Assessment of bank erosion and its impact on land use and land cover dynamics of Mahananda River basin (Upper) in the Sub-Himalayan North Bengal, India

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Abstract

Bank erosion is the predominant character of River Mahananda in the Sub-Himalayan North Bengal. The present study aims to identify the bank erosion mechanism as well as the impact of river bank erosion on land use and land cover (LULC) dynamics of the study area. Survey of India (SOI) topographical map 78 B/5 (1975) and satellite imageries for the temporal year of 1991 and 2019 from USGS have been used for the study. For the assessment of bank erosion process Bank erosion hazard index (BEHI) model has been adopted here. The channel migration has been delineated by the superimposition of temporal bank lines extracted from the temporal satellite imageries. LULC analysis has been carried out through the supervised classification technique using remote sensing and GIS tools. From the assessment of BEHI it can be visualized that the scores have been ranging from 30.75 to 44.30 which indicates high to very high vulnerable areas under fluvial erosion. The channel migration for the temporal period from 1991 to 2019 is ranging from 7.72 to 411.16 m along the studied reach which reflects the high erosion effectiveness. From LULC classes it has been assessed that settled or built-up areas have been increased and the water body is gradually decreased overall in the study area. The study resulted that the river bank erosion has its direct impact on land use of the studied area. In the study vulnerable sites to fluvial erosion have been delineated and unplanned land use can be managed through sustainable way.

Keywords Bank erosion · BEHI · Channel migration · LULC · Accuracy assessment

1 Introduction

Riverbank erosion is an inevitable natural phenomenon of any floodplain region. Bank erosion involves the mechanism of removal of bank materials from river banks by the fluvial actions like channel head pressure, velocity, discharge etc. The fluvial erosion takes place when the shear stress exceeds and the basal support is collapsed. Liquefaction of basal materials of a riverbank occurs when the effluent flow of ground water added into the river [1]. Though the bank erosion is a

natural and unimpeded phenomena but it accelerates by anthropogenic interferences like changes of LULC over the time. The flood plains are the most endangered geomorphic units struggling against enhanced land use pressure [2, 3]. Riverbank failure is the process which is leading to the fact of shifting of the river and the ultimatum is normally excessive river bank erosion and the erosion study from the environmental point of view always been designated as a hazardous situation for the local inhabitants though it has geared-up by some anthropogenic interferences [4]. River course always struggles to

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attain an equilibrium condition through space and time and the differences in periodical discharge and sediment transportation control the mobility of the bank lines of a river to some extent to reach its equilibrium condition [5]. Sometimes lateral mobility as a process of fact brings catastrophic changes in both local and regional scale and the erosion-accretion process has its clear impact on the society [6]. Many researchers have considered Remote Sensing and GIS techniques to study spatio-temporal changes of river courses like channel oscillation or migration and shifting as many of them focused on the LULC changes of a river basin [7–10]. The present study is a combination of both and tries to find out the results of erosion and accretion processes along with the channel and its impact on LULC dynamics of the study area. Also the study of erosional process is the prime aim of the present study. River bank erosion vis-à-vis LULC change is the simple correlation study which is mostly visible in almost all alluvial tracts of the world in fluvial environs [11, 12]. An integrative study of erosion, its causes and mitigation processes are always a necessary document and strategic step towards the adjustments in fluvial dynamicity to the society in the Himalayan foothill region [13]. Modelling of the erosional process and its impact on LULC change and vice-versa is very effective for any environmental research and also for the fluvial geomorphology [14]. Very few studies have been carried out on the LULC changes of the study area and there is a still need of projecting the fact from last two decades over the region. Land loss or soil erosion is also a considering factor for the study of fluvial geomorphology as its impact on land use carries a major role behind the upbringing of local inhabitants and the nature of the vulnerability to cope-up with the erosion [15]. Besides land use change impacts on the soil properties of any floodplain and those changes along river bank make further changes in the bank soil property and leads towards the fluvial migration [16, 17]. Human induced river bank failure is commonly found in the floodplains where the population concentration is very high [18, 19]. The changes in hydro morphology of the Himalayan Rivers are mostly affected by anthropogenic activity as well as land use changes. Bank soil properties, ratio of bank materials, cohesiveness, vegetation cover and the extremity of flood discharge are the responsible factors for the river bank failure of any region [20, 21]. Overtopping and cantilevered blocks along the obtuse angular dispositions eventually receive the thalweg closer to the bank [22]. Sediment transportation and deposition of sediments over the bank tops during the flood situation on any floodplain enhances the chances of soil erosion where the seasonal rainfall extremity is quite high [23, 24]. Remote Sensing study is very effective to find out

