Sustainable Water Resources Management (2020) 6:35
https://doi.org/10.1007/s40899-020-00393-9

ORIGINAL ARTICLE

A morphology-independent methodology to assess erosion, accretion and lateral migration of an alluvial channel using geospatial tools: a study on the Raidak-I river of Himalayan Foothills

Md. Hasanuzzaman[1] · **Sujit Mandal**[1]

Received: 26 January 2018 / Accepted: 4 May 2020 / Published online: 14 May 2020

Abstract
Channel migration is a significant geomorphological process in the floodplain region. Human intervention in the form of engineering constructions (bridges, embankment, etc.) regarded as another dominant issue which is pulverizing the ways of natural channel adjustment as well as channel behavior. In the study, the channel adjustment in terms of lateral migration is lucidly illustrated with the application of modern tools of geoinformatics, i.e., the techniques of RS and GIS. At present, RS and GIS are capable of detecting as well as representing the channel changes over space and time. The Raidak-I river is a meandering course stretching for about 81.9 km through alluvial plains of Cooch Behar and Alipurduar districts of West Bengal. To study erosion–accretion and lateral migration of Raidak-I river, sequential changes in the position of bank line have been studied with the help of USGS satellite data for the year 1972, 1978, 1990, 1996, 2002, 2009 and 2016. Using Arc GIS10.1 software and Arc GIS extension tools, bank centerline, the average length of migration of channel, shape area migration of the channel and different segments-wise erosion and accretion were assessed. The river bank line shifting due to bank erosion has been carried out considering various time spans, i.e., 1972–1978, 1978–1990, 1990–1996, 1996–2002, 2002–2009 and 2009–2016. The average migration of channel, shape area migration of channel and erosion–deposition decreased from 1972 to 2016 except during the period 1990–1996. Such changes in meander morphology of the Raidak-I river have made the channel more dynamic in the Himalayan foothill region.

Keywords Raidak-I · Lateral migration · Centerline · Channel adjustment · Erosion and accretion

Introduction

Geomorphic analysis of a river presents unique challenges and requires a systematic and organized approach in terms of system complexity involved. Progress in the study of fluvial geomorphology has been aimed to develop the capability to identify, investigate and understand the continuity and connectivity of the flow processes and fluvial landforms in a river system. This prescribes the need to recognize and explore the links that bind the fluvial system in space and time. Knowledge of the history and sequence of antecedent events and trends of morphologic evolution during the months, years and decades preceding the study will definitely help to understand the process–form relationships of a river. River engineers, policymakers and managers recognize the importance of accounting channel morphology and the dynamics of the fluvial system of alluvial rivers. Modern approaches to the river management require engineers to work with the natural process–form relationships of the river, by retaining as much as possible of the natural hydraulic geometry of the self-formed channel at the time of river regulation, channel training, navigation, flood defense and land drainage. It is essential to identify correctly the current morphological status of the river and to predict its future development with and without the proposed engineering interventions. The latter requires the knowledge of predicting the reaction of river channel, for example flow regulation (for hydropower or flood defense), or bank stabilization and training works (to control channel migration). Morphological impacts are assessed from the point of disturbance

✉ Md. Hasanuzzaman
md.hzaman20@gmail.com

Sujit Mandal
mandalsujit2009@gmail.com

[1] Department of Geography, University of Gour Banga, Malda, India

through process–form feedback mechanisms operating in the fluvial system. Channel migration perhaps is a very common phenomenon found profoundly in braided and meandering rivers over the earth's surface characterized by wide and flat valley floors and erodible banks. In a general sense, channel migration is simply the movement of a river channel back and across its valley during a specific time span.

Riverbank erosion is an endemic and recurrent natural hazard. When rivers attain the mature stage, they become sluggish and form meander bends. These oscillations cause massive riverbank erosion (Rahman 2010; Das and Bhowmik 2013). Lateral migration is a process that can cause catastrophic local or regional changes (Hickin and Nanson 1984; Thakur et al. 2012). The comprehensive effect of such changes introduces a socioeconomic hazard to the floodplain dwellers in a respective river basin. A number of factors determine the lateral migration of a river along its pathways such as drainage basin area, topography, vegetation cover, tectonic activity, land use patterns and climate factors in a particular region. Erosion may be caused either by undercutting of the bank materials by channels. Such undercutting during catastrophic flood situation produces an overhanging cantilevered block that eventually fails or by over-steepening of bank materials due to the migration of the thalweg closer to the bank during the falling stages (Goswami 2002). Various studies have been carried out for some major rivers with the help of remote sensing and GIS technique for detecting spatiotemporal changes in river erosion (Nanson and Hickin 1986; Yang et al. 1999; Bhakal et al. 2005; Kotoky et al. 2005; Kummu et al. 2008; Thakur et al. 2012; Sarma and Acharjee 2012; Chakraborty and Datta 2013; Gogoi and Goswami 2013, Neog 2017). From the scientific point of view, the migration of a river channel with respect to space and time is an expression of response by a river channel to its natural and anthropogenic drivers. This response manifested the changes in the physical form of a river channel owing to the actions of various drivers. Such changes may incorporate 1D change (e.g., changes in width, depth and thalweg length) along with certain 2D changes (e.g., adjustments in channel planform) in the riverine morphology (Wallick et al. 2007).

Migration of a river channel comprehensively encompasses the temporal width–depth adjustments of a river as well as alterations in its planform geometry. The obvious act centering the study of channel migration is thus, unquestionably, the stipulated 'timeframe' over which a river channel is expected to move through a defined corridor. In fact, it is the timescale which extends the limits of channel migration. A period of 100 years is very often used as an appropriate timeframe (Bolton and Shellberg 2001). While considering the variables of such migration, Hickin and Nanson (1984) defined channel migration as the collective output of stream power, boundary resistance, bank height, meander bend radius and channel width. The dynamics of channel adjustment in terms of lateral migration can be lucidly illustrated through the application of modern tools of geoinformatics, i.e., the techniques of remote sensing and geographic information system (GIS) which are widely capable of detecting as well as representing the changes that took place over space and time. A meticulous endeavor has been made to assess the channel dynamics in 44 years and to unveil the nature of channel migration in terms of changes in the historical bank line, centerline positions and alterations in meander geometries through numeric and graphical methods coupled with field observations of the Raidak-I river.

Study area

The Raidak River is one of the main right bank tributaries of the Brahmaputra River. It is a trans-boundary river and flows through countries like Bhutan, India and Bangladesh. The river rises in the Himalayas and is known as Thimphu Chhu in its upper reaches. It passes through various mountains and valleys in Bhutan. In its journey, it is joined by several small tributaries flowing from nearby mountains. The river is known as the Wong in its upper course in Bhutan. The river after traversing through the mountainous terrain in Bhutan comes back to the plains in India, into the plains in Alipurduar District and then flows through Cooch Behar District in the state of West Bengal. After flowing in the Indian subcontinent, the river enters Bangladesh. The Raidak River merges with the Brahmaputra River within the nation limits of Bangladesh. The confluence takes place at the chainage of 327 km.

Among the three course of river Raidak, the middle one is old Raidak, western flow is named as Raidak-I or Deepa Raidak and lastly, the eastern one is named as Raidak-II. The name of middle flow signifies that old Raidak is the ancient course of the Raidak River. The study area river Raidak-I is located in between two districts of West Bengal, which are Cooch Behar and New Alipurduar. The region is situated between 26° 34′ 30.18″ to 26° 12′ 57.58″ North latitude and 89° 43′ 12.12″–89° 41′ 38″ East longitude. The length of the river in the study area is 81.9 km and divided into part AB and BC (Fig. 1).

Methodology and database

Database preparation

The most important aspect of the present work is developing a morphology-independent methodology. The authors have identified channel migration by using satellite imagery with the help of remote sensing and GIS

