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Erosion–deposition and land use/land cover of the Brahmaputra river in Assam, India

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The Brahmaputra is a unique dynamic river in the world with intense braiding and critical bank erosion. Both erosion and deposition are continuous processes in the river in an attempt to reach a new equilibrium in channel geometry and morphology by the ever dynamic nature of flow. Erosion and deposition of the river have link to land use and land cover (LULC) as the land cover is under constant change in a dynamic landscape constantly shaped by continuous erosion and deposition. The objective of the present work is to evaluate the extent of erosion and deposition along the Brahmaputra river and change in the LULC of the Brahmaputra river in Assam, India. Remote sensing and geographic information system (GIS) techniques were utilised to extract information from Landsat images. Total area of erosion and deposition during 1973–2014 was 1557 and 204 km^2, respectively. Increase in area (28%) of the Brahmaputra during 1973–2014 is not solely due to bank erosion, but also for the bifurcation of streams without the loss of land. LULC study has revealed that 29% area was occupied by active channels and 71% was occupied by bars in 2014. Maximum reaches experienced reduction of the submerged part in 2014 compared to 1994 in the post-monsoon months with an overall decrease from 37% to 29%. A reduction in natural grassland and forest has been observed with a corresponding increase in agricultural practices in different bars and islands of the Brahmaputra in Assam during 1994–2014.

Keywords. Alluvial river; erosion–deposition; LULC; Brahmaputra; Assam.

1. Introduction

Erosion, transportation and deposition are the three major processes in a fluvial system (Schumm 1977) that are influenced by the supply of the sediment at the upstream end and sediment that is locally eroded from the bed and banks (Charlton 2008). Thus, the morphological changes of an alluvial river channel are the consequence of sediment erosion, sediment transport and sedimentation in the river (Church 2006). Different categories of alluvial river patterns, i.e., straight, meandering and braided rivers (Leopold and Wolman 1957) are due to the sediment supply along with the flow regime. Braided rivers are those that flow in two or more channels around alluvial bars or islands. The primary causes of braided channels are the overloading of sediments and steep slopes (Lane 1957). Highly variable discharge, erodible banks and a high width/depth ratio are the other factors responsible for

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braiding (Schumm and Kahn 1972; Knighton 1998). They have a braided look at the low flow stages with exposed bars, but all or some of the bars are submerged during the high flow stages.

The Brahmaputra is an extremely dynamic and predominantly braided river (Coleman 1969) in the world. The Brahmaputra originates as the Yarlung Tsangpo from the Angsi glacier near the Manasarovar lake in the Kailash range in southern Tibet, and it is a trans-boundary river flowing from the Himalayas to the Bay of Bengal through China (Tibet), India and Bangladesh. The river is unique due to its peculiar drainage pattern, diverse geological setting, high sediment load and critical bank erosion problem (Mahanta and Saikia 2015). The Brahmaputra supplies an estimated 1000 million ton of suspended material to the Bay of Bengal (Milliman and Meade 1983; Milliman and Syvitski 1992; Hay 1998). There is an additional strong indication that erosion is a major factor of river instability in the Brahmaputra due to the very large amount of sediment intrusion from bank erosion itself. This sediment causes further instability downstream, triggers more bank erosion, and apart from the loss of land and flood protection, hampers navigation (ADB 2007). The valley of the Brahmaputra river has been facing a heavy instability of landmass due to river bank erosion, believed to be accelerated after the 1950 earthquake. The stretch falling within Assam, India, has already lost about 7.4% of its total land due to bank erosion and channel migration (Kakati and Changkakati 2013). Erosion during 1990–2008 in the north bank and south bank of the Brahmaputra (within Assam) were 544 and 920 km^2, respectively, whereas the corresponding amount of deposition were 145 and 68 km^2 (Sarkar *et al.* 2012). The recurrent erosion has caused irreparable damage to many important places along the river bank in addition to the permanent loss of cultivable and homestead lands.

Both erosion and deposition are continuous processes in the river in an attempt to reach a new equilibrium in channel geometry and morphology by ever dynamic nature of flow. Erosion and deposition of the river has link to land use and land cover (LULC) since the land cover is under constant change in a dynamic landscape constantly shaped by continuous erosion and deposition. The objective of the present work is to evaluate the extent of erosion and deposition along the Brahmaputra river and change in the LULC of the river. In the post-monsoon season, the most important use of the LULC study is to evaluate the newly emerged morphology after the flood and erosion events. This will help in planning mitigation measures for both flood and erosion in a correct perspective, instead of drawing from the morphology of the previous year which undergoes much change during the monsoon flood. In this paper, the erosion and deposition behaviour of the Brahmaputra river was directly studied for 1973 and 2014. LULC due to erosion and deposition was studied for a later period covering 20 yrs, i.e., 1994–2014. Time periods of 1973–2014 for the erosion–deposition study and 1994–2014 for the LULC study were chosen as per the availability of satellite data and to study the change during the 20-yr period.

