reason of enthusiastically erosion in Paharpur Katuli village is the under-construction bank protection work in opposite side (south bank) of that village. Due to this, the flow of mainstream has turned to Paharpur Katuli village, and actively erosion is happening here. It is extremely vulnerable area and approximately 2 Km of land has been washed-out in last two months. The erosion is very active, and approx. 150 m of land is eroded every day, and villagers urged for an immediate action.

Keywords

Braided River, Morpho-dynamics, Trend Analysis, Brahmaputra River, Remote Sensing, GIS

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1. Introduction

Braiding is a fluvial pattern characterized by a sophisticated dynamic where different channels merge and divide persistently along their floodplain. It is one of Earth's most dynamic surface processes, and it belongs to the continuum of river channel patterns [1]. Braiding rivers are generally not found in nature, and extraordinary permutations of the conditions required to make them are needed [2]. These necessary conditions may occur a laterally active bed and the presence of bars, a quiet particular type of fluvial bed form, which may be forming in piedmont plain (lesser Himalayas, Siwalik hills, Brahmaputra valley) or wide river deltas (Sundarbans delta) [3]. The combination of all these elements makes braiding a fascinating, highly complex, dynamic system [4]. A braided-river system can be described as a complex network of river channels within a braided belt. Its morphology is dynamic, and significant morphological changes such as new channel branching, changing thalweg direction, and secondary channel closing

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take place within a short period [5].

The Brahmaputra river is a large world-wide river originate from ChemaYundung glacier of the Kailash range near the Mansarovar lake in southwest Tibet at an elevation of 5300 m amsl, and flowing through Tibet, India, and Bangladesh. The Brahmaputra river travel a total distance of 2880 Km, out-of-that 1625 Km traverses in Tibet, 918 Km traverses in India, and 337 Km traverses in Bangladesh. It has ranking third in the world in terms of very high sediment discharge, fifth in terms of water discharge, and eleventh in terms of drainage area. The dominant discharge is about 38000 cumecs, which is a high in-bank flow [6]. Brahmaputra river has flow in Tibet (higher and lesser Himalayas and Siwalik hills) in very deep gorges with a high gradient from 4.3 m / Km to 16.8 m / Km, till the Pasighat of Arunachal Pradesh, India. In Pasighat, the width of Brahmaputra river is only 0.6 Km, while only 13 Km downstream of Pasighat, the river width has increased from 0.6 Km to 10 Km. Due to sudden decrease of gradient to 0.27 m / Km, the huge sediment deposition development of a braided channel consisting of a network of small channels separated by transitory braid bars. The river is braided with shifting anabranches, moveable sand bars, meta-stable islands, and severe bank erosion.

Majority of studies related to the morphology of Brahmaputra river system focuses on the main river channel of Brahmaputra [7-12]. Sedimentation study of the char bars of the Brahmaputra river was analyzed by [13-15]. Erosion rate and bankline migration of the Brahmaputra river have been analyzed by [7, 12, 16-17] in Assam. Danish Hydrological Institute (DHI) has set-up the river morphological model, real-time flood forecasting and early warning model, and embankment breach prediction model in Brahmaputra river for Flood and Riverbank Erosion Management Agency of Assam (FREMAA) under Assam Integrated Flood and Riverbank Erosion Risk Management Investment Program (AIFRERMIP) [18]. Recently, [12, 19-23] have carried-out various studies of Brahmaputra river in Assam, these are: (a) cause of shrinking of Majuli island, (b) bank and embankment failures, (c) identification of vulnerable areas to natural hazards, (d) historical morphological study, (e) hydromorphogeobathymetry investigation of Dibru-Saikhowa national park, and (f) morpho-dynamics of Brahmaputra river near Bogibeel bridge.

The present paper focusses on the braided river morpho-dynamics and trend analysis of Brahmaputra river bankline between Pandu and Goalpara, Assam. The main aim of this study is to analysis and investigate the (i) mean river width from 1996 to 2021, (ii) braided bars analysis, (iii) braided channel morphology and active channel water spread area analysis, (iv) thalweg profile analysis, (v) river bankline migration and trend analysis, and (vi) field assessment of most vulnerable areas.

2. Study Area

The Brahmaputra is one of the largest rivers in the world and ranks fifth in terms of its average discharge. The river originates from the Kailash ranges of the Himalayas at an altitude of 5300 meters. After flowing through Tibet, it enters India through Arunachal Pradesh and flows through Assam and Bangladesh before joining the Bay of Bengal. Based on the Landsat satellite imageries from 1996 to 2021, the average width of Brahmaputra river in Assam is 9.33 Km. Studies on morpho-dynamics and trend analysis, first look to identify the order of streams and the river reaches (or stretches) throughout the length of the rivers. The Brahmaputra river has been divided into 6 reaches. The lengths of reaches range from 74 Km to 151 Km. It has been taken care of that the intersection of two reaches should not be close to vulnerable sites and areas with major river morphological changes (Table 1).

Table 1. Reach Name and its Total Lengths.

S. No.	Reach No	Reach Name	Length of Reach (Km)
1	Reach-01	Confluence of Dihang, Dibang and Lohit to Bogibeel Bridge	120.91
2	Reach-02	Bogibeel Bridge to Nimati Ghat	73.95
3	Reach-03	Nimati Ghat to Tezpur	151.19
4	Reach-04	Tezpur to Pandu	131.18
5	Reach-05	Pandu to Goalpara	113.23
6	Reach-06	Goalpara to Dhubri	90.80
		Total	681.26

For the study of braided river morpho-dynamics and trend analysis of Brahmaputra river, reach-05 (Pandu to Goalpara) has been selected. This reach lies between latitude 26° 02' 13" N to 26° 20' 20" N, and longitude 90° 33' 49" E to 91° 39' 54" E. The maximum river width variation is found in this reach. The minimum river width of Brahmaputra river in Assam has observed at Saraighat bridge with 1.49 Km, while the maximum river width of Brahmaputra river in Assam has observed just 37 Km downstream of Saraighat bridge, which is 18.83 Km. In only 37 Km of river reach, we can see the world biggest variation of river width. The river's width increased from 1.49 Km to 18.83 Km, and we see a difference of 17.34 Km. In only 37 Km of river reach, on an average the river width increases by 2.13 Km / Km. The location map of study area is shown in Figure 1.

3. Data Used and Sources

Data used, and their sources which have been used for analysis of braided bar, braided channel morphology, thalweg profile, river bankline trends are shown in Table 2.

Table 2. Data Used and their Sources.

S. No.	Data Type	Data Sources
1.	Landsat Series Satellite Imageries from 1996 to 2021	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, 2021 Spatial resolution: 30 m Acquisition period: Pre-Monsoon (March to May) Source: https://earthexplorer.usgs.gov
2.	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. Slope map has been created using Spatial Analyst Extension in ArcGIS 10.7, and SRTM DEM data with 30 m spatial resolution. Source: http://glcfapp.glcf.umd.edu:8080/esdi