the vegetal coverage of any region and its spatio-temporal study is quite effective to trace the dynamicity of the vegetal cover as it has a major role to reduce the soil erosion as well as river bank stabilization [25–27]. Also the analysis of any remotely sensed data of any region can make a clear visibility towards sustainability of land uses and further assessments along spatial dimension [28]. For a Neo-tectonic active area it seems to be found many of adjustments through a number of Neo-tectonic activities as it also affects the hydro dynamicity of rivers and associated fluvial processes [29]. For the assessment of channel bank erosion potentials BEHI is one of the most used techniques for the alluvial rivers as it delineates the erosion vulnerable sites combining the scores of some erosion determining parameters [30]. Satellite-based LULC dynamic study is needed for the management of any fluvial environment of any region [31, 32] as the river bed aggradation has also a major role in case of fluvial adjustments [33]. Measurement of lateral shifting of any river course is quite effective and easy to study through the remotely sensed data. Land use changes and its conversions are the major analysis of any dynamic region and for any hydro-geomorphic condition [34, 35]. Not only the preparation of LULC changes scenario but also the calculation of conversion statistics and accuracy assessments are also important for the detailed study of any land use preparation and analysis and it helps for a scientific analysis of any region [36]. Relatively the assessment of bank erosion hazard for the detailed study of fluvial erosion is foremost important aspect to correlate among erosion and land use changes [37–39]. The Mahananda River is one of the major rivers flowing down the Sub-Himalayan foothills with monsoonal flush of more than 200 m³ after a 2–4 days of incessant rain wash in almost every year [40]. The River is averagely characterized by overtopping its levees at brisk level and it reshapes channel morphology, enhancement of bed aggradation and bank erosional activity. Himalayan foothills carry the imprint of fluvial dynamicity and changes in land use over the time. The study area consists of metamorphosed rocks like Phyllite, Slates, Schist, etc., especially in the hilly part of the river basin and the foothills and the southern flat plains are the assemblage of various topographic segments with the weathered metamorphosed rocks. Basically the geological structure and the drainage pattern are mainly responsible for this type of floodplain evolution in the southern section of the river basin. The region receives an abundant rainfall especially in the monsoon months when the discharge of the river increases. The absence of the forest cover in the southern plain accelerates the soil erosion and riverbank erosion. Though the degree of inclination of land remains towards south, plenty of

rainfall and anthropogenic activities are also the key factors of bank erosion. The vulnerable geological structure and high precipitation cause bank erosion over the sites composed of loosely compact bank material and removal of basal support takes place almost in the every year especially during the flash [41].

2 Description of the study area

River Mahananda is originated from the Mahaldhram range of Darjeeling hills, near Chimli (latitude $26^{\circ} 55' 40''$ N and longitude $88^{\circ} 14' 04''$ E) at the east of Kurseong, Darjeeling with an elevation of about 2100 m above mean sea level. From origin towards its debouchment it is termed as Mahanadi river receiving the catchment streams and finally below *Gulma* popularly called as Mahananda (SOI Topographical Map). The upper Mahananda basin is located within the co-ordinates of $26^{\circ} 40' 00''$ N to $26^{\circ} 56' 00''$ N and $88^{\circ} 19' 00''$ E to $88^{\circ} 29' 00''$ E. After leaving the hills, it flows through Champasari, Tarabari, Betgada, Salugara, and Siliguri greater urbanity (Fig. 1) and turns to the west and forms the

boundary line between the Darjeeling (*Terai*) and Jalpaiguri. The slope declining propensity of the river is 1:185 (maximum elevation: 2048 m, minimum elevation: 50 m) with a watershed length–width ratio of 2.28. The study area is located in a Neo-tectonic zone of haphazard load outfall with average annual monsoon rainfall of about 2500 mm and peak discharge of about 950 cumec. For 5 ~ 10 days critical to turbulent flows are observed within the channel in almost every year with a velocity acceleration of $1 \sim 2 \text{ m s}^{-1}$. The precipice and obtuse angular bank slope chiefly composed of colluvial admixtures and affected by seasonal spates are the factors to cause erosion here. The study area is under various LULC categories and it defines the variability of slope as well as different types of activities of the local inhabitants too. The vegetation cover alongside the river bank is mostly riparian open, mixed and dense type (Table 1).

