



# Assessing the Status of Changing Channel Regimes of Balason and Mahananda River in the Sub-Himalayan West Bengal, India

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Received: 8 March 2020 / Accepted: 7 June 2020 / Published online: 16 June 2020  
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## Abstract

Rapid infrastructural development, triggered by the economic policies implemented in 1991, subsequently modified the river channel planform of the Terai region of northern West Bengal, India, through perceptible channel fragmentation, excessive in-channel sediment mining and rampant landuse alterations of the floodplains. In this context, this study has attempted to assess the impacts of anthropogenic interventions on fluvial regime of the lower reaches of Balason and Mahananda River of the sub-Himalayan region over the last 30 years by adopting a combined methodological framework of remote sensing and field survey. Results showed that initially the naturally vegetated areas had converted into crop land and grass land, tea plantation or bare land, and afterwards, the majority of it had been converted into built-ups. Besides, a noticeable amount of channel narrowing was directly proportionate to unrestricted sediment mining and embanking of the river channels, evidenced between 1987 and 2017. Comparison of measured multi-temporal channel width along with cross-profiles showed remarkable channel narrowing (18.8 m/year) as well as significant bed lowering (3.15 m). Studies reveal that the rivers have started showing signs of losing their existing equilibrium condition and if that happens then that will lead to the sinking of the ground water table, decreasing flood occurrence interval, destabilization of existing infrastructures associated with rivers, and destruction of river ecology. In order to restore the state of socio-hydrological as well as eco-hydrological amenities of these rivers, certain recommendations have also been made towards promoting the wise use of riverine resources by the local communities and policy makers.

**Keywords** Anthropogenic intervention · Bed lowering · Channel narrowing · Landuse alteration · Sediment mining

## 1 Introduction

River planform or river topography is the function of several natural and anthropogenic factors which primarily deals in varying sediment as well as water flux (Strahler 1956; Gregory 2006). Among several natural factors; climate change, tectonic movement, large floods and volcanic eruptions are such elements, which play a crucial role in regulating

the water and sediment flux of river systems worldwide. Along with that anthropogenic activities such as landuse transformation, damming, embanking, in-channel mining and construction of overpasses on the river channels, can also amplify channel modification (Strahler 1956; Surian and Rinaldi 2003; Paul and Meyer 2001; Gregory 2006; Khaleghi and Surian 2019; Bireley and Fryirs 2005). At this time of growing anthropogenic pressure on environment, it cannot be possible to discuss channel adjustments without assessing the nature and degree of human intervention experienced by it. Genetically, the river itself has the inherent feedback mechanism which helps it regain its previous equilibrium after large scale catastrophic events. However, since anthropogenic activities have become integrated into the fluvial system; consequently, the river cannot attain its previous equilibrium as earlier (Strahler 1956; Paul and Meyer 2001). Thus, human-induced channel adjustments in several geo-environmental setups have been drawing the attention of the researchers for the last 70 years (Scorpio and

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Roskopf 2016; Khaleghi and Surian 2019; Radecki-Pawlik et al. 2014; Chin 2006).

Cumulative effects of anthropogenic activities can cause irreplaceable alterations to the river's physiography and among all these, urbanisation has become one of the most critical ones (Abass et al. 2018; Ramachandra et al. 2012; Pradhan 2004; Hollis and Luckett 1976). It has been revealed from several literatures that urbanisation has substantial effects on the sediment regime as well as on effective discharge of a channel. Furthermore, with increasing impervious area, infiltration rate decreases, and in connection with that peak discharge also increases alternatively; which may result in-channel widening through abrasion of loose bank materials (Gregory 2006; Paul and Meyer 2001). Damming and embanking act as the major constraining factors to river's longitudinal and lateral connectivity (Gregory 2006). Concretized large dams and embankments can directly alter sediment and water flux by disconnecting the rivers from its headwaters as well as floodplains and thus river planform will adjust to an irreparable extent. Due to damming, water gets stored in the reservoirs and consequently become sediment free. This water, often termed as hungry water, possesses higher potential energy and after being released from dams it can instantaneously increase the stream power, which may lead to vigorous down cutting. Similarly, as the river channel gets embanked, its lateral movements halt, thus at the time of storm water flux loaded with bedload and suspended sediment load, cannot get spilled over the floodplain. Now to reallocate the storm water flux, the channel starts scouring its bed and thus the river starts incising its course (Gregory 2006; Kondolf et al. 2002). Deep incised valley floor may cause disconnection to any interactions with the groundwater table and also may expose the bridge pillars caused due to vigorous down cutting of channel (Gregory 2006; Kondolf et al. 2002). Past evidences showed that these kinds of channel modification eventually stimulate channel incision and channel narrowing, which is capable of causing higher magnitude of flood vulnerability at the downstream during sudden storm water flux (Strahler 1956; Gregory 2006; Paul and Meyer 2001; Rinaldi et al. 2005; Kondolf et al. 2002). Heavily encroached river banks, bars can face severe damages due to this as narrowed channels can't hold the sudden storm water flux into it.