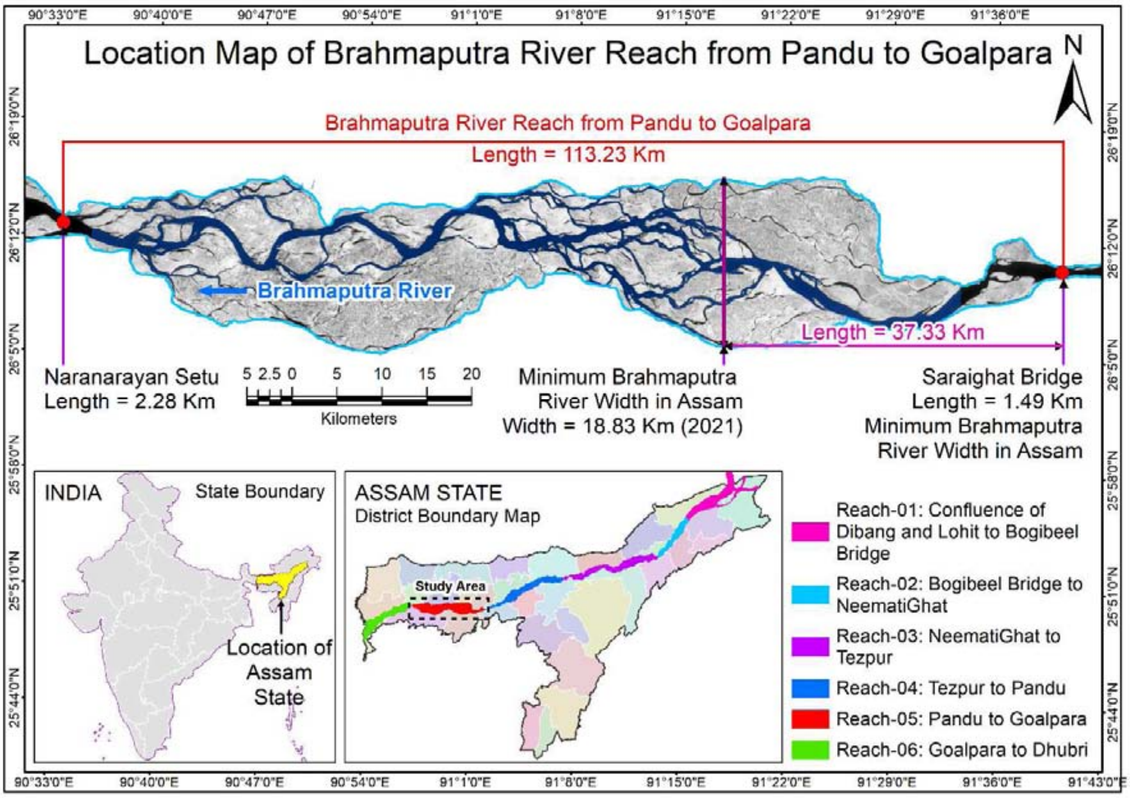

Figure 1. Location Map of Study Area.

4. Methodology

Satellite remote sensing data download from Earth Explorer, USGS had been geo-processed and analyzed through digital image processing.

4.1. Geo-Processing of Satellite Imagery

The raw data acquired from USGS has been stored in a specific folder in the computer. Image processing software has been used for viewing the raw satellite imagery and for geo-referencing. The satellite imageries have several tiles because study area covers a very large area. Therefore, all the tiles have been mosaicked into a single image for easy geo-referencing. Edge matching was done by bringing two adjoining images of the same area into the same map file and matching their edges to form a seamless map file. After the mosaicking, the satellite imagery was processed for the removal of haze and noise and then image enhancement allowed for better readability and analyses by using the image processing software. Ground Control Points (GCP) have been collected from Survey of India (SoI) toposheet. Processed GPS acquired point data was used for referencing the satellite imagery. Using GCP's from Survey of India (SoI) toposheet the satellite imagery was geo-positioned / geo-referenced in required projection and datum as per the standard process of the image processing software. The projection system - Universal Transverse Mercator (UTM) zone 46, and datum - World Geodetic System 1984 (WGS-84) has been used for better calculation and verification of distances between utilities, bank line, river infrastructure, area calculations and the span length. Nearest neighbourhood method has been taken for the transformation of the raw satellite data to geo-referenced satellite data. An automatically generated Root Mean Square Error (RMSE) has been maintained of less than 0.23.

4.2. Satellite Imager Analysis and Digital Image Processing

The remote sensing and geographic information system methods and other statistical data techniques have been used for the assessment of riverbank erosion-accretion and identification of river bankline migration and trend analysis of the Brahmaputra river. Landsat satellite images from 1996 to 2021 of twenty-six different time periods during the dry season (March-April-May) have been considered in this study, dry season was taken place in order to avoid over-estimation of the river expanse which is common with the images taken during high stages of flow or monsoon and flooding seasons. The satellite image data selected was cloud free.

Digital Image Processing (DIP) techniques have been used for extraction of braided bar, braided and active channel water spread area in ArcGIS 10.7 software.

5. Result and Discussion

5.1. Mean River Width

The river width has been measured at 113 cross-sections (1 Km interval) of Brahmaputra river reach from Pandu and Goalpara by using multi-temporal satellite remote sensing data from 1996 to 2021. 113 cross-sections vs river width (m) has been plotted and shown in Figure 2. it is observed that river width is large in the flood year. Based on the Landsat satellite imageries from 1996 to 2021, the average width of Brahmaputra river in Assam is 9.33 Km. World biggest river width variation has witnessed here, which is ranging from 1.49 Km at Saraighat bridge to 18.83 Km (just 37 Km downstream of Saraighat bridge).

5.2. Braided Bar Analysis

The Brahmaputra river is a multi-channel river system with a connection between braided, meandering of active channel within the bankline, and anastomosed rivers [24]. Braided rivers display several channels that are separated and interconnected to appear in a braid. Braided river systems are considered by more than one braiding parameters, low sinuosity, low slope, abundant sediment supply, high and variable discharge, and high width / depth ratio [25]. As the flow regimes in a river vary, braiding is developed by systematic sorting as the stream accumulates load sizes that are no longer able to be carried. This bedload deposition will result in many different types of bars and red forms, which in turn disrupt and divert the flow. Banks that are easily destroyed will facilitate this process [25].

Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI satellite remote sensing data with 30 m spatial resolution between 1996 to 2021 (26 years in total) have been used for extraction of braided bars using digital image processing (DIP) in ArcGIS 10.7 software. Year wise braided bars with number of bars, and total braided bars areas are given in Table 3.

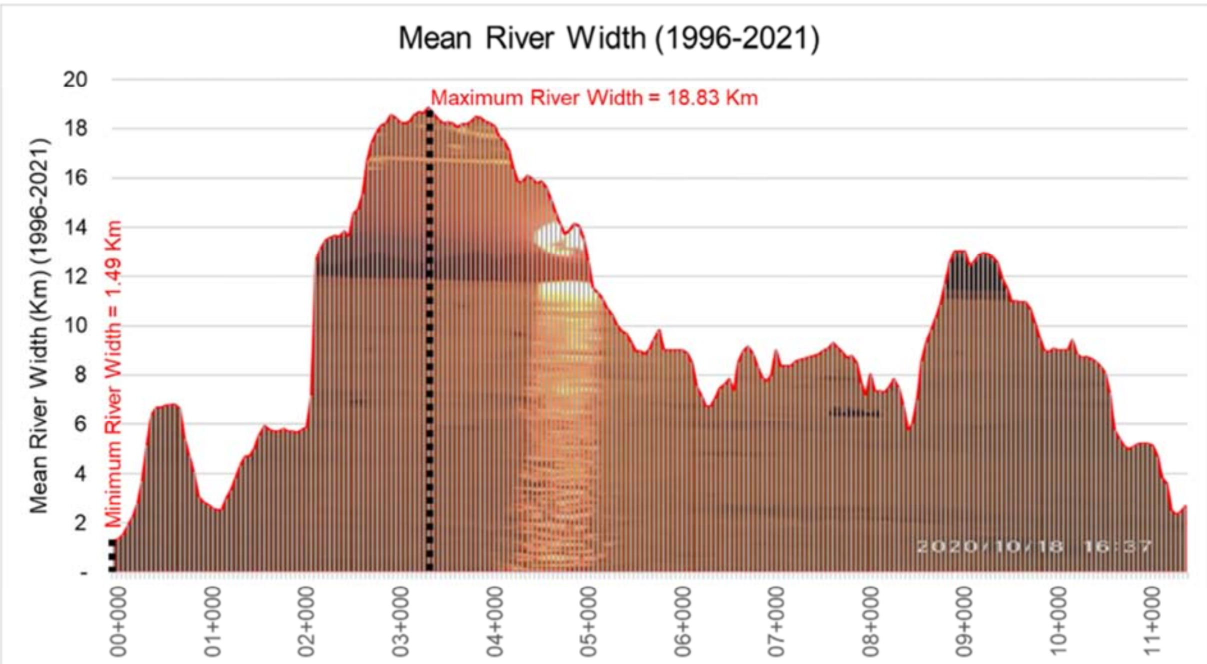

Figure 2. Mean River Width (1996-2021).

