ORIGINAL PAPER

An assessment on the nature of channel migration of River Diana of the sub-Himalayan West Bengal using field and GIS techniques

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Abstract Lateral movement of river channel within its valley with time is a universal phenomenon. Various processes of fluvio-geomorphological environment such as rapid valley fill deposition due to very low channel gradient and resultant migration of active channel, bank failure and bankline migration, frequent occurrence of floods, capturing of lower courses of the tributaries by the trunk streams, and abandonment of tracks and avulsion are the most prominent factors behind channel dynamics in the sub-Himalayan part of West Bengal. Additionally, human interventions in the form of engineering constructions (bridges, flood embankments, etc.), tea plantation, mining and quarrying, and agricultural encroachment have emerged as another dominant issue which is pulverizing the ways of natural channel adjustment as well as also the channel behaviors. Both these processes are carrying significant messages of immense vulnerability for the study area known for its geomorphological instabilities. 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 is 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 of the Diana River of this concerned region for an 85-year spanning period to unveil the nature of channel migration in terms of changes in historical bankline and centerline positions and alterations in meander geometries through numeric and graphical methods coupled with field observations to define the overall zone of channel migration for three subsequent reaches of the Diana River.

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Introduction

Understanding river channel and its dynamics in terms of its migration and planform evolution or alteration possess significant investigation in geosciences arena as it correspond numerous questions for suitable channel design, river restoration, flood mitigation, watershed planning, and many other hydraulic engineering issues. River channels being one of the most effective universal agents of landscape change needs a clarification. Very commonly, river channels are the watered area confined within a river valley; concretely, they are 3D forms described by their slope, cross-section, and pattern (Petts and Foster 1985). Among the wide variety of fluvio-geomorphologic phenomena, channel migration perhaps is a very common phenomenon found profoundly in braided and meandering rivers from all over the earth's surface especially 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 over a timeframe.

From 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 changes (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 also the alterations in its planform geometry. The obvious

fact 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 time scale 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.

Moreover, channel migration zone (CMZ) can roughly be defined as the zone of oscillation of a river channel. In fact, CMZ is a kind of flood hazard area and thus is critical for planning issues (King County 2004). Besides this, it is the area where a river is inclined to erosion. Actually, it is a corridor consists of the present river channel and its adjacent areas which bear the signatures of historical channel movement and the area likely to be affected by channel migration in future. Very certainly CMZ is the area over which the channel processes occur during the specified timeframe and its boundary is stationary for the design life of that CMZ delineation (Rapp and Abbe 2003).

Pollack and Kennard, 1999 (in Bolton and Shellberg 2001) labeled the concept of CMZ in the context of geologic timeframe. Accordingly, CMZ is the area that a stream and/or its side channels could potentially occupy under existing climatic conditions. They exemplified that if the 'existing climatic conditions' comprises of the period since last glaciation, then the CMZ would likely incur the entire valley bottom together with lower terraces and hillslopes neighboring the floodplain where the stream is likely to meander.

Hence, the study of channel migration is of immense significance exactly from the point of its spatial-temporal dimensions. It is indeed necessary to map the CMZ for not only river engineering concerns but also to assess vulnerability issues assigned to its immediate environments. Circumstantially, the mapping of channel migration zones should stand upon the firm belief that rivers are dynamic in nature and they move laterally over their flood plains through a timeframe. Temporal analysis of channel migration corridor indicates towards an area over which the active channel may relocate itself in the future. However, as the rivers are exposed to numerous influents, the migration rates may vary and it can inject a certain amount of uncertainty (Boyd et al. 2010).

Keeping these very basics of channel migration studies, the present paper has attempted to enquire the ongoing fluvial and hydro-geomorphological processes along the Bhutanese Himalayan piedmont region that encompasses the historical movements of the Diana River in terms of its unstable banklines and shifting centerlines, dynamic meandering nature to delimit its historical migration zone for a period of 85 years (1929–2014) based on multitemporal database, field

observations, and numeric assertions. The novelty of this meticulous attempt is different from earlier works on channel migration that it does not only care for the lateral migration (bankline migration, meander migration, and centerline dynamics) phenomena only rather it includes the systematic mapping and scientific description of the final output, i.e., the zoning of channel migration for the Diana River; it subsequently moves on describing the potential zones where the river may invade in upcoming years through the processes of erosion and avulsion. This present work is unique as it has studied a major dynamic river of the sub-Himalayan zone of West Bengal famed for its highly vulnerable behavior. In fact at local and at national levels, attempts to define CMZ are absolutely absent, and additionally, lateral migration trends of rivers flowing over the concerned zone have yet not been studied. Thus, it not only encompasses the delineation of an 85-year spanning historical CMZ but also records the historical lateral migration trends in it. From this point of view, this painstaking attempt can be regarded as the pioneering one for the rivers flowing over the sub-Himalayan West Bengal.

Study area

Originating from the Samtse province of Bhutan, the Diana River constitutes the most important left bank tributary of the Jaldhaka river system in the sub-Himalayan parts of West Bengal. The area is roughly bounded within the 26° 25′ N and 26° 57′ N latitudes and 88° 48′ E and 89° 05′ E longitudes in the district of Jalpaiguri (Fig. 1). The Diana River rises at an elevation of 3,300 above mean sea level and entered into the Indian Territory along the 300 m. contour near Chengmari Tea Garden and ultimately debouches into the Jaldhaka River at an altitude of 87 m near Nathua Hat. Before joining the Jaldhaka River, it drains about 203.31 km^2 of Indian Territory (Table 1).

The area owes significant fluvio-geomorphic significance characterized by abundant forms like abandoned tracks, palaeochannels, crevasse splays, etc. and processes such as avulsion and river capture activities. It is a transitional zone between the Himalayan Mountains and fertile alluvial Teesta-Brahmaputra plains commonly known as the 'Dooars' region.