Among all the other anthropogenic actions, in-channel sediment mining acts as a direct modifier to river topography as it directly affects the sediment flux and thereafter minimises the carrying capacity of streams and its energy. Due to heavy sediment withdrawal, the river channel was almost freed from its bedload and thus dominant sediment size would reduce to smaller particles which resulted in increasing stream flow energy; and in connection with that valley deepening and channel pattern alteration occurred (Gregory 2006; Paul and Meyer 2001; Kondolf 1997; Kondolf et al.

2002; Knighton 1989). Since rivers flowing in the sub-Himalayan foothills are excellent suppliers of riverine sediments of various sizes from boulder and pebble to sand which are chiefly used in infrastructural developmental works, hence it is heavily mined to fulfil the need of the construction aggregates (Tamang and Mandal 2015).

Degree of channel planform dynamics is significantly dependent on the pattern of landuse transformation of the riparian zone of a river. Riparian zones act as a buffer to the fluvial system since it controls river's lateral migration, and sediment discharge to the river; it influences overland flow and the fluvial ecosystem as well (Gordon and Meentemeyer 2006; Picco et al. 2017). Specifically, urbanization acts as one of the most influential altering forces of landuses, which rapidly impacts the channel planform with the increasing pressure of settlers at the river banks. If the pace of planform dynamics is high enough then through reshaping and reconfiguring the channel, the river will quickly attain another stage of equilibrium. However, in the slower pace of change, the river will maintain a quasi-equilibrium stage, which may last for several years to decades (Leopold 1968; Morisawa and La Flure 1979; Grable and Harden 2006).

Channel adjustment instigated by human intervention has become a worldwide phenomenon, especially in the fast-growing countries like India (Gregory 2006; Douglas 1996; Bandyopadhyay and De 2018; Birerley and Fryirs 2005). Being a river-dominated landmass and having prolonged history of river valley civilizations; India has an intricate river-human interaction over the ages. Since the industrial infrastructural development gained rapidity after the economic reform of 1991, the anthropogenic pressure on natural resources has increased many folds. These developmental activities have not been restricted only to the major cities or towns but also expanded to the areas which were resourceful and characterised by lesser accessibility. Ecologically diverse and topographically distinct sub-Himalayan foothills or Terai region is an appropriate example of such area which is going through significant landuse alterations along with degradation of natural landscape or natural features (Debnath et al. 2017; Ramachandra et al. 2012; Rao and Kadam 2016; Panagariya 2005). In this region nearly 30% area under forest cover had decreased, mostly in the last century; and simultaneously 35% and 82% area under tea plantation and built-up area respectively were increased (Prokop 2018). Eventually, the fluvial system of Terai region, which is characterised by a unique transitional spatial extent between lesser Himalaya and floodplains of Himalayan foothills, is at present under serious anthropogenic pressure and can't be evaluated without measuring the dimension of anthropogenic intervention.

A significant research gap had been found regarding landuse alteration and other anthropogenic disturbances and its impact on river planform especially in the Terai region, since

most of the previous works were only focused on the impacts of anthropogenic activities such as damming, degrading quality of river water due to contamination etc. (Bandyopadhyay and De 2017, 2018; Wierzchka et al. 2014). In this context, very few investigations were conducted on the sub-Himalayan Terai rivers with special reference to human-induced landuse alterations on the floodplain landscape and its ultimate effect on channel planform modification. Keeping in mind this research gap, the present study aims to give an insight on how the landuse landcover (LULC) pattern of Siliguri and its surrounding areas has evolved over the last 30 years and along with this, assessment of the nature and degree of other anthropogenic activities on the channel of Balason and Mahananda River. This study also tries to establish the relationship between the various responses of the fluvial system to human intervention, through the assessment of channel physiography and quantification of anthropogenic activities using geospatial technologies.