Table 3. Year wise Braided Bars with Number of Bars and Total Areas (1996-2021).

S. No.	Years	Total Number of Char Bars	Total Char Bars Area (Km^2)	Changes in Char Bars Area (Km^2)	Cumulative Change (Km^2)
1	1996	176	435.63		
2	1997	177	433.77	1.86	1.86
3	1998	358	266.66	167.12	168.97
4	1999	178	305.88	-39.22	129.75
5	2000	177	436.02	-130.15	-0.40
6	2001	180	483.21	-47.19	-47.59
7	2002	208	477.21	6.00	-41.58
8	2003	224	711.68	-234.47	-276.05
9	2004	144	378.80	332.88	56.83
10	2005	165	262.95	115.85	172.68
11	2006	205	506.91	-243.97	-71.29
12	2007	166	279.20	227.72	156.43
13	2008	127	245.05	34.14	190.58
14	2009	148	407.61	-162.56	28.02
15	2010	201	438.36	-30.75	-2.73
16	2011	161	346.77	91.59	88.86
17	2012	146	543.76	-196.98	-108.13
18	2013	200	478.43	65.32	-42.81
19	2014	250	508.83	-30.39	-73.20
20	2015	210	535.94	-27.12	-100.32
21	2016	161	274.60	261.34	161.02
22	2017	117	293.49	-18.89	142.14
23	2018	131	266.26	27.23	169.37
24	2019	347	296.59	-30.33	139.04
25	2020	131	248.25	48.34	187.37
26	2021	105	285.75	-37.49	149.88
	Average	184	390.29	5.99	

Referring to Table 3, the average char bars in around 113 Km Brahmaputra River reach between Pandu to Goalpara are 184, while the mean char bars area in that reach is 390.29 Km^2. It is notices that from 26 years data (1996-2021), when extreme flood occurred in Brahmaputra River, the number of char bars have also increased, but the total char bars area has decreased. These has inverse correlation between number of char bars and total char bars area, when extreme flood event occurred, as Brahmaputra River had been experienced the extreme flood in 1998, and 2019 (Figure 3), but it may vary in other reach of Brahmaputra River or any other braided river. Between that Brahmaputra River reach from Pandu to Goalpara, it has also noticed that the total char bars areas are continuous decreasing, and erosion is more active in that reach (Figure 4). The average (mean) change in char bars area is 5.99 Km^2 / year, while the cumulative change in char bars areas from 1996 to 2021 is +149.88 Km^2 (Figure 5).

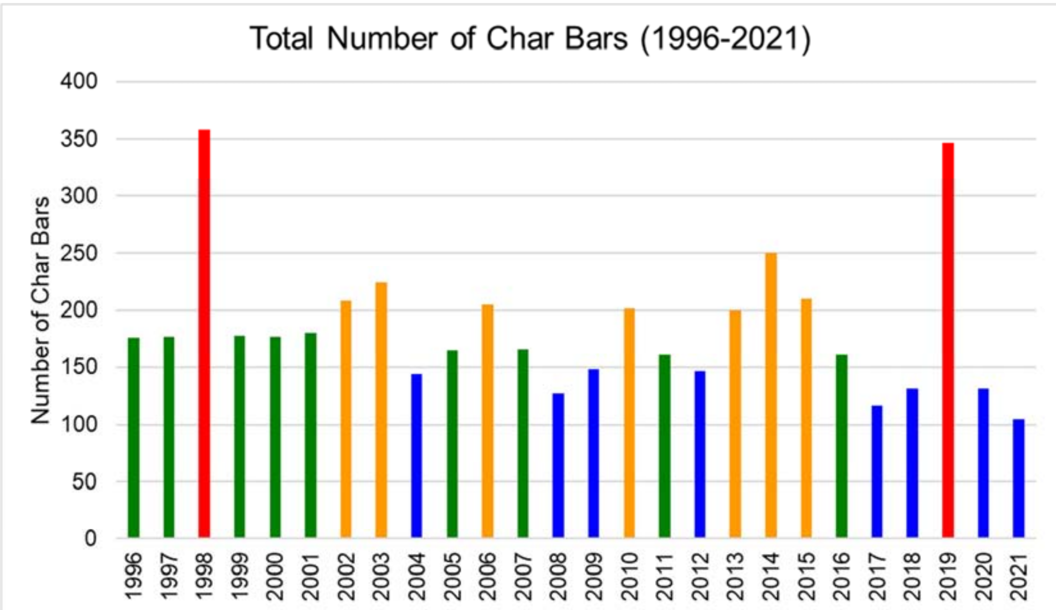

Figure 3. Total Number of Char Bars (1996-2021).

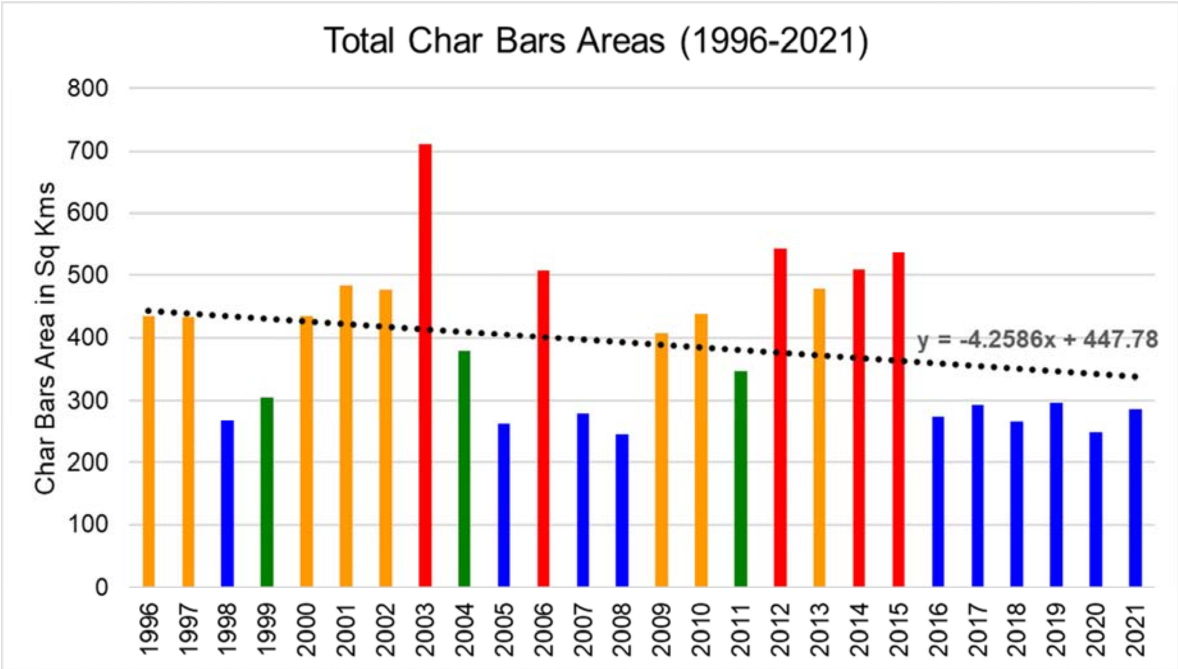

Figure 4. Total Char Bars Areas (1996-2021).