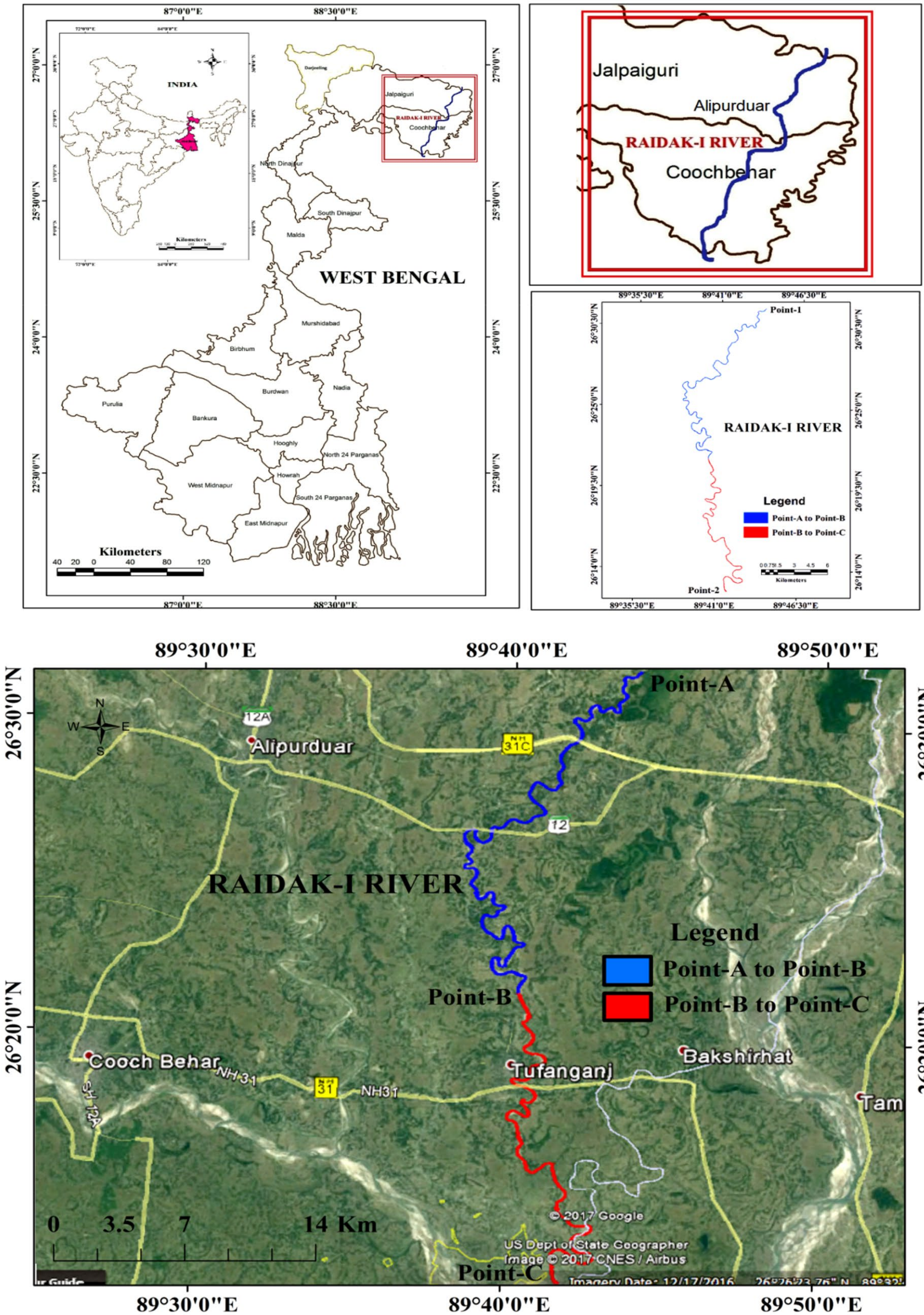

Fig. 1 Location map of study river Raidak-I

technique. GIS is the effective and accurate tool of quantifying channel changes both at medium-term and at short-term geomorphic scales (Winterbottom 2000). For identifying bank line migration, calculation of shape area migration and erosion and deposition of the study area, remote sensing techniques and satellite imageries have been used (Table 1). This work adopts to regularly use sophisticated software ArcGIS 10.1 and extensions to identify centerlines, centerline migration, shape area migration and calculation of erosion and accretion area.

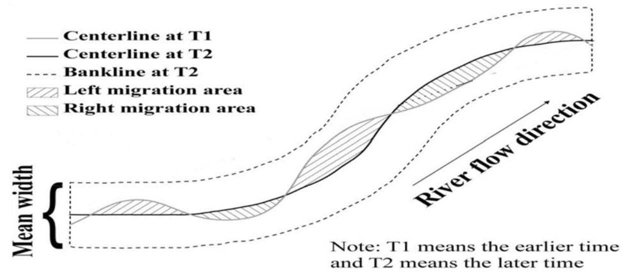

Fig. 2 Schematic diagram of centerline migration area

Delineation of channel centerline migration

The location of the riverbank in the six datasets was determined using the Arc GIS software and its extensions. The changes in the locations of both riverbanks were assessed during six periods, i.e., 1972–1978 (6 years), 1978–1990 (12 years), 1990–1996 (6 years), 1996–2002 (6 years), 2002–2009 (7 years) and 2009–2016 (7 years). For the determination of centerlines of the active river channels of different time periods, ArcGIS extension, namely 'River Bathymetry toolkit,' has been applied. The extension has been used in ArcGIS 10.1 to generate centerlines automatically from the active bank lines. These centerlines display the nature of lateral migration of the river. Another extension Channel Migration Toolbox (CMTB) was used in Arc GIS 10.1 to determine how to reach average channel migration, the average length of migration of channel and shape area migration of channel, which eventually helps to understand the lateral migrating nature of the river Raidak-I. The migration of the centerline was measured with the help of the migration area, which was defined as the area enclosed by successive channel centerlines (Fig. 2). The migration area of the centerline can be divided into the left and right parts according to the river flow direction by using the old centerline as the reference. If the left migration is larger than the right migration, then the river shifting direction is toward left, and vice versa.

Table 1 Characteristics of selected satellite images

Images	Years	Spatial resolution (in m/p)	Source
Landsat–MSS	1972	60	http://earthexplorer.usgs.gov
Landsat–MSS	1978	60	http://earthexplorer.usgs.gov
Landsat-TM5	1990	30	http://earthexplorer.usgs.gov
Landsat-TM5	1996	30	http://earthexplorer.usgs.gov
Landsat-ETM+	2002	30	http://earthexplorer.usgs.gov
Landsat-TM5	2009	30	http://earthexplorer.usgs.gov
Landsat-OLI	2016	30	http://earthexplorer.usgs.gov

Determination of erosion and accretion areas

Riverbank lines during different time periods have been superimposed, and through the transect generation, the river channels have been divided into several segments. The amount of erosion and accretion was calculated separately for each side of the river. Digitization of the active bank lines of each period of 1972 and 2016 superimposed into a single layer and processed them using the GIS software to create polygons that represented the difference between the first and second positions of different segments. If a polygon was positioned to the left of the 1972 bank line, it represented an erosion polygon; if a polygon was positioned to the right of the 1972 bank line, it represented a deposition polygon. The same process was adopted to assess erosion and deposition along the right bank. But following the changes of polygons to the left and right of the 1972 bank line represented deposition and erosion, respectively. Summing the areas of these polygons, the total eroded and deposited areas from 1972 to 2016 were assessed. After determining these areas, we added 1978, 1990, 1996, 2002 and 2009 bank lines sequentially to subdivide each of the polygons into smaller polygons that represented the bank lines of each period (Fig. 3). The GIS software was used to calculate the areas of overlap between the bank line in each year and the boundaries of the polygon that contained that portion of the bank line. The same approach we used for the period from 1972 to 2016 to calculate the erosion and deposition between consecutive years.