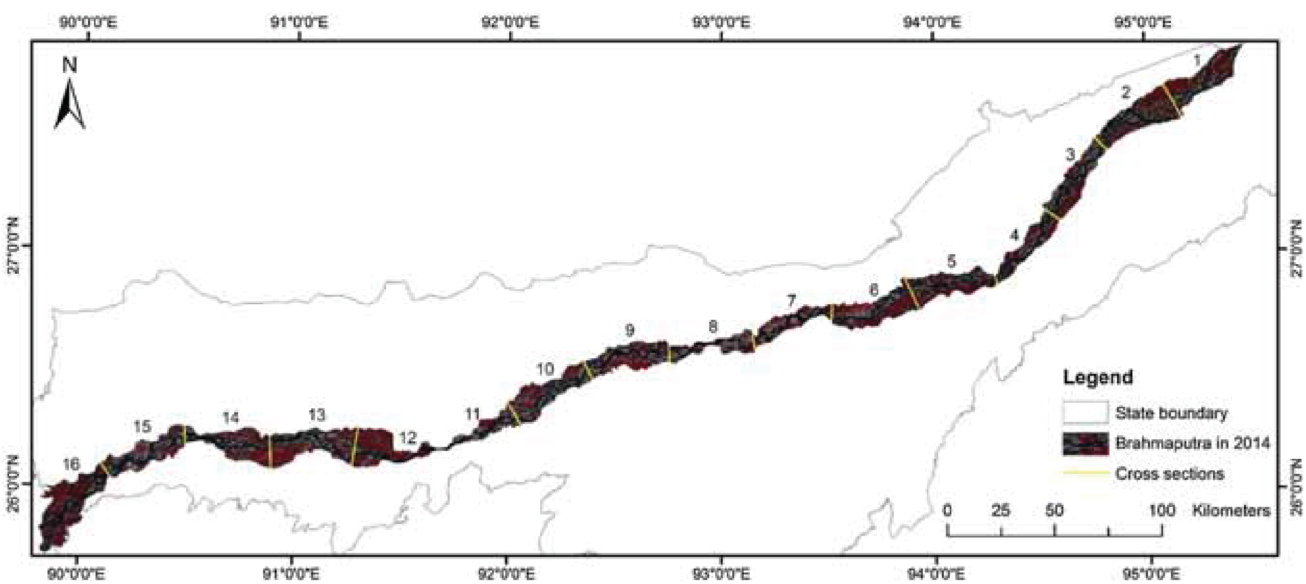

Figure 1. Map showing different reaches of the Brahmaputra river in Assam.

2. Materials and methods

The erosion–deposition of the Brahmaputra river for the period 1973–2014 was studied from Landsat images using remote sensing (ERDAS Imagine) and GIS techniques (ArcGIS 10.1).

Images were procured for the same season of the year to minimise the inconsistencies in the data. Post-monsoon data were used due to low cloud cover and proper channel and sandbar definition available during this season. Raw data consisting of individual bands of each satellite image were combined in ERDAS Imagine image processing software to create a composite image. The images were then pre-processed for image enhancement techniques like haze reduction, brightness and contrast to make the process of information extraction easier. Images were then stitched to create a single seamless mosaic image for the entire stretch of the river which was utilised to visually interpret and extract the bank line. The Brahmaputra river in Assam in three different years, i.e., 1973, 1994 and 2014 was divided into 16 reaches at a length of 40 km and the reaches were numbered from 1 upstream to 16 downstream as shown in figure 1. Erosion–deposition and LULC were studied for different reaches to know the longitudinal variation.

LULC analysis for 1994–2014 was carried out by categorising the Landsat images (table 1) into different classes, i.e., river/water, sandbar, vegetation (including natural grass land) and agriculture (including human settlement), using unsupervised classification in image processing software, i.e., ERDAS Imagine. Error in the unsupervised classification of the LULC maps of 1994 and 2014 were 15% and 12.5%, respectively. The overall classification accuracy was 85% and 87.5% in 1994 and 2014, respectively (table 2).

Table 1. *Satellite dataset used.*

Sl. no.	Sensor	Path/row	Date of acquisition	Spatial resolution (m)
1	MSS	145/41	15-11-1973	60
2	MSS	146/41	16-11-1973	
3	MSS	147/41	05-12-1973	
4	MSS	147/42	22-11-1973	
5	MSS	148/42	21-02-1973	
6	TM	135/41	20-11-1994	30
7	TM	136/41	26-10-1994	
8	TM	136/42	26-10-1994	
9	TM	137/42	01-10-1994	
10	TM	138/42	11-12-1994	
11	OLI	135/41	27-11-2014	
12	OLI	136/41	18-11-2014	
13	OLI	136/42	18-11-2014	
14	OLI	137/42	09-11-2014	
15	OLI	138/42	02-12-2014	

3. Results and discussions

3.1 *Erosion and deposition in the Brahmaputra in Assam*

Both erosion and deposition of the channel materials continue to be happening constantly. Erosion and deposition in both the banks of the Brahmaputra river in Assam during 1973–2014 are shown

Table 2.. *Error matrices.*

Classified data	Reference data				Producer accuracy (%)	User accuracy (%)	Kappa
	River	Sandbar	Agriculture	Vegetation			
Error matrix for 2014 classification							
River	10	0	0	0	90.91	100	1
Sandbar	0	10	0	0	71.43	100	1
Agriculture	1	2	7	0	100.00	70	0.6364
Vegetation	0	2	0	8	100.00	80	0.75
Overall classification accuracy			87.50%				
Overall kappa statistics			0.83				
Error matrix for 1994 classification							
Water	8	2	0	0	80.00	80	0.7333
Sand	0	9	0	1	81.82	90	0.8621
Agriculture	1	0	8	1	100.00	80	0.75
Vegetation	1	0	0	9	81.82	90	0.8621
Overall classification accuracy			85.00%				
Overall kappa statistics			0.8				

in figure 2 with course of the main channel in different reaches. The reasons for the spatio-temporal variability in the erosion processes are dynamically linked to hydrological (high water discharge, high sediment load), hydraulic (intense and erratic braiding, unequal discharge and intensity of channels, angle at which the channel approaches the bank line, poor drainage and interspersed layers of sand), geochemical (organic content, particle size distribution) and geotechnical factors (low cohesion and low internal friction of bank materials).