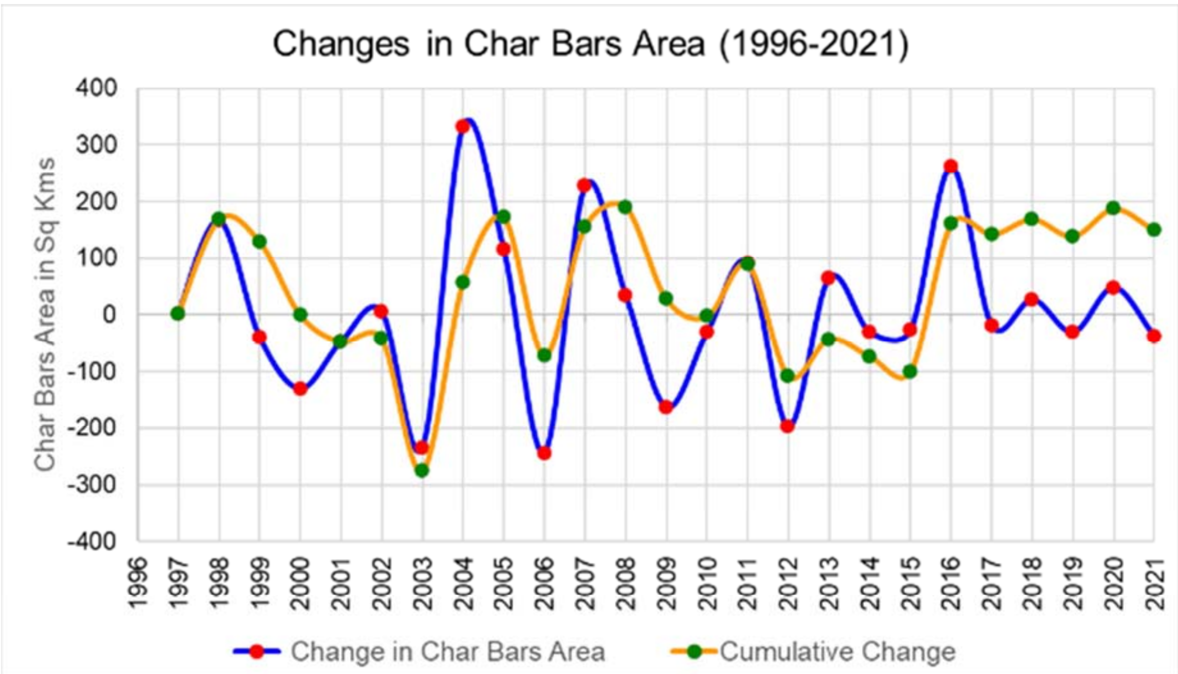

Figure 5. Changes in Char Bars Area (1996-2021).

5.3. Braided Channel Morphology

A fundamental aspect of braided morphology is the complexity of the channel pattern, commonly referred to braiding intensity [26-28]. Braiding intensity may refer to all wetted channels ('total braiding intensity') or may be limited to active braiding intensity in which active channels are transporting bedloads or showing measurable morphological changes at a certain time or during a certain time interval [29-30]. Channel counts and total sinuosity indexes have been widely used in the analysis of braided channel-pattern changes over time and the response of external controls [26, 29, 31-33].

Active channel water spread area from 1996 to 2021 have been extracted from pre-monsoon (March-April-May) Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI satellite imageries. Brahmaputra river reach between Pandu to Goalpara with an aerial length of 113 Km has been analyzed and given in Table 4 and shown in Figure 6.

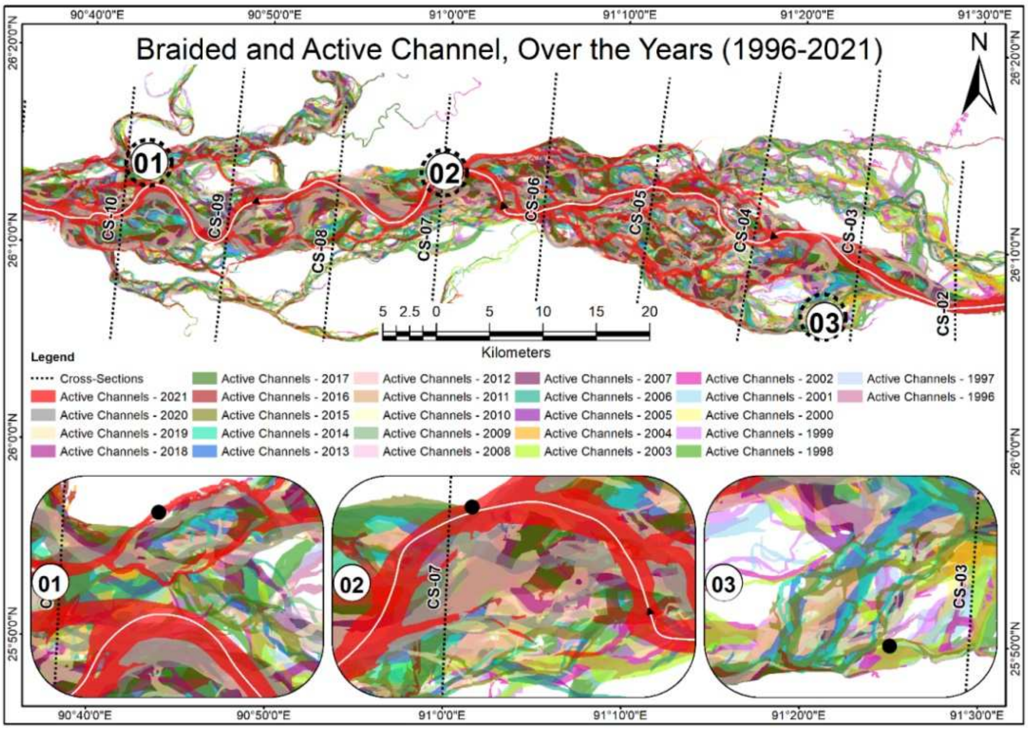

Figure 6. Braided and Active Channel, over the Years (1996-2021).

Table 4. Active Channel Water Spread Area (1996-2021).

S. No.	Years	Column (3)*	Column (4)#	S. No.	Years	Column (3)*	Column (4)#
1	1996	236.90		15	2010	289.30	-60.75
2	1997	403.64	-166.74	16	2011	262.32	26.99
3	1998	352.41	51.22	17	2012	264.79	-2.47
4	1999	238.47	113.95	18	2013	294.26	-29.47
5	2000	209.77	28.70	19	2014	339.86	-45.60
6	2001	245.63	-35.86	20	2015	437.88	-98.02
7	2002	295.32	-49.69	21	2016	269.88	167.99
8	2003	336.62	-41.30	22	2017	209.68	60.20
9	2004	233.93	102.69	23	2018	227.15	-17.47
10	2005	216.26	17.67	24	2019	280.86	-53.70
11	2006	309.04	-92.78	25	2020	206.55	74.31
12	2007	233.79	75.25	26	2021	270.60	-64.05
13	2008	217.66	16.13	Average		273.50	-1.35
14	2009	228.55	-10.89				

Where: Column (3)* = Active Channel Water Spread Area (Km^2), Column (4)# = Change in Water Spread Area (Km^2)

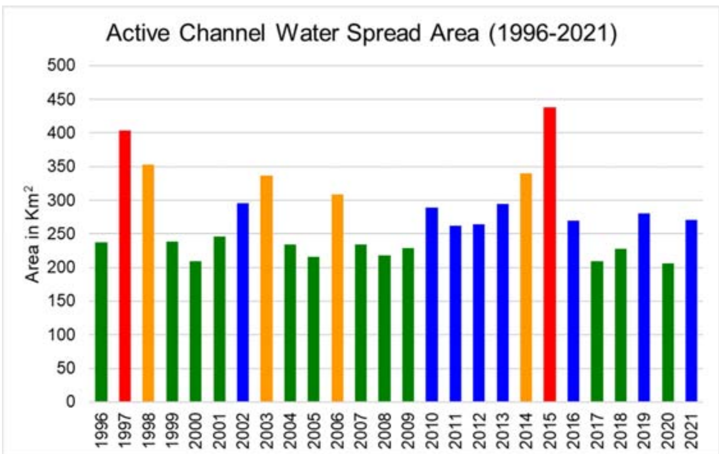

Figure 7. Active Channel Water Spread Area (1996-2021).