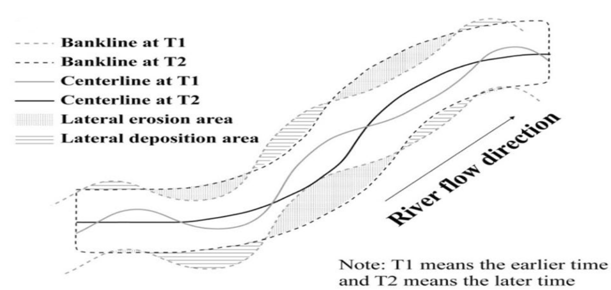

Fig. 3 Schematic diagram of lateral erosion–accretion area

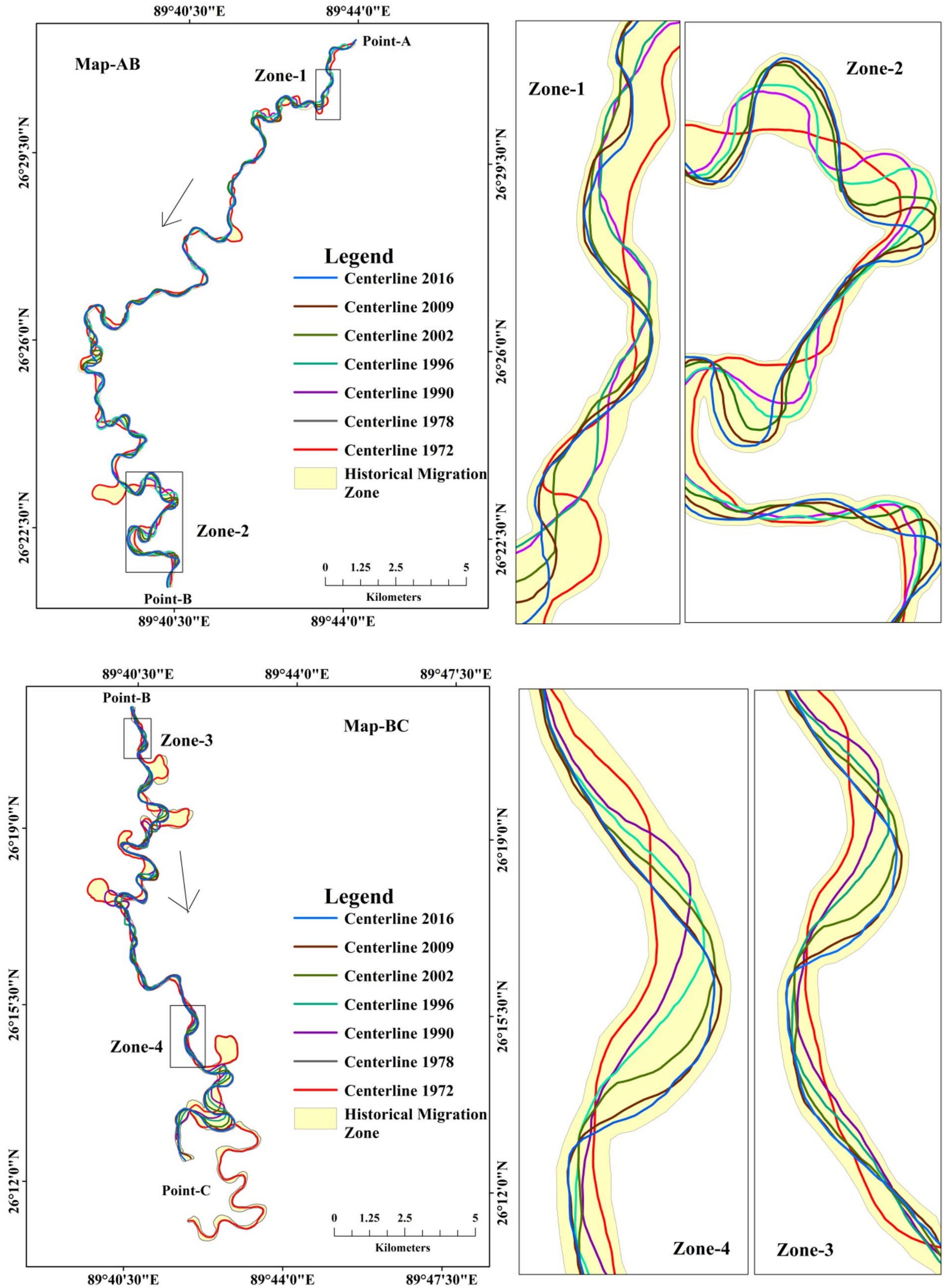

Fig. 4 Historical centerline positions of Raidak-I river (1972–2016)

Results and discussion

Graphic representations and illustrations have been generated based on computational derivations. The ArcGIS (Version 10.1) software and ArcGIS extension tools have been used to process and prepare the graphics outputs with regard to centerline migration, bank line movements, river meander dynamics and erosion–accretion and to delineate historical centerline position reach average centerline migration and shape area migration of channel.

Centerline migration

The centerline of the river channel was derived from the boundary based on the bank lines by using the mathematical morphology method which was an improved method to extract skeleton line of the polygon. The reach average length of channel migration and reach shape area migration of channel were measured by its centerline. The distance between two intersecting centerlines is considered a river reach. The centerline of the Raidak-I river from 1972 to 2016 is the historical migration zone (Fig. 4). Historical migration zone (HMZ) is the area of historical channel occupation recorded on photographic evidence.

Zone-1

Zone-1 is showing centerlines of the period 1972–2016 in the historical migration zone. The centerline of 1972 is near to left bank, the centerline of 2009 is near the right bank, and other centerlines are located in between the two banks. Here, different centerline is displaying an oscillating nature.

Zone-2

Zone-2 clearly indicates the changing nature of centerlines of the Raidak–I River during 1972 to 2016. Within these

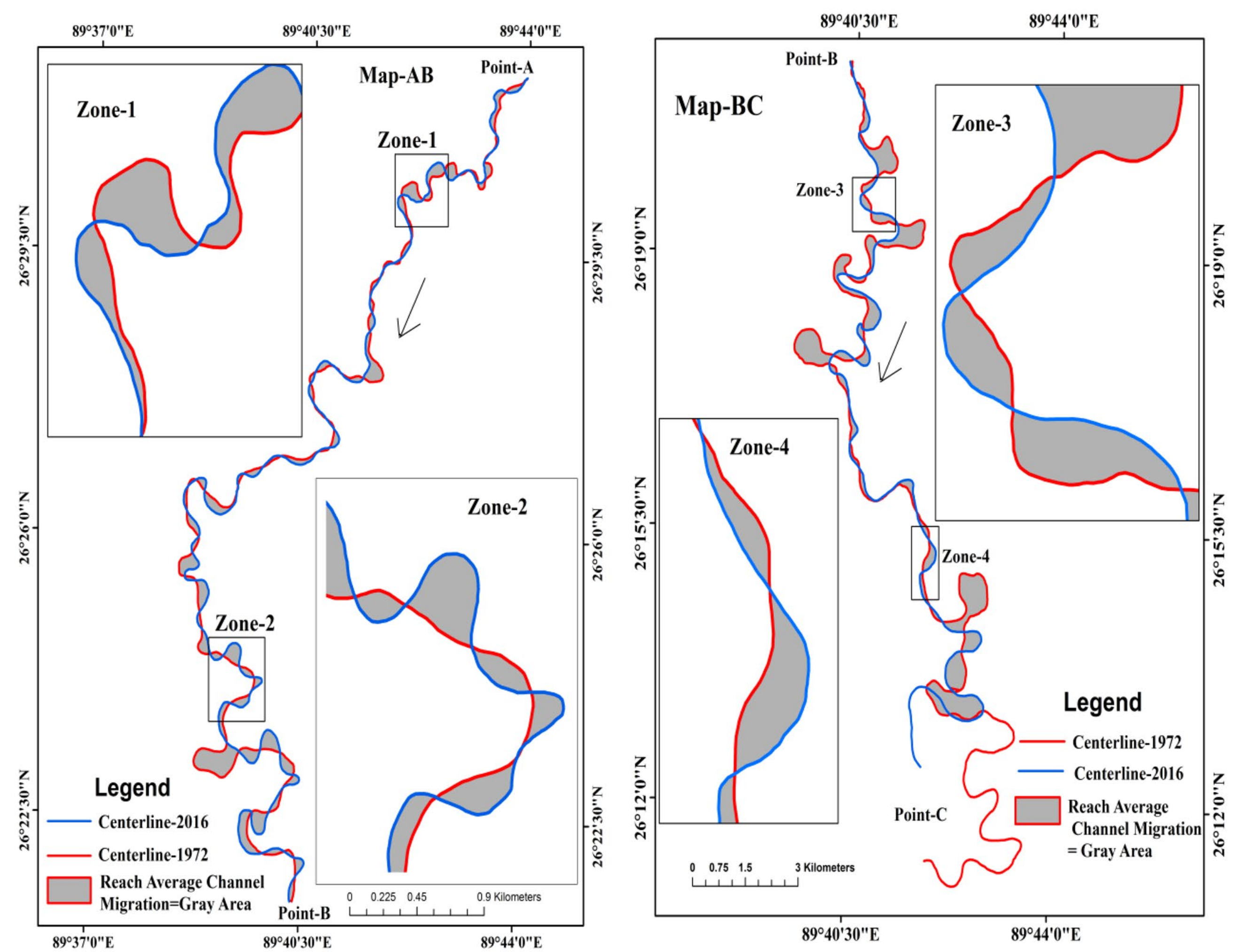

Fig. 5 Channel migration of Raidak-I river. The channel centerlines and how to reach average channel migration would be calculated

time periods, it is evident that the meander bands have shifted toward a specific direction.

Zone-3 and Zone-4

The two zones are showing very well in the 1972 centerline on the right bank, and the centerline 2016 is on the left side. However, from 1972 to 2016, this change took place from right bank to left bank of the river, which means that this change is unidirectional.

The reach average length of 154.26 m, 100.13 m, 49.87 m, 75.60 m, 49.48 m and 30 m migration of the channel occurred during the periods of 1972–1978, 1978–1990, 1990–1996, 1996–2002, 2002–2009 and 2009–2016, respectively.

Channel migration

Following the criteria used in centerline migration, i.e., the methods of assessing reach average length of migration and shape area migration of channel, it was observed that in the past 44 years (1972–2016), the reach average length of migration and shape area migration of centerlines of Raidak-I river were 231.88 m and 10.53 km^2, respectively.

It has been shown through various zones in 1972–2016, how the changes or migrate in different parts of the Raidak-I river and how to reach average channel migration would be calculated. Gray area is the reach average channel migration area of the river. The zones (zone-1, zone-2, zone-3 and zone-4), it show that the two centerlines intersect in each other and the area of division between them is the moving zone or migrated area, and this migration is calculated according to different river reach; it is called reach average channel migration.