The migration of the main channel and erosion–deposition in the Brahmaputra during 1973–2014 are shown in figure 3. There was severe erosion in the south (left) bank of the river during 1973–2014 with the downward shifting of the main channel in the first two reaches. The area under erosion in the first two reaches (reach no. 1 and 2) was 128 km^2 of which 101 km^2 was in the south bank. Places like Rohmoria were highly affected from the erosion problem. Compared to erosion (128 km^2), there was low deposition (6 km^2) in the first two reaches during 1973–2014.

Reach no. 3 experienced the least erosion (35 km^2) among all the reaches. Higher erosion was observed in the north bank than the south bank at reach no. 3, 4, 5, 6, 8, 9, 11, 13, 14, 15 and 16. However, the extent of erosion was more in the south bank at reach no. 1, 2, 7, 10 and 12. More than 100 km^2 area was affected by erosion in the reach no. 5, 6, 10, 13 and 16. High erosion area in these reaches was mainly due to two factors:

(i) Migration of the main channel with the loss of land in reach no. 1, 2, 5, 6, 7, 8, 10, 12, 13, 14, 15 and 16.
(ii) Bifurcation of distributaries or migration of mid-channels with the development of sandbars or islands in reach no. 3, 4, 9, 11 and 16.

Deposition was comparatively lesser in all the reaches. No deposition was observed in reach no. 12 and 16. Total area of erosion during 1973–2014 was 1557 km^2 out of which 728 km^2 was in the north bank and 829 km^2 in the south bank of the river. The area of deposition during the period was 204 km^2 with 122 km^2 in the north bank and 82 km^2 in the south bank. Thus, the south bank experienced higher erosion whereas deposition was prominent in the north bank of the river.

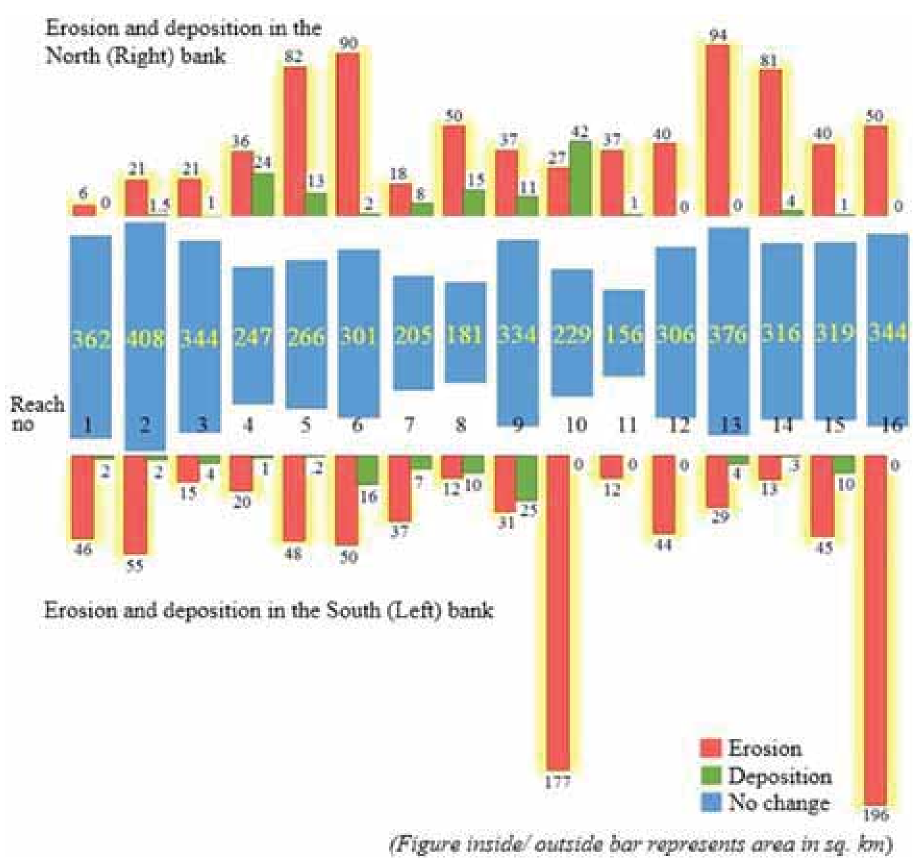

Figure 2. Bank erosion and deposition in different reaches of the Brahmaputra in Assam, India during 1973–2014.