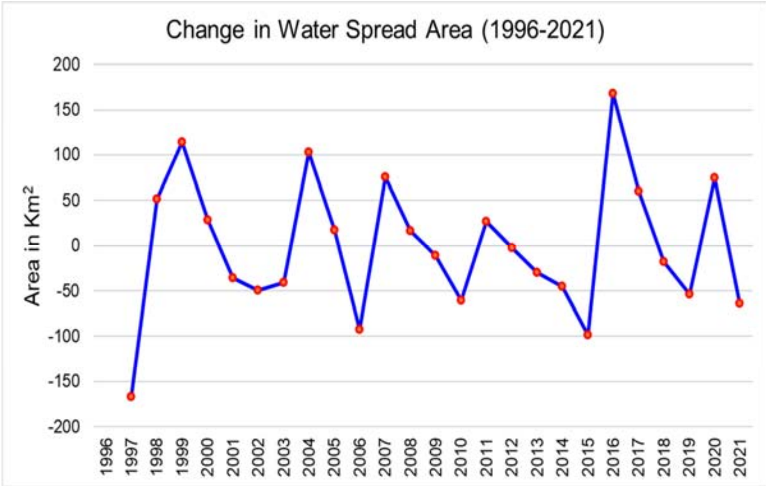

Figure 8. Change in Water Spread Area (1996-2021).

Active channel water spread areas are ranging from 206.55 Km^2 to 437.88 Km^2 between 1996 and 2021, while the average active channel water spread area is 273.50 Km^2 (26-years average). The maximum active channel water spread area has been found in 2015 as 437.88 Km^2, then in 1997 as 403.64 Km^2 (Figure 7). It has also noticed during the analyzing of change in active channel water spread area (1996-2021) that the active channel water spread area is continuous decreasing, and it has decreased 1.35 Km^2 per year (Figure 8).

5.4. Thalweg Profile Analysis

The thalweg is the line connecting the deepest bed levels of successive cross-sections of a river. The deepest bed elevations in all the available cross sections of a year were plotted to understand the bed elevation trend between the years. In wide multi-channel rivers like Brahmaputra, these deepest points can switch from one channel to another from one transect to another within a year, and between two successiveyears. Therefore, the changes in the thalweg profile do not give us a definite value of rising or fall in a channel, but an average representation of changes in the bed of the channel. Thalweg (mainstream) length from 1996 to 2021 is given in Table 5. The thalweg profiles from 1996 to 2021 have been generated and shown in Figure 9.

Table 5. Thalweg Length (1996-2021).

S. No.	Years	Thalweg Length (Km)	S. No.	Years	Thalweg Length (Km)
1	1996	123.830	15	2010	111.847
2	1997	116.921	16	2011	110.477
3	1998	118.527	17	2012	111.356
4	1999	109.039	18	2013	110.688
5	2000	118.034	19	2014	117.471
6	2001	115.499	20	2015	110.090
7	2002	111.437	21	2016	110.509
8	2003	111.833	22	2017	114.846
9	2004	116.237	23	2018	112.308
10	2005	114.430	24	2019	112.770
11	2006	111.406	25	2020	115.539
12	2007	114.609	26	2021	115.981
13	2008	108.341	Average		113.755
14	2009	113.615			

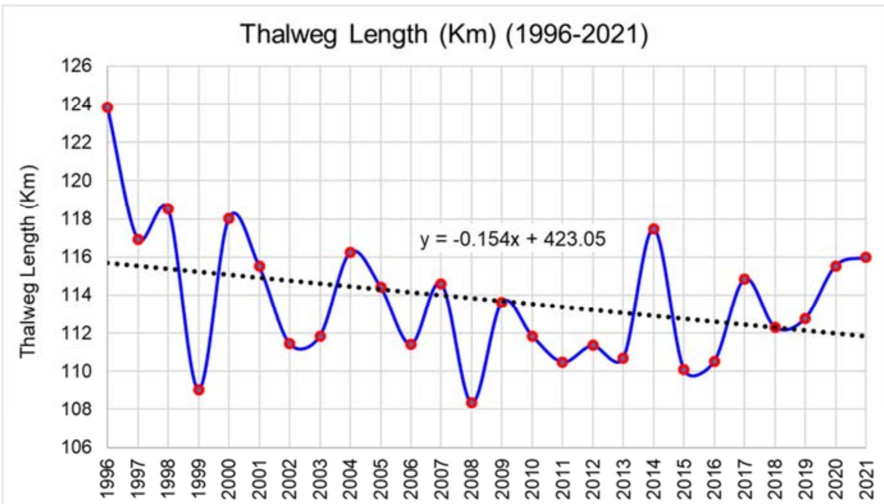

Figure 9. Thalweg Length (1996-2021).

The analysis of change in the thalweg gives the following results: the river is highly dynamic in the entire reach; the average change in the riverbed level is found to be -0.33 m (fall of 0.33 m); maximum fall in the bed level was found to be 1.23 m from the year 2007 to 2008; the major bed level changes were observed at Paharpur Katuli village of Barpeta district. According to thalweg profile analysis, the Paharpur Katuli village is situated in very vulnerable areas for erosion.

5.5. River Bankline Trend Analysis

Extreme flood events in Brahmaputra river cause instability to the channel and the banks. The trends of channel migration have been established by comparing satellite images for 1996 to 2021. The approach is based on geospatial analysis of bankline changes along the river. The banklines migration are digitized manually using Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI satellite imageries for the respective years. Examination of the bankline migration of Brahmaputra river has been carried out in a 113 Km river reach from Pandu to Goalpara.

The river bankline migration has been measured at every 10 Km cross-section lines. The bankline migration has been measured in both bank lines i.e. right bankline (north bank) and left bankline (south bank) with reference to length (in metres) and direction from 1996 to 2021. A positive value (+) indicates that the river bankline has migrated in the right direction from previous year, while a negative value (-) indicates that the river bankline has migrated in the left direction from previous year. For trend analysis, the cumulative bankline migration (m) is also measured from 1996 to 2021 and shown in Table 6.

Table 6. Measurement of River Bankline Migration (m) on Right Bankline (North Bank) and Left Bankline (South Bank) of a 113 Km River Reach of Brahmaputra River.