Significant gradual decreasing trends of the average length of migration and shape area migration were observed during the period of 1972–2016 (Fig. 5). Compared with the earlier period (1990–1996), the average length of migration and shape area migration increased slightly during the period

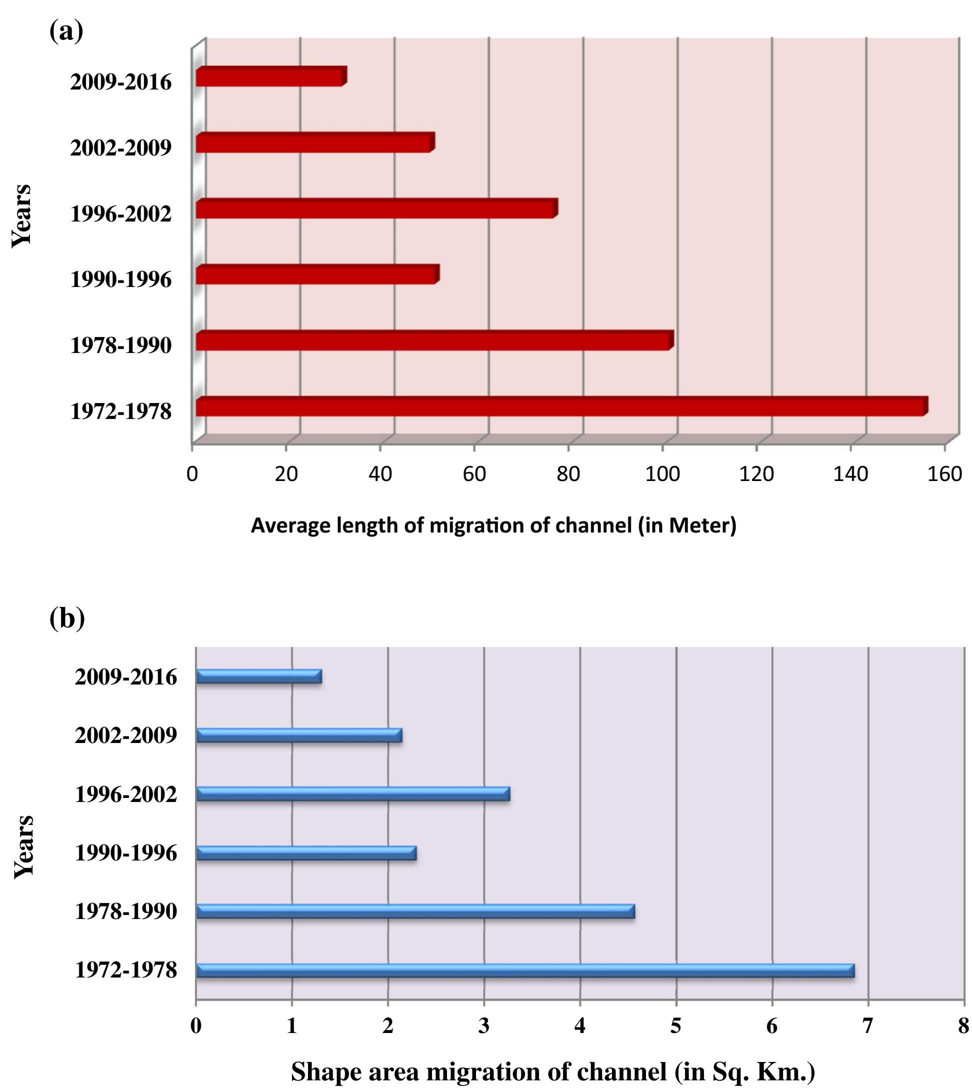

Fig. 6 **a** Average length of migration of Raidak-I river. **b** Shape area migration of Raidak-I river

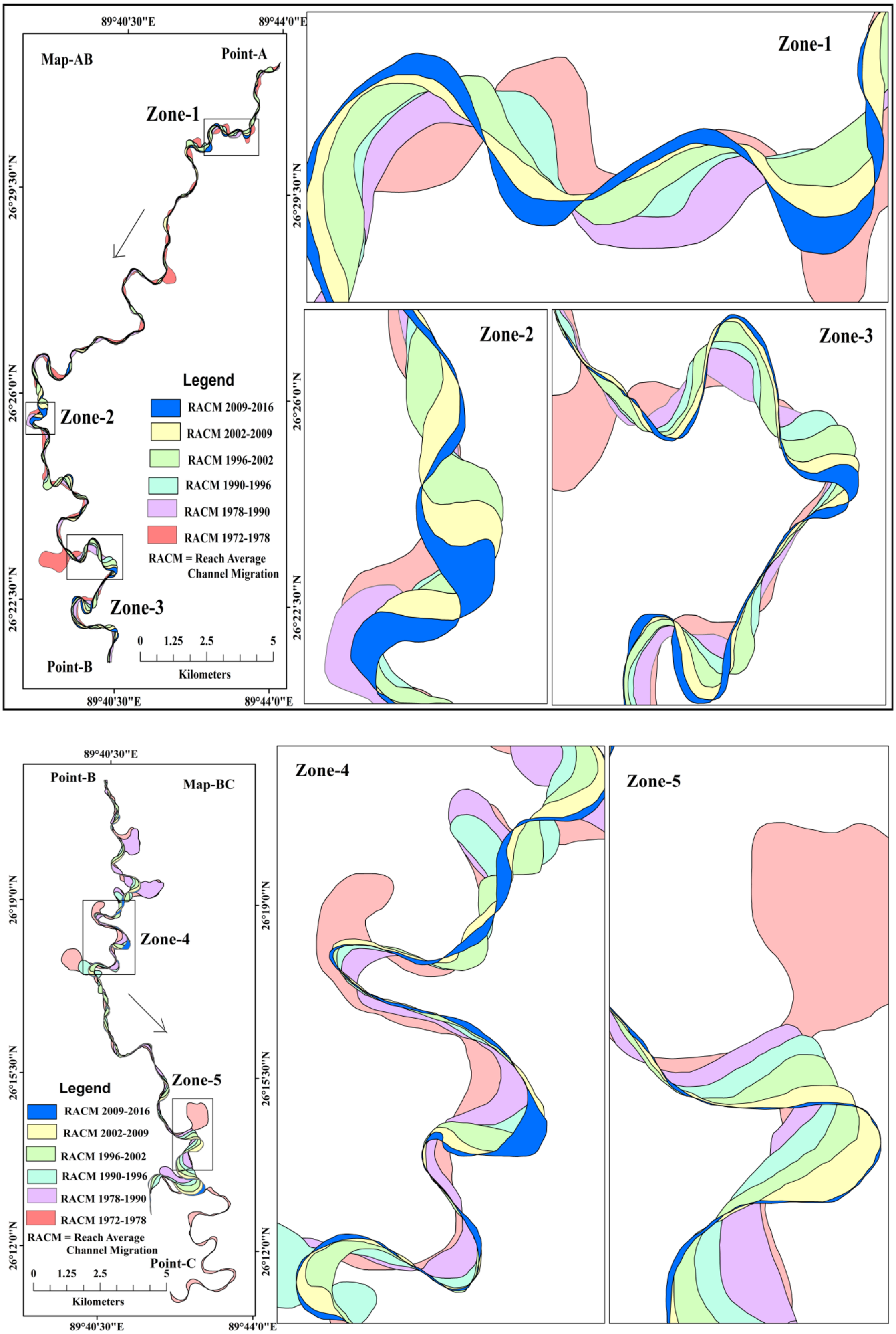

Fig. 7 Reach average channel migration of Raidak-I river

Table 2 Erosion and deposition of Raidak-I river during 1972 to 2016. *Source*: primary data

Year	Right bank		Left bank	
	Erosion (m^2)	Accretion (m^2)	Erosion (m^2)	Accretion (m^2)
1972–1978	1,220,000	1,772,000	1,717,000	1,250,000
1978–1990	943,000	1,056,000	1,103,000	979,000
1990–1996	583,000	638,000	663,000	654,000
1996–2002	979,000	1,358,000	1,070,000	1,224,000
2002–2009	1,040,000	775,000	923,000	1,022,000
2009–2016	490,000	491,000	369,000	434,000

of 1996–2002. In this situation, the reach average length of migration decreased in periods (1972–1978, 1978–1990, 1990–1996, 1996–2002, 2002–2009, 2009–2016). During the periods of 1972–1978 and 1978–1990, the maximum reach average length of channel migration is displayed. But the study revealed that from 1972 to 2016, there is a decreasing tendency of reach average length of channel migration in Raidak-I river. The reach average shape area of migration in all the periods was 6.86 km^2, 4.57 km^2, 2.30 km^2, 3.27 km^2, 2.15 km^2 and 1.31 km^2 (Fig. 6a) which showed a decreasing trend.

Reach average channel migration

On this map showed different high channel migration parts of the Raidak-I river in the different zones according to the different period. **Zone-1:** In this section of the river, it is clearly shown that channel migration has decreased during the entire period and the meandering of the river has increased over the time. **Zone-2:** This zone depicted that the channel migration is increasing from 1996 to 2016. **Zone-3**: This part of the river showed increasing bending or meandering and unidirectional shifting during the period 1972 to 2016 and an oxbow lake is formed. **Zone-4**: This part of the river created several oxbow lakes due to river high dynamicity and oscillating change. **Zone-5:** Sequentially change and unidirectional shifting scenarios of a meander bend are represented during the period 1972 to 2016 in this zone. An oxbow lake was created from 1972 to 1978.

