



# An Appraisal to Anthropogeomorphology of the Chel River Basin, Outer Eastern Himalayas and Foreland, West Bengal, India

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## Abstract

The Eastern Himalayas is ecologically fragile and at the same time is also home to some of the world's poorest people. Thus, to assess the nature and extent of resource utilization by the locals and its implications on the geomorphology, the present work attempts to present the prevailing scenario of anthropogenic alteration of the fluvial environment of outer Eastern Himalaya and its immediate foreland through an anthropogeomorphic assessment of a small river basin named the Chel. The assessment was carried out using SRTM DEM, Landsat images, Topographical maps, Google Earth images in ArcGIS 10.1 environment, and MS excel sheets coupled with extensive field surveys. Sediment mining, extensions of embankments, bridge construction, land-use change, extensive cultivation on channel bars, growth of tourism, road widening are the major human activities identified, altering the geomorphology and a few of its individual and combined implications on Chel basin are bed elevation changes, instability of

channel bars and thalweg shifting, shifting of pool-riffle sequence, deformation of channel beds, channel planform changes, channel migration, effects on channel geometric and hydraulic parameters has been discussed in detail. Overall, the work reinforces the fact that humans have emerged as one of the most dominant factors among all, changing or altering the natural environment of the earth in this Anthropocene.

## Keywords

Anthropogeomorphology · Human alteration · Eastern Himalaya · Sediment mining · Anthropocene

## 2.1 Introduction

The Anthropocene represents the time since human impacts have become one of the major external forcings on natural processes and humans have interacted with rivers from the time of ancient civilizations (CWC 2000; Sinha et al. 2005). The human imprint on the global environment has now become so large and active that it rivals some of the great forces of nature in its impact on the functioning of the earth system (Steffen et al. 2011). Anthropogeomorphology deals with the human impact on the earth's landforms where human actions transform, correct, and modify natural processes by increasing

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or decreasing their rate of action and by causing the rupture of certain equilibriums that nature will try to reconstitute in different ways (Goudie and Viles 2016). The human–environment interactions are characterized by great diversity, with much feeding back, and many nonlinear processes, thresholds, and time lags (Rudel et al. 2005; DeFries 2008; Lambin and Meyfroidt 2010; An 2012). Human impacts are most frequently related to changing patterns of land use and are of special importance in environmental studies (Dale et al. 1998; Geist and Lambin 2002; Carr et al. 2006). While landforms and soils are subject to the formation, change, and even destruction by natural forces over a geological time scale, changes resulting from human activity usually occur more rapidly and have a strong impact on vegetation, water resources, and soil (Lambin et al. 2003; Vanacker et al. 2003; Geist and Lambin 2006). The industrialization and developmental activities of man during the last few centuries have led to the crossing of the threshold value of balance between man–nature relationships (Ghosh et al. 2016). At times anthropogenic factors dominate and change the channel morphology more significantly than natural events such as floods, drought, and landslides (Petts and Amoros 1996; Rinaldi 2003).

The major river basins of India are considered the important repository of the Anthropocene (Ghosh and Ilahi 2021). It has been found that the fluvial systems are the most sensitive elements of the earth's surface, and any shift in climatic parameters, environmental conditions, and human interferences instigates a rapid response from the fluvial systems (Alila and Mtiraoui 2002; Sridhar 2008; Mujere 2011; Ewemoje and Ewemooje 2011). The Indian subcontinent, which hosts many large and perennial rivers with significant hydrological and geomorphic diversity, is also home to an ancient civilization and is currently one of the most populated and polluted regions on the globe (Sinha et al. 2005; Jain et al. 2016). For example, 61,948 million liters of urban sewage are generated daily in India and more than 38,000 million liters of wastewater go into the major rivers

of India (Sengupta, 2018). The estimated polluted riverine length (mainly the rivers of West Bengal, Maharashtra, Assam, Madhya Pradesh, and Gujarat) is 12,363 km, having a BOD (biological oxygen demand) range of 10–30 mg l<sup>-1</sup>, i.e., severely polluted (Sengupta 2018). On the other side, India has by now about 4500 reservoirs (created by dams on rivers) which have now lost their storage capacity and functionality due to excessive siltation rate (0.475–9.44 mm year<sup>-1</sup>) (CWC 2019). The anthropogenic disturbances have caused a significant decrease in forest cover from 89 million ha to 63 million ha and an increase in agricultural area from 92 million ha to 140 million ha in India (Jain et al. 2016). Large dams have caused more pronounced dysconnectivity in the sediment fluxes, and as a result, the sediment supply from rivers to oceans has decreased by around 70–80% in most of the Indian river basins (Gupta et al. 2012). Despite this situation of Indian rivers, the impact of anthropogenic forcing on natural geomorphic systems has not been analyzed in detail (Das et al. 2021). The human dimension of geomorphology is a vital area of research that has been largely neglected beyond the local and sub-regional scale (James et al. 2013). Much less has been written about the effectiveness of humans as geomorphic agents in the tropical densely populated countries, like India. The multidisciplinary river studies at modern and historical timescales must be pursued vigorously, for securing the health and future of the Indian rivers (Jain et al. 2016).

The densely settled piedmont zones of young mountains constitute an example of areas where human activity is superimposed on changes induced by natural forces (Tiwari 2000; Liebault and Piegay 2002; Starkel et al. 2008). On a regional scale, the tectonically active Darjeeling–Sikkim Himalayas, with lithology, which is prone to the mass movement, receive the highest annual rainfall along the whole Himalayan front (Starkel 1972; Dhar and Nandargi 2000; Soja and Starkel, 2007). Their margins and piedmont, as a transitional zone down to the lowland plains, is under the strong influence of the adjacent mountains. The nature and extent of the

Himalayas' impact on their piedmont is largely a product of adjustments in the fluxes of water and sediment (Starkel and Basu 2000; Grujic et al. 2006; Ghosh and Carranza 2010). Both are frequently accelerated by various forms of human activity such as agriculture, logging, mineral extraction, and road building at the mountain margin (Froehlich and Starkel 1993; Tiwari 2000).

The present-day economy of the Darjeeling-Sikkim Himalayan margin and piedmont depends mainly on tea estates established in the late nineteenth century (Ray 2002; Prokop and Sarkar 2012). Cultivation of other crops (e.g., rice, millet, areca nut) is largely for local consumption (Bhandari and Kale 2009). A significant part of the region constitutes reserved forests, and tea gardens. Forestry based on commercially valuable trees and tourism is an important contributor to the economy, as well as being an employer of large numbers of people (Government of West Bengal 2008–2009; Madhusudan 2011).

Like other Himalayan margin and piedmont environments, the study area has been experiencing heightened human pressures resulting in environmental degradation from a variety of causal factors, such as deforestation, sediment mining, bridge construction, extensions of embankments, and growth of tourism, etc. In this paper, we have attempted to provide a preliminary account of the anthropogeomorphology of the Chel River basin to highlight the major detrimental types and extent of anthropogenically-induced changes observed in the basin.

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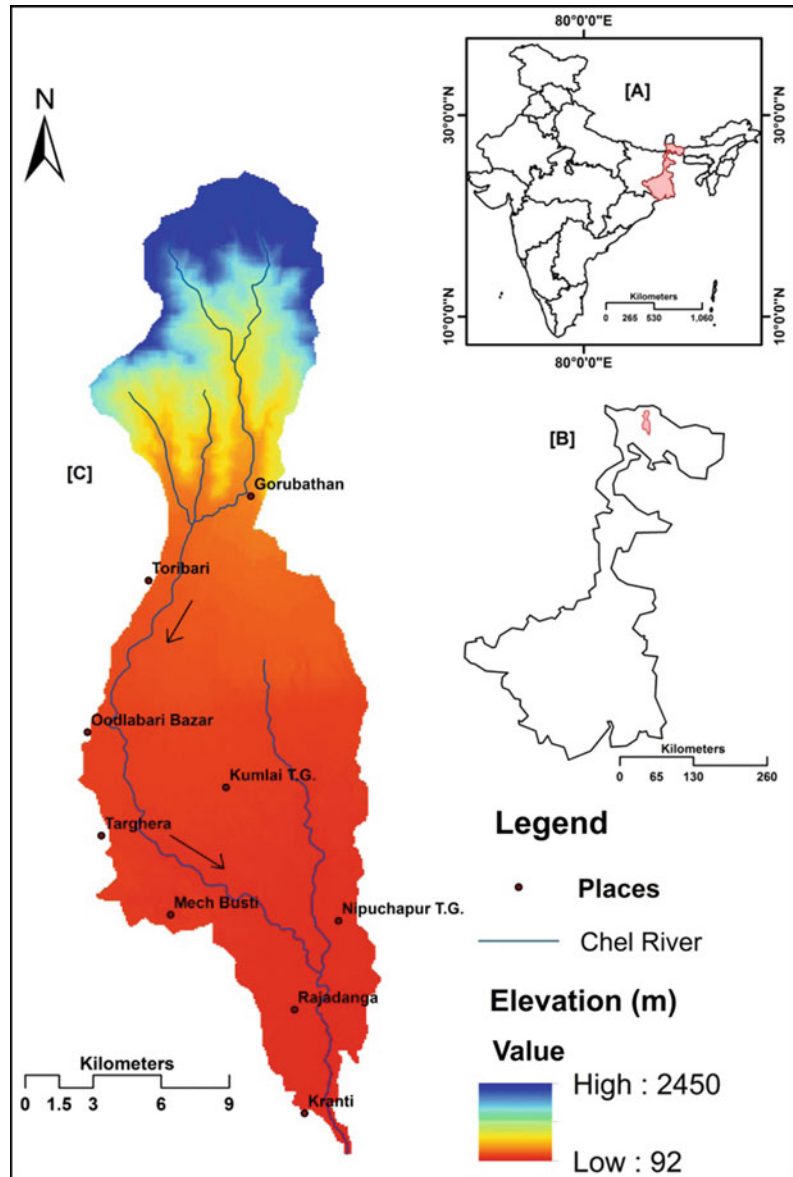
## 2.2 Study Area

With highly dissected northern hilly terrain having high altitudinal variation and gently rolling piedmont surface in the south, Chel River basin has a straddle-like situation between the outer Eastern Himalayan hill surface and sub-Himalayan piedmont North Bengal plains. Chel lies to the left of river Tista after Lish and Gish and unlike Lish and Gish runs parallel to Tista

for a considerable length on the piedmont and joins Neora to become Dharala Nadi at 88° 44' 13" E, 26° 41' 45.6" N which ultimately merges with mighty Tista about 13 km downstream. The study area extends between 26° 41' 30" and 27° 5' 15" north latitudes and longitudes 88° 37' 00" and 88° 45' 15" east (Fig. 2.1). The entire watershed covers an area of 321 km<sup>2</sup> with a watershed perimeter of 115.21 km. Elevation ranges from 92 to 2449 m. Geomorphologically, the basin comprises the alluvial plain, piedmont surface, terrace surfaces, lesser Himalayan surfaces, etc. Agriculture in the watershed is largely tea plantation. Chel is one among many other rivers (Gish, Diana, Chamurchi, Rehti, Gabur-Basra, Jainti, etc.) that are dissecting the southern part of Lesser Himalaya with catchment sizes between 50 and 100 km<sup>2</sup> and are in the belt of higher precipitation and form large alluvial fans. "Aggradation follows upstream into the hills, while farther downstream the braided channels change into meandering ones". The basin experiences a tropical monsoonal (Am) type of climate according to Koppen's Climate classification system. The annual total precipitation ranges between 250 and 500 cm, 90% of which happens during four-five months of the high-sun season (May–September) whereas very little precipitation happens during the low-sun season. Mean monthly temperature usually ranges between 18 and 30 °C. (Lama and Maiti 2019a).