Fig.1 Location of the Upper Mahananda River basin

Table 1 Introduction to the geomorphic features of the selected reaches of River Mahananda in study area. *Source:* Field assessment and Annual Flood Report of West Bengal, 2019

Features	Reach-1	Reach-2	Reach-3	Reach-4
Reach identity	Mahananda forest to Gulma bridge	Gulma bridge to Sisabari	Sisabari to Jantanagar	Jantanagar to Shaktigarh colony
Reach length (km)	4	5	6.5	4.5
Channel category	Colluvio-Alluvial	Colluvio-Alluvial	Colluvio-Alluvial	Colluvio-Alluvial
Bed material type	Sand, gravels and pebbles	Sand and pebbles	Sand and pebbles	Sand and pebbles with little of silt
Sinuosity Index (SI)	1.14	1.45	1.07	1.41
Channel pattern	Straight	Sinuuous	Sinuuous to Straight	sinuuous
Average annual rainfall (mm)	3250 (mean 2500 mm)			
Average annual discharge (cumec)	990–1000			
BEHI* score	36.75	40.25	30.75	40.25
BEHI category	High	Very high	High	Very high

Table 2 Introduction to the metadata of the Satellite Imageries

Data	Sensor	Path/row	Scale/ resolu- tion	Acquisition	Source
Landsat 5	TM	139/041	30	08/11/1991	USGS
Landsat 8	OLI-TIRS	139/041	30	27/10/2019	USGS

Table 3 Land use land cover classes and their land use details

LULC classes	Types of land use
Water body	Surface water bodies: rivers, ponds, lakes etc
Dense forest	Intense unaltered forest cover
Open forest	Scattered forest: plantation
Cultivated land	Lands under crops/harvested crop lands
Settlement	Residential cum other built up coverage

3 Materials and methods

3.1 Database preparation

Mahananda river basin (upper) has been considered here to study the retrospective reconstruction which has been done using SOI topographical map for study area delineation. Landsat imageries collected from the USGS official website have been used for the preparation of LULC categories and for the analysis of channel migration of the river over the time (Tables 2 and 3). Google earth images are used and field visits have been done for ground truthing and validation of the LULC conversion statistics.

3.2 Bank erosion mechanism

Rosgen's (2001) BEHI model has been adopted here which was carried out through field investigation for

Table 4 Modified guidelines for field assessment of BEHI after Rosgen, 2001

BEHI category	BH/BFH	Score	Rt.D (%)	Score	R D (RD) (%)	Score	Mean SP (%)	Score	B A (Degree)	Score	MA	SA	TS
Very low	1.0–1.1	1.45	90–100	1.45	80–100	1.45	80–100	1.45	0–20	1.45	4	3	≤ 7.26
Comprehensive average: 1–5 (1.45)													
Low	1.11–1.19	2.95	50–90	2.95	55–80	2.95	55–80	2.95	20–60	2.95	5	4	7.26–14.75
Comprehensive average: 2.5–3 (2.95)													
Moderate	1.2–1.5	4.95	30–50	4.95	30–55	4.95	30–55	4.95	60–80	4.95	6	5	15–25
Comprehensive average: 1–5 (1.45)													
High	1.6–2.0	6.95	15–30	6.95	15–30	6.95	15–30	6.95	80–90	6.95	7	6	24.76–34.75
Comprehensive average: 6–7 (6.95)													
Very high	2.1–2.8	8.5	5–15	8.5	5–15	8.5	5–15	8.5	90–120	8.5	8	7	34.76–42.50
Comprehensive average: 8–9 (8.5)													
Extreme	> 2.8	10	< 5	10	< 5	10	< 5	10	> 120	10	10	8	42.5–50 and ≤
Comprehensive average: 9–11 (10)													

identifying the mechanism and process of bank erosion (Table 4). In order to develop the BEHI rating, key stream bank characteristics like bank height, root depth, root density, bank angle, surface cover, bank material and bank layers were taken into consideration that would have been sensitive to the bank instability and failure. Identified BEHI categories were extreme, very high, high, moderate, low and very low and were rated from 1 to 10 based on level of vulnerability. For this assessment 8 field sites have been considered (Table 5). For the analysis of BEHI parameters as mentioned some specifications were considered after pilot visits for scoring of BEHI which are Bank Height (BH), Bank-full Height (BFH), Root Density (Rt. D), Root Depth (RD), Surface Protection (SP), Bank Angle (BA), Material Adjustment (MA) and Stratification Adjustment (SA) (Fig. 2).