The Diana River starts its journey into the study area after meeting its tributary Chamurchi River from the east separating the southern blocks of the Himalayas. These two rivers meet at the piedmont, where the steep scarp of the Himalaya rapidly turns south from latitudinal to longitudinal. Both these rivers form an extensive combined fan sloping to the SW–S. The fan is inclined at its root part at about 25‰ and then decline downstream to 15‰ (Starkel et al. 2008). As these rivers suddenly reached the plains from the mountains, there is a
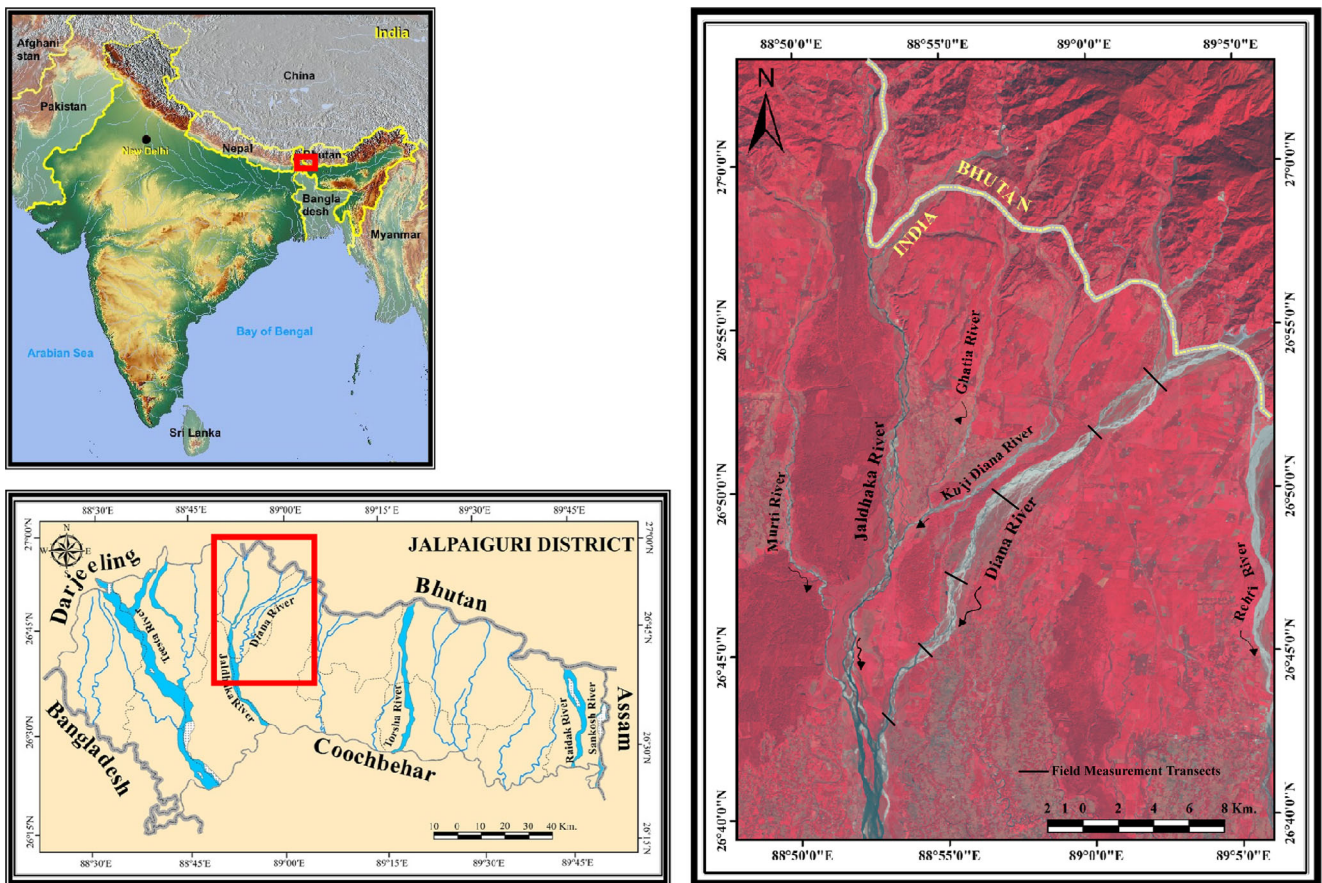
Fig. 1 Reference map of the study area

quick decrease in the channel gradient causing the rivers to deposit the immense detritus they have carried from upstream mountain catchments. This huge deposition of boulders, cobbles, gravels, and sand has clogged the river flow, and thus, the sluggish waters are forced to follow a wide and braided pattern. Apart from a straight upstream reach, the river follows a quasi-meandering pattern along its middle catchments while at its lower reaches meandering patterns are obvious. From its

Table 1 Reach wise morphological features of River Diana

Parameters	Reach-A (upper course)	Reach-B (middle course)	Reach-C (lower course)
Spatial extent	Chengmari Tea Garden to Kalabari Bazaar	Kalabari Bazaar to Nathua Hat	Nathua Hat to Purba Dobbari
Reach length (in km)	12.87	12.56	5.75
Sinuosity	1.04	1.03	1.03
Channel type	Mixed bedrock and gravel	Alluvial	Alluvial
Active channel width (in m)	46.36	55.24	72.85
Nos. of secondary channels	1–3	1–3	1–2
Dominant bed material	Gravel and boulders	Sand and pebbles	Sand and silt
Morphological appearance	Braided	Braided	Braided and transitional
Stream gradient in (m/km)	11.52	7.17	3.16
Avg. valley width (in m)	906.72	942.71	676.32
Total catchment area in the Indian Territory (in km^2)	203.31		
Annual rainfall (in mm)	3,750 (2012)		
Peak discharge (m^3/sec)	1,753.54		

Computed by the Authors from Field Studies and 2013 LANDSAT 8 OLI/TRIS Image

starting point into the Indian Territory up to its confluence with Jaldhaka River, the entire stretch of the Diana River is arrested by severe deposition because of insignificant flow conditions. Worse situations can be noticed at downstream reaches where rapid valley fill deposition in form of gravels, sand, and silt has caused the riverbed to rise incessantly, and thus, very often the river overtops its banks and finds another route to carry its load during peak flows.

At its upstream, the Diana River runs through the uplifted terraces. Here, the wide channel floor built of gravels and boulders is bounded on the left by a 12–15 m high scarp (lowering downstream to 5–7 m) and it subsequently arrives at the distal fan surface at its lower course bounded by 2- to 5-m high floodplains on both sides.

The area is well under active neotectonic activities inheriting certain structural weaknesses which owe significant control on the movement of river courses. Geological studies in this region have pointed out the presence of certain faults and lineaments and some of these structural elements are proved to be active in recent geologic times while some are supposed to be still active (Chakraborty and Datta 2013). This piedmont zone has two oldest geologic formations namely Samsing and Matiali formations restricted within the Himalayan arc. These two formations either terminate abruptly or progressively lobe out southwards (Gupta 2008).

Materials and methods

This whole work has been aimed towards (a) assessing the past episodic changes across the Diana River in terms of its bankline positions, meander, and centerline migrations over the last 85 years; (b) preparing a baseline for the overall channel dynamics and investigate their possible causes; and (c) delineating the historical channel migration zone to define the 'Corridor of Freedom' for the Diana River based on geographic information system (GIS), numeric outputs as well as field assessments on erosional and geotectonic settings.

Methods are almost identical to most of the previous works on channel migration that have been conducted in past years at various levels. Most of these works emphasized on meander migration (Hickin and Nanson 1984; Howard and Knutson 1984; Micheli et al. 2004; Heo et al. 2009; Hickin and Nicoll 2010; Giardino and Lee 2011; Micheli and Larsen 2011; Parker et al. 2011; Robinson 2013; Gogoi and Goswami 2014), bankline changes (Nanson and Hickin 1986; Lawler et al. 1997; Harrison et al. 2011; Sarma and Acharjee 2012; Sarkar et al. 2012; Gogoi and Goswami 2014) and centerline migrations (O'Connor et al. 2003; Guneralp and Rhoads 2009; Parker et al. 2011) while accounting for channel migration.