The northern mountainous portion of Chel basin lies to the east of Lesser Himalayan Duplex (LHD) and Gish Transverse zone (GTZ), a sinistral strike-slip transverse fault (Mukul et al. 2017). The major portion of the Chel basin south of the mountain front is a part of the Gorubathan recess wherein the absence of Siwalik and Damuda series of rocks and consequent minimal North–South width of the Himalayan arc makes it unique in the Eastern Himalayan belt (Heim and Gansser 1939; Goswami et al. 2013; Srivastava et al. 2017). Further, the Ramgarh Thrust (RT) rather than the Mountain Front Thrust (MFT) defines the mountain front here (Matin and Mukul 2010). The Chel River and its major tributaries namely Manzing and Sukha Khola

**Fig. 2.1** a India with the state of West Bengal, b West Bengal with the location of Chel River Basin, and c the elevation character and major drainage lines of the Chel River Basin (elevation derived from SRTM 30 m)



having originated in the higher reaches of outer marginal Himalaya quickly lose much of the surface gradient reaching Putharjhora (300 m approx.) at the tip of the piedmont within 10 km (approx.) from their source. These situations coupled with intense and concentrated rainfall within the basin lay all favorable conditions for a copious amount of sediment aggradation in the piedmont zone. A significant area of the basin is under forests (35.76%) and Tea Gardens

(30.11%). As typical of the region, the higher elevated terraces in the Chel basin are stable LULC covered mostly by forests and tea gardens whereas the low-lying areas are cultivated with paddy and seasonal vegetables are much dynamic and frequently get flooded (Table 2.1).

Administratively, the basin spreads over parts of Gorubathan and Malbazar blocks of Kalimpong and Jalpaiguri districts, respectively of West Bengal. These two blocks have

**Table 2.1** Hydro-geomorphic characteristics of the Chel River (after Dutt 1966; Starkel et al. 2008; Prokop and Sarkar 2012; Wiejaczka 2016)

River	Mountain catchment (km <sup>2</sup> )	Forest area (%)	River gradient in mountains (‰)	River gradient in piedmont (‰)	Maximum discharge (m <sup>3</sup> s <sup>-1</sup> )	Minimum discharge (m <sup>3</sup> s <sup>-1</sup> )	Annual rainfall in the catchment (mm)
Chel	97	52.2	156.6	9.5	184.5	0.06	6096

been considered to get an idea about the demographic aspects of the basin. The municipality of Malbazar and census town of Odlabari lies at the eastern and western edges of the basin boundary, therefore the demographic aspects of these two towns have not been included to avoid getting an inflated figure. The basin is characterized by a higher rate of decadal growth of population 14.12% during 1991–2011 with sizable percentage of SC (16.74) ST (29.05) population coupled with low literacy (67.28%) and a lower percentage of working population (38.87%) (Tables 2.2 and 2.3). Thus, the study area exhibits a very dynamic natural environment superimposed with all traits of a socio-economically backward demographic environment.

Since the Chel River has a flow length of only 16 km in the outer Himalayan mountainous course with 97 km<sup>2</sup> of the catchment area and much of the human activities are concentrated on the piedmont, the study, therefore, has focused much on the piedmont zone of the basin. Further sediment mining has been explained in much detail, for it has emerged as the most widespread and detrimental human activity changing the geomorphology of the region.

### 2.3 Material and Methods

The study is mostly based on extensive fieldwork conducted during the post-monsoon season (December to February) of 2014–2017. Thalweg shifting and channel bed elevation changes were studied by cross-section measurements at 400 m upstream of the railway bridge and 400 m

downstream of the road bridge during 2014, 2015, and 2017. Channel cross profiling was achieved by using a dumpy level and measuring staff considering several change points. The benchmark of 157 m of CWC Chel office located along NH-31C Road Bridge on Chel River at Odlabari has been used for calculation of reduced levels at all the stations. All the cross-profile readings were taken with dumpy level starting from the right bank toward the left in the downstream direction of the river flow. Topographical maps and multi-temporal Landsat data were used to study channel planform dynamics and channel migration in response to the sediment mining and bridge construction. SRTM DEM 2000 (30 m) was compared with ASTER GDEM 2011(30 m) to show the changes in surface terrain both upstream and downstream of the bridges. Extension of embankments was computed from the topographical map of 1970 and Landsat 8 OLI/TIRS 2017. All the Landsat scenes and DEMs were collected from the USGS site (<http://earthexplorer.usgs.gov/>). One topographical map (1955) 1:250,000 scale U.S. Army corps of Engineers NG 45–8, Series—U502 was acquired from the University of Texas site (<https://legacy.lib.utexas.edu/maps/india.html>) and two 1:50,000 scale topographical maps (Map no.—78 B/9 and 78B/10) surveyed during 1969–71 were obtained from the Survey of India (SOI). ArcGIS (version 10.1; ESRI, Redlands, CA) software package has been used for the preparation of the GIS database. All the images were processed through ERDAS imagine (v. 9.0) software and then were georeferenced based on Universal Transverse Mercator (UTM) projection system (Northern hemisphere 45 zone and world

**Table 2.2** Demographic and socio-economic characteristics of the study area (Census 2011)

Blocks	Population	Sex ratio	Scheduled caste (%)	Scheduled tribe (%)	Literacy (%)	Male literacy (%)	Female literacy (%)	Working population (%)	Working female out of the working population (%)	Main workers (%)
Gorubathan	60,663	953	6.64	23.6	76.88	84.21	69.23	39.79	37.03	23.81
Malbazar	299,556	973	26.84	34.5	57.67	56.72	43.28	37.94	31.63	27.94
Average		963	16.74	29.05	67.28	70.47	56.26	38.87	34.33	25.88

Source Census of India, 2011

geodetic system (WGS 84) manually using GCPs collected during GPS survey.

Channel migration in response to bridge construction was analyzed through channel centerline migration dynamics. This was achieved by drawing transects at 1 km intervals perpendicular to the general trend of the 1994 polygon along the 36 km long study reach of River Chel from near Putharjhora T. E to its confluence with River Neora near Kranti. Thus altogether 35 transects (T1–T35) were drawn and the entire study reach was divided into three smaller reaches namely Reach-A (T1–T11), Reach-B (T11–T25), and Reach-C (T25–T35) (Fig. 2.2). Migration distances of centerlines were computed based on works of Leopold (1973), Gurnell et al. (1994), Yang et al. (1999), and Giardino and Lee (2011). The centerline of the earliest channel (1955) was taken as the origin (Yang et al. 1999) and then the centerline of the later dates was overlaid on the previous ones. The distance between the points of intersection between the centerlines along transects for subsequent years was measured (Chakraborty and Mukhopadhyay 2014). Channel planform dynamics have been attempted through the application of several channel planform indices namely Braiding Index (Brice 1964), Braid-Channel Ratio, and Sinuosity Index (Friend and Sinha's method 1993) for the period 1976–2017 from Landsat images. LULC changes in the study region have been adopted and incorporated from the studies of Prokop and Płoskonka (2014) and Biswas and Banerjee (2018). Secondary data from the Census of India has been largely consulted to understand the socio-economic profile of the basin. All other human activities have been documented by direct observation and in-situ photographs collected during the field works.

## 2.4 Results

The most detrimental human activities changing the geomorphology of the basin have been discussed in the following section.

**Table 2.3** Decadal growth of population in the study area (Census 2011)

Blocks	Decadal growth, 1991–2001 (%)	Decadal growth, 2001–2011 (%)	Average (1991–2011) (%)
Gorubathan	17.03	11.76	14.1
Malbazar	15.39	12.87	14.13
Average	16.21	12.32	14.12

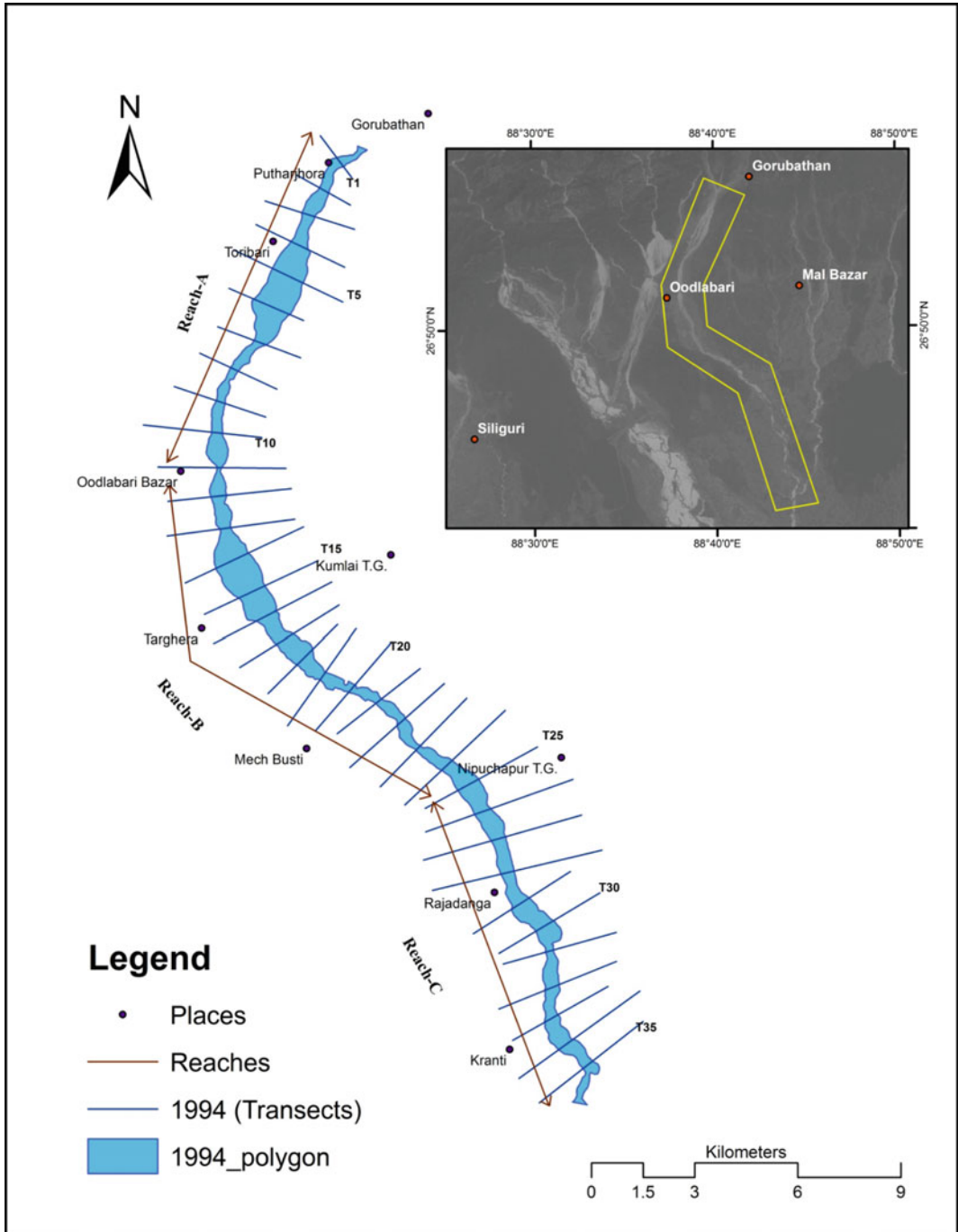
### 2.4.1 Sediment Mining

Alluvial channels have historically been an attractive source of sand and gravel for a variety of construction activities. The floodplains and terraces are mostly the sites of sediment storage in stream systems and can contain large quantities of boulders, gravel, and sands that can be mined economically (Langer 2003).