3.3 Channel migration

For identifying bank line migration superimposition of bank lines extracted from satellite images has been done under GIS platform. The river bank-lines were identified, delineated and finally extracted from successive and temporal satellite images for two reference time points 1991 and 2019. The extracted river bank lines with temporal overlaying layers denoted the degree of erosion and deposition as well as the unchanged areas. The plan map of corresponding mouzas and ward boundaries has been superimposed on bank lines for visualizing the affected areas in this foothill region (Fig. 3). The total reach was considered from Gulma (upstream (U/S)) to the confluence with Balason River (downstream (D/S)) with 27 consecutive cross sections (CS 1-27) (Figs. 4 and 5) and divided into 4 reaches which covered a length of 20 km in Siliguri (Tables 6, 7).

Table 5 Site-wise Bank Erosion Hazard Index Score (BEHI) within the study area

Sl. no	Site	BH/BFH	RD/BH	Rt.D	SP	BA	MA	SA	Total score	BEHI categories
1	Gulma	6.95	2.95	4.95	2.95	2.95	5	5	30.75	High
2	Devidanga	8.5	2.95	4.95	2.95	1.45	5	5	30.80	High
3	Champasari	6.95	4.95	6.95	2.95	4.95	5	5	36.75	High
4	Gurung basti	6.95	2.95	4.95	2.95	2.95	5	5	30.75	High
5	Naukaghat	8.5	6.95	6.95	4.95	6.95	5	5	44.30	Very high
6	Mahananda para	8.5	2.95	2.95	4.95	1.45	5	5	30.80	High
7	Naukaghat Bridge	8.5	6.95	4.95	2.95	2.95	10	5	41.30	Very high
8	Shaktigarh Colony	6.95	4.95	6.95	4.95	1.45	10	5	40.25	Very high
	Total	61.8	35.6	43.6	29.6	25.1	50	40	285.7

Fig. 2 Schematic diagram of river bank for calculation of BEHI (SLT: Silt, C: Coarse, SN: Sand, FN: Fine, V: Very)

Fig. 3 Plan map of corresponding mouzas and wards affected by channel migration

3.4 LULC change detection

LULC analysis has been carried out using Arc-GIS 10.2 after noise reduction and necessary radiometric corrections of the satellite images which have been attempted confirming the projection of Universal Transverse Mercator (UTM Zone 45; Northern Hemisphere and datum of WGS 84). The processed data has been prosecuted further for supervised classification under maximum likelihood classification algorithm. For the analysis of LULC change dynamics of the basin was divided into five classes based on dominant LULC types in particular. The attesting signatures are based on the principle of the maximum probability of belonging to a particular class under the maximum likelihood algorithm. Classified images were validated through Google earth images and field visit based verifications.

3.5 Accuracy assessment

Accuracy assessment was done to quantify and check the validity of the classified image as essential for prominent LULC study by taking presumed random points of 150–200

as reference points and minimum of 30 points for each class and more than 150 for the entire classified area. From the combined table, confusion matrix was rendered and used by the pivot table tool. Confusion matrix table was done to determine the relationship between the classified map and the reference data summarized in an error matrix and used for computation of the reliability between controller and explainer. Percent of omission, percent of commission, accuracy of producer and accuracy of users (Tables 8 and 9) were computed while dealing with this matrix table and exporting to MS Excel. The two equations for accuracy assessment were considered which are as follows:

Kappa Coefficient equation

$$k = \frac{N \sum_{i=1}^r X_{ii} - \sum_{i=1}^r (x_{i+} * x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} * x_{+i})} \quad (1)$$

Overall accuracy assessment

$$\text{Over all accuracy} = \frac{\text{Total number of correct samples}}{\text{Total number of samples}} \times 100\% \quad (2)$$

Fig. 4 Location of selected Reaches (01–04)

Overall accuracy was validated by Kappa coefficient which falls from 0 to 1. If it is more than 0.80 strong acceptance of classification accuracy is found and less than 0.4 signifies poor quality of the same. The classified area from each map and class-wise percentage of area change were extracted from processed and classified images. For identifying the conversion of LULC (1991 to 2019) conversion map was attempted through intersect model under GIS environment (Fig. 6).