For the present study, a two-way approach inclining both towards field observations and GIS techniques have been followed. Field studies incorporate intensive river tracking guided by GPS surveys, discharge, and cross-section measurements along six transect and perception surveys among the local residents. The data regarding gauge heights and local rainfall have been gathered from the Central Water Commission's (CWC) station over the NH 31-C road bridge on Diana River at Red Bank Tea Garden. However, it was not possible for the authors to gather river discharge data as no discharge measurements are done at the CWC site. Additionally, the erosional and depositional setbacks, bank stratigraphy and compositions, floodplain heights, and channel composition datasets were collected from field observations.

For preparing a GIS database for the entire timeframe of 85 years, channel characteristics and historical channel positions have been mapped and measured from Survey of India topographical maps (1928–30), U.S. Army Corps. of Engineers Series- U502 maps (1955), and multi-temporal cloud-free Level-1 LANDSAT images (1977, 1990, 2001, and 2013) by using the ArcGIS™ (Version 10.0) software package. To remove the geometric and radiometric distortions of the raw satellite images, the authors have followed the methods applied by Mujabar and Chandrasekar (2013). After processing the images with ERDAS IMAGINE 9.2 software, these were geo-referenced and projected with UTM (Northern Hemisphere, Zone 45; Datum WGS 84) manually using ground control points (GCPs) collected through GPS surveys. The root mean square error (RMS) is kept below 0.005 of a pixel. As the river consists of multi-thread channels, the outermost boundaries of the main and secondary channels at medium water stages (2-m depth or 200-m gauge height at CWC gauging site underneath NH-31C road bridge) were defined manually as channel boundaries. Channel boundaries and centerlines were digitized at a scale of 1:5,000 to minimize the digitization errors.

To quantify the channel planform features, we have used the same field measurement transects (6 in nos.) in the GIS environment. The channel centerlines or thalweg lines for the older datasets have been drawn along the centre of the active channel for straight reaches and along the cut banks for meandering ones. The latest (2013) channel centerline has been drawn from current Google Earth imagery and is verified with field datasets. The subsequent centerlines have been superimposed upon each other and their movement from the base survey year (1929) has been computed. The migration rates of the channel centerlines have been derived following the method of Giardino and Lee (2011). The migration of the centerlines was measured with the help of 'migration polygons' which were drawn on adjacent and sequential centerlines. The respective total area of a migration polygon was then divided by half the perimeter of that polygon, or the length of the migration polygon centerline. The migration

rates of channel centerlines were then measured by using the following formula as suggested by Giardino and Lee (2011).

$$Rm = \frac{A}{L} \Big/ y \tag{1}$$

where, Rm is the migration rate; A is the polygon area, L is the length of centerline time-1 for each polygon, and y is the time interval involved in the computation.

Migration distances have also been computed for all the survey years based on the methods previously applied by Leopold (1973), Gurnell et al. (1994), and Giardino and Lee (2011). This method incorporate delineation of a series of transects perpendicular to the river floodplain and measuring the distance between the points of intersection between the channel centerline and transect for subsequent survey years. Transects were drawn 2.5-km apart from each other to reduce biasness of selecting migration locations. The formula that we have used following Giardino and Lee (2011) is as follows:

$$D_m = T_1 - T_2 \tag{2}$$

where, D_m is the migration distance, and T_1 and T_2 are the concerned survey years of subsequent channel migration.

Furthermore, the bankline migration trends have been simply measured by superimposing the digitized bankline shapefiles in temporal sequence and the corresponding bankline migration distances and their average annual rates were measured following Wallick et al. (2006). Accordingly, the assessments have been done by using the following formulae:

$$Be = 2A / P \tag{3}$$

where, Be is the average distance of bank erosion perpendicular to the channel; A is the area of the bank erosion polygon; and P is the perimeter of the concerned polygon. The migration rates were derived by dividing the migration distance by the time interval:

$$Be. = \frac{Be}{T} \tag{4}$$

where, T is the time interval in years.

In addition with these, three meander bends starting from upper-middle reach to the lower course have been studied and are numbered as 1 to 3 in downstream direction. The geometric properties of these bends, i.e., radius of curvature (Rc) and meander amplitude have been measured for each of the survey years and then mapped accordingly following Wolfert and Mass (2007).

Finally, based on the above computations and graphic representations as well as considering the actual field conditions, a base map of an 85 year spanning channel migration zone of the Diana River has been prepared on a reach scale. This ultimate output, i.e., mapping of historical CMZ incorporates each of the four major constituents of CMZ analysis as documented by Rapp and Abbe (2003), the method widely known as the most scientific and appropriate classificatory way of delineating CMZ. Accordingly, a CMZ is the cumulative collection of the following:

$$CMZ = HMZ + AHZ + EHA - DMA$$

where,

1. Historical migration zone (HMZ) the area of historical channel occupation recorded in photographic evidences.
2. Avulsion hazard zone (AHZ) are floodplain areas geomorphologically susceptible to abrupt channel relocation.
3. Erosion hazard area (EHA) is the area outside the HMZ and AHZ which is at stake of bank erosion due to river flow and mass wasting. The EHA incorporates two segments (a)erosional setback (ES) and (b)geotechnical setback (GS), which solely has been assessed from field observations.
4. Disconnected migration area (DMA) is also known as restricted migration area (RMA) and is the area where man-made structures have terminated the process of channel migration, i.e., the area where engineering construction (bridges and flood embankments) has eliminated the future potentialities of channel migration.

Sources of mapping historical channel positions

For a comprehensive mapping purpose, a good number of reliable topographical maps and satellite images have been used in this current study. These sources and their prime features have been summarized in Table 2.

Results and discussions

Graphic representations and illustrations have been generated based on computational derivations. The ArcGIS^{TM} (Version 10.0) software package (ArcInfo) has been used to process and prepare the graphic outputs for each category, i.e., centerline migration, bankline movements, and river meander dynamics and to delineate reach-scale channel migration zones.