The study reach is characterized by highly fluctuating discharge, copious amount of aggradation due to break of slope situation and erodible banks. This altogether has resulted in the development of a braided channel pattern with ever-changing bars. The upper catchment experiences surface runoff and landslides during high-intensity concentrated rainfall months and adds more sediment to the channel downstream. These sediments are available for easy extraction directly from the riverbed and surrounding terraces right from Putharjhora (near mountain front and the tip of break-in slope) up to the confluence of Chel with River Neora. It is not certain when sediment mining began in the Chel basin but through surveys among locals, it was understood that a major peak in the demand for sediments from the Chel basin came during the construction of Teesta Barage at Gazoldoba, in the 1980s. The barrage construction was completed in 1987 but the barrage operation of the water diversion was started at the end of 1997 (Ghosh 2012). Initially, only boulders and large-sized gravels were extracted but with the growth of demand, extraction of other grades of sediments began. In recent years the development of higher connectivity in the form of better and new roads further has increased the demand. Further, the basin is well linked with major growing towns of North Bengal which has made Chel River a great source of sediments. This has

attracted an influx of laborers from neighboring areas and far-off places from different regions of North Bengal, Bihar, and even Bangladesh (Gan 2008). Presently the sediments from the Chel River are a major source for growing construction industries in the region, neighboring states, and countries as well. The extraction of sediments is mostly done manually with simple tools throughout the entire stretch of study reach but mechanized extraction to a significant extent was observed up to 10 km upstream and downstream of the Odlabari road and rail bridges (Fig. 2.4a–d). There are two operational local sediment processing units- one at Toribari, 5 km upstream of Odlabari, and another at Odlabari, 1 km downstream of Odlabari Road Bridge (Fig. 2.5a–b). The extracted sediments from the river are brought to these processing units and the materials are processed mechanically with the help of sieves of various sizes. The sieved materials are kept separate, according to their sizes for ready transportation to places of demand. The common methods of sediment extraction practiced are Dry-pit mining, Wet-pit mining, bar skimming or scrapping, and pits on the river terrace or adjacent flood plain.

The types and amount of sediment extraction are seasonal. During the dry season, all grades of sediments ranging from large boulders to fine sand are extracted directly from the riverbed, bars, and surrounding terrace of the entire stretch of the study reach. Generally, large size boulders are collected from the upper section of the Reach-A (Putharjhora-Odlabari), medium-size boulders, gravels, and little proportion of sand are collected from the rest portion of Reach-A and upper portion of Reach-B (Odlabari-Nipuchapur T.G.) whereas sand mining dominates along the rest of Reach-B and entire Reach-C (Nipuchapur T.G.-Kranti) (Fig. 2.3a–d). With



**Fig. 2.2** Location of transects at 1 km interval. Channel polygon encompasses all mid-channel bars

the onset of the monsoon season, the extraction activities gradually cease near bank and higher terrace locations as high flow and water depth

hinder the in-stream extraction. This season records the lowest extraction volume in the entire year, especially for lower grade sediments and





**Fig. 2.3** Field photographs showing Boulder lifting at Toribari, Upper Reach (a); mid-channel gravel bar skimming at Odlabari, Middle Reach (b); sand mining at Rajadanga, Lower Reach (c, d)

sand. As soon as monsoonal winds weaken and flow velocity and depth lowers in the channel by the month of late September and early October, labors lift the larger-sized boulders first that are brought down to greater distance by the higher monsoonal flow. The cycle continues, in the same way, year after year. Various impacts of sediment mining on channel dynamics are discussed below.

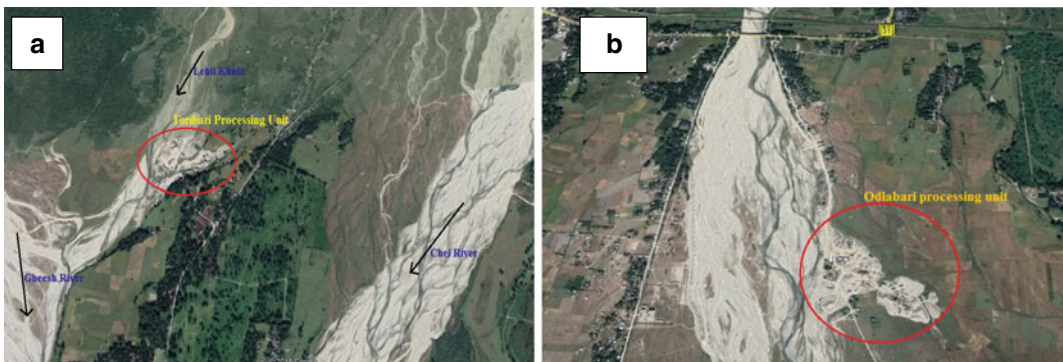
#### 2.4.1.1 Thalweg Shifting and Instability of Channel Bars

Thalweg shifting happens when sediment is extracted very close to the river thalweg. The extraction leaves pits of different sizes separated from thalweg by a narrow strip of land. As the water level rises during high flows, the thalweg may capture the pits. Thus, the former off-channel pit transforms into an in-channel pit (Rinaldi et al. 2005).

It has been observed from cross profiles measured at 400 m upstream and 400 m downstream of the Odlabari road and rail bridge, respectively that thalweg points have oscillated to the right and left with time (Fig. 2.6a, b). In the upstream cross profile, the thalweg point migrated near to the right bank in 2015 from its near left bank position in 2014 and it occupied near center position in the year 2017. In the downstream cross profile, the thalweg has consistently moved toward the center from its near left bank location in 2014. The river exhibits a braided channel pattern for most of the lengths of the studied reach except the lower reach (Reach-C). In this multi-channel braided system, there are multiple lower elevation points with very little variation and are separated by low height bars as exhibited by both cross profiles. In such a situation, little disturbance of channel bars separating these multiple flows induced by sediment mining is leading to significant shifting of



**Fig. 2.4** Manual way of sediment extraction wherein crushing, and segregation is done on the riverbed only (a–c); mechanized sediment extractions collect large volume but crushing and segregation happens with sieves at processing units (d)

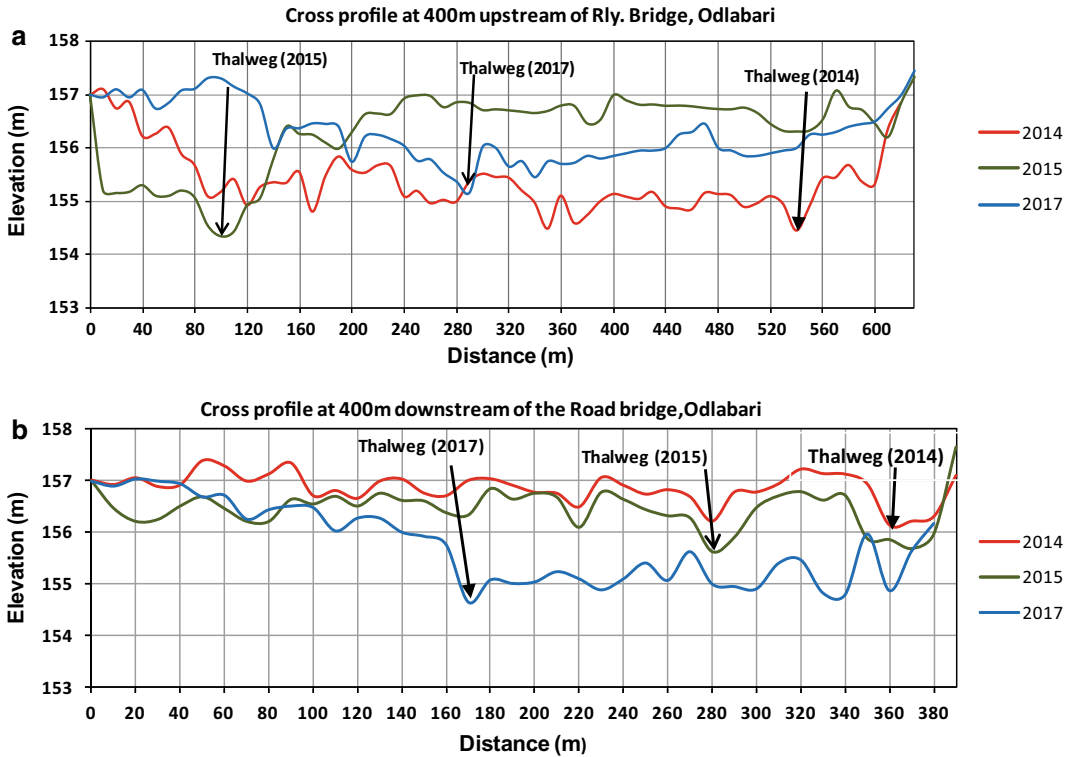


**Fig. 2.5** Google Earth images showing sediment processing units. a at Toribari and b at Odlabari

thalweg points. Thus, due to braided channel pattern and massive sediment mining, thalweg shifting is much more dynamic in the Reach-A and Reach-B.

### 2.4.1.2 Bed Elevation Change

The drawn cross profiles display a wide variation in terms of shape, configuration, and degree of asymmetry. In terms of bed elevation, the



**Fig. 2.6** Cross profiles showing bed elevation changes and movement of thalweg during 2014 and 2017 at 400 m upstream of Rail Bridge (a) and 400 m downstream of the Road Bridge, Odlabari (b)

upstream cross profile exhibits alternate phases of lowering and rise in bed elevation. In the year 2015, its bed elevation has risen by 1.5 m on an average throughout the cross-profile length except near the right bank where the bed elevation has gone below the 2014s bed elevation and the new thalweg point has developed at an elevation of 154.54 m. The 2017 bed elevation falls almost between the bed elevations recorded in 2014 and 2015. It is observable that, close to the right bank, the section experienced deposition of about 2 m and the rest of the cross-profile length experienced erosion by 1 m on average. The fact that this cross profile falls upstream of the twin Odlabari bridges and is nearer to the mountain front explains the bed level rise of 2015. (Fig. 2.6a). Whereas it seems that a huge amount of both manual and mechanized sediment extraction activity operating is the most probable cause for the lowering of bed elevation (Fig. 2.6b). The downstream cross profile on the

other hand exhibits consistent lowering, much on the center to left bank section of the cross profile. The consistent lowering of bed elevation in the downstream cross profile can be attributed to the coupled impact of bed scouring caused by the increased flow velocity induced by the twin bridges and huge mechanized sediment extraction being very close to the Odlabari processing unit (Fig. 2.7).

**2.4.1.3 Shifting of Pool-Riffle Sequence**

Pools are defined as topographic lows and riffles are the topographic highs along the longitudinal profile of a stream. Huge extraction activities, especially the mechanized ones, are creating artificial pools along the studied reach of Chel River (Fig. 2.8b, c). These artificial pools increase the gradient of the upstream channel from the extraction hole, which leads to headward erosion that will tend to move several kilometers upstream and changes the natural



**Fig. 2.7** Huge mechanized mining pits near to Odlabari processing unit



**Fig. 2.8** Channel bed deformation due to manual sediment mining (a); mechanized wet-pit mining creating huge longitudinal depressions (negative topography) (b–c); dumping of a huge amount of sediments at Odlabari processing unit creating positive topography of sediment mounds (d)

sequence of pool and riffles and then change in channel morphology happens (Ghosh et al. 2016).