4 Results and discussion

4.1 Assessment of bank erosion

In the Reach 1 near the Gulma bridge area the river Mahananda has been constricted and resultantly undergoes massive bank erosion as well as breaching along the left bank. The rating of bank height and bankfull height is averagely 6–7 and the root density and root depth in comparison to bank height is very low. The bank angles for most cases are 70°–90° and transverse to flow and which

Fig. 5 Location of Cross Sections (cs) (01–27)

is susceptible to collapse. Material adjustments and the stratification adjustments are related with non-cohesive admixtures types. As per the presumed criteria the score exceeding 30 is prescribed as erosion vide ground truthing. Near Devidanga the bank height is higher and shows total BEHI score of 30.80. Near Champasari forest the low bank heights and the composition of sandy material of the bank is responsible for high rate of BEHI (36.75). Near Gurung basti higher susceptibility has found with score of 30.75. Near Noukaghat low root depth vs. root density and less surface protection has held responsible for the hazard with score of 44.30. At Mahananda para area moderate surface protection and moderate root density as well as reposing bank angles have resulted comparably low score of 30.80 but more than Gulma and Champasari site. Near Noukaghat bridge and Shaktigarh colony high non cohesive bank materials with very low root density has been the main factors for erosion. The scores for both of the sites are 41.30 and 40.25 respectively. The assessment of bank erosion hazard related to the composition of the bank material and the prevailing weather

Table 6 Cross section wise changes in channel width (m) of the River Mahananda from 1991 to 2019

CS (Cross sections)	1991	2019	Changes in width (in m)
1	358.96	770.12	411.16
2	438.73	787.43	348.7
3	595.33	726.26	130.93
4	445.03	536.20	91.17
5	407.78	509.08	101.3
6	190.63	240.15	49.52
7	532.38	631.02	98.64
8	581.24	791.31	210.07
9	385.90	675.48	289.58
10	537.79	558.87	21.08
11	243.79	529.97	286.18
12	295.54	349.04	53.5
13	240.13	431.50	191.37
14	391.98	497.59	105.61
15	266.56	523.09	256.53
16	321.01	415.31	94.3
17	188.95	357.58	168.63
18	236.28	264.96	28.68
19	188.93	196.65	7.72
20	248.23	437.39	189.16
21	241.23	266.86	25.63
22	150.63	234.70	84.07
23	141.47	125.88	15.59
24	355.78	141.97	213.81
25	187.12	108.35	78.77
26	234.92	162.63	72.29
27	166.41	189.01	22.6

Table 7 Bank line shifts and its directions of River Mahananda from 1991 to 2019

CS (cross sections)	Left Bank shifts (in metre)	direction	Right Bank shifts (in m)	Direction
1	224.27	Westward	186.74	Eastward
2	185.26	Westward	171.18	Eastward
3	26.75	Westward	101.54	Eastward
4	43.65	Eastward	47.64	Eastward
5	83.58	Eastward	7.21	Eastward
6	20.44	Eastward	29.76	Eastward
7	70.90	Westward	28.83	Eastward
8	140.98	Westward	69.16	Eastward
9	459.01	Westward	169.58	Westward
10	455.75	Westward	434.69	Westward
11	466.20	Westward	186.01	Westward
12	37.99	Westward	23.34	Eastward
13	227.59	Eastward	36.46	Eastward
14	115.21	Eastward	10.34	Eastward
15	266.51	Eastward	10.98	Eastward
16	182.22	Eastward	91.37	Westward
17	181.27	Eastward	13.64	Eastward
18	56.16	Eastward	27.48	Eastward
19	24.36	Eastward	16.64	Eastward
20	152.52	Eastward	39.41	Eastward
21	68.09	Eastward	43.63	Eastward
22	9.22	Eastward	100.07	Eastward
23	5.52	Eastward	6.43	Westward
24	64.05	Eastward	149.76	Westward
25	61.58	Eastward	37.19	Westward
26	112.78	Eastward	40.49	Eastward
27	11.28	Westward	11.37	Eastward

condition is very much fitted for the studied region. The banks are predominantly composed of sands and coarser materials which are basically non cohesive type. In case of Mahananda non-cohesive colluviums with admixture of materials shows sedimentological evidences of occasional flood. Vulnerability due to the impinge flow attacks especially during the monsoon is the triggering factor of such incidence. Slumping, slipping, and sudden collapse have been witnessed during field investigation. Banks are mainly affected by high flow velocity that enhanced massive erosional signatures. In July 2017 torrential rainfall was responsible for the massive bank erosion which caused incessant bank failures.