One thing can be concluded from the above analysis of centerlines position of different periods of Raidak-I river that Raidak-I river is very dynamic. But some parts are not

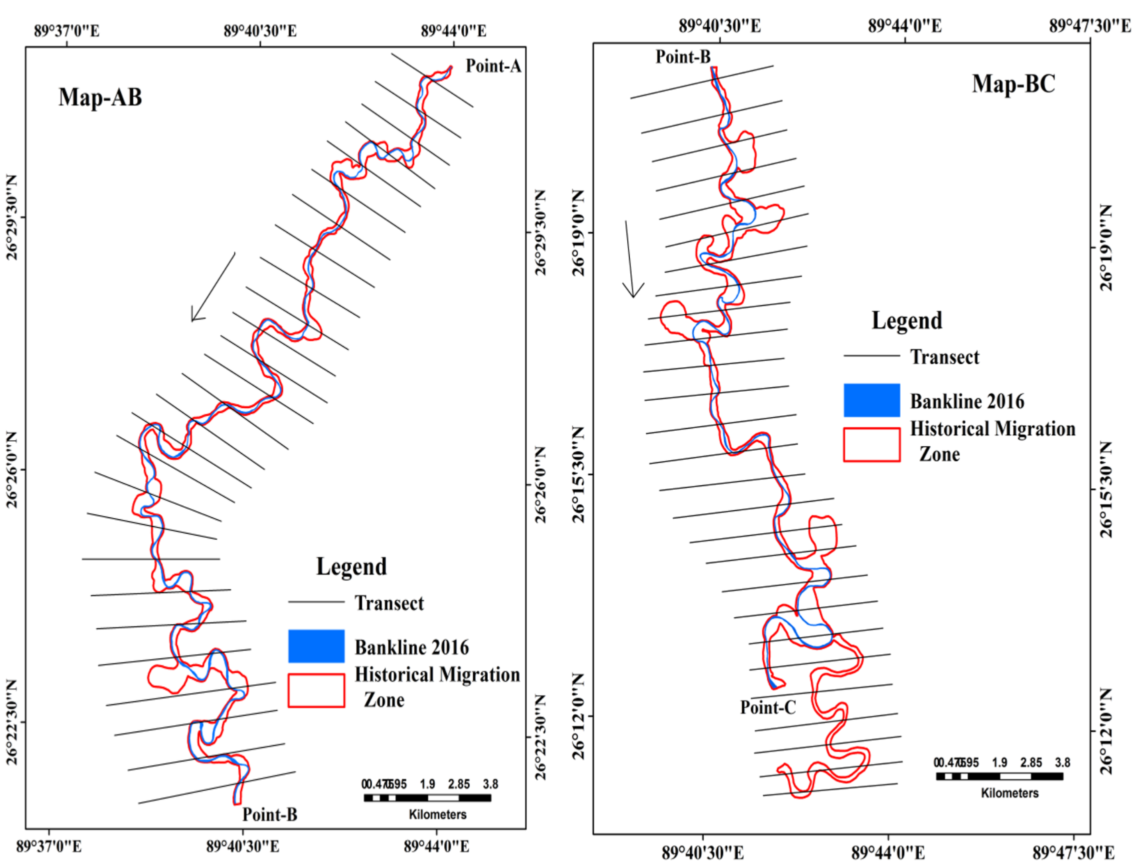

Fig. 8 Various segments of the Raidak-I river created by Transect

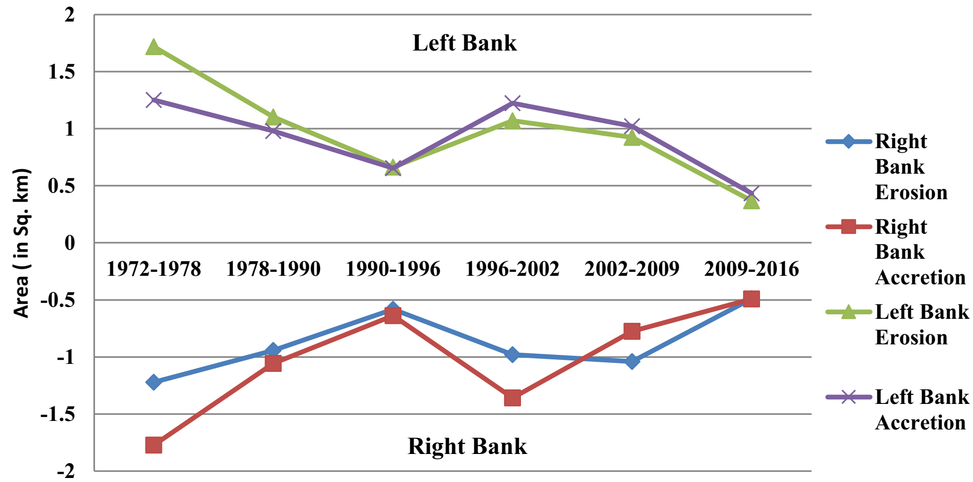

Fig. 9 Erosion and accretion of Raidak-I river during 1972 to 2016

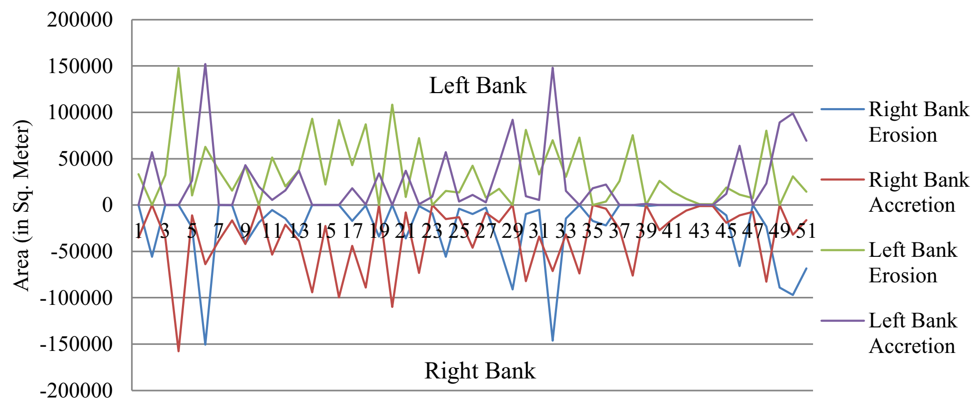

Fig. 10 Right and left bank erosion–accretion of Raidak-I river during 1972–1978

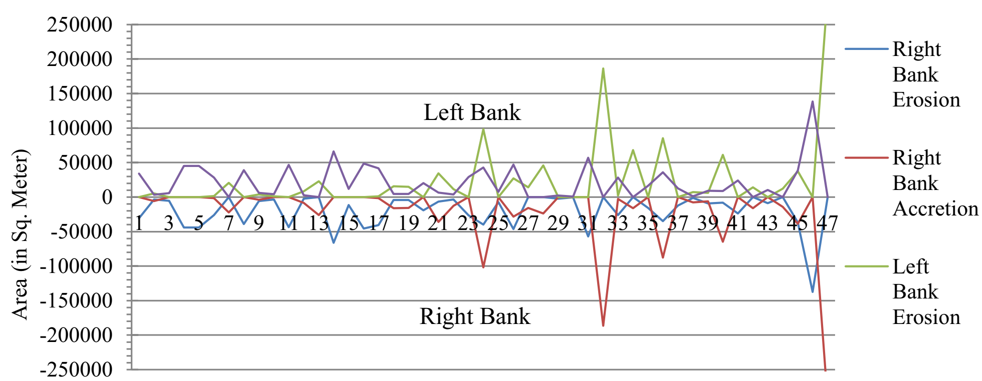

Fig. 11 Right and left bank erosion–accretion of Raidak-I river during 1978–1990

dynamic. However, the parts which are very dynamic are also very sequential in meandering as noticed in Fig. 7. The number of river reach or intersection of centerlines increased over time like 115 in 1972–1978, 105 in 1978–1990, 175 in 1990–1996, 126 in 1996–2002, 149 in 2002–2009 and 218 in 2009–2016.

Erosion and accretion

The activity of erosion–accretion processes of Raidak-I river has been evaluated for five successive periods of 1972–1978, 1978–1990, 1990–1996, 1996–2002, 2002–2009 and 2009–2016.