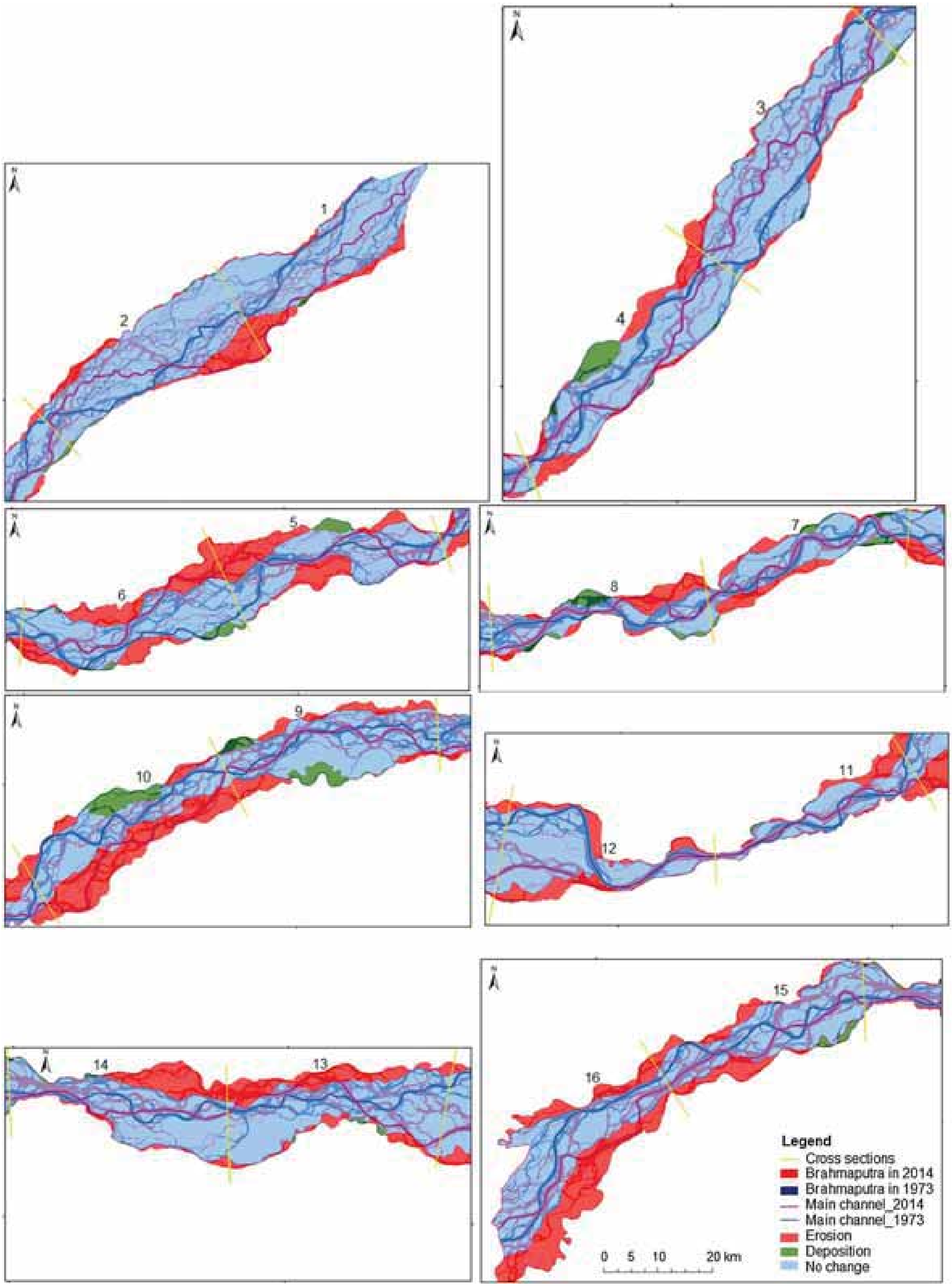

Figure 3. Migration of the main channel and erosion–deposition in the Brahmaputra during 1973–2014.

Unequal erosion in both banks of the Brahmaputra is unique compared to other Tibetan rivers like the Yellow. Bank retreat on both sides of the Yellow River from 1958 to 2008 was almost equal as the erosional area on the left bank and the right bank was 257.3 and 261.09 km^2, respectively (Yao *et al.* 2011). But in the Brahmaputra, higher erosion in the south bank is mainly due to the downward shifting of the main channel in most of the reaches. Maximum shifting of the main channel

Table 3. *LULC of the Brahmaputra river in 1994.*

	Area (km^2)					Area covered (%)			
		Sandbar/Island							
Reach no.	Water	Sand	Agriculture	Vegetation	Total	Water	Sand	Agriculture	Vegetation
1	84	149	63	103	398	21	37	16	26
2	112	184	94	65	455	25	40	21	14
3	115	151	0	104	371	31	41	0	28
4	88	126	14	86	313	28	40	4	27
5	93	140	57	95	385	24	36	15	25
6	106	122	100	74	401	26	30	25	18
7	110	72	8	60	250	44	29	3	24
8	100	54	20	45	218	46	25	9	20
9	144	93	125	42	404	36	23	31	10
10	168	72	93	22	355	47	20	26	6
11	114	16	29	16	176	65	9	16	9
12	187	28	141	35	390	48	7	36	9
13	237	40	172	14	464	51	9	37	3
14	203	44	132	8	386	52	11	34	2
15	137	225	7	0	370	37	61	2	0
16	177	261	122	0	559	32	47	22	0
Whole river	2174	1776	1178	768	5896	37	30	20	13