Centerline migration

Following the criteria used in centerline migration, i.e., the methods of assessing mean centerline migration rates

Table 2 Summary of sources used for mapping historical channel positions

| Types of data	Publisher	Index/map no.	Spatial coverage	Survey year	Scale	
Topographical Maps	Survey of India	78 B/13, 78 B/14	Jalpaiguri district	1928–1930	1:66,360	
Edition-2 Army Map Service (AMS) Series- U502	US Army Corps of Engineers	NG 45-8	Jalpaiguri and Kochbihar districts	1955–1956	1:250,000	
Satellite images	Satellite/sensor	Path/row	Spatial reference	Acquisition date	No. of bands	Spatial resolution (in m)
	LANDSAT-2 MSS	138/41, 138/42, and 139/41	UTM Zone: 45 Datum: WGS 84	25/02/1977	4	60.00
	LANDSAT-5 TM			14/11/1990	7	30.00
	LANDSAT-7 ETM$^+$			20/11/2001	8	30.00 (15 m for PAN)
	LANDSAT-8 OLI/TRIS			20/11/2013	11	30.00 (15 m for PAN)

(reach wise) and mean centerline migration distance (transect wise) certain irregular, and indefinite changes have been observed along the Diana River's centerline. These changes are in fact, did not have followed any specific pattern of migration. The overlay operation, i.e., superimposing centerline shapefiles upon each other in chronological order reveals several uncertainties (Fig. 2). A general picture evolved from this overlay action which depicts that the maximum dynamics in centerline positions occurred at the lowermost reach followed by moderate shifts in extreme upper and middle reaches. From 1929, the channel centerline has shifted more than 2 km in a NW direction along the lower course of the Diana River. This shift initially was triggered by a sudden partial avulsion guided by a massive flood in 1948. The nodal origin was near Dhumpara when the Diana River had almost deserted its previous lower course of 1929 which was then used to flow through the present Doikhowa River. At its upstream and middle reaches centerline movements are largely under control of aggradation activities. Upstream to NH-31C bridge near Red bank Tea Garden, centerlines shifted solely as a result of the switching off the main active channel on either bank over time. Here, the main channel is largely affected by the deposition of huge mountainous detritus which clogs the river flow and force it to bifurcate into multiple threads. At middle reaches gradual deposition of coarse sands and gravels along the eastern bank is significantly compelling the main channel to shift towards the unprotected western bank made of porous and non-cohesive sands. The uninterrupted raise in the Diana River bed due to excessive aggradations is in fact the primary reason behind the westward shift of the channel centerline along the upstream and middle reaches in recent times. The river bed raised as much as 2.012 m underneath the NH-31C road bridge crossing between 1990 and 2005 (Sarkar 2008). Contrarily, the tendency towards centralizing the channel centerline within the valley floor at lower course can be attributed to the boosting effect of aggressive eastward encroachment of the Jaldhaka River which seems to be determined in capturing

the lower course of the Diana River coupled with the incessant emulsifying effect of rising river bed. Datasets and field studies have revealed that near its confluence with the Jaldhaka River, the Diana River bed raised about 0.5 to 2 m between 1990 and 2011.

The analysis of mean migration rates also supports the aforesaid. Throughout the upper and middle reaches, the migration rates are raising while lowering down along the lower course. During the last 85 years, the entire centerline has migrated at an average of 27.25 m/year recording reach-wise average values of 29.26 m/year for the upper, 30.24 m/year for the middle, and 22.25 m/year for the lower reaches. However, periodical values are much irregular and vary considerably (Fig. 3). For example, during 2001–2013, the centerline migration has recorded average values of 45.92 m/year for the upper, 43.45/year for the middle, and 12.09 m/year for the lower reaches. Contrastingly, the earliest phase of 1929–1955 has recorded 15.49 m/year for the upper, 14.13 m/year for the middle, and 22.48 m/year for the lower reaches, respectively.

The study of transect wise mean centerline migration distance indicates that values are much abrupt and higher in upstream (transects 1 to 4) while it is quite certain and definite along the middle (transects 5–7) and lower stretches (transects 8–10). However, historical figures are exhibiting changes at consistent levels for the whole 85-year span (Fig. 4). It can be seen that for majority of the historical period, the mean migration distance has never crossed the 100 m/year mark except for the recent periods of 1990–2001 and 2001–2013 entirely along the upstream reach. This upheaval in migration distances claims its origin solely to the incessant aggradation and resultant gravel-bar formation. The migration distances along the middle segment are also rising at alarming rates of 85 m/year during the recent most phase of 2001–2013, keeping parity with the main channel favoring abandonment of it is the older track and thus has endangered the existence of the bank dwellers located along the western bank. At lower reaches, the movements of the channel centerline are much more regular and shows significant signs of coming down rapidly over recent decades. Out of the consecutive five
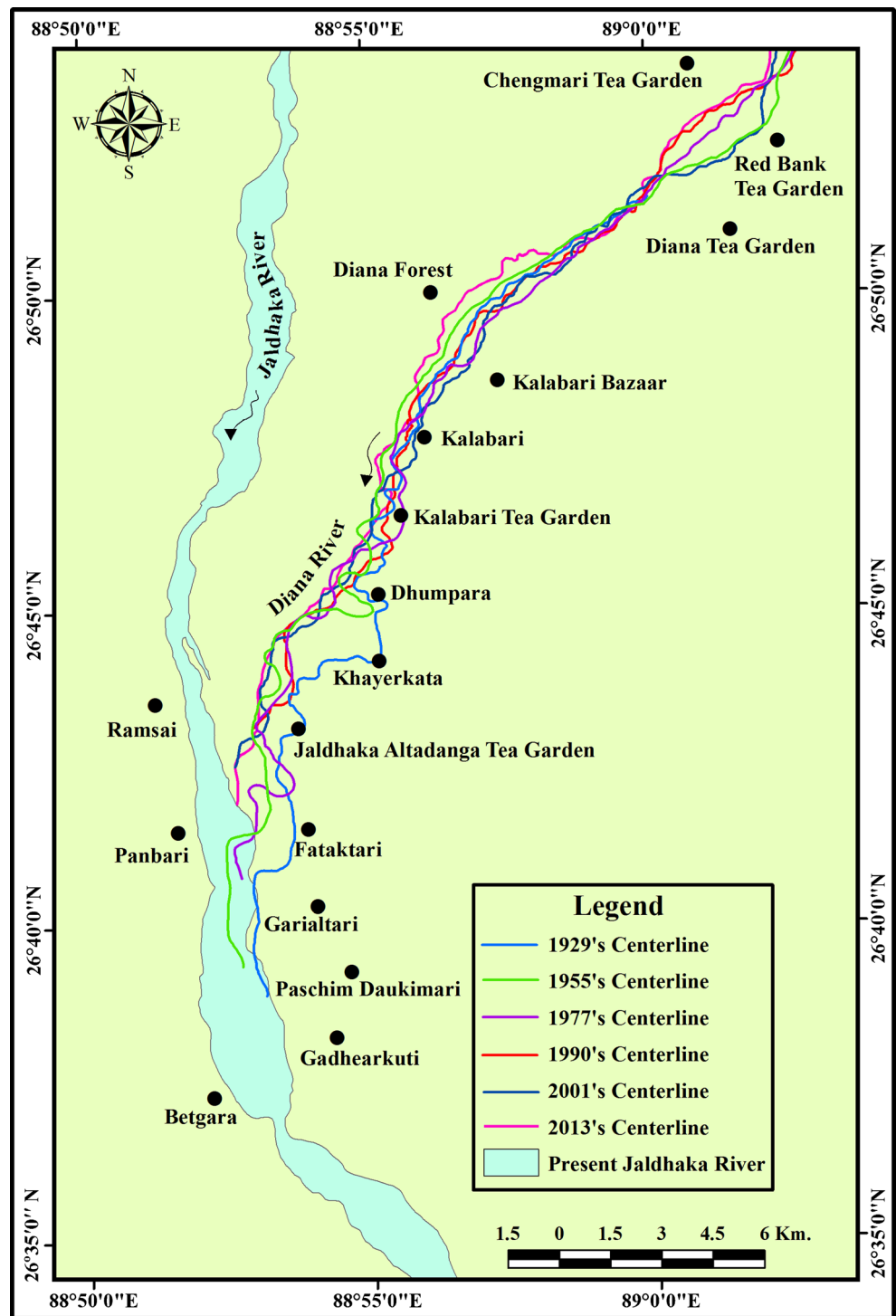
phases, the earliest phase of 1929–1955 showed the least migration trends followed by the phase of 1977–1990 when minimum migrations were seen. However, contrary to their present trends, a reach-wise chronological analysis of centerline migration exhibited quite dissimilar image. During the entire 85 year period, it is the lowermost course which have recorded the highest values of migration distance