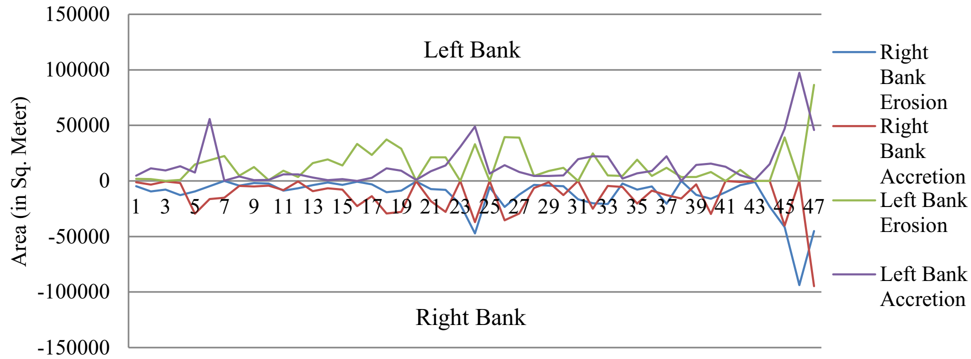

Fig. 12 Right and left bank erosion–accretion of Raidak-I river during 1990–1996

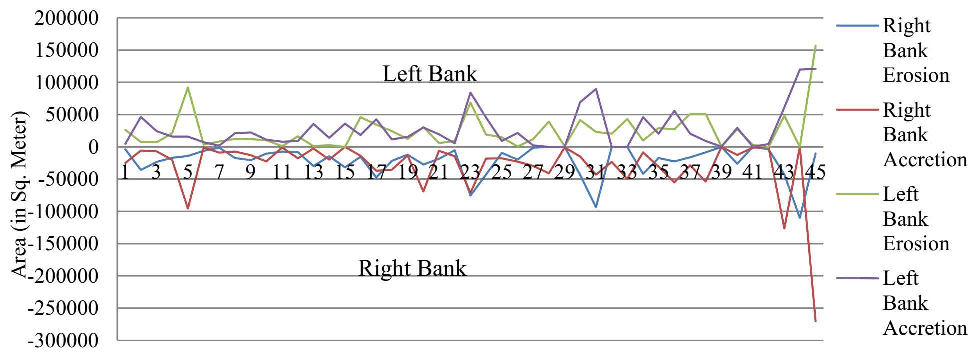

Fig. 13 Right and left bank erosion–accretion of Raidak-I river during 1996–2002

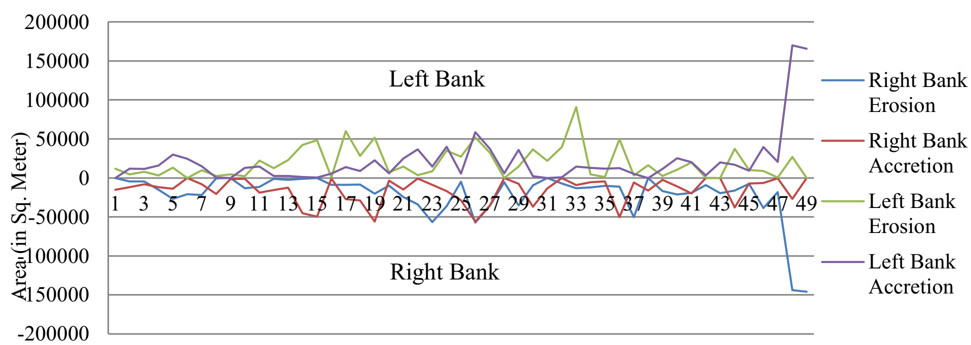

Fig. 14 Right and left bank erosion–accretion of Raidak-I river during 2002–2009

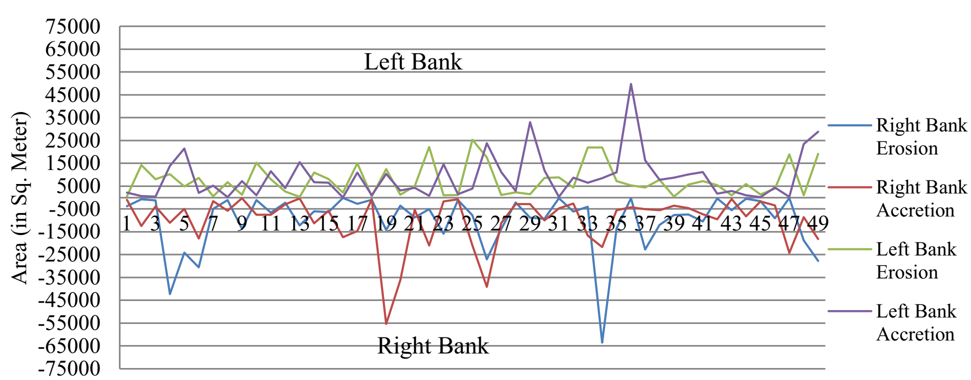

Fig. 15 Right and left bank erosion–accretion of Raidak-I river during 2009–2016

Table 3 Right and left bank erosion–accretion of Raidak-I river during 1972–1978 and 2009–2016. *Source*: primary data

Segments	1972–1978				2009–2016			
	Right bank		Left bank		Right bank		Left bank	
	Erosion (m^2)	Accretion (m^2)	Erosion (m^2)	Accretion (m^2)	Erosion (m^2)	Accretion (m^2)	Erosion (m^2)	Accretion (m^2)
01	0	35,295	33,175	0	3765	1029	495	2182
02	55,790	0	0	56,890	807	12,429	14,225	623
03	0	35,196	32,127	0	1250	3869	8039	410
04	0	157,810	147,890	0	42,267	11,065	10,265	13,917
05	24,237	11,240	10,230	26,337	24,107	4989	4898	21,514
06	150,503	63,870	62,769	152,166	30,571	17,909	8616	2007
07	0	38,390	37,383	0	4977	1582	536	5200
08	309	16,559	15,559	109	1146	5800	6751	147
09	41,478	41,907	41,492	42,902	13,710	239	1188	7178
10	18,866	0	0	19,860	1074	7510	15,328	990
11	5501	53,420	51,420	5602	6653	7503	8072	11,568
12	14,646	21,005	20,005	15,796	2274	2922	2692	4164
13	33,076	38,569	37,565	37,089	12,269	392	326	15,503
14	0	94,144	93,133	0	6007	11,229	10,937	6743
15	0	22,567	22,222	0	6323	5784	8150	6536
16	0	99,473	91,721	0	176	17,336	2189	102
17	17,216	43,989	42,934	18,217	2683	14,648	15,029	11,001
18	590	88,906	87,003	602	1042	712	512	1034
19	33,981	0	0	34,098	14,167	55,347	12,409	10,390
20	0	109,853	10,8153	0	3583	36,148	1246	3102
21	35,922	7998	8702	36,901	8713	5329	4945	4261
22	991	73,301	72,270	1001	5027	21,007	22,125	783
23	8868	0	0	8979	15,843	1696	1008	14,514
24	55,751	15,200	15,226	56,971	1099	700	1109	1458
25	3846	13,000	13,632	3900	7802	20,951	25,287	3960
26	9683	46,010	42,510	10,881	27,064	39,099	17,578	23,805
27	2846	8190	8078	2900	13,719	11,184	1066	11,184
28	44,756	18,509	17,567	45,700	2102	2809	2342	2847
29	91,023	0	0	92,044	8779	2848	1477	33,042
30	9573	82,265	81,212	9607	9244	9982	8604	11,847
31	5091	34,090	33,086	5509	285	4743	8834	302
32	146,368	71,139	69,965	148,221	6149	2682	4374	8699
33	14,557	31,821	30,261	15,095	4078	16,714	21,901	6456
34	0	73,868	72,757	0	63,520	21,669	21,916	8506
35	17,182	0	0	17,981	13,537	5589	7163	11,108
36	22,015	3900	3707	22,115	305	4238	5284	49,813
37	0	26,100	25,920	0	22,700	5047	4356	16,278
38	0	76,255	75,244	0	12,040	5557	7797	7771
39	1203	0	0	1320	7710	3511	468	8778
40	0	27,223	26,123	0	7390	4566	5736	10,172
45	0	15,009	14,449	0	10,414	7340	7197	11,137
46	0	5989	6738	0	405	9518	5506	1719
47	209	1200	1029	390	5535	630	1008	2893
48	0	1009	989	0	532	8239	5906	1006
49	11,231	19,002	18,982	12,100	1545	1677	1396	191
50	65,727	11,002	11,111	63,950	9063	3494	3974	4413
51	0	7523	7564	0	190	24,283	18,922	356

Table 3 (continued)

Segments	1972–1978				2009–2016			
	Right bank		Left bank		Right bank		Left bank	
	Erosion (m^2)	Accretion (m^2)	Erosion (m^2)	Accretion (m^2)	Erosion (m^2)	Accretion (m^2)	Erosion (m^2)	Accretion (m^2)
52	23,033	82,594	80,094	23,281	18,720	8562	1056	23,474
53	89,108	0	0	89,209	27,769	18,125	19,180	28,796
54	96,960	32,041	31,041	98,752				
55	68,307	16,265	14,242	69,407				

The erosion–accretion is prevalent at different segments during different time periods (Table 2). The intensity of erosion–accretion decreased through time since 1972. It is revealed that the Raidak-I river experienced a higher intensity of erosion along its left bank than the right bank and accretion is higher along the right bank than the left bank (Fig. 8). During the period 1972–2016, the total average annual erosion and accretion were 250,000 and 260,000 m^2/year, respectively, signifying a net gain of sediment/land area (Fig. 9).