#### 2.4.1.4 Deformation of Channel Beds

It is been observed that the mining of sediments is deforming the riverbed. The mining pits are creating artificial pools and lows which can be considered as topographic negatives whereas the extracted materials are sorted and stored on riverbeds only which creates temporary topographic positives of mounds ranging anywhere from 1 to 8 m in height. Some of the spoil dumps at the Odlabari processing unit measure 30 m high approximately (Fig. 2.8a, d). These mounds of sediments are stored temporarily from few days to few months. Sometimes it is left till even next season. Some of the excavation pits on the other hand can also last longer if the river cannot fill it in the next high flow season or if the pit remains cut off and thus abandoned from the main channel flow. These artificial highs and lows are creating defaced channel beds and are affecting the river morphology (Fig. 2.8 a–d).

#### 2.4.1.5 Channel Planform Changes

The values of the braid-channel ratio have consistently decreased from its highest mark of 2.27 in 1976 to the lowest value of 0.96 in 2005 and then by 2017, the values in each segment (Reach) became near 1 which is suggestive of the fact that Chel River is gradually transforming itself from a braided channel to a straight one (Table 2.4 and Fig. 2.9). The recent years' clustering of points which otherwise were scattered horizontally elongated further confirms the transition of channel form from braided to straight. Continuous wet-pit mining creates deep elongated trenches on the riverbed and lack of sediments can be partly responsible for this gradual transition. This limits the scope for multi-channel flow.

#### 2.4.1.6 Others Impacts

Due to sediment mining, human pressure is increasing on the channel beds. During daytime, thousands of people tread the riverbed on foot,

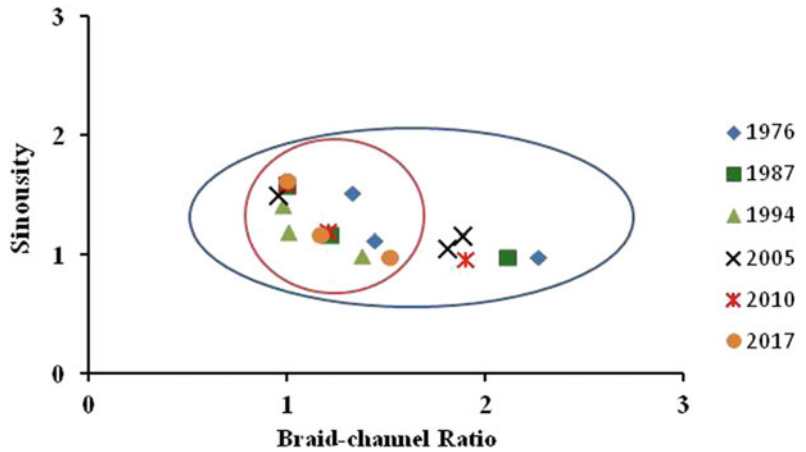
on bicycles, and on motorbikes. Further sediment transporting vehicles, i.e., pickup trucks, full-size trucks, tractors, tipper, or dumper trucks continuously move on the riverbed. All these movements generally happen across riffles as they are the natural topographic highs. Thus, riverbeds get very compacted across the riffles and along haul ways of the river due to the continuous movement of vehicles. Naturally, the river needs larger stream power to erode these human compacted sections of riverbeds and thus remains largely undisturbed during the entire low flow duration, whereas the river concentrates its energy on a loose section of the bed. The vehicular movements also degrade the growth of vegetation on the riverbeds, banks, and adjacent floodplains, which leads to increased erosion. Further, the surface vibration produced from the continuous vehicular movements loosens weak and high bank materials and thus assists in an accelerated rate of bank erosion. It was found during field surveys that embankments or natural levees were deliberately broken or lowered for easy and short access for men and vehicles to the riverbed (Fig. 2.10). During the high flow time, these points are much more likely to be breached and cause movement of flow toward the low-lying surrounding floodplains. Thus, it also accentuates channel dynamicity. Sediments are generally collected from the base of the banks to get the advantage of easy and quick transportation of sediments which leads to diversion of flow toward the banks and causes bank erosion. Further, the lifting of specific size sediments and leaving behind the others is disrupting the natural distribution and dispersal of sediments both across and along the channel. This is creating an unnatural imbalance in the distribution of critical shear stress ( $\tau_c$ ) both across and along the river channel. Further, though the West Bengal Minor Minerals Rules, 2002; Schedule V (Tamang 2013) prohibits extraction of minerals within a distance of 200 m from any hydraulic structure, reservoir, bridge, canal, road, and other public works or buildings, it was noticed during the field surveys that sediment extraction in the Chel basin is operating flaunting all rules and regulation according to the ease of miners. Sediment

**Table 2.4** Reach-wise temporal dynamics in planform

Reach	Year	Lctot (km)	Lcmax (km)	Li (km)	Lr (km)	Sinuosity index (P) = Lcmax/LR	Braiding index, Brice 1964 (B) = 2(?Li)/Lr	Braid-channel ratio, B = Lctot/Lcmax
A	1976	16.18	11.23	8.26	10.45	1.07	1.58	1.44
	1987	14.19	11.6	7.08	10.46	1.11	1.35	1.22
	1994	12	11.83	8.83	10.8	1.1	1.64	1.01
	2005	22.1	11.66	14.13	10.6	1.1	2.67	1.89
	2010	14.23	11.73	4.04	10.7	1.1	0.76	1.21
	2017	13.76	11.8	5.25	10.84	1.1	0.97	1.17
B	1976	26.1	11.5	9.69	12.24	0.94	1.58	2.27
	1987	24.23	11.49	8.73	11.98	0.96	1.46	2.11
	1994	16.01	11.61	8.82	12.04	0.96	1.46	1.38
	2005	22.32	12.32	10.96	12.2	1.01	1.8	1.81
	2010	21.29	11.21	12.67	12.7	0.9	2.01	1.9
	2017	17.5	11.53	7.4	12.23	0.94	1.21	1.52
C	1976	19.71	14.84	6.69	10.9	1.36	1.23	1.33
	1987	15.34	15.34	1.65	11.29	1.36	0.29	1
	1994	13.98	13.98	7.6	10.81	1.29	1.4	0.98
	2005	14.82	14.82	5.75	11.26	1.32	1.02	0.96
	2010	15.51	15.51	4.68	10.52	1.47	0.89	1
	2017	15.46	15.46	6.77	10.46	1.48	1.29	1

Source Computed by authors based on Landsat images (1976–2017)

**Fig. 2.9** Temporal variability of sinuosity (B) and braid-channel ratio (P) of River Chel



extraction barely 100 m upstream of the rail bridge and even under the road bridge of Odlabari was noticed, most probably to get the comfort of shade provided by bridges on scorching days of March (Fig. 2.11a, b).

### 2.4.2 Bridge Construction

Human-induced modifications through engineering infrastructures like roads, bridges, dams, and urban landscape when takes place across and



**Fig. 2.10** One of the many humans breached embankment points for easy access of men and vehicles into the river



**Fig. 2.11** Sediment mining operating barely 100 m upstream of the Odlabari rail bridge (a); sediment mining operating under the Odlabari Road Bridge (b). Photographs were taken on 21.03.2013

along a river channel, experience severe geomorphologic impacts upon that channel in terms of its transport capacity, sediment supply, riverbed modification, and downstream hazards

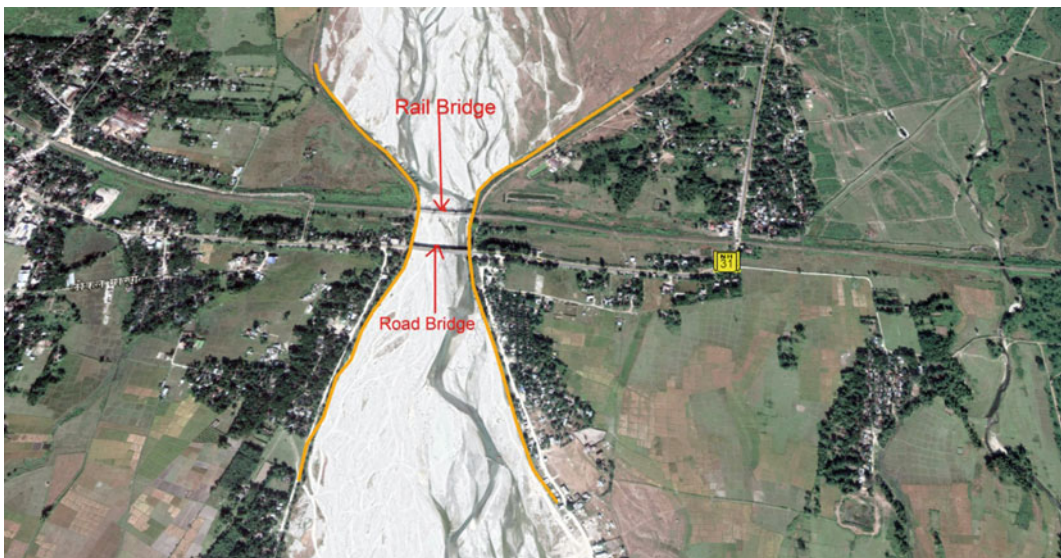
(Thomas 1956). Several scholars have studied the impact of these infrastructures on the river channel and have established an alteration in the natural state of the channels (Ismail 2009;

Forman and Alexander 1998; Gregory 2006). Bridges, railways, and highways that are built to facilitate surface connectivity affect channel morphology negatively much like the dams. Road-stream crossings especially affect both upstream and downstream of the channel. It also affects the riverine ecology and habitat (Suvendu 2013; Khalifa et al. 2009; Bouska et al. 2011). In the case of the Chel, one rail and one road bridge cross the Chel basin from the middle and thus divides the Chel River into two halves of almost equal lengths. The road bridge is over NH31 connecting Siliguri and Alipurduar which joins the newly built Asian Highway at Telipara, Binnaguri, and the rail bridge is overbroad-gauge line of NEFR (North East Frontier Railway) division connecting Siliguri with Alipurduar. During the construction of bridges, engineers kept the width of bridges minimum for structural efficiency or cost-cutting (Biswas and Banerjee 2018). Chel basin falls within the annual total precipitation range of 250–500 cm much of which is concentrated in the high-sun season from May to June. During 2015 an annual total precipitation of 432.02 cm was recorded at Rangamutee Tea Garden (Rainfall data of Rangamutee T.G.). The concentrated amount of

rainfall during monsoon brings down huge sediments and water into the channel but the twin bridges of Odlabari, barely 150 m in across length pose as a great impediment to the natural passage of water and sediments downstream. Very less spacing between the upstream rail bridge and downstream road bridge further aggravates the situation. Presently the channel has been constricted to a greater extent and a bottleneck situation has developed (Fig. 2.12). The morphological and hydrological alterations that the channel is facing upstream and downstream of these twin bridges are discussed below.