Table 4. *LULC of the Brahmaputra river in 2014.*

	Area (km^2)					Area covered (%)			
		Sandbar/Island							
Reach no.	Water	Sand	Agriculture	Vegetation	Total	Water	Sand	Agriculture	Vegetation
1	100	177	52	90	420	24	42	12	21
2	136	221	58	69	484	28	46	12	14
3	94	189	0	100	383	24	49	0	26
4	76	149	3	77	305	25	49	1	25
5	110	162	54	72	397	28	41	14	18
6	91	160	101	89	442	21	36	23	20
7	81	109	12	63	265	30	41	4	24
8	83	110	0	51	244	34	45	0	21
9	104	150	77	71	402	26	37	19	18
10	131	189	94	15	429	30	44	22	4
11	74	83	41	9	207	36	40	20	4
12	103	83	171	32	389	27	21	44	8
13	147	168	165	17	498	30	34	33	3
14	143	129	126	11	409	35	31	31	3
15	140	150	106	4	401	35	37	27	1
16	170	176	234	5	585	29	30	40	1
Whole river	1783	2404	1295	776	6258	29	38	21	12

took place during 1973–1994 compared to 1994–2014. Average shift of the main channel was 3 km during 1973–1994 and 2 km during 1994–2014. Total erosion during 1973–1994 was 1166 km^2 with 564 km^2 in the north bank and 602 km^2 in the south bank. Again, total deposition during 1973–1994 was 172 km^2 with 96 km^2 in the north bank and 76 km^2 in the south bank. Compared to 1973–1994, there was less erosion (589 km^2) and more deposition (197 km^2) during 1994–2014. Total erosion during 1973–2014 (1557 km^2) was not numerically equal to the erosional area of 1973–1994 (1166 km^2)

and 1994–2014 (589 km^2) as some area eroded during 1973–1994 was deposited in 1994–2014. Similarly, some area deposited during 1973–1994 was affected by erosion in a later period (e.g., reach no. 2, 6, 7, 8, 11, 13 and 14).

3.2 *LULC in the Brahmaputra during the post-monsoon months*

Increased braiding and erosion–deposition has resulted in different LULC of an alluvial river including the floodplains. The dynamic nature of the Brahmaputra and its tributaries modifies the floodplains frequently, at times to an undesired magnitude (Goswami *et al.* 1999; Kotoky *et al.* 2004; Sarma and Phukan 2004; Das *et al.* 2012; Lahiri and Sinha 2012). Associated changes in the LULC (linking it with river dynamics) are rarely documented in quantitative terms (Kotoky *et al.* 2012; Mondal *et al.* 2013) which are essential pre-conditions for the formulation of the floodplain management programme. While both river bank erosion and scouring of the river bed lead to the formation of new sandbars and braids due to the new deposition of the eroded sediments, thereby influencing channel migration, the ever dynamic nature of the flow subsequently results in the erosion of the other parts of bank and bars in an attempt to reach a new equilibrium in channel geometry and morphology.

LULC is linked to the erosion and deposition of the river since the land cover is under constant change in a dynamic landscape constantly shaped newly by the ongoing erosion and deposition each season. Often it is the vegetated and the sparsely vegetated banks and sandbars that get eroded and, consequently, barren sandbars emerge. Although the land cover undergoes a significant change leading to the need for a re-evaluation of LULC, precise quantification and location of the corresponding erosion–deposition is challenging.

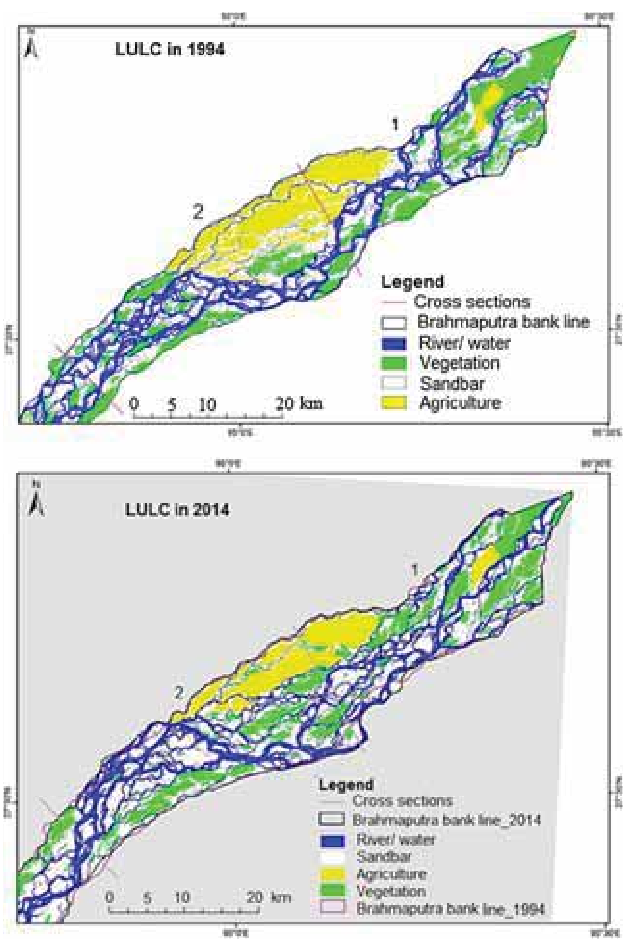

Figure 4. LULC of the river bed of the Brahmaputra in reach no. 1 and 2 during the post-monsoon months of 1994 and 2014.