4.2 Measurements of channel migration

Widening of the channel is eventually associated with erosion, deposition and unchanged land area or unaffected lands. In case of left bank westward shift is maximum than

eastward with mean of 230 m and reach 2 is receiving maximum westward than eastward shift but for reach 3 and 4 maximum frequency of oscillation is for eastward with mean of 120 m amplitude of deflection but for right bank westward in case of reach 2 which is maximum with mean amplitude deflection of 200 m.

Swinging and winding nature is very much observed as the channel is very much serpentine in character creating simultaneously erosion and deposition for alternative run. Evidently in case of both right and left bank C/S 07–12 have maximum winding of both west and eastward for an amplitude shift of about 350–400 m whereas C/S 13–22 are having same propensity though the magnitude is quite less almost 2 times less amplitude of deflection (150–200 m). Conclusively auto cut-and fill processes are really prominent in case of most of the Foothill Rivers of Sub-Himalayan North Bengal due to over-laden load and slope loss. Urbanisation is one of the most important reasons that cause change in microclimate and hydrological

Table 8 Data quality cum output accuracy of LULC Map 1991

LULC classes	Ground truth (%)	Commission (%)	Omission (%)	Producer's accuracy (%)	User's accuracy (%)
Water body [W]	93.02	0	6.98	93.02	100
Dense forest [F(D)]	88.89	15.79	11.11	88.89	84.21
Open forest [F(O)]	77.78	26.32	17.65	77.78	43.68
Settlement [S]	87.50	0	12.5	87.50	100
Cultivated land [C]	100	7.14	0	100	92.86
Overall accuracy	90.50				
Kappa coefficient	0.88				

Table 9 Data quality cum output accuracy of LULC Map 2019

LULC classes	Ground truth (%)	Commission (%)	Omission (%)	Producer's accuracy (%)	User's accuracy (%)
Water body [W]	97.50	2.50	2.50	97.50	97.5
Dense forest [F(D)]	97.50	4.88	2.50	97.50	95.12
Open forest [F(O)]	95.00	2.50	5.00	95.00	95.00
Settlement [S]	92.50	5.13	7.50	92.50	94.87
Cultivated land [C]	97.50	2.50	2.50	97.50	97.50
Overall accuracy	96.00				
Kappa coefficient	0.95				

characteristics of any area which is an exorbitant factor of flood plain modification here. Morphological change of bank was diagnosed by studying temporal channel width variations, i.e. 1991 and 2019 as this case. The frequency of bank erosion enhances after monsoon rainfall almost every year. Non-cohesive bank material, i.e., coarse sand leads to maximum erosion causing widening and recession of the channel bank. Mahananda received 115.98 m of danger level (DL) discharge in 2019 and 116.59 m as per Annual Flood Report of 2019, Govt. of West Bengal, signifying extremely high danger level (EDL) of discharge which depicts character of hydrostatic pressure within the channel and is quite high in July to August almost every year. Whereas at Sonapur and Chopra far off downstream from Siliguri it accounts for only 75.77 m (DL) and 76.38 m (EDL) as the channel width is engulfed more and pressure on bank is relatively low than Siliguri adjacent areas. Seasonal variation of in-channel water level is not very high and shows single peak sudden sub-tropical maxima during late July with Skewness of 0.60 (60%) which indicates the hydrological graph of sharp peak and sharp recession, i.e. long limbs but short lag times (6 days). 02% of R^2 indicates that negligible data is found explainable of the response data around its mean. For 5–7 days every year pocket area inundations are found. Peak maxima are normally found in late July (Figs. 7 and 8).