The period 1972–1978 showed phenomenal river bank erosion where the deposition is very less (Fig. 10). The right and left bank eroded areas are 1,220,000 and 1,717,000 m^2, respectively, during the period 1972–1978. During this period, accreted areas in both right and left bank are 1,772,000 and 1,250,000 m^2 (Table 2). The erosion and accretion are higher in this period compared to other periods. During this period, the erosion and accretion are higher in both right bank and left bank, but the sifting direction is toward the left side. During the period 1978 to 1990, right bank and left bank eroded areas are 943,000 and 1,103,000 m^2, respectively. But, the accreted areas in both right bank and left banks are 1,056,000 and 979,000 m^2, respectively. Both side erosion and accretion decreased in this period. During the period of 1990–1996, 583,000 m^2 area eroded from the right bank and 663,000 m^2 area eroded from the left bank which are the lowest of both side erosion and accretion of corresponding periods of Raidak-I river. The pattern of erosion and accretion is different during the period of 1996–2002 compared to earlier periods. In this period, right and left bank erosions were 979,000 and 1,070,000 m^2, where depositions were 1,358,000 and 1,224,000 m^2, respectively. Erosion and accretion of both sides of the river increased in this period. The study showed that the accretion in the right bank is less in comparison with the left bank in the period of 2002–2009. Such a trend at erosion and accretion continued in the next period (Table 2). Right bank deposition of this period is lower than the left bank accretion. A decreasing trend is seen continuously in the period 2009–2016. More specifically, during this period, right and left bank erosion and accretion are 49,000, 369,000, 491,000 and 434,000 m^2, respectively (Figs. 11, 12, 13, 14 and 15).

From the year 1972, lateral migration of the river has decreased although both the side amount of erosion and accretion of the river have been increased. Thus, the river migrated laterally, but in the later phase the amount of erosion and accretion has been increased in both the banks; as a result, the amount of erosion in the left bank and accretion in the right bank and the amount of erosion in the right bank and accretion in the left bank balance each other (Table 3). Among the different segments, 03-05, 22–25 and 30–35 segments are very active for erosion and accretion during the study period 1972 to 2016.

Direction of shifting

Erosion and accretion over the river beds and transport of sediment are the common characteristics of the alluvial river channel. All these processes occur throughout a river system, but certain processes may dominate in particular areas. In case of an idealized fluvial system, erosion dominates in the upper reaches, whereas accretion dominates in the lower reaches. The sediment transport process dominates in the so-called transfer zone connecting the upper and lower extremes. The part of the fluvial system known as the transfer zone consists of meandering streams. The meandering part usually occurs in the lower reaches where slopes are less pronounced. The transfer zone approaches toward the stability condition as a result of the process of aggradation and degradation processes. In this situation, the amount of sediment entering the zone will be equal to that leaving the zone.

The Raidak-I river shifting is mostly oscillating, but some locations are unidirectional in nature (Fig. 16). In most of the locations, the river shifted to the opposite side of the concrete embankment. The length of the river is 81.9 km in the present study, out of which 7.95 km long is attributed to embankments (Fig. 17). Riverbank erosion is absent along the embankment. Zone-1, zone-2, zone-3, zone-4, zone-5, zone-6 and zone-7 are depicting the unidirectional shifting part of the Raidak-I river. This river meandering patterns

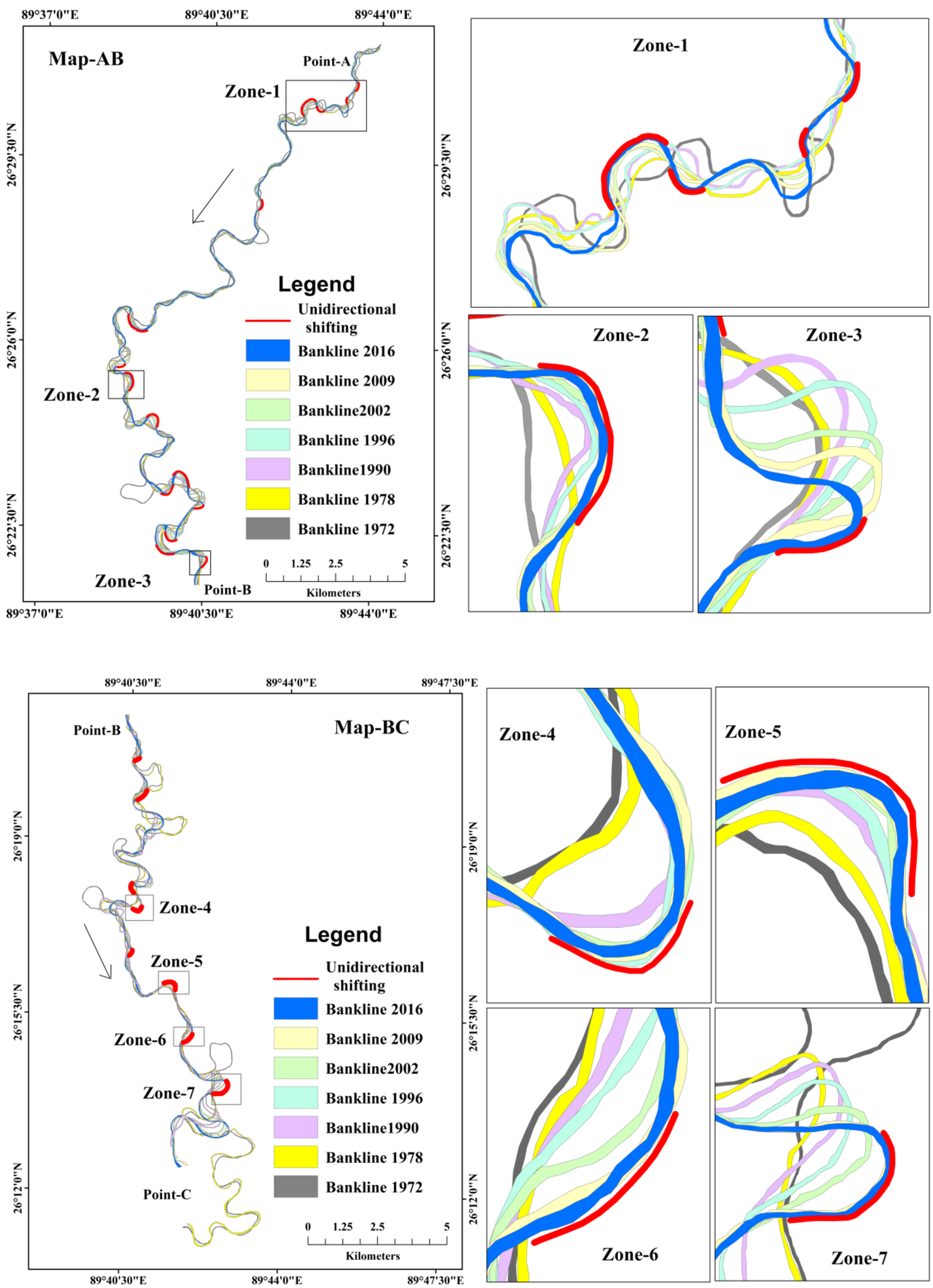

Fig. 16 Unidirectional shifting of Raidak-I river. The different windows (window 1, 2, 3, 4, 5, 6 and 7) display the unidirectional shifting