Years		CS-01	CS-02	CS-03	CS-04	CS-05	CS-06	CS-07	CS-08	CS-09	CS-10	CS-11
	1997	0.0	-9.9	209.2	91.9	40.8	208.3	0.0	334.0	113.1	-23.8	184.6
	1998	0.0	0.0	54.2	79.8	5.8	0.0	51.9	166.8	-93.2	-292.9	0.0
	1999	-6.8	31.0	-1.1	141.1	171.6	80.9	9.0	210.4	548.7	311.3	851.4
	2000	0.0	0.0	0.0	25.8	188.3	0.0	91.5	152.0	-84.9	0.0	-344.7
	2001	0.0	0.0	0.0	69.2	36.0	35.3	85.3	324.0	105.3	80.9	0.0
	2002	0.0	0.0	-610.4	0.0	-25.8	152.3	0.0	622.9	110.9	75.2	-229.2
	2003	0.0	0.0	-309.9	79.2	47.7	0.0	161.0	141.0	19.9	403.5	195.4
	2004	0.0	0.0	0.0	59.2	0.0	22.9	0.0	-939.9	29.2	2069.9	71.1
	2005	73.6	0.0	34.7	44.5	0.0	208.3	0.0	88.5	100.5	47.6	80.1
	2006	0.0	0.0	0.0	0.0	0.0	164.3	27.3	855.4	0.0	0.0	0.0
	2007	43.0	5.8	-34.0	-52.8	-5.6	111.1	-69.6	-525.9	-0.2	21.5	-18.2
	2008	0.0	0.0	36.0	0.0	0.0	287.7	-5.4	0.0	128.2	-189.5	61.8
Right Bankline	2009	-170.8	0.0	0.0	0.0	-14.7	325.1	32.7	518.7	33.3	0.0	36.2
	2010	-77.1	20.5	0.0	0.0	7.5	174.6	315.7	60.8	262.5	-75.8	-31.7
	2011	-33.4	-17.7	-16.5	0.0	0.0	0.0	0.0	0.0	-19.4	384.5	29.1
	2012	0.0	0.0	8.1	-69.7	40.3	26.2	118.9	-100.9	51.1	0.0	0.0
	2013	0.0	0.0	0.0	0.0	-43.3	0.0	18.5	-59.4	0.0	0.0	0.0
	2014	0.0	0.0	0.0	0.0	43.3	0.0	135.3	-517.3	-47.9	-228.5	0.0
	2015	55.2	0.0	99.4	0.0	0.0	0.0	40.8	0.0	115.9	0.0	29.4
	2016	0.0	0.0	0.0	0.0	46.2	0.0	0.0	0.0	0.0	187.1	0.0
	2017	27.4	0.0	0.0	0.0	80.4	11.4	-0.1	0.0	0.0	0.0	18.1
	2018	0.0	0.0	-53.1	0.0	-36.1	0.0	0.0	0.0	0.0	0.0	0.0
	2019	22.3	0.0	0.0	-74.2	0.0	0.0	0.1	0.0	3.7	0.8	0.0
	2020	118.2	0.6	0.2	0.4	0.0	-0.2	1.5	173.9	0.5	1.2	-43.6
	2021	2.2	1.3	-24.3	16.4	24.3	75.3	42.3	62.7	57.4	115.5	37.1
Right Bankline Trends in 2021		53.9	31.5	-607.7	410.8	606.9	1883.5	1056.7	1567.6	1434.4	2888.6	927.0
Years		CS-01	CS-02	CS-03	CS-04	CS-05	CS-06	CS-07	CS-08	CS-09	CS-10	CS-11
	1997	0.0	-49.9	190.9	-9.4	-31.6	-194.9	0.0	0.0	-12.3	112.8	-100.4
	1998	0.0	-28.5	-94.8	8.1	-14.7	0.0	0.0	0.0	0.0	-111.1	-41.9
	1999	-12.9	-54.6	-35.6	-130.2	-116.2	-428.6	0.0	0.0	-110.6	0.0	-117.5
Left Bankline	2000	0.0	0.0	0.0	-179.3	12.9	-154.0	0.0	0.0	-22.5	0.0	0.0
	2001	157.9	0.0	42.9	-161.7	929.7	0.0	0.0	0.0	0.0	0.0	0.0
	2002	-60.7	0.0	-42.9	0.0	-107.5	-10.1	0.0	0.0	23.5	47.6	0.0
	2003	-97.2	0.0	0.0	-60.2	-1.3	-60.7	0.0	0.0	0.0	0.0	0.0
	2004	0.0	0.0	0.0	0.0	-862.6	-47.7	0.0	0.0	36.8	-64.7	0.0
	2005	0.0	-1.2	0.0	0.0	-102.8	-240.0	0.0	0.0	138.1	0.0	0.0

Years	CS-01	CS-02	CS-03	CS-04	CS-05	CS-06	CS-07	CS-08	CS-09	CS-10	CS-11
2006	0.0	0.0	0.0	0.0	-70.3	0.0	0.0	0.0	0.0	0.0	0.0
2007	12.9	-3.6	-13.9	-52.8	-298.8	-130.8	0.0	0.0	0.0	0.0	21.2
2008	0.0	0.0	0.0	0.0	-199.1	-194.6	0.0	0.0	-75.3	-14.7	-24.4
2009	0.0	0.0	92.5	0.0	190.5	0.0	0.0	0.0	0.0	0.0	0.0
2010	0.0	0.0	0.0	0.0	0.0	947.1	0.0	0.0	13.1	0.0	0.0
2011	0.0	4.2	31.4	-2.5	-80.6	0.0	0.0	0.0	0.0	0.0	0.0
2012	0.0	0.0	0.0	0.0	-32.5	0.0	0.0	0.0	0.3	0.0	0.0
2013	0.0	0.0	0.0	0.0	-915.1	-19.4	0.0	0.0	0.0	0.0	0.0
2014	0.0	0.0	0.0	0.0	-399.4	-84.7	0.0	0.0	0.0	0.0	0.0
2015	0.0	-41.4	0.0	0.0	-37.6	-2962.4	0.0	0.0	0.0	0.0	0.0
2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	440.6
2017	0.0	0.0	0.0	75.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2018	0.0	0.0	0.0	0.0	415.7	-4.4	0.0	38.2	-46.1	0.0	0.0
2019	0.0	0.0	0.0	-75.3	74.8	0.0	0.0	0.0	0.0	0.0	0.0
2020	-3.0	-43.6	-19.0	-1.1	-574.7	-7.8	-26.7	-61.0	-48.1	-1.1	-33.2
2021	-0.1	-9.1	6.3	-24.5	-92.5	-149.7	-1.1	-0.9	-4.3	-1.3	6.0
Left Bankline Trends in 2021	-3.1	-227.5	158.0	-613.6	-2313.7	-3742.7	-27.8	-23.7	-107.3	-32.6	150.5