(33.68 m/year) followed by the unstable middle (32.38 m/year) and upper reaches (27.43 m/year). Considering both these assertions as well as the affirmations on the basis of the analysis of centerline migration rates, it can be obviously stated that centerline dynamics are perhaps more severe along the middle reach than along the relatively stable lower or highly unstable upper reaches.

Fig. 3 Mean centerline migration
rates across the Diana River
during 1929–2013
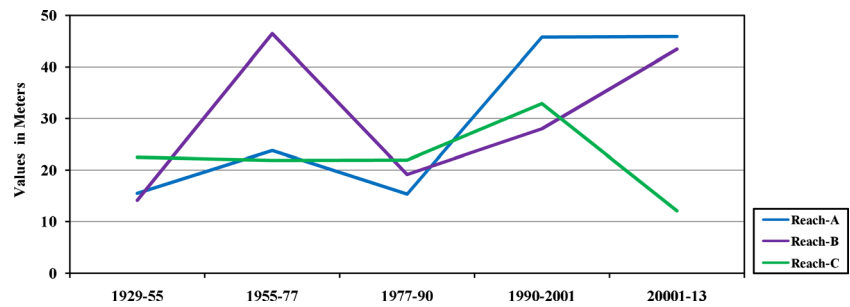
Bankline migration

For a comprehensive analysis and representation, the entire
stretch of the Diana River in the study area has been divided
into three reaches, namely A (upper), B (middle), and C
(lower). Historical positions of the banklines derived from
the maps and images and from the mathematical outputs have
indicated differential trends in bankline shifts and certain
changes are rapid and vigorous while some are exclusively
nominal. A simple superimposition of the historical banklines
represents a simple but puzzled nature of bankline move-
ments. However, a common pattern has evolved that both
the banklines favor a westward shift along all the reaches
(Fig. 5).

Many variations can be observed in case of reach scale
analysis of mean bankline migration (Fig. 6). During the entire
timeframe of 85 years, migration tendencies are highest
(15.64 m/year) along the lower courses where the banklines
are shifting irregularly although mostly westwards; however,
the rates are declining now because of the eastward
encroaching Jaldhaka River. The dynamics of the banklines
here are predominantly under the control of structural arrange-
ments as well also by excessive aggradations. Banklines shift
abruptly not only by the process of bank erosion but rather is
governed by over-bank spilling even during medium water
stages. Bank erosion rates also have recorded a worrisome
figure of 12.93 m/year at the middle reaches where the river is
vigorously shifting towards the Diana Forest located along its

west bank seems intended to capture the lower course of the
Kuji Diana River. At upstream reach banklines are well con-
fined by physiographic barrier on NW and by concrete-like
gravel-boulder bank along the NE side. Thus, the rate
of bankline migration is somehow neutralized, although
lateral migration of banklines are occurring at a steady
rate of 6.03 m/year particularly through toe erosion and
collapse of gravel banks through rapidly moving waters
as well as by occasional over-bank spills.

Actually, bankline migration of the Diana River is particu-
larly a concern for its middle and lower catchments. It has
been computed that, during the entire 85-year timeframe, the
river has eroded around 27.25 and 61.14 km^2 along its middle
and lower reaches, respectively. Bankline migrations at these
reaches are highly controlled by overbank spill during peak
monsoon. The riverbed is rising because of deposition of
boulders and mountainous detritus the river carries from the
Bhutan Himalayas into its bed. This huge deposition has
further clogged the river water through innumerable formation
of bars and islands. The channel gradient is negligible and the
river is forced to spill its waters through the adjoining flood-
plains culminating regular floods and partial shifts in its
course. This overbank spill is unquestionably widening the
river valley transforming it into much shallower and flat.