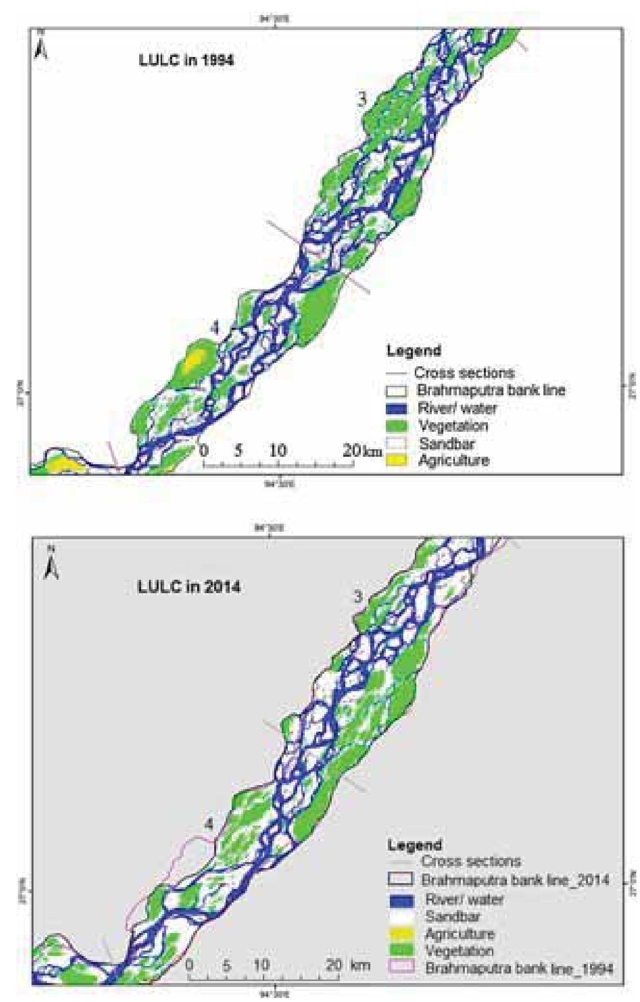

Figure 5. LULC of the river bed of the Brahmaputra in reach no. 3 and 4 during the post-monsoon months of 1994 and 2014.

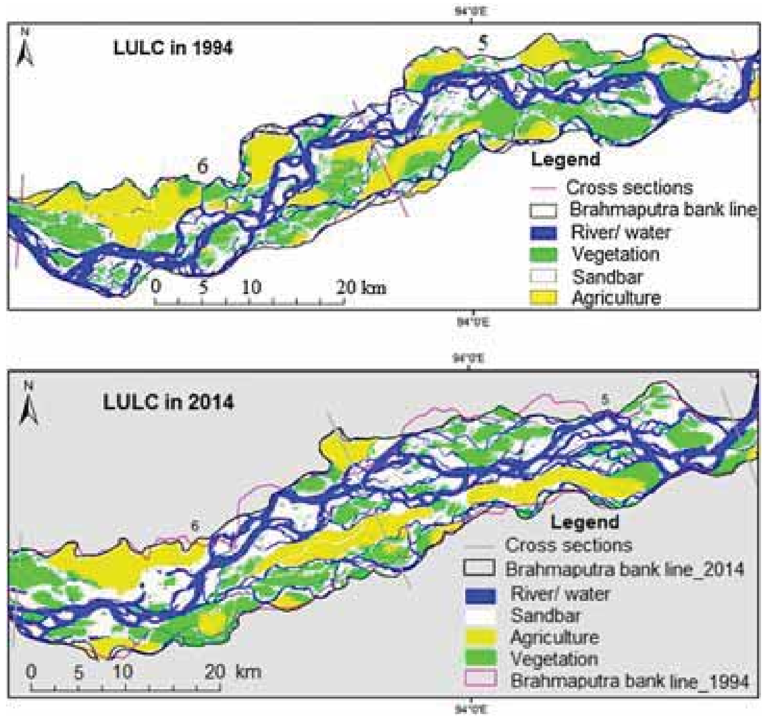

Figure 6. LULC of the river bed of the Brahmaputra in reach no. 5 and 6 during the post-monsoon months of 1994 and 2014.

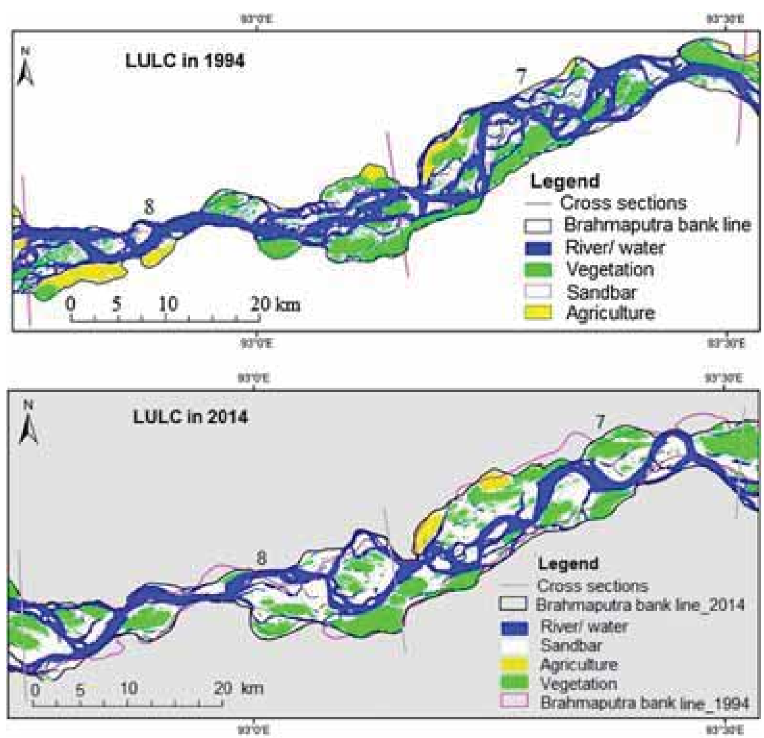

Figure 7. LULC of the river bed of the Brahmaputra in reach no. 7 and 8 during the post-monsoon months of 1994 and 2014.