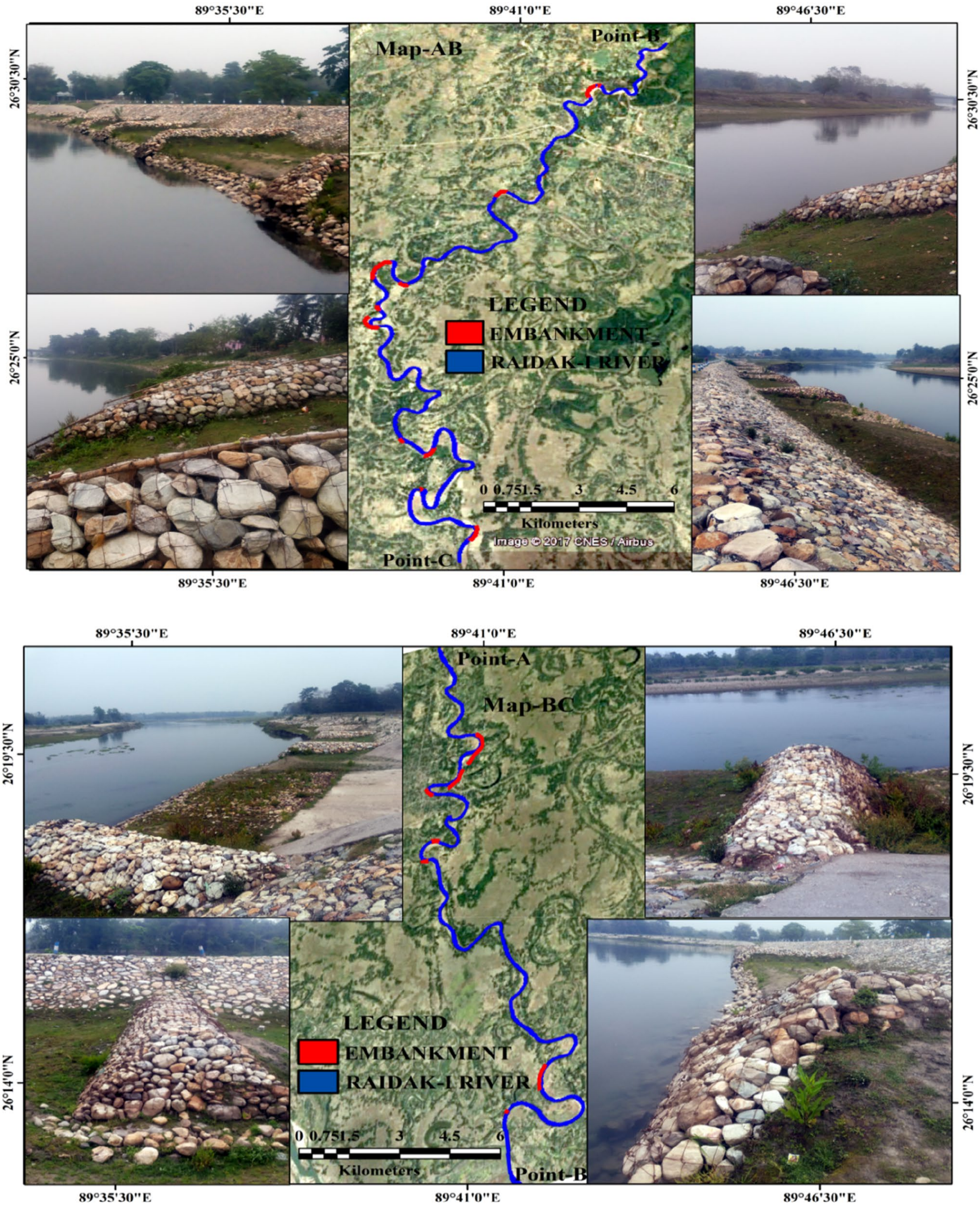

Fig. 17 Boulder-made embankment along the Raidak-I river

Table 4 Shifting direction of Raidak-I river at different time periods. *Source*: primary data

Years	Shifting direction
1972–1978	Left bank
1978–1990	Left bank
1990–1996	No change
1996–2002	No change
2002–2009	Right bank
2009–2016	No change

are followed by neck cutoffs, chute cutoffs and meandering shifting. Zone-1 and zone-4 are experienced with neck cutoff. Neck cutoff usually occurs in a highly sinuous part of this river and are often initiated by floods. During this process, the long meandering path is by past. Zone-2, zone-5 and zone-6 are represented by some chute cutoffs. A chute cutoff is less drastic than a neck cutoff and tends to increase the radius of the bend. Zone-3 and zone-7 showed the normal trend of meander shifting of Raidak-I river. Migration by meander shifting usually occurs in the downstream direction. These movements can be quite drastic, and a shift of up to 288 m during 1996–2002 has been reported (Fig. 16).

The trend of lateral migration and erosion–accretion of the Raidak-I river demonstrated that the shifting direction has been changed through time (Table 4). Since 1972–1990, the river shifted to the left, but there has been no change since 1990–2002. But since 2002–2009, the river shifted toward the right and again there has been no change from 2009 to 2016. It is evident that lateral migration of the river occurred on both sides.

Conclusion

From the above discussion, it can be concluded that the concerned Raidak-I river is very dynamic in nature throughout the study period. During the study period, the river shifted its course in both sides. From the year 1972, the amount of lateral migration of the river has been decreased although both side amount of erosion and accretion of the river have been increased. Though the river migrated laterally in earlier periods, in the later phase the amount of erosion and accretion has been increased in both the banks; as a result, the amount of erosion in the left bank and accretion in the right bank and the amount of erosion in the right bank and accretion in the left bank balance each other. Thus, the river now becomes less vulnerable in terms of lateral shifting and presenting steady phase. According to different historical evidence and results of the study about this river, both bank lines are stabilized with the time but within the bank line, the oscillations of concave and convex slopes increased. The present work deals with the channel shifting of the river only and does not seek the causes of that shifting although it can be said that shifting of the Raidak-I river may be the result of construction of embankment along the banks of the river and decreased discharge of the river.

Acknowledgements The authors would like to acknowledge the Department of Geography, University of Gour Banga, Malda, for providing all sorts of the facility during this work. I would also like to pay my sincere gratitude to United States Geological Survey (USGS), Rocky Mountain Research Station (US Forest Service), department of ecology, the state of Washington, for providing the necessary information regarding this article. The authors are also thankful to Mehedi Hasan Mandal and Dev Kumar Maity. This work has been done by self-funding.

References

Bhakal L, Dubey B, Sarma AK (2005) Estimation of bank erosion in the river Brahmaputra near Agyathuri by Using Geographic Information System. J Ind Soc Remote Sens 33(1):81–84. https://doi.org/10.1007/BF02989994

Bolton S, Shellberg J (2001) Aquatic habitat guidelines white paper: ecological issues in floodplains and riparian corridors. Prepared for WA State Dept of Fish and Wildlife and others

Chakraborty S, Datta K (2013) Causes and consequences of channel changes—a spatio-temporal analysis using remote sensing and GIS—Jaldhaka-Diana River System (Lower Course), Jalpaiguri (Duars), West Bengal, India. J Geogr Nat Disast 3(1):1–13

Das N, Bhowmik M (2013) Qualitative assessment of river bank erosion risk in Jirania rural development block, Tripura. Ind J Appl Res 3(6):274–276

Gogoi C, Goswami DC (2013) A study on bank erosion and bank line migration pattern of the Subansiri River in Assam using remote sensing and GIS technology. Int J Eng Sci 2(9):1–6

Goswami DC (2002) Channel pattern, sediment transport and bed regime of the Brahmaputra River, Assam. In: Tandon SK, Thakur B (eds) Recent advances in geomorphology, quaternary geology and environmental geosciences: indian case studies. Manisha Publications, New Delhi, pp 143–156

Hickin EJ, Nanson GC (1984) Lateral migration rates of river bends. J Hydraul Eng Am Soc Civil Eng 110(11):1557–1567

Kotoky P, Bezbaruah D, Baruah J, Sarma JN (2005) Nature of bank erosion along the Brahmaputra River channel, Assam. India. Curr Sci 88(4):634–640

Kummu M, Lub XX, Rasphonec A, Sarkkulad J, Koponen J (2008) River bank changes along the mekong river: remote sensing detection in the VientianeNong Khai Area. Quater Int 186(1):100–112

Nanson GC, Hickin EJ (1986) A statistical analysis of bank erosion and channel migration in Western Canada. Geol Soc Am Bull 97(4):497–504

Neog R (2017) A GIS-based study on channel variation, erosion and deposition along the bank of Dibru Saikhowa National Park (1967–2016), Assam, India. Sustain Water Resource Manag. https://doi.org/10.1007/s40899-017-0131-6

Rahman MR (2010) Impact of river bank erosion hazard in the Jamuna floodplain areas in Bangladesh. J Sci Found 8(1 & 2):55–65

Sarma JN, Acharjee S (2012) A GIS based study on bank erosion by the river Brahmaputra around Kaziranga National Park, Assam, India. Earth Syst Dyn Discuss 3:1085–1106

Thakur PK, Laha C, Aggarwal SP (2012) River bank erosion hazard study of river Ganga, upstream of Farakka barrage using remote sensing and GIS. Nat Hazards 61:967–987

The Channel Migration Toolbox Department of ecology, state of washington, October 2014, publication no. 14-06-032. www.ecy.wa.gov
Wallick JR, Grant GE, Lancaster ST, Bolte JP, Denlinger RP (2007) Patterns and controls on historical channel change in the Willamette River, Oregon, USA. In: Gupta A (ed) Large rivers: geomorphology and management. Wiley, Boca Raton, pp 492–516
Winterbottom SJ (2000) Medium and short-term channel planform changes on the rivers Tay and Tummel, Scotland. Geomorphology 34:195–208
River Bathymetry Toolkit Rocky Mountain Research Station, U.S. Forest Service 322 E. Front St., Suite 401 Boise, ID 83702. http://www.essa.com/tools/RBT/download.html
Yang X, Damen MCJ, van Zuidam RA (1999) Satellite remote sensing and GIS for the analysis of channel migration changes in the active Yellow River delta, China. Int J Appl Earth Obs Geoinf 1:146–157