The non-cohesive bank materials indeed are major deter-
minants of bankline dynamics. Very likely to the other rivers
belonging to the Brahmaputra watershed, most parts of the
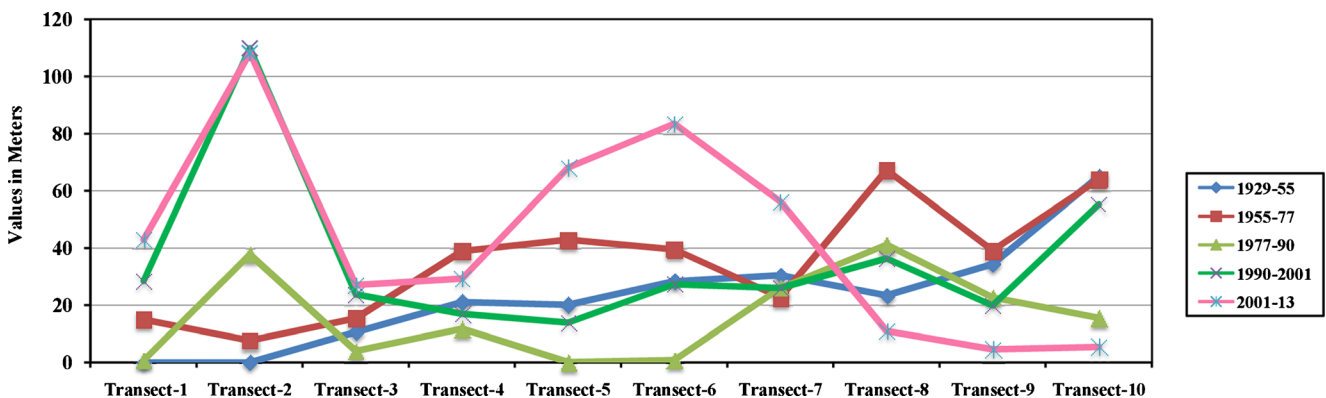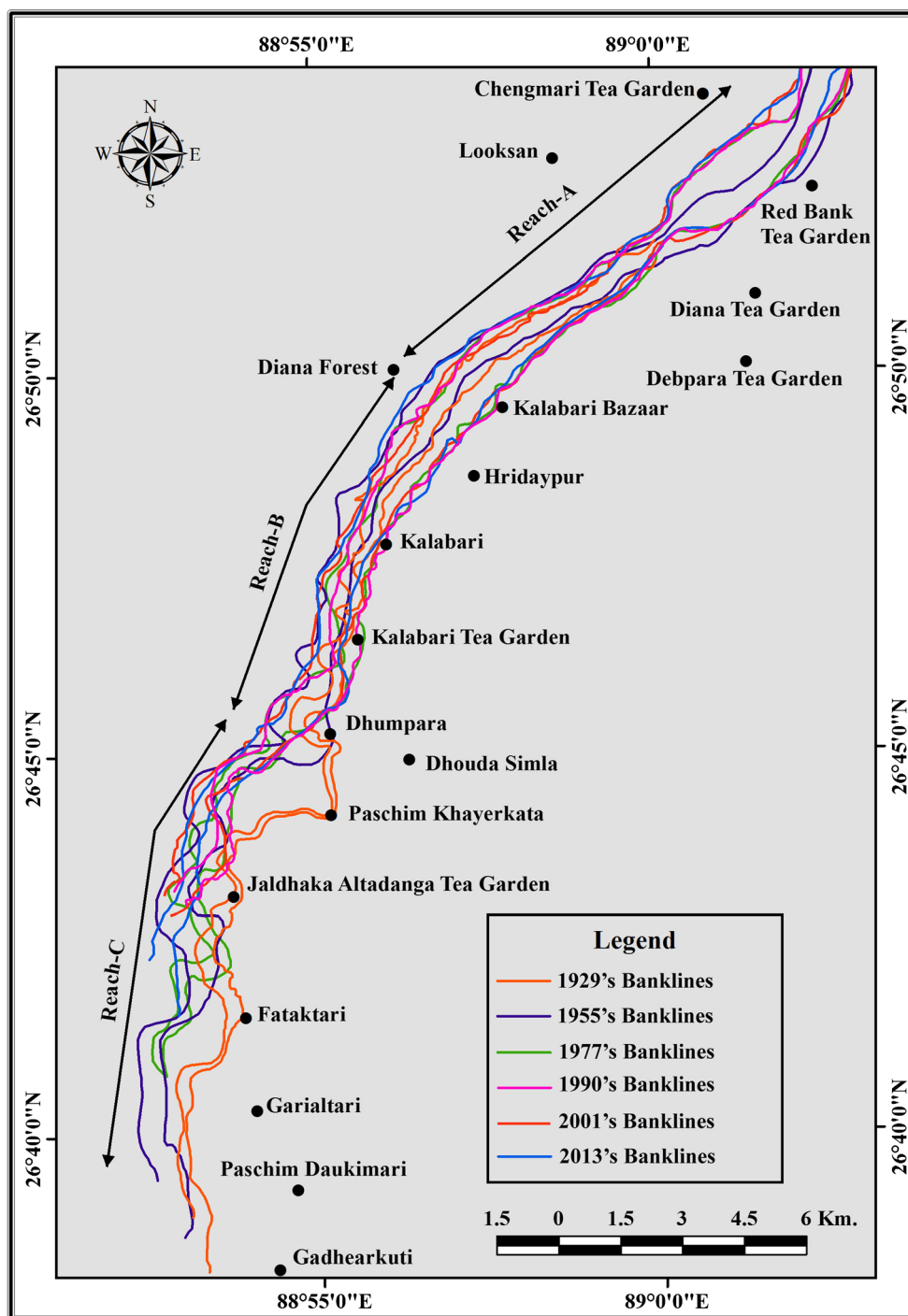banks along the middle and lower courses of the Diana River

Fig. 4 Temporal trends in mean centerline migration distance for the Diana River (1929–2013)

Fig. 5 Chronological bankline positions of the Diana River

are made off coarse sands, and silt in alternate layers. These kinds of bank materials are loosely bounded and provide pore spaces for water during high flows resulting in an increase in pore pressure in the bank strata, but during recession stage, the pressure on banks is lessened and the water from the bank strata started to move into the river causing lateral flow of sands and silts into the river culminating subsequent failure of the bank (Kotoky et al. 2005). Like other alluvial rivers which flow through this region, bank erosion rates for the Diana

River are much higher during recession or falling water stages rather than the rising stages. Thus, maximum bank erosion occurs between mid-August to late September (recorded average discharge values between 1,150–1,400 m³/sec as measured during field surveys). At times of peak monsoons (peak discharges reach even to about 2,500 m³/sec during early July to early August), banklines retreat towards the villages nearby as a result of bank-wash caused by annual over-bank spilling. A contrast evolved in the scene as most of the rivers flowing

Fig. 6 Historical trends of mean bankline migration of the Diana River (1929–2013)
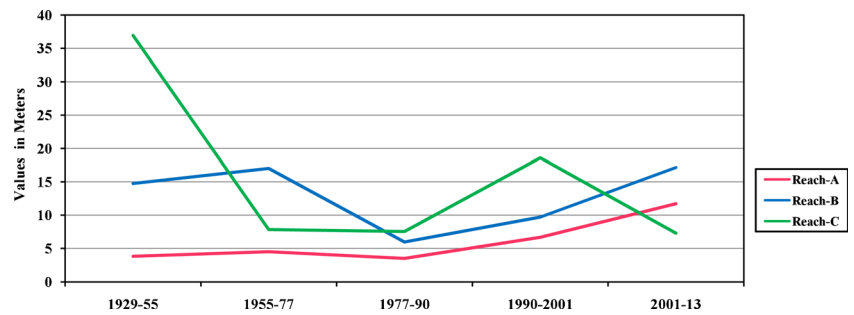
over this region like the Teesta, Jaldhaka, Torsha, Raidak, and Sankosh are shifting eastward while the Diana River has shifted mostly towards the west; this is because of the regional slope and tectonic factors which have portrayed this distinct panorama (Chakraborty and Datta 2013). Besides these, the bankline movements of the Diana river particularly in its lower course are highly controlled by the aggressive behavior of its trunk river Jaldhaka which very often capture the lower