#### 2.4.2.1 Surface Elevation Change

The surface relief in both upstream and downstream of rail and road bridges has changed and is observable even within a short period of 2000–2011. The upstream section is experiencing an increment in elevation in response to sedimentation as is evident from the comparison of the Aster GDEM of 2011 (30 m resolution) with the SRTM DEM of 2000 (30 m resolution). The areas within elevation zones of 192–239 m and 239–312 m are growing in size and are increasing downslope which implies sediment increment in the upstream of twin bridges (Fig. 2.13a,



**Fig. 2.12** Bottleneck condition of the River Chel (marked with yellow lines) due to Rail and Road Bridge at Odlabari. Source Google Earth Image, dated 11.07.2017

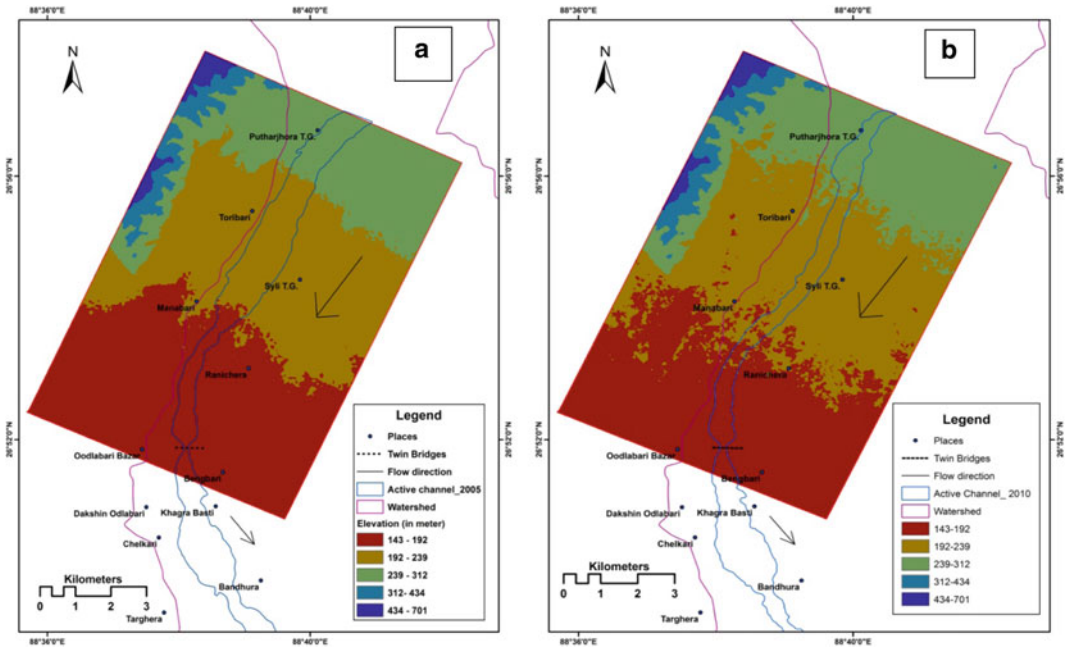


b). The bridges hinder the free passage of water and hence the flow velocity gets reduced considerably upstream leading to the deposition of sediments that the river could not carry at that velocity. Whereas the opposite scenario is prevailing in the downstream section of the bridges. This stretch is characterized by bed scouring and bank erosion. Unlike upstream twin bridges, the downstream stretch is experiencing intrusion of low elevation surface zones toward the higher elevation zones in a fragmentary but linear pattern, which suggests bed scouring along these linear zones (Fig. 2.14a, b). It is quite evident from the comparison of DEMs of 2000 and 2011 that the temporary impounding situation occurs during high monsoonal flow in the upstream of the bridges causing an increase in the potential energy of the river which must pass through a constricted section of the bridges increasing downstream flow velocity, i.e., the conversion of potential energy to kinetic energy. This increased velocity translates itself through bed scouring

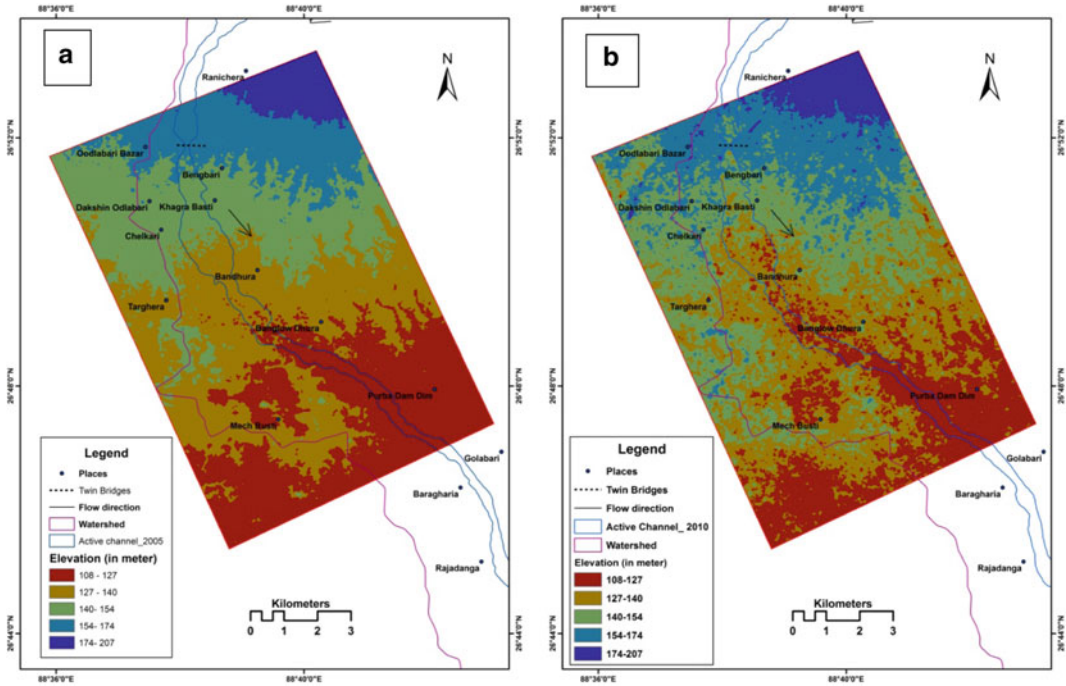
and bank erosion. These findings are well consistent with the bank erosion results wherein the Reach-B (downstream of bridges) accounted for maximum channel migration and consequent bank erosion (Lama and Maiti 2019b).

**2.4.2.2 Channel Migration**

The general trend of the channel centerline movement is rightward (Fig. 2.16). Out of 35 transects, only nine transects (T12, T13, T14, T15, T21, T27, T29, T33, and T34) show the leftward movement of the centerline. T14 exhibits a maximum total leftward movement of -1081.57 m with a yearly average of -17.44 m whereas T27 demonstrates the minimum leftward centerline movement of -22.98 m with an annual average of -0.37 m. Among the rightward movements, transects T17 record the maximum movement value of 1747.49 m with an annual average movement of 28.19 m whereas T7 exhibit the least movement of 72.2 m only with an annual average movement



**Fig. 2.13** Surface elevation change from Putharjhora to Odlabari bridges in the upstream section in 2000 (a) and 2011 (b)



**Fig. 2.14** Surface elevation change from the Odlabari bridges till Purba Damdim in 2000 (a) and 2011 (b)

of 1.16 m (Table 2.5 and Fig. 2.15). Thus, it is evident that the channel section immediately downstream of the twin bridges has experienced maximum migration (both rightward and leftward). The results are consistent with the findings of Biswas and Banerjee (2018), wherein based on the six cross-sections drawn along the river, they argue that maximum shifting of the channel has happened across the cross-sections downstream of the twin bridges. Shifting of almost 2.5 km (approx.) has happened since 1913 between downstream bridges to Damdim. Further, they add that the channel is shifting westward in the upstream and eastward, downstream of the twin bridges. Chel River has started sediments deposition soon after the construction of rail bridge and well-formed bars appear by the year 1942. From 1913 to 1942 there was only a rail bridge across its course, but, with the addition of a road bridge soon after 1984, the hydro-morphological impact has amplified significantly. In subsequent years, there have been phases of bar enlargement and modifications (Biswas and Banerjee 2018).

### 2.4.2.3 Effects on Hydraulic and Geometric Parameters

The bridges have also impacted the hydraulic and geometric parameters of the river. It has been found that the flow velocity is highest in between the bridges. The same is higher in the downstream of the bridges compared to the upstream section. The higher recorded flow velocity in the downstream section compared to the upstream section of the bridges plays a vital role in bed scouring and extensive right bank erosion in the Reach-B (Oodlabari Bazaar-Nipuchapur Tea Garden) section (Lama and Maiti 2019b). The concentration of the highest flow velocity between the bridges is causing scouring and incision of bridge piers threatening their stability (Fig. 2.17a, b). This very process seems responsible for the damage to an old railway bridge and therefore a new bridge has been constructed upstream and is operational presently (Fig. 2.18a). Further, the flood-prone channel width and the width-depth ratio are least in between the bridges whereas it is higher in the

**Table 2.5** Statistics of centerline migration dynamics over time

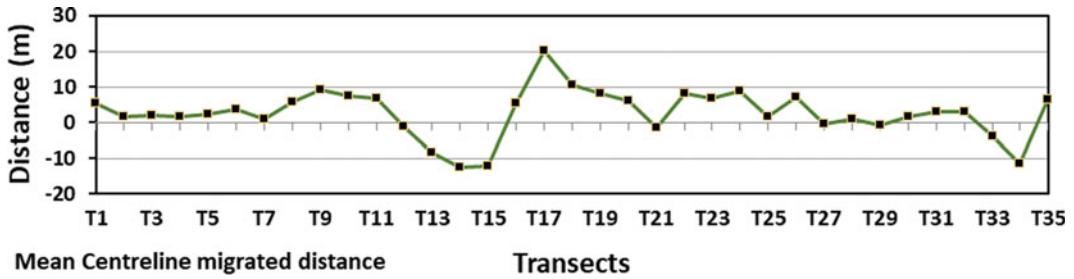
Centerline movement		1	2	3	4	5	6	7	8	Total migration (m)	Average migration (m year <sup>-1</sup> )
S. No.	Time	1955	1970	1976	1987	1994	2005	2010	2017		
Years (accumulative)		1	16	22	33	40	51	56	62		
T1	0	278.1	646.92	-283.3	-84.69	112.9	245.05	-444.4	470.58	7.59	
T2	0	382	312.15	66.1	-146.86	180	-645.23	-12.6	135.56	2.19	
T3	0	517.39	15.66	-85.1	25.6	190.97	-461.4	-44.37	158.75	2.56	
T4	0	605.29	-97.42	-167.48	-122.01	679.02	-979.7	218	135.7	2.19	
T5	0	528.15	-2.16	-13.37	-232.35	731.77	-916.72	103.6	198.92	3.21	
T6	0	343.12	-258.91	35.24	13.34	601.22	-524.6	108.79	318.2	5.13	
T7	0	-163.06	103.94	163.71	9.03	377.99	-539.9	120.49	72.2	1.16	
T8	0	-236.26	153.54	581.19	-1.66	178.95	-177.73	1.75	499.78	8.06	
T9	0	-153.25	164.81	680.6	18.34	-53.87	240.4	-90.24	806.79	13.01	
T10	0	-58.76	195.53	576.94	-115.75	280.42	-90.3	-146.19	641.89	10.35	
T11	0	-105.99	676.51	-243.14	-8.69	277.62	-16.34	4.55	584.52	9.43	
T12	0	-170.51	117.42	115.58	-44.68	24.71	-300.19	167.5	-90.17	-1.45	
T13	0	74.21	-1056.5	283.73	6.71	206.37	-246.82	14.04	-718.26	-11.58	
T14	0	57.15	-1232.92	837.92	-619.16	876.66	-712.9	-288.32	-1081.57	-17.44	
T15	0	-14.65	-1049.97	613.22	-435.05	657.39	-914.9	79.05	-1064.91	-17.18	
T16	0	1463.36	-1456.69	135.29	210.69	226.21	-233.25	115.6	461.21	7.44	
T17	0	2841.63	-2448.93	547.17	395.84	246.3	-165.66	331.14	1747.49	28.19	
T18	0	715.56	-895.61	350.21	502.03	491.02	-528.54	278.5	913.17	14.73	
T19	0	341.97	-73.11	173.2	189.02	43.7	-214.32	257.9	718.36	11.59	
T20	0	32.18	272.34	57.74	113.5	108.64	-144.64	82	521.76	8.42	
T21	0	-125.63	139.5	25.17	-162.59	74.92	48.03	-135.64	-136.24	-2.20	
T22	0	340.98	90.78	153.14	-29.44	97.2	-15.48	72.52	709.7	11.45	