## 2 Methodology

### 2.1 Delineation of the Study Area

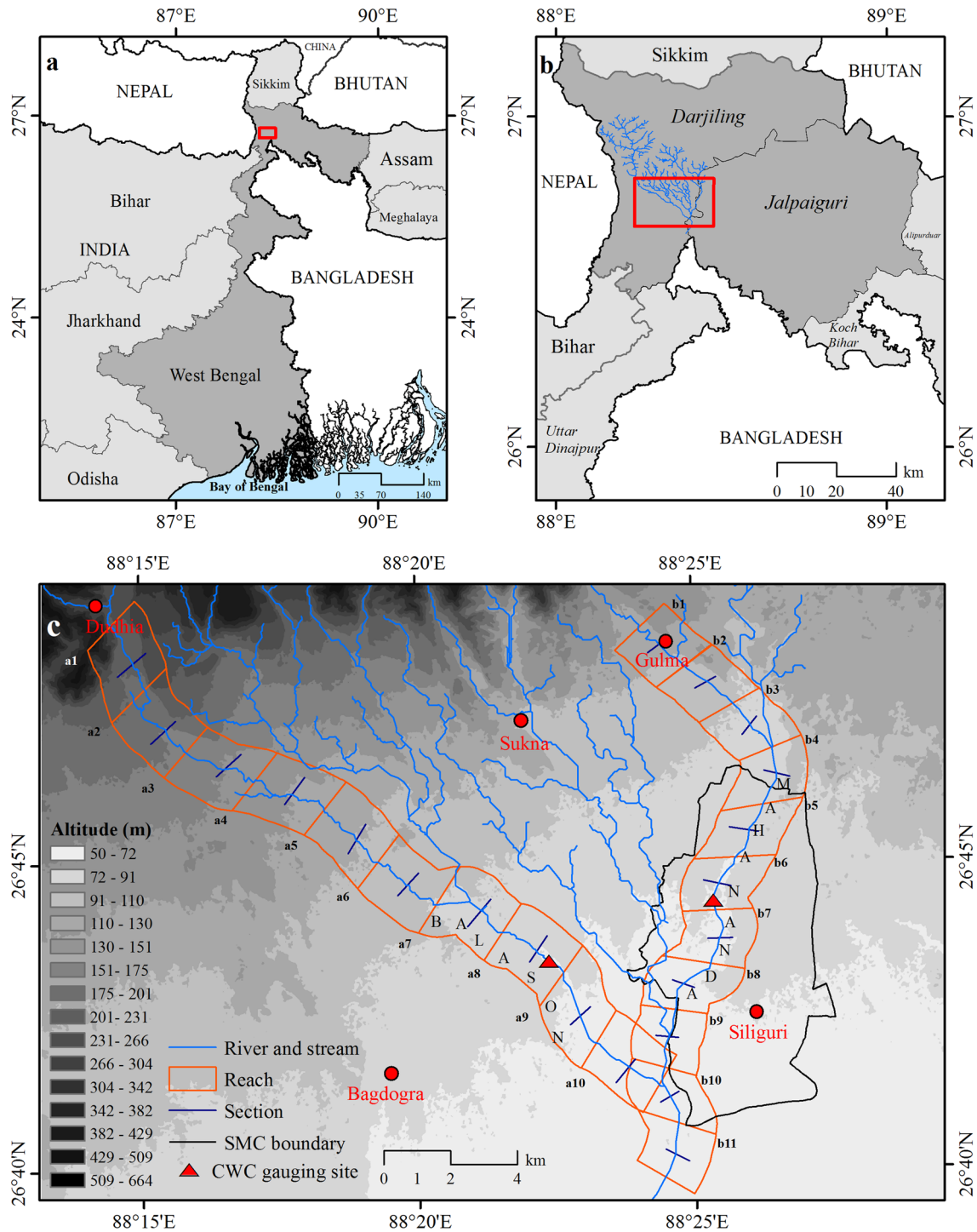
A well-defined area of interest (AOI) has been selected from the lower part of the catchment with a spatial coverage of 393.18 km<sup>2</sup>. The area lies between the latitudinal extension of 26°40' N to 26°49' N and longitudinal extension of 88°14' E to 88°28' E with a mean elevation of 100 m comprising of the floodplains of two studied rivers i.e. Balason and Mahananda (Fig. 1). The upper stretches of the Balason and Mahananda floodplains are situated at a topographical transition between the Siwalik Himalaya and its expansive piedmont plain also known as Terai. Hence, this topographic integration between two landscape