course of the Diana River about 1.5 km upstream from their current confluence point. Along with this, partial or local avulsion of both Diana and Jaldhaka rivers have played significant roles in the historical movements of their bankline positions, for example, the earlier avulsion of the Diana River in 1948 not only has caused a shift in its course but also has induced widening of the river by shortening the actual length of the Diana River for about 4.65 km.
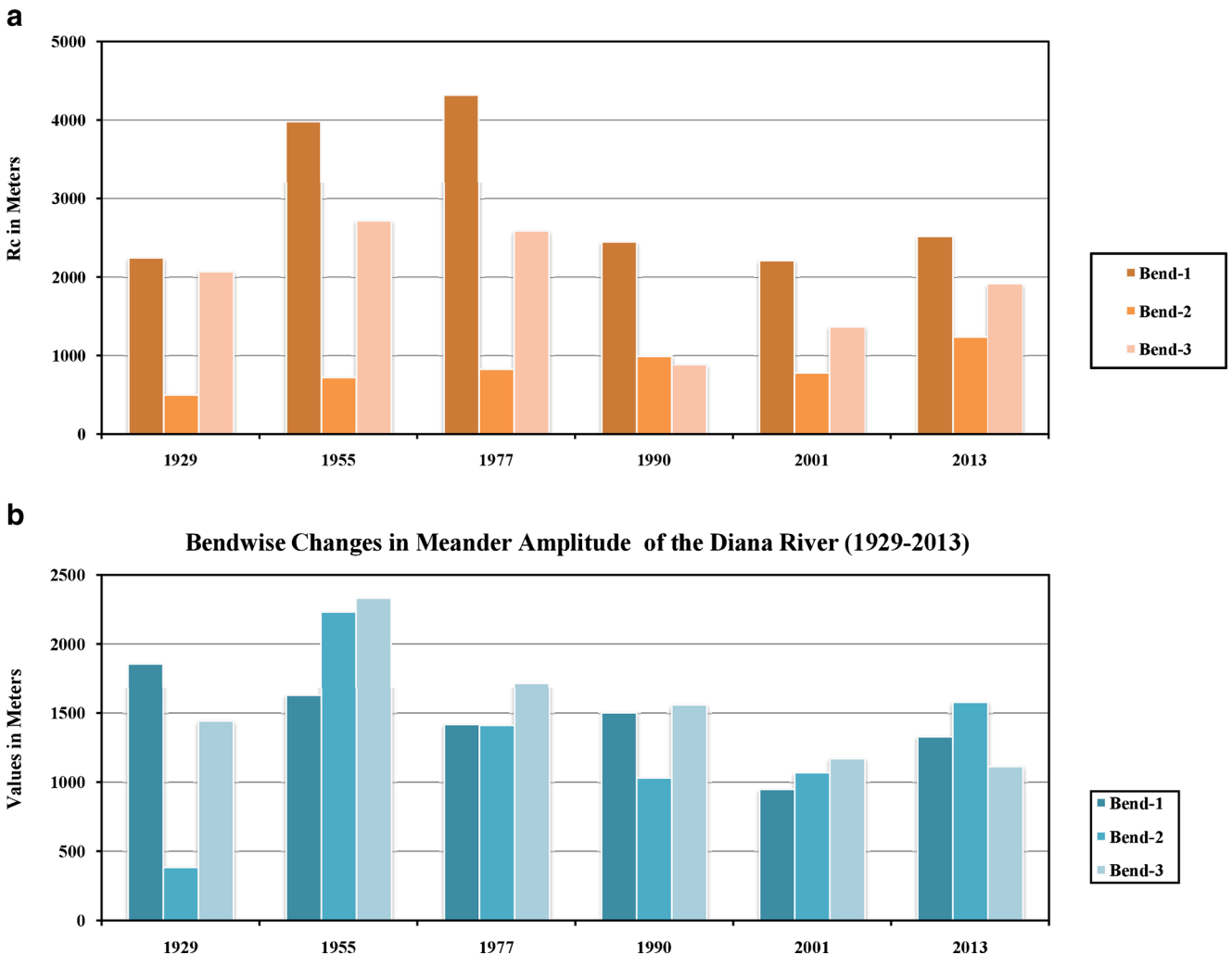

Fig. 7 a Downstream changes in meander radius of curvature for River Diana (1929–2013). **b** Dynamics in meander amplitude for River Diana during 1929–2013 timeframe

Meander migration

Historical analysis of meander bends has cleared the fact that meandering tendencies of the Diana River have reduced much from the earlier times. Careful investigations of the older datasets have cultivate a clear picture of a old meandering course of the Diana River than the present day straight reach dominated one. Sinuosity calculations (following Schumm 1977) for the entire Indian segment of the Diana River have recorded a value of 1.25 for 1929's Diana River which fell significantly to 1.04 for the present river implying the fact that the river is steadily losing its meandering behavior and is transforming into a straight one.

A study of meander geometry of all the three bends has recorded irregular and indefinite values (Fig. 7a, b). For bend-1 (located near Kalabari Bazaar), it has been found that, both the radius of curvature (Rc) and meander amplitude values are now rising steadily. This increase is solely due to continuous shifting of the Diana River towards the west due to depositional impingements. Bend-2 (located near Dhumpara) has also recorded increasing values of Rc and meander amplitude. However, this tendency of rising is quite irregular and is also determined by huge deposition across the left bank. Bend-3 (located along Jaldhaka Altadanga Tea Garden) is probably most dynamic in nature characterized by several neck-cutoffs which are transitional in nature. This bend recorded declining

trends in its Radius of curvature while possessing contrastingly increasing amplitude values. This haphazard trend in meander geometry is entirely influenced by a lineament trending NE–NW along the right/western bank of the river as well as assisted by eastward shifting of its trunk stream Jaldhaka River which occasionally captures the neighboring lower stretches of the Diana River by reactivating some of its old and deserted channels.