(continued)

**Table 2.5** (continued)

Centerline movement		1	2	3	4	5	6	7	8	Total migration (m)	Average migration (m year <sup>-1</sup> )
S. No.	Time	1955	1970	1976	1987	1994	2005	2010	2017		
Years (accumulative)		1	16	22	33	40	51	56	62		
T23	0	631.7	-756.823	674.75	354.36	-493.71	325.96	-151.16	585.077	9.44	
T24	0	642.47	-431.16	540.14	59.95	-46.35	-127.08	137.14	775.11	12.50	
T25	0	-43.82	264.9	155.79	120.8	-177.89	-170.43	-17.15	132.2	2.13	
T26	0	508.13	103.53	415.39	-5.89	-363.78	35.56	-81	611.94	9.87	
T27	0	-75.82	203.62	74.62	-22.17	-142.04	-56.4	-4.79	-22.98	-0.37	
T28	0	232.35	84.28	-37.81	-232.8	254.9	-216.74	-16.47	67.71	1.09	
T29	0	-108.71	-280.5	658.47	-473.48	448.6	-342.9	42.1	-56.42	-0.91	
T30	0	-147.87	292.36	298.58	-386.79	586.42	-478.22	-15.5	148.98	2.40	
T31	0	-181.43	190.17	17.78	172.07	15.27	164.45	-120.74	257.57	4.15	
T32	0	-122.95	590.57	66.72	-282.31	-0.29	-39.51	56.75	268.98	4.34	
T33	0	573.12	-935.25	-32.66	267.82	41.8	-249.24	-12.59	-347	-5.60	
T34	0	-783.56	-419.85	-59.39	384.8	-169.8	234.51	-184.63	-997.92	-16.10	
T35	0	-6.94	137.52	386.94	152.6	-73.3	31.73	-82.7	545.85	8.80	

Source Computed by authors based on Landsat images (1955–2017)



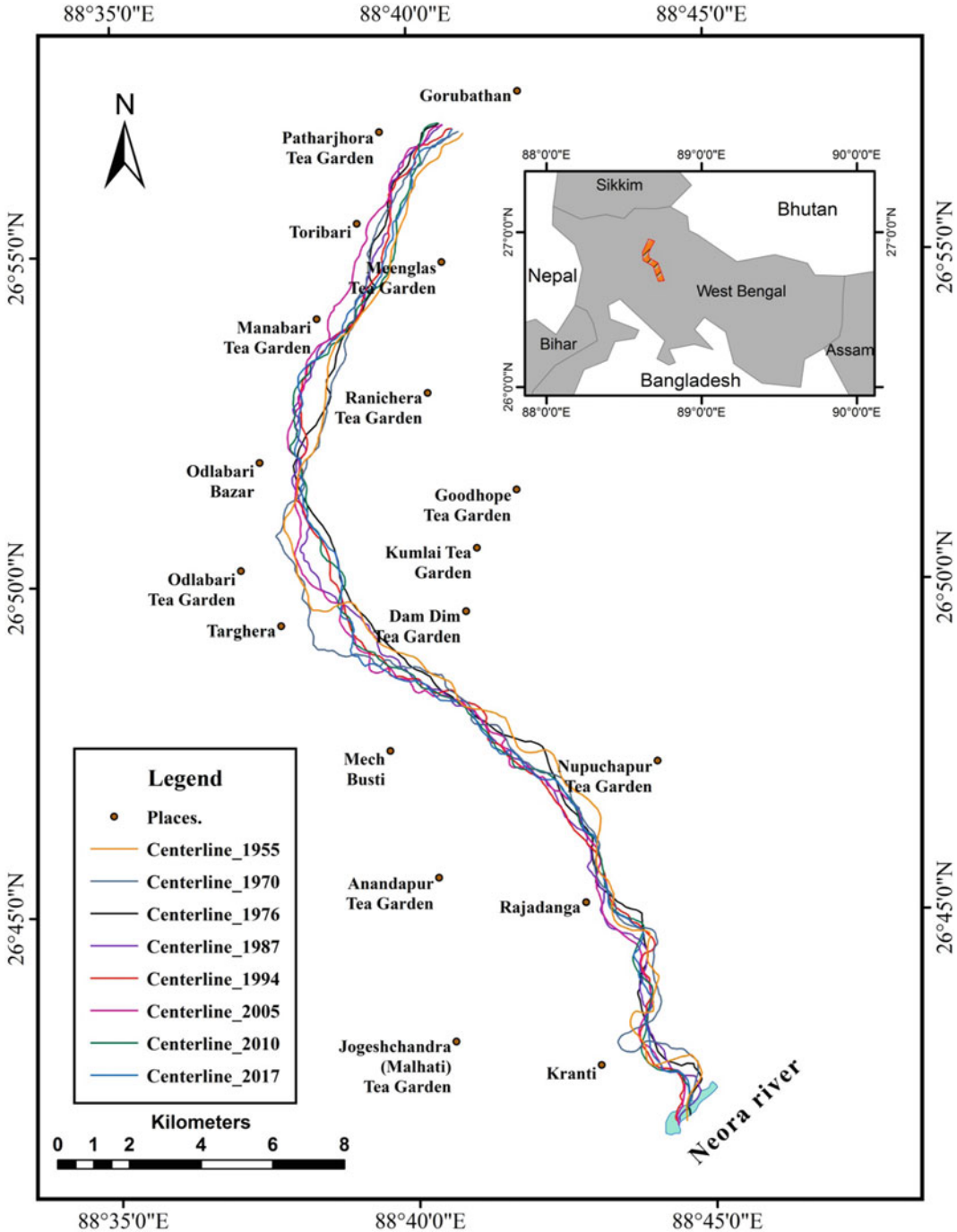
**Fig. 2.15** Transect wise mean centerline migrated distance of Chel River (1955–2017)

upstream section compared to the downstream section of the bridges which is suggestive of backwater effect and, consequently, extended flood plain in the upstream section due to obstruction caused by the bridges (Biswas and Banerjee 2018). Thus, the bottleneck condition has enormously increased flood probability both up and downstream with bank erosion and noticeable impact on land uses (Fig. 2.18b).

### 2.4.3 Extension of Embankments

The embankments (locally known as Bandh) are constricting the active floodplain and thus compelling Chel River to dissipate its energy within the narrow channel bed. During 1970, the total length of the embankment was only 14 km which grew to 41.25 km in 2017 along with 2.53 km of dykes. Dykes have been constructed along severe erosion reaches to strengthen embankments. Thus, there has been three times extension in the length of the embankments and now covers almost 58.1% of the total active channel length of 71 km (Fig. 2.21). The right bank line is almost embanked completely with very little embankment free stretch between Dakshin Odlabari and Targhera. Erection of embankment along the almost entire stretch of the right bank can be explained by the fact that the area beyond the right bank is largely settlement area and cultivable land and the channel is progressively migrating toward the right as seen in (Fig. 2.16). Contrary to this, areas along the left bank are physiographically higher than the

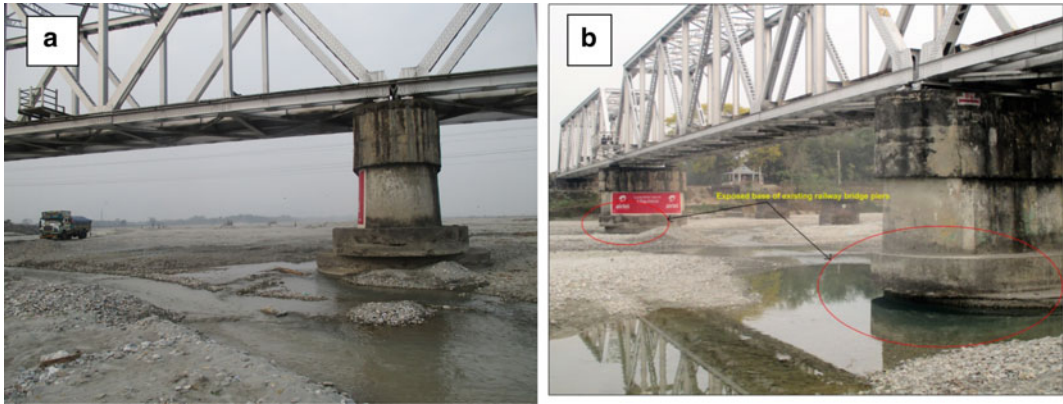
right bank area as suggested by the basin asymmetry factor of 40.31 which implies that the basin is tilted toward the right in the downstream flow direction. Thus, the main channel flow reaches near the left bank only at or along with sites of concave channel bends and thus erosion is confined only along these small and fragmented cut banks (Transverse section A–B in Fig. 2.21). But since the main channel flow is mainly concentrated along the left bank, large stable point bars have developed on the inner banks of the channel bend. This development and growth of point bars along the inner banks of left coupled with tiltation toward the right are pushing the main channel more toward the right and thus creating more pressure on the right embankments, especially along stretches where channel bends are near to right banks (Transverse section B–C in Fig. 2.21). Thus, it is been noticed that this has resulted in damage to right embankments along these bends (Fig. 2.19a). Few cases of erosion along the banks without embankments have been noticed which falls on the opposite of banks with embankments (Fig. 2.20b). The area beyond the left bank hosts forests, tea gardens, and agricultural land with no large settlements or towns which altogether explains why much length of the left bank is still free from embankments. Almost the entire left bank upstream of Odlabari bridges has no embankment and similarly the stretch from Bengabari to Purba Damdim the downstream still does not have any embankment. Since the river is flowing confined between higher terraces along the left bank and heavily embanked right bank,



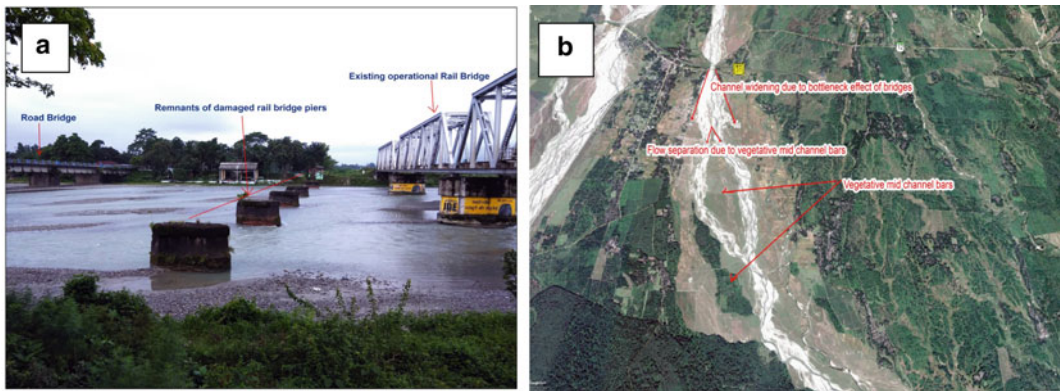
**Fig. 2.16** Temporal trends in total centerline migration distance for the Chel River (1955–2017)

unless and until there is very heavy high flow it cannot access and deposit the sediments in the lower flood plains. Due to this the channel bed is

rising constantly and thus the difference between channel bed and embankment heights is decreasing progressively (Fig. 2.20a). This



**Fig. 2.17** Bed incision at the foot of railway piers (a, b)

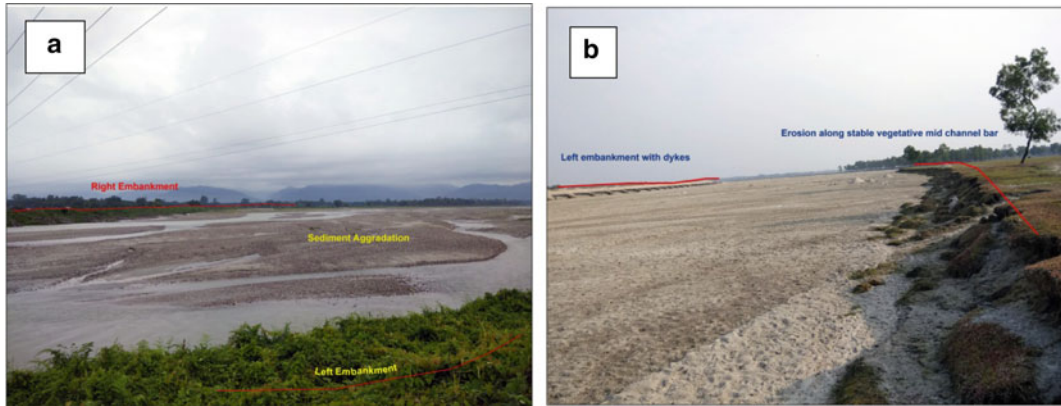


**Fig. 2.18** Remnants of old damaged railway piers in between functional Rail and Road Bridge at Odlabari. The number of piers in the new railway bridge has been reduced to only two instead of five in the older one (a).