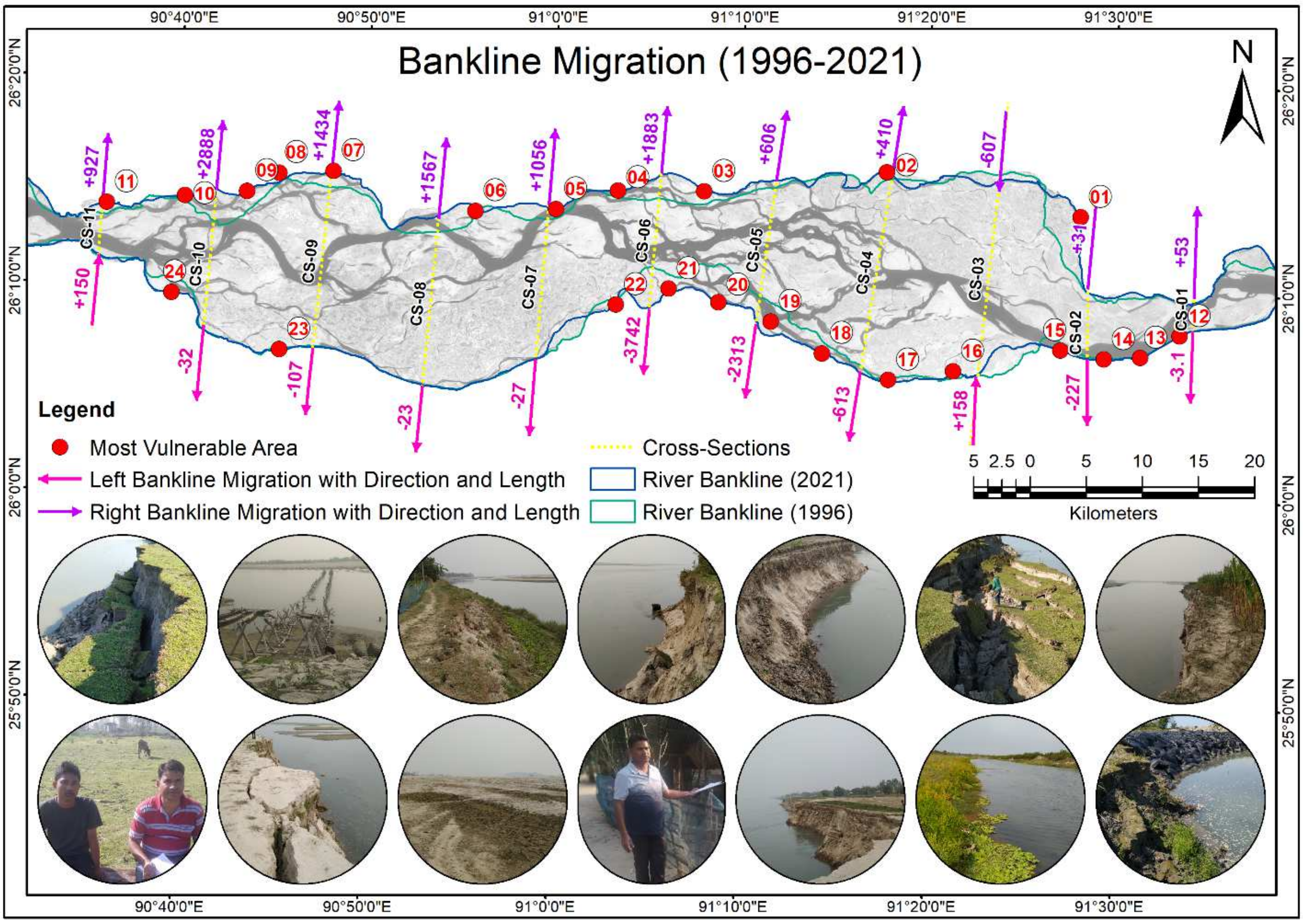

Figure 10. Bankline Migration Map (1996-2021).

River bankline trends have shown through cumulative bankline migration with direction and length in Figure 10. North bankline is more morpho-dynamic then the south bankline. Based on the bankline trend analysis, frequency of river bankline migration, and erosion / deposition pattern over the years, total 24 erosional vulnerable areas were identified, and given in Table 7. These vulnerable areas have been visited and collected the data through field assessment survey. After the data analysis in GIS, and field assessment survey, it has notice that the Paharpur Katuli village (located at north bank and CS-07) is situated at very danger node and need urgent treat. Field assessment data with photographs of Paharpur Katuli vulnerable area is given in below section.

Table 7. List of Erosional Vulnerable Areas.

Site No.	Nearby Village	Block	District	Vulnerable Classes
01	Gendhilatri	Hajo	Kamrup	Highly Sensitive
02	No. 2 Kaplabori	Barkhetri	Nalbari	Highly Sensitive
03	Bahari Koltali	Chenga	Barpeta	Highly Sensitive
04	Balatery	Gomaphulbari	Barpeta	Very-Highly Sensitive
05	Paharpur Katuli	Mandia	Barpeta	Very-Highly Sensitive
06	Kanara Gaon	Mandia	Barpeta	Moderate Sensitive
07	Chikni Rejab	Mandia	Barpeta	Highly Sensitive
08	Paschim Moinbari	Mandia	Barpeta	Low Sensitive
09	Tarakandi	Mandia	Barpeta	Very-Highly Sensitive
10	6 No. Char	Mandia	Barpeta	Moderate Sensitive
11	Mohanpur Part-1	Boitamari	Bongaigaon	Very-Highly Sensitive
12	Majirgaon (Sedilapur)	Sualkuchi	Kamrup	Highly Sensitive
13	Dokala Colony (Palasbari)	Rampur	Kamrup	Moderate Sensitive
14	Purana Karipara	Rampur	Kamrup	Highly Sensitive
15	Futuri Gaon (Mukardhuj)	Rampur	Kamrup	Highly Sensitive
16	Ambari (Gumi)	Goroimari	Kamrup	Highly Sensitive
17	Zaharpur	Goroimari	Kamrup	Highly Sensitive
18	Tukrawara	Goroimari	Kamrup	Moderate Sensitive
19	Bordianayapara	Goroimari	Kamrup	Moderate Sensitive
20	Panikheti	Chamaria	Kamrup	Moderate Sensitive
21	Chintamuni	Chenga	Barpeta	Moderate Sensitive
22	Kachumara	Chenga	Barpeta	Low Sensitive
23	Mornoi Singimari Char	Matia	Goalpara	Low Sensitive
24	Baladmari Char	Balijana	Goalpara	Very-Highly Sensitive

5.6. Field Assessment Survey

The detailed field assessment data of Paharpur Katuli village of Barpeta district, Assam is given in Table 8.

Table 8. Field Assessment Data of Paharpur Katuli Village.

S. No.	Details of Field Assessment Form	
1	General Information	
1.1	Geographical Location	
1.1.1	Site No.	Site No. 05
1.1.2	Village name	Paharpur Katuli
1.1.3	CD block name (according to census of India)	Mandia
1.1.4	District name	Barpeta
1.1.5	State name	Assam
1.2	Site Position	
1.2.1	Survey of India (1: 50,000 scale): toposheet no. and open series map (OSM) No. (in brackets)	78 N / 04 (G46H04)
1.2.2	Latitude (degree decimal-DD) 'Y'	26.231187
1.2.3	Longitude (degree decimal-DD) 'X'	91.000059
1.2.4	Elevation (Above mean sea level, m) (based on handheld GPS device and SRTM DEM data)	42 m
1.2.5	Pre-fix cross-section number	07+000
1.2.6	River name	Brahmaputra River
1.2.7	Bankline (bank to be determined by looking downstream)	Right bankline (north bank)
1.2.8	River flow direction	NE to SW
1.2.9	River width (Km) (based on Landsat-8 OLI satellite imagery, 2020)	10.39
1.2.10	Distance between river and vulnerable area	30 m
1.2.11	Distance between approach road and vulnerable area	30 m
1.2.12	Erosional bankline length (Km) (1996 to 2021)	5.656
1.2.13	Erosional bankline length (Km) (2020 to 2021)	6.099
2	Vulnerable area situated at …..…. reaches	Reach-05: Pandu to Goalpara
3	Lithological, Slope and Soil Information	
3.1	Stratigraphic classification	Sedimentary rock
3.2	Lithological information	Sand, silt with pebbles, gravels and cobbles
3.3	Slope (surrounding area)	Gentle
3.4	Soil primary classification	Younger alluvial soils
3.5	Soil texture	Sandy
4	Physical Attributes of Riverbank	