LULC of the Brahmaputra river in 1994 and 2014 is shown in tables 3 and 4 and figures 4–11. In 1994, 37% area of the river bed was occupied by water, i.e., river and 63% area was bars, out of which 30% was sand and 33% was under agricultural practice and vegetation. Thus, more than

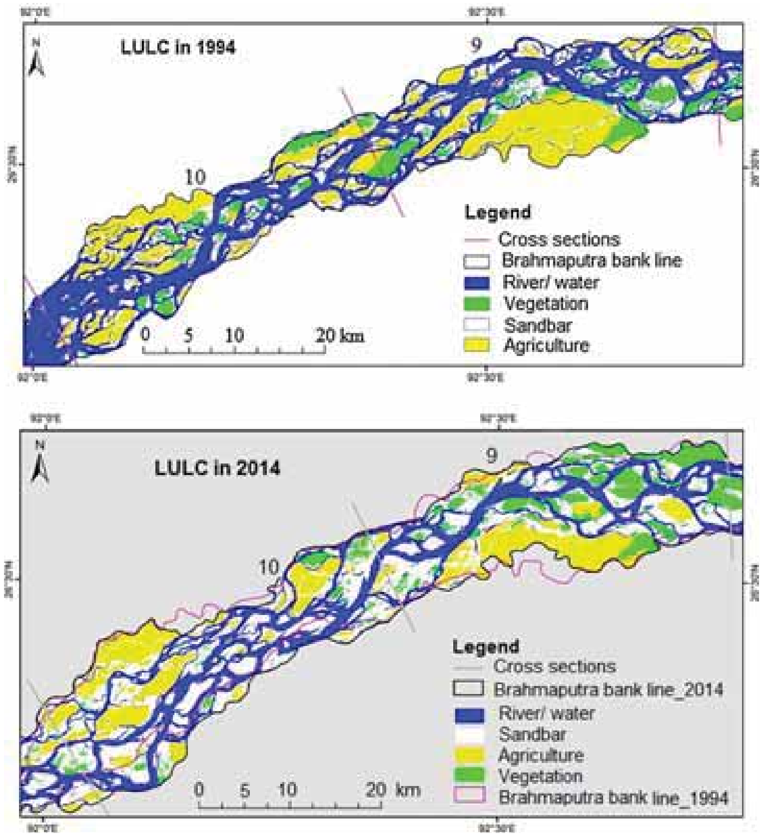

Figure 8. LULC of the Brahmaputra in reach no. 9 and 10 in 1994 and 2014.

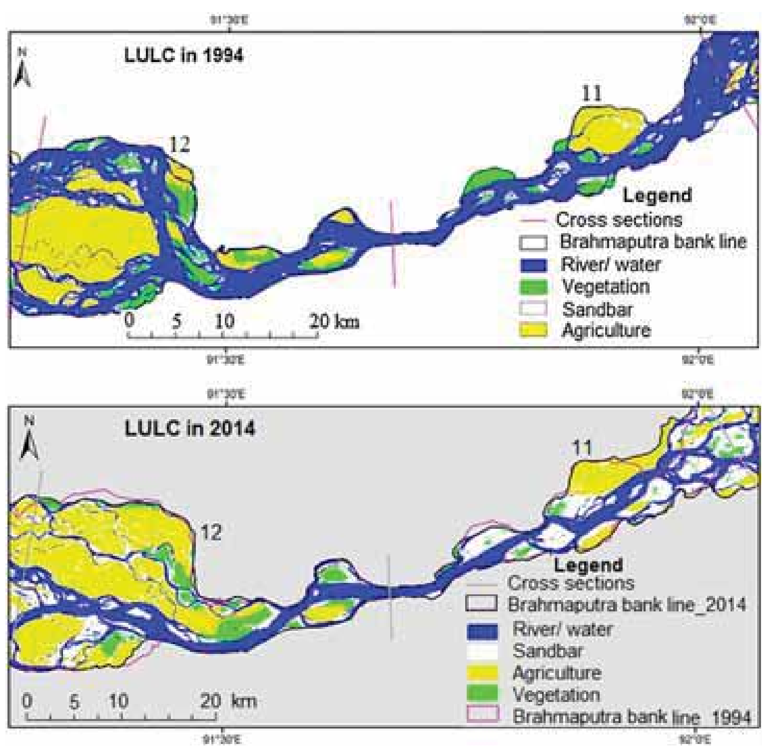

Figure 9. LULC of the river bed of the Brahmaputra in reach no. 11 and 12 during the post-monsoon months of 1994 and 2014.