Channel widening due to cumulative effects of bottleneck condition and vegetative mid-channel bars in the middle reach of River Chel (b). *Source* Field photograph (a), Google Earth Image dated 11.07.2017 (b)



**Fig. 2.19** Damaged right embankment at transverse section C–D (a) (photograph was taken on 21.03.2013). Repairing and strengthening of the embankment by addition of dykes (b) (photograph 10.08.2014)



**Fig. 2.20** Copious sediment aggradations forming huge gravel bars in the immediate upstream of a railway bridge, Odlabari. Note the least difference in elevation between

the riverbed and the embankments (a); left embankment with dykes and erosion on the opposite along the mid-channel bars near Rajadanga (b)

implies an ever-decreasing threshold level of bank full discharge with a higher probability of flood and channel avulsion at lower discharge in the future.

#### 2.4.4 Change in Land Use

Biswas and Banerjee (2018) have compared the land use of the Chel Basin and surrounding region from 2005 and 2015 classified Landsat images. They found that there have been significant changes in the areas within settlements and tea gardens. The areas within settlement and roads have increased from 5 to 11% and agricultural land from 11 to 30%. Most notably the area with tea gardens has reduced from 25.9% to 10.75%. Forest coverage also has reduced from 37 to 32%. Scrubland has recorded zero in 2015 compared to 10% in 2005 (Fig. 2.22). Altogether it can be said that there has been a decrease in land under natural elements and an increase in land under anthropogenic activities except for tea gardens. The altered land uses harm the channel and it can be seen in the increment of areas within sand and boulder riverbed from 5% in 2000 to 9% during 2015. Much of the areas on both sides of the river below the twin bridges of Odlabari have been converted into settlements and agricultural land and even the channel bars

are cultivated intensively seasonally. During monsoon, it is used for paddy cultivation whereas, during the dry winter season, vegetables are cultivated largely.

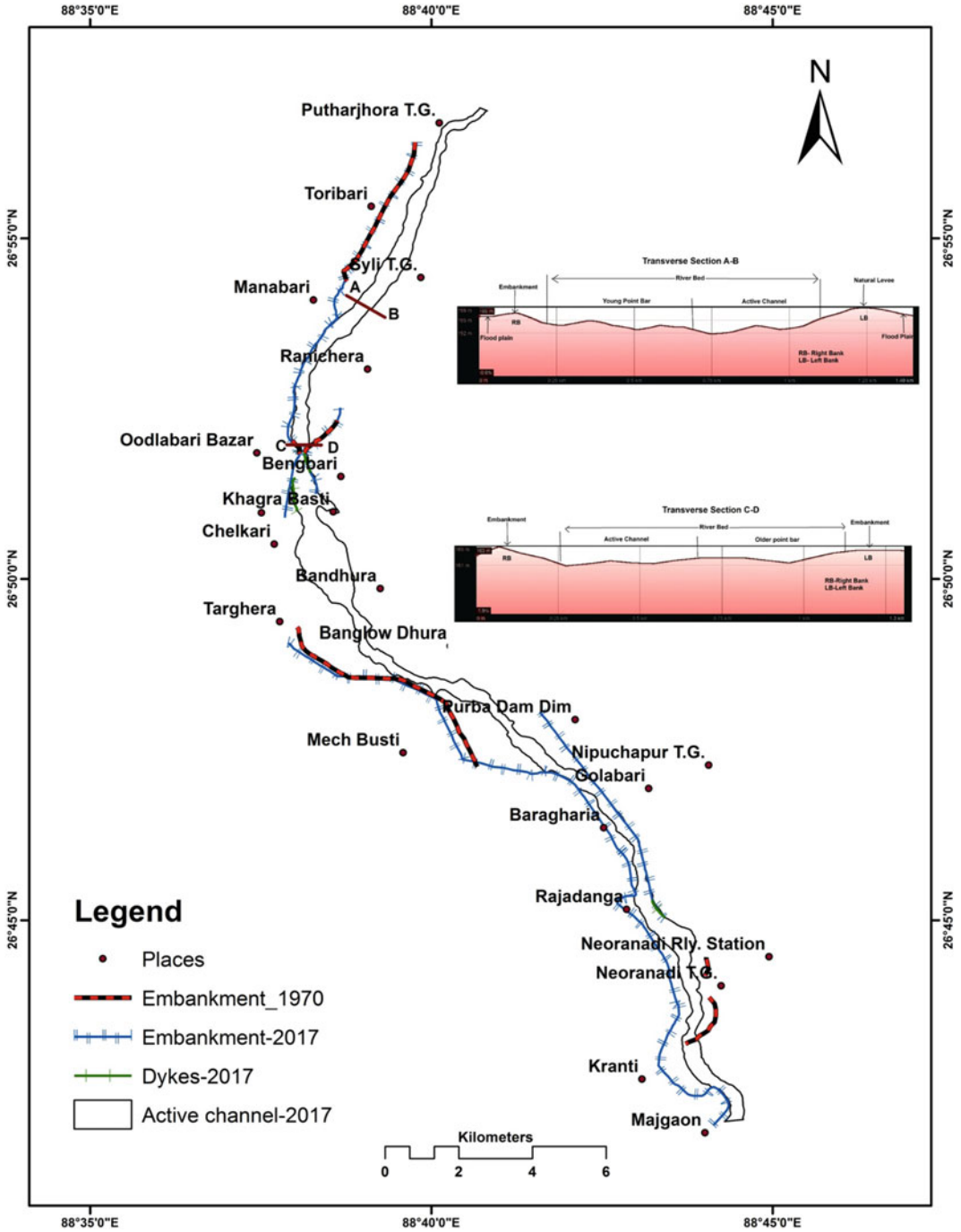
#### 2.4.5 Intensive Cultivation of Channel Bars

During field surveys, it was noticed that many of the channel bars (both point bars and mid-channel bars) are cultivated. Formation of channel bars begins near Gorubathan as upstream from here the channel flow through the deep constricted valley. Large beetle nut plantations cover much of the mid-channel and point bars from Gorubathan to Putharjhora (Fig. 2.23b). Whereas cultivation of paddy during summer monsoon and vegetables during winter was observed during winter from Toribari till confluence with Neora at Kranti (Fig. 2.23a).

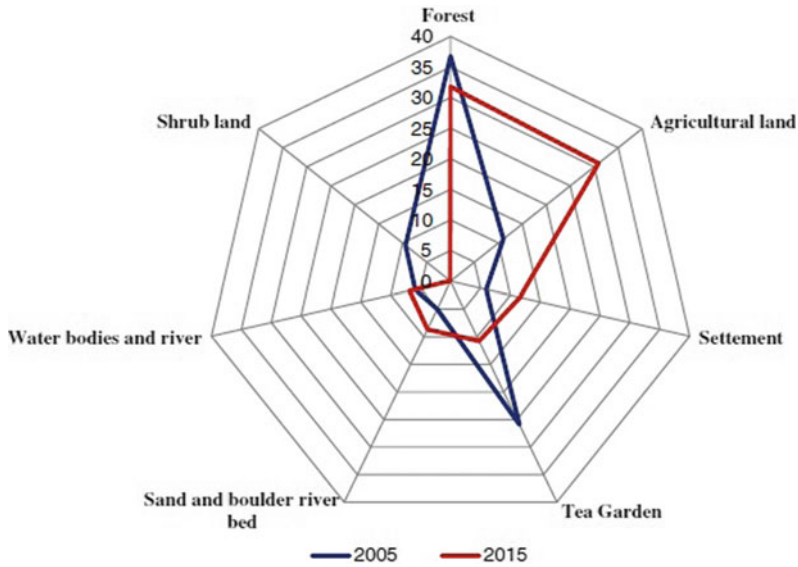
#### 2.4.6 Road Widening

During 2015–2016, the Damdim-Lava road was widened and repaired thoroughly. Fieldworks that coincided during that time revealed the fact that road widening activity affects channel morphology and dynamics mainly in two ways.

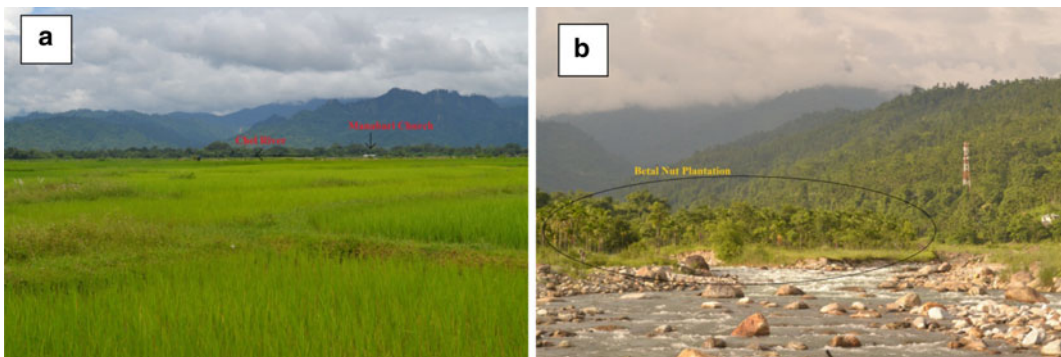




**Fig. 2.21** Extension of Embankments between 1970 and 2017. *Source* SOI Topographical Map (1970) and Landsat 8 OLI/TIRS (2017)



**Fig. 2.22** Graphical representation of LULC change (%) during 2005–2015. Adopted from Biswas and Banerjee (2018)



**Fig. 2.23** Extensive Paddy field in the foreground being cultivated on the huge left bank point bar at the upstream of Odlabari Rail Bridge (a); Betel Nut plantation on mid-channel bar at Gorubathan (b)

Firstly, the boulders and loose sediments generated during the slope cutting for road widening were getting dumped into the channel which generally constricts the channel and compels it to divert. Sometimes the dumped sediments completely dam the channel and thus creates temporary channel impoundment upstream until discharge and flow velocity increase enough to breach the newly dammed material (Fig. 2.24c, d). Road widening requires slope cutting above the road which destabilizes the slope and at times triggers landslides which add more sediments to

the river (Fig. 2.24a, b). Secondly, it increases the demand for sediments of specific grades for laying and pitching on the road. Further huge quantity of boulders and sand is needed for repair, extension, and construction of new retention walls, culverts, drains, and bridges. The sediments from Chel River were entirely used during the whole widening and repairing phase due to its proximity and thus cost efficiency as well. Thus, it was learned that road widening especially in the upper catchment areas of higher elevation puts pressure on the channel through



**Fig. 2.24** Road widening at near Ambik T.G. (a); road widening near Chittong Bridge (b); dumping of loose sediments generated during road widening into the

channel near Chitong Bridge (c); a dumper/tripper truck marked with a red circle can be seen returning after dumping the sediments marked with a blue circle (d)

both addition and removal of sediments which individually and combinedly increases channel instability and thus dynamicity.