S. No.	Details of Field Assessment Form	
4.1	Riverbank material	Dry coarse sand
4.2	Riverbank modification	Embanked (partly washed-out)
4.3	Riverbank features	Unvegetated mid-channel bar
4.4	Riverbank profiles - natural / unmodified	Vertical erosion (on-going)
4.5	Riverbank profiles - artificial / modified	Set-back embankment
5	Physical Attributes of Channel	
5.1	Channel bed material	Clay-sand-clay
5.2	Channel flow-type	Free-fall
5.3	Channel modifications	None
5.4	Channel features	Unvegetated mid-channel bar
5.5	Valley form (within the horizon limit)	Braided Channel
6	Geomorphic Features	
6.1	Out-of-channel - geomorphic features	Active floodplain (between current bankline and embankment)
6.2	In-channel - geomorphic features	Braided river, non-sinuous braided river, mid-channel bar
7	Landuse / Landcover (within 100 m of vulnerable area)	
7.1	Land cover	Scrub land, river
7.2	Land use	Agricultural crop land, agricultural fallow land, rural area / village, school, religious place, transportation
8	Any infrastructure (nearby the vulnerable area)	Embankment (Yes. breached in 2019. repaired)
9	Major impacts from vulnerable area	Transportation (road), residential area (rural), agricultural area (crop/fallow), embankment damage, erosion
10	Evidence of recent management	Embankment (Installed in 2019)
11	Flood related Information of the Village nearby the Vulnerable Area	
11.1	About the Village	
11.1.1	Name of village	Paharpur Katuli
11.1.2	Approx. population of the village	4500
11.1.3	Major occupation of the village	Farming
11.1.4	How long have community been living here?	More than 100 years
11.1.5	Majority of construction material	Tin-shed, khas
11.2	Flood Occurrence and Severity	
11.2.1	How many times did community experience flood while living at this village?	Flooded every year during the monsoon season (2019)
11.2.2	What was the maximum water level and duration of flood entering your village?	
11.2.2a	Flood year	2019
11.2.2b	Flood depth	5 feet (Over the embankment)
11.2.2c	Duration	15 days
11.3	Flood Emergency Response	
11.3.1	Just before the flood, how did your community first become aware that flood waters might reach your home?	Observing the river water level
11.3.2	Did share the warning with others?	Yes
11.3.3	How many hours were there between the time your community became aware that flooding might reach your village until the water actually reached to your village?	12 hours
11.3.4	What is the minimum warning time would your community need to move all your transportable contents to a safe location?	2 hours
11.3.5	What is the shortest distance between your village and river?	30 m
11.3.6	Do your community have a safe place to move in case of flooding?	Yes (On embankment)
11.3.7	How far is it from your village?	1 Km
11.4	Flood Impact on Infrastructure	
11.4.1	During the flood, water supply was interrupted?	No water supply
11.4.2	During the flood, the electric supply was interrupted?	Yes
11.4.3	During the flood, the telephone supply / mobile network was interrupted?	No
11.4.4	Was there any secondary source for water supply?	Yes (Handpump, but some villagers are used the river water for drinking)
11.4.5	Was there any secondary source for electric supply?	No
12	Flood Management Activities	
12.1	Which type of flood protection activities, planning, or mitigation your community need in that area.	Increase height of embankment with 5 feet, Boulder pitching or geo-bag pitching is immediately required to stop the ongoing vertical erosion process.
13	Significant Observations, and Conclusions This site is situated nearby the Paharpur Katuli village of Barpeta district. It is extremely vulnerable area and approx. 2 Km of land has been washed-out in last two months. The erosion is active, and 500 feet of land is eroding every day. Erosion is high from last 2-3 months and villagers urged for an immediate action. Instant geo-textile fabric bags or boulder pitching onthe bank is required. Villagers have suggested to increase the height of the embankment. This village and its nearby villages like Jadhavpur, Bamumdungra is under great threat. Large land blocks were falling frequently into the river. During the field assessment work, we have seen approx. 15 feet of land has been eroded in only 10 minutes. 150 to 200 houses have been washed out in 2019.	

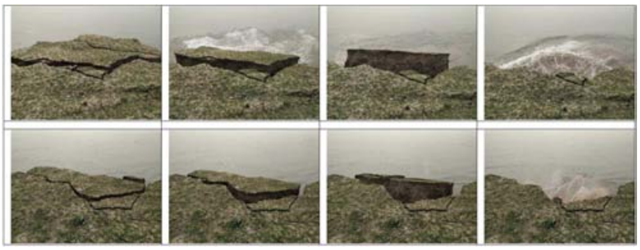

Figure 11. Process of Riverbank Failure (Slumping) at Paharpur Katuli at Location-1 and Location-2.

Figure 12. Various Soil Layers at Paharpur Katuli at Location-3.

The main reason of actively erosion in Paharpur Katuli village is the under-construction bank protection work in three villages Panikheti, Chintamuni, and Kachumara, which are located in opposite side (south bank) of Paharpur Katuli village. Due to these bank protection works (i.e. increase of height of existing embankment, and installed of new spurs), the flow of mainstream has turned to Paharpur Katuli village, that why too much erosion is happening here. In addition to that, four horizontal soil layers of silt-sand-sandy clay-sand (top-to-bottom) has formatted in Paharpur Katuli village and now the flow of water is bump into straight sand layer. Here sand is very loose and eroded very quickly (Figure 12). It is extremely vulnerable area and approx. 2 Km of land has been washed-out in last two months. The erosion is active, and 500 feet of land is eroding every day. Erosion is high from last 2-3 months and villagers urged for an immediate action.

6. Conclusion

Braiding is a fluvial pattern characterized by a complex dynamic where different channels merge and divide continuously, and it is most dynamic earth-surface processes, which are usually not found in nature. For forming of braided channel various extraordinary conditions are require, which may be laterally active bed and the presence of bars, a quiet particular type of fluvial bed form. Landsat-5 TM, Landsat-7 ETM+ and Landsat-8 OLI satellite remote sensing data with 30 m spatial resolution between 1996 to 2021 (26 years in total) have been used for the study of braided river morpho-dynamics and trend analysis of Brahmaputra river bankline between Pandu and Goalpara, Assam.

The average (1996-2021, 26 years average) width of Brahmaputra river in Assam is 9.33 Km (2021). World biggest river width variation has observed here, which is ranging from 1.49 Km at Saraighat bridge to 18.83 Km (just 37 Km downstream of Saraighat bridge). In only 37 Km of river reach, on an average the river width increases by 2.13 Km / Km. The average (1996-2021, 26 years average) number of braided bars and braided bar areas in Brahmaputra river reach between Pandu to Goalpara is 184, and 390.29 Km^2 respectively. The average (mean) change in char bars area is 5.99 Km^2 / year, while the cumulative change in char bars areas from 1996 to 2021 is +149.88 Km^2. From thalweg change analysis, it has observed that the river is highly dynamic in the entire reach; the average change in the riverbed level is found to be -0.33 m (fall of 0.33 m); the major bed level changes were observed at Paharpur Katuli village of Barpeta district.

River bankline trends analysis indicated that the north bankline is more morpho-dynamic then the south bankline. Based on the bankline trend analysis, frequency of river bankline migration, total 24 erosional vulnerable areas were identified. Following remote sensing and GIS based analysis and field assessment survey, it has notice that the Paharpur Katuli village is situated at very danger node and need urgent treat. The main reason of actively erosion in Paharpur Katuli village is the under-construction bank protection work in three villages i.e. Panikheti, Chintamuni, and Kachumara, which are located in opposite side (south bank) of Paharpur Katuli village. Due to these bank protection works (i.e. increase of height of existing embankment, and installed of new spurs), the flow of mainstream has turned to Paharpur Katuli village, that why too much erosion is happening here. In addition to that, four horizontal soil layers of silt-sand-sandy clay-sand (top-to-bottom) has formatted in Paharpur Katuli village and now the flow of water is bump into straight sand layer. Here sand is very loose and eroded very quickly. It is extremely vulnerable area and approximately 2 Km of land has been washed-out in last two months. The erosion is very active, and approx. 150 m of land is eroding every day. Erosion is high from last 2-3 months and villagers urged for an immediate action.

This study has made use of remote sensing data to provide a braided river morpho-dynamics and trend analysis of river bankline over the past two-and-half decades and to uncover many specific features. The study has demonstrated the potential of applying remote sensing data for the rapid interpretation of the features of the braided river covering a large area. The study has revealed the benefits of effective use of geospatial data and riverbank mapping. The results can be made more precise with high-resolution satellite imagery e.g. QuickBird, GeoEye, WorldView.

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