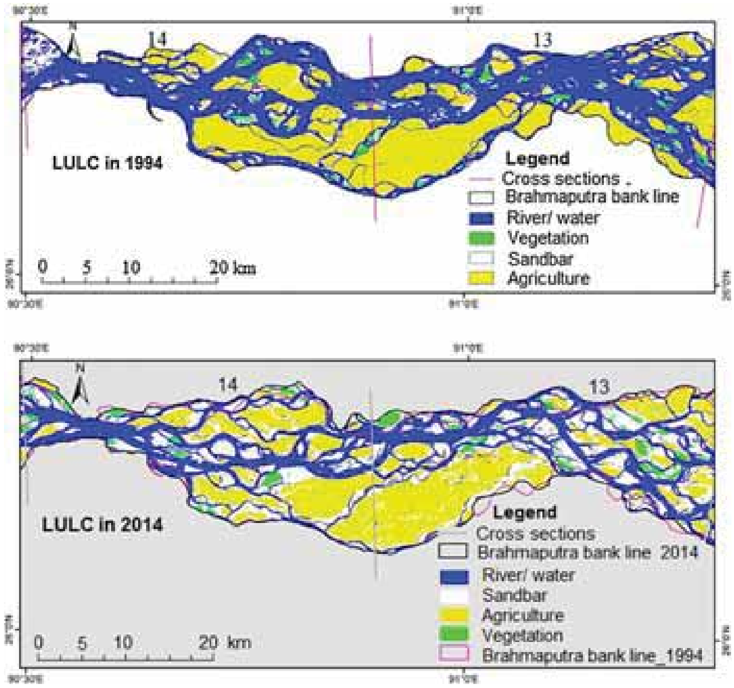

Figure 10. LULC of the river bed of the Brahmaputra in reach no. 13 and 14 during the post-monsoon months of 1994 and 2014.

60% of the river bed of the Brahmaputra was covered by temporary sandbars and permanent islands in the post-monsoon months. However, reaches had a varied amount (range 34–79%) of sandbars and islands.

In 2014, 29% of the area was occupied by channels and 71% of the area was occupied by sandbars, vegetated bars and agriculture. Thus, amount of water in the post-monsoon months has decreased (from 37% to 29%) during 1994–2014. All the reaches except reach no. 1, 2 and 5 experienced reduction of water in 2014 compared to 1994. Again, different reaches had an almost uniform (range: 65–76%) area covered by bars with sand, vegetation and agriculture. Vegetation has decreased and agricultural practices have increased in the different bars and islands of the Brahmaputra during 1994–2014. Agricultural activity has increased in the lower reaches of the Brahmaputra, i.e., reach no. 15 (25%) and 16 (18%). Socio-political factors are a major driving force of LULC change in the upper reaches of the Yangtze river during 1980–2000 (Wu *et al.* 2008) and the same factor is responsible for the LULC change in the Brahmaputra river, particularly in the lower reaches. The loss of agricultural land and homestead land due to river bank erosion and the growing population in the lower reaches has compelled these riverine people to explore agricultural activities on the river bed during the post-monsoon months.

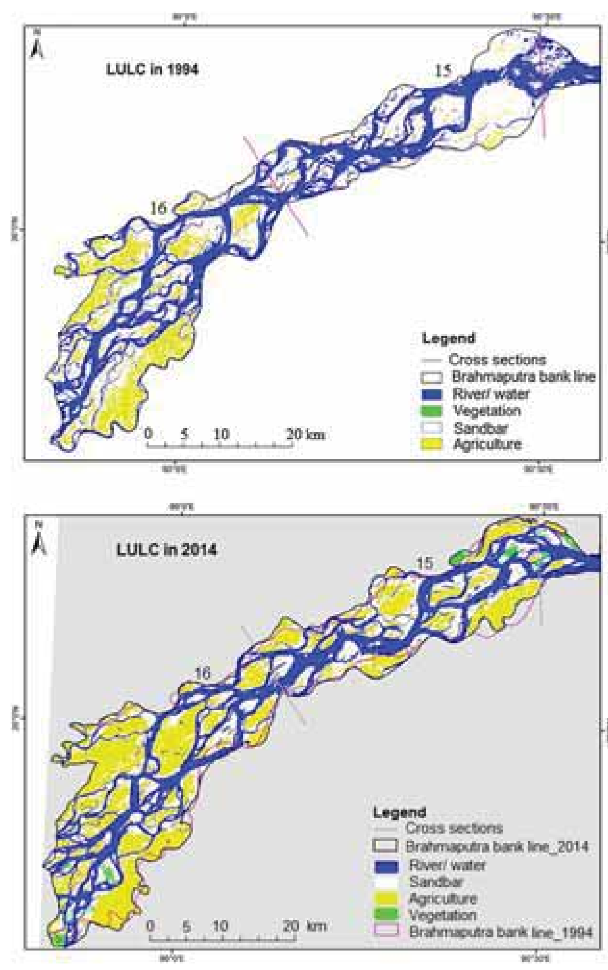

Figure 11. LULC of the river bed of the Brahmaputra in reach no. 15 and 16 during the post-monsoon months of 1994 and 2014.

4. Conclusions

Total area of erosion and deposition in the Brahmaputra river in Assam during 1973–2014 were 1557 and 204 km^2, respectively. There was more erosion in the south bank (829 km^2) and more deposition in the north bank (122 km^2). However, the increased area of the Brahmaputra is not necessarily linked to river bank erosion in every case. The increase in area (28%) of the Brahmaputra during 1973–2014, besides the bank erosion is also due to the bifurcation of streams without any significant loss of land. LULC change of the Brahmaputra in the post-monsoon months has revealed that the amount of the submerged part in the post-monsoon months has decreased (from 37% to 29%) during 1994–2014. A reduction in natural grassland and forest has been observed with the corresponding increase in agricultural practices in different bars and islands of the Brahmaputra in Assam during 1994–2014. Agricultural activity has increased in the lower reaches of the Brahmaputra, i.e., reach no. 15 (25%) and 16 (18%). Socio-political factors are responsible for LULC change in the Brahmaputra floodplain particularly in lower reaches. Loss of agricultural land and homestead land from river bank erosion and growing population in the lower reaches has compelled the riverine people to explore agricultural activities in inter fluvial landmasses in post-monsoon months. Identification of sandbars/islands is necessary for better agricultural utilization or other activities in post-monsoon months. Improved regulation and management strategies are also necessary to enhance the retention of land resources in changed socio-political scenario.

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