### 2.4.7 Growth in Tourism

Due to near saturation and degradation in some aspects, of tourism in Darjeeling and Sikkim, the focus is turning into the vast, still largely unexplored region of Dooars with immense tourism potentiality. The “Dooars” region also serves as a gateway of tourism to Nepal, Bhutan, Assam, and Meghalaya. Thus, the whole region comprising the districts of Darjeeling, Kalimpong, Jalpaiguri, and Coochbehar is gaining huge popularity among tourists looking for a taste of mountains and riverine landscape, forests, and wildlife, lush

green tea gardens, adventure, culture, etc. The Chel basin, in particular, falls in the advantageous location as physiographically its upper catchment falls within the lower Himalayas and the middle- and lower part falls within gently rolling North Bengal plains hosting lush green forests and tea gardens. Three popular tourist towns of its basin Odlabari, Gorubathan, and Malbazar are all within a distance of 70 km and 60 km from Bagdogra Airport and New Jalpaiguri Railway Station (NJP), respectively. The basin is in high proximity to many tourist spots of the region such as Neora Valley, Jaldhaka Hydel power projects, Murti, Lataguri, Chapramari Forest, Suntale Khola, Jhalong, Bindu. The Department of Tourism, Govt. of West Bengal promotes tourism in the region with the tagline “Majestic Mountains and Mesmerizing Dooars”. Thus, huge



**Fig. 2.25** Vacant right lower terrace of Chel River just upstream of Mukti Bridge, Odlabari (Photograph 08.08.2012) (a); amenities for tourists and picnickers developed on the same site (13.01.2016) (b); close up photograph showing various amenities developed for tourists and picnickers on the same site (13.01.2016) (c);

billboard erected by Department of Tourism, Govt. of West Bengal along the roadside at Odlabari T.G. near Targh era showing master plan to convert Gazaldoba region into a mega Tourism Hub (Photograph taken 15.01.2016) (d)

tourist infrastructures and amenities are growing in the entire basin (Fig. 2.25a–d). Lot more homestays are opening in the rural areas, especially above Gorubathan. Jhandi Eco Hut project in Gorubathan is one such recent and already an established venture. During December and January, people from near and far-off places throng to the Gorubathan area for picnicking. Mukti Bridge over Chel River at Gorubathan has grown into the most popular Picnic destination in the region. Thus, this massive boom in tourism within and in the region of the Chel River basin is affecting the land use and will affect the dynamism of Chel River.

## 2.4.8 Surface Coal Mining

During fieldwork, it was noticed that the Chel River basin bears very small and fragmentary pockets of coal seams with a very little volume of very low-quality coal at the confluence zone of Chel, Manzing, and Sukha Khola. Due to little volume and poor grade, commercial mechanized mining has not developed as it is not cost-effective. But because of the diminishing tea industry of the region, some locals especially from Putharjhora T.G. and Gorubathan areas excavate these coals illegally. The coal is collected manually in rice sacks and transported in

cycles mostly during the night. They sell it at the rate of Rs. 200–300 mostly to the restaurant and dhaba (local name for roadside informal budget restaurants) owners of Odlabari and Malbazar. This coal mining activity though very small in extent and volume can destabilize the upslope and downslope of the mining hole, pits, or seams. Thus, it may cause landslides of smaller to a larger extent which adds more sediment to the channel and increase its dynamicity. Basu and Ghatowar (1988, 1990) have attributed surface coal mining along with widespread deforestation of mountain catchments and high population density (about 200 inhabitants  $\text{km}^{-2}$ ) to the highest rates of channel widening in the Lish and Gish at the vicinity draining Indian Sikkimese Himalayas and its piedmont.

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## 2.5 Discussion

The study has tried to give an account of the impacts of human actions from socio-economically backward demographic setting on fluvial geomorphology of a very dynamic natural environment. Basin is characterized by a higher rate of decadal growth of population 14.12% during 1991–2011 with a sizable percentage of SC (16.74) ST (29.05) population coupled with low literacy (67.28%) and a lower percentage of working population (38.87%). Sediment mining is happening all along the course of River Chel on the piedmont. Large boulders from Reach-A, gravels from Reach-B, and sand from Reach-C are predominantly extracted. The volume of sediment extraction highly depends on season. Reach-B accounts highest extraction volume of sediment of its nearness to NH-31C and two processing units. Extensive sediment extraction has rendered the Chel River unnatural to a great extent as evident through highly undulating cross profiles suggesting unstable bars leading to frequent thalweg shifting. Wit-pit mechanized sediment extraction along the course is creating elongated deep trench-like topography which creates artificial pools disrupting natural pool-riffle sequence. The riverbed has become deformed with human-induced high and low

topography. Chel River is gradually transforming itself from a multi-thread braided channel to a single-thread straight one as suggested by a consistent decrease in the values of the braid-channel ratio from its highest mark of 2.27 in 1976 to the lowest value of 0.96 in 2005 and then by 2017, the values in each segment (Reach) became near to 1. Twin bridges that cross the Chel basin across in West–East direction have constricted the channel to a great extent and a bottleneck situation has developed which seems to have a profound impact on topography, hydraulics, and channel instability upstream and downstream of it. The section upstream of the twin bridges is showing an increment in elevation in response to sedimentation whereas the downstream section is experiencing bed scouring, incision, and bank erosion due to coupled impact of twin bridges and extensive sediment mining (especially mechanized mining). It is been found that the flow velocity is highest in between the bridges. The same is higher in the downstream of the bridges compared to the upstream section. These findings are consistent with the results of Wiejaczka (2016) wherein he accounts that the incision rate of Chel in the foreland is  $5 \text{ cm year}^{-1}$  and he attributes this trend to the massive bed material extraction from the river. He claims that about 3200 tons of material are extracted every day during the dry season from 2–3 km section of the river just below and above the bridges. The concentration of the highest velocity in between the bridges has translated the energy through scouring and incision of bridge piers. This very process seems responsible for the collapse of an old railway bridge. Twin bridges are also responsible for increasing the instability of the channel as maximum shifting of the channel has been across the transects downstream of the twin bridges.

The length of embankments has grown from 14 km in 1970 to 41.25 km in 2017 along with 2.53 km of dykes. These three times extensions in the length of the embankments have restricted the active floodplain and thus is compelling Chel River to dissipate its energy within the narrow channel bed. Due to this the channel bed is rising constantly and thus the difference between channel bed and embankment heights is

decreasing progressively. This also implies an ever-decreasing threshold level of bank full discharge with a higher probability of flood and channel avulsion at lower discharge in the future. Another important human-induced change in channel geomorphology can be LULC change. Changes in land use from forested to agricultural use, in headwater areas, are known to increase discharge and sediment supply, which influences downstream channel morphology in complex ways (Liebault and Piegay 2002; Vanacker et al. 2003; Price and Leigh 2006; Wohl 2006). Widespread deforestation started in the Lish, Gish, and Chel mountain catchments in the mid-nineteenth century and it is continued to the present day, as the result of agriculture, surface coal mining, and settlement expansion (Basu and Ghatowar 1988, 1990; Prokop and Sarkar 2012). Land-use changes are accompanied by parallel enlargement of the landslides which are the most important factor in generating large surface runoff volumes and coarse sediment delivery during rainfall events (Vanacker et al. 2005; Pike et al. 2010). Findings from Biswas and Banerjee (2018) suggest that the areas within settlement and roads have increased from 5 to 11% and agricultural land from 11 to 30%. Most notably the area with tea gardens has reduced from 25.9 to 10.75%. Forest coverage also has reduced from 37 to 32%. Scrubland has recorded zero in 2015 compared to 10% in 2005. There has been a decrease in land under natural elements and an increase in land under anthropogenic activities except for tea gardens. Apart from these major human activities, road widening, surface coal mining intensive cultivation of channel bars, and growth of tourism have also proven significant anthropogenic activities in shaping the geomorphology of the Chel basin.

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## 2.6 Conclusions

The margin and piedmont of Darjeeling-Sikkim Himalaya are gradually shifting from a natural to a human-dominated landscape. Based on the extensive analysis done, it can be concluded that:

1. Sediment mining destabilizes the channel bars separating multi-channels and thus results in migration of thalweg line during little high flow. It is also responsible for lowering and raising the channel beds.
2. Mechanized sediment extraction along wet pits is creating elongated depressions which force water to flow concentrated through these depressions. These pits act as large pools storing much of the water during the low flow time and thus deprive surrounding and downstream reaches by not providing enough flow to these areas.
3. Mechanized wet-pit mining also disrupts the natural pool-riffle sequence and deforms the channel beds. Sediment mining creates both negative and positive topography in the form of mining pits and sediment storing mounds, respectively.
4. Human alteration in the form of twin bridges at Odlabari is disrupting the natural state of hydrological and geometrical properties of the upstream and downstream sections of the bridge. The twin bridges have constricted the channel to such an extent that there is large-scale variation in the elevation surface, velocity, transport capacity, and erosion and deposition the upstream and downstream of the bridges.
5. The embankments have grown in length. It has constricted the flood plain and has disconnected the main channel from its flood plain to a large extent. It reduces the elevation gap between embankments or natural levees and river channel beds due to constant aggradations, the threshold level of bank full discharge, and increasing the likeliness of embankment breaching even in low flow.
6. The areas covering settlement and roads have increased from 5 to 11% and agricultural land from 11 to 30%. Most notably the area with tea gardens has reduced from 25.9 to 10.75%. Forest coverage also has reduced from 37 to 32%. Scrubland has recorded zero in 2015 compared to 10% in 2005. Altogether it can be said that there has been a decrease in land under natural cover and an increase in land

under anthropogenic activities except for tea gardens. The altered land uses harm the channel and it can be seen in the increment of areas within sand and boulder riverbed from 5% in 2000 to 9% during 2015.

7. With less literacy and a higher percentage of SC and ST population, the basin portrays social backwardness. Less than 40% work participation and a higher percentage of marginal workers within and decadal population growth rate (1991–2011) of 14.12% further implies higher exploitation of existing natural resources which is getting reflected by an increase in areas under agriculture, settlement, and sand and boulder riverbed whereas a decrease in area under forest and water bodies and river. A substantial size of the population is engaged in low-wage menial works, which includes sediment mining on the aggradation zone of piedmont after Tea Garden and cultivation. Presently the dwindling tea industry of the region is also forcing the local population to get engaged in the sediment mining process. The same reason is driving locals to coal mining in the nearby Lish and Gish basins.

River Chel is not yet a regulated river in terms of damming or any other major engineering infrastructure but due to the higher decadal growth of human population and socio-economically backward characteristics of the region, the basin is observing the heightened impact of other types of human activities. For the ease of description and understanding, the anthropogenic activities and their impacts have been presented separately but we need to understand that impacts of these activities are all entangled ones and it is difficult to discern the impact of one human activity from another. So, many of the impacts witnessed in the basin are coupled impacts of many human activities. The presented results are of great importance in the context of limiting and maintaining an optimum scale of human impact on the basin for receiving sustained ecological services. Lastly, the findings and scenario presented in this paper can be considered as a typical representation of

human-induced changes in fluvial geomorphology along the margin and piedmont (Terai and Dooars) belt of Darjeeling-Sikkim-Bhutan Himalaya.

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