4.3 Erosion and deposition assessments

Bank failure has been triggered by factors like discharge, bank lithology cum stratigraphic structure and bank angle. Erosivity depends on the discharge and velocity together causing bank collapse. Here average channel oscillation since last 25 years is 15 m year⁻¹. Total erosion is 594.79 ha and deposition is 489.31 ha with a differential of 105.48 ha, i.e. erosion is more than deposition. But mean erosion and deposition is mostly same with a differential of 7 ha (Fig. 9). Maximum erosion vs. Maximum deposition is of low differential (0.06 ha only) but minimum erosion vs. minimum deposition is of high differential (8 ha). Kurtosis is less than 3 and negative and refers platykurtic form mnemonic to uniform distribution. Differential of mean and standard Deviation for erosion is moderate (16.31 ha) but low for deposition (5.28 ha) which signifies considerable variability of erosion but low variability of deposition. In both cases skewness is moderate (50% skewness, normal range – 2 to + 2). Statistical and parametric analysis explains the fact that amount of land eroded in a reach results to deposition downstream as the flash discharge is of very shorter duration and outwash is not capable in long run. Reasonably except minimum erosion versus minimum deposition the total, maximum, mean and SD of erosion versus deposition is very close. Similarly very persistent

Fig.6 Flow chart for the execution of the study unit wise using Remote Sensing and GIS tools

and similar pattern is noticed in case of temporal variation of erosion and deposition from 1991 to that of 2019 and skewness and Kurtosis is also very nominal again. Same scenario in case of channel width is evident which documented similar pattern of width enlargements in 1991 and 2019 viz. for total, maximum, minimum, mean and SD of channel width area exhibited no such remarkable variation as witnessed in field also.

4.4 LULC dynamics and accuracy assessment

From the LULC analysis the LULC classes under water body consists of 9.54 sq.km (3.94%), dense forest was 85.13 sq.km(35.13%), open forest was 86.25 sq.km (35.59%), settlement was 28.65 sq.km (11%), cultivated land was 32.76 sq.km (13.52%) in the year 1991. On the other hand in 2019 water body consists of 10.50 sq.km (4.33%), dense forest is

Fig. 7 CS-wise Left Bank line shifting from 1991 to 2019

Fig. 8 CS-wise Right Bank line shifting from 1991 to 2019

75.79 sq.km(31.19%), open forest is 94.24 sq.km (39.71%), settlement is 30.49 sq.km (12.58%), cultivated land is 29.51 sq.km (12.18%). The LULC changes from 1991 to 2019 can be visualized in terms of both positive and negative, i.e., in case of water body 0.96 sq.km (0.39%), dense forest – 9.54 sq.km (-0.06%), open forest 9.99 sq.km (4.12%), settlement 1.84 sq.km (1.58%) and cultivated land -3.25 sq.km (-1.34%) (Figs. 10 and 11; Table 10). Dense forest and cultivated land area are only under the negative change which denotes the over utilization of land resources as well as for the population pressure of the present scenario. The LULC pattern of 1991 and 2019 was quite contrasting conforming dynamic nature of the river. The area of water body has been positively changed though with low magnitude from 1991 to 2019 due to engulfment of newer pools and increment of cross sectional area. More astonishingly settlement areas have not been increased much as assumed that psychologically feared people leaving riverside areas went for safer dwelling places. Reduction of cultivated lands and dense forest has been witnessed due to bank erosion and channel oscillation. But open forest has been increased almost of 10 ha which attributed to regeneration of forest over the reclaimed char lands (sand deposited

areas). The phenomenon is seriously an indication of dynamic LULC conversions very often as the case of the Foothill rivers.

Output of error matrix is applied for knowing the producers accuracy, accuracy for users, overall accuracy and Kappa coefficient for both the images. The 1991 LULC map yielded overall accuracy of 90.50% and kappa coefficient of 0.88 and classes marked as to be high. In the classified map of 1991, both accuracies for all classes are 80–90% and 90% ≤; except open forest which is 77%. User's accuracy for open forest is really low (43.68%) having a confusion level of 56.32% but ground truthing has eliminated misleading signature recognitions after rectification, but for other categories it is quite satisfactory of having 80–100%. For 2019 layout/scene both the producers and users accuracies are 90–100% of range for all classes which is more than expectation and overall accuracy is 96% with Kappa co-efficient of 0.95.