Reach-scale historical channel migration zones of River Diana

Based on the application of the above numeric and graphic-based derivations and considering the erosional and geotechnical setbacks, the reach-wise base map of historical (85-year spanning) channel migration zone for the Diana River has been prepared to define a scientific approximation of its "Corridor of Freedom" (Fig. 8). The boundary of the channel migration zone (CMZ) has incorporated the area within which the riverine processes will be active in the future. Accordingly, three potential avulsion hazard zones (AHZs) have been designed within the middle and extreme lower reaches. Additionally, two disconnected or restricted migration Area (DMA) have been observed where engineering constructions in the form of flood and bridge protection embankments have ceased the further chances of migration; one being located exactly at the NH-31C road bridge site and one being located along the left bank at extreme lower reaches. However, the
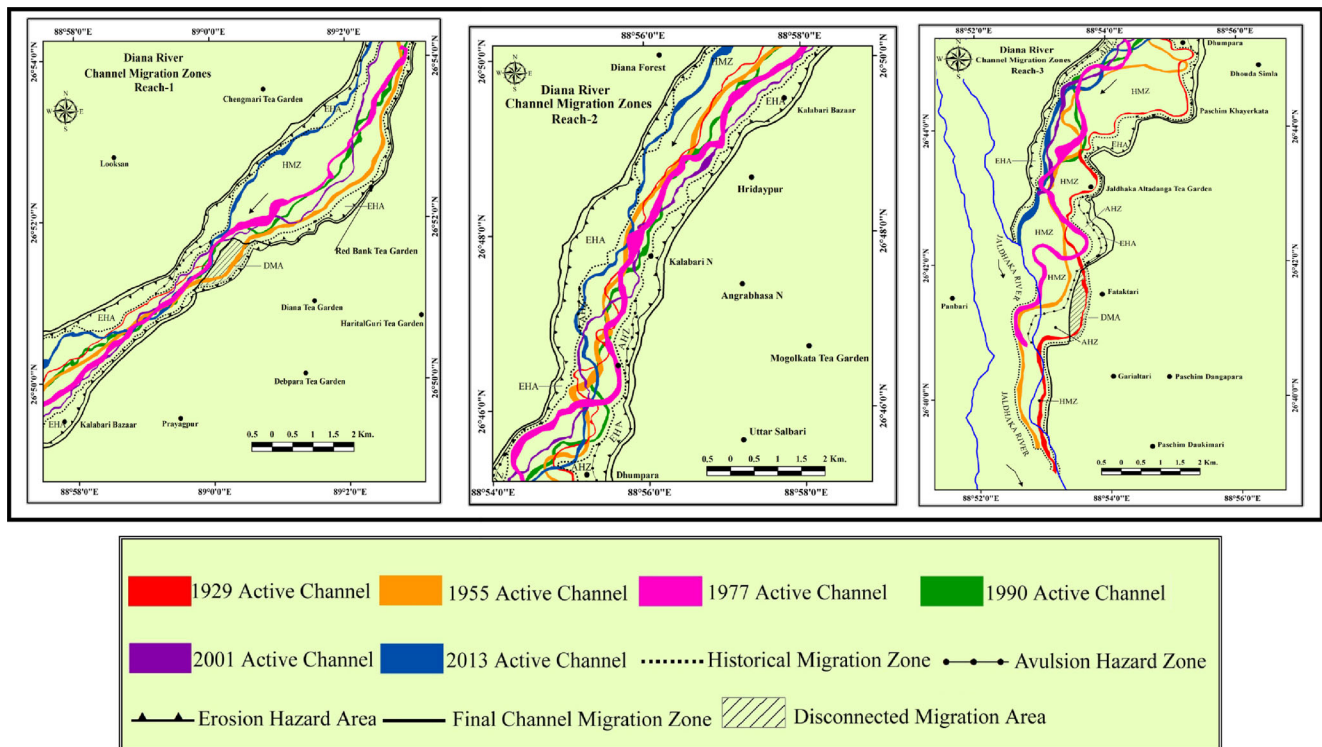

Fig. 8 Reach-scale-based historical channel migration zones for River Diana over 85 year timeframe

designed CMZ boundary is stationary for its design life of 85 years. Therefore, this boundary may vary with changes in the stipulated timeframe as well as also because of the future activities of geotectonic and anthropogenic drivers.

As most part of the left bank of the Diana River is well guarded by flood-protection embankment and several bank protection revetments, tendencies of erosional activities may become vigorous along the unprotected right bank. Instead of riparian forest cover, the nearby floodplains along the right bank may face several fluvial hazards in form of bank erosion, shifting courses and prominently avulsion and capturing of the lower course of the Kuji Diana River by the Diana River.

The designed CMZ boundary has included mostly areas surrounding the left bank neighboring the NH-31C road bridge as changes may take place here because of unscientific blockage of the spill areas where signs of recent fluvio-geomorphic activities are still visible. At middle reaches, the CMZ includes majority of the unprotected and forest covered Diana-Kuji Diana interfluve (650-m wide). This interfluve is primarily consisted of non-cohesive sands and gravels and has a slope similar to the immediate surroundings of the western bank of the Diana River. In fact, during field studies, it has been observed that the sand-gravel choked Diana may invade and capture the Kuji Diana in a very near future, which is evident through its rapid westward encroachment. Erosional-tectonic setbacks, complex riverine movements, and annual floods at the lower course may fetch sudden avulsion of the Diana River through its 1929 counterpart, which now flows as Doikhowa River, positioning itself within a close ambit of the Diana. In fact, overbank topping may culminate embankment breaches through the already weakened and cracked portions of the earthen-boulder embankment causing not only serious channel avulsions as well as massive floods and loss of lives and properties.

Conclusion

Mapping of channel migration zones are of no doubt one of the best developed tools for river engineering and obviously for development of societies inhabiting along the river banks. Besides these, by enlightening us about historical riverine behavior, it also guides us to a planned and regulated future accordingly to the river's behavior. It guides us to define the approximate areas where a river may live naturally by own will. It envisions us about developing a perfect mutually adjusted riverine-human landscape. In reality, natural processes may inherit sole responsibilities in channel dynamics; however, it will be misleading if we subtract the moderating effects of human interventions within a river network. In fact, starting from local levels to global levels human factor has become a

serious concern for riverine alteration. Anthropogenic activities like river restoration, channel straightening, construction of dams and barrages across rivers, developing canal networks, removal of riparian vegetation, alteration of bank materials, sand-gravel mining, encroaching landuse, etc. are the quintessence of intervening operations imposed upon rivers by us. In this present case too, both natural and human dimensions are there behind overall channel dynamics. During this 85-year timeframe, the Diana River has adjusted a lot according to its needs and we have to adjust with these changes; however, the river's behavior has changed dramatically and thus become very complex to understand. In fact, the geomorphic area over which it flows is undoubtedly one of the most active hotspots of geomorphic transition where a lot of processes are going on; so further changes are inevitable which may introduce newer challenges in boundary delineation of historical CMZ. Besides this, our confidence in assessing the overall channel migration is somehow paralyzed because of the acute shortage of historical river discharge data as no discharge measurements are carried on this river by any governmental or private authorities. However, an attempt has been made to improve this by field measurements of river discharge for a short span of a year. Additionally, because of border situation, some remote locations at the upper reaches could not get careful observation; however, the proportion of such neglected locations is much lesser. Nonetheless, the present study has made painstaking attempt to provide an insight into the historical migration behavior of the river Diana for the sub-Himalayan piedmont region, and undoubtedly, it could guide the policymakers to seek for the appropriate channel design schemes combining local area and floodplain development plans for the concerned region. Additionally, it could help in understanding the processes operating behind channel dynamics along the eastern Himalayan foothills and thus can be served as a guideline for assessing the channel migration studies for the rivers having almost identical nature of channel compositions and which flow over similar kind of environments. The designed CMZ boundary is not just a scientific assumption based on numeric methods coupled with field experiences to assess the limits of lateral erosion rather it incorporates and indicates the historical dimensions regarding the very dynamic nature of the Diana River, particularly from its avulsive nature and the severe bank erosion it is causing in recent years. In fact, from vulnerability perspectives, the area is a hazardous one endangered by close proximal positioning of highly dynamic rivers; so it is equally important to build up certain plans to demarcate the areas the river may invade in upcoming future not only to cope with the hazards it may culminate but also to ensure the river's 'corridor of freedom' where it can flow naturally without being hampered and hampering the human communities live nearby.

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