Maximum land conversion noticed for open forest to cultivated land and minimum for cultivated to new plantation forest, i.e. re-vegetation, moderate change detected for about 10% in case of cultivated to settled land and water body to cultivated land. Water body has been

Fig. 9 Reach-wise computation of erosion, deposition and unchanged channel areas since 1991 to 2019 alongside Mahananda River; **a** Reach 1, **b** Reach 2, **c** Reach3, **d** Reach 4

converted into settled land registering negative change. Mean conversion is around 10–12% and less variation with low standard deviation. Very negligible areas have found as new water bodies as reoccupied channel portions and may be dug ponds or wells and rainwater harvesting plus new pools within the flood plains naturally developed. For few cases abandoned settled areas have been converted into low ends cultivation may be seasonal vegetables.

The land use adjustments of River Mahananda can be visible from the LULC predominance of the eroded and deposited areas. Most of the cultivated land undergoes in the erosion section in an amount of -0.59 sq.km. The water body in the new alluvium deposited areas could not dominant as the settled area covers about 0.72 sq.km. Both the river banks have been affected by these erosion and accretion processes (Figs. 12, 13). About 1.30% of settled areas have permanently eroded by the avulsive action of the river and a quite positive about 0.19% open forest area is lying under the deposited section which includes the forestry. Only 1.20% sq.km area

lies under cultivated land which has occupied on the deposited areas leaving the cyclic sign of readjustments towards sustainability of land use.

5 Conclusions

Bank erosion of Mahananda over the engulfing foothill plain section of North Bengal is clearly observed near Galmakhari, Champasari, Duramarir Chatt, Dabgram-I and Patiram where the land use change drastically has taken place in this section. Almost in every year a large amount of colluvium deposits which are the prime bank materials are washed away due to heavy precipitation and resultant high discharge during the monsoon months. As the embankments are constructed along both the sides of the river bank, the main channel width shrinkages have resulted for hydrodynamic modification of the lower reaches of Mahananda. As a

Fig. 10 Land use and land cover classification scene **a** 1991 **b** 2019

result intense rainfall causes high discharge within the river which is the main responsible factor for riverbank erosion. Embankment breaching is a common phenomenon which can be observed in this studied section. This problem directly impacts the near bank inhabitants. Most of the erosion affected areas belong to active encroachment due to excessive population pressure in Siliguri and its surroundings. Illegal encroachments on the floodplain section is enhancing the pressure on river bank along both the sides and making vulnerable to erosion. Besides, removal of vegetal cover for spreading up built-up areas is also a major responsible factor for bank erosion in the lower section. In 2020, embankment breaching in massive scale has taken place in the Nougkhat area along the left bank of Mahananda. Most of the erosion affected areas have adversely changed their land use by anthropogenic interferences and river regime modifications. To reduce the adverse effects

of erosion immediately some important management measures should be taken up. Firstly, the construction of spurs, boulder jacketing, etc., should be implemented before the rainy season. As the population pressure is high the Government and the concerned authorities should strictly monitor the further illegal constructions and encroachments. Green plantation along the river bank sides, rock rip-rap along with wooden fencing etc. can be implemented in the erosion vulnerable sites to reduce the impact of riverbank erosion. Also arranging the rehabilitation for the affected people is the management part to reduce the effects. Lastly, reducing riverbank pressure from this foothill area is very complicated and sometimes the erosion is an inevitable natural occurrence. So for finding out a proper solution of this present problem of the study area needs more research in this context.

Fig. 11 **a** and **b** Land use and land cover conversion scene from 1991 to 2019

Table 10 LULC classes and their temporal and areal change detection

LULC classes	1991		2019		% Change 1991 to 2019	
	Area in sq.km	Area in percentage (%)	Area in sq.km	Area in percentage (%)	Sq.km	Percentage (%)
Water body [W]	9.54	3.94	10.50	4.33	0.96	+0.39
Dense forest [F (D)]	85.13	5.13	75.59	31.19	−9.54	−0.06
Open forest [F (O)]	86.25	35.59	96.24	39.71	9.99	+4.12
Settlement [S]	28.65	11.00	30.49	12.58	1.84	+1.58
Cultivated land [C]	32.76	13.52	29.51	12.18	−3.25	−1.34
Total	242.33	100	242.33	100	–	–

Fig. 12 Land use and land cover conversion scenario from 1991 to 2019

Fig. 13 Land use and land cover adjustments in the areas under erosion and deposition

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Declaration

Conflict of interest The authors express that there is no conflict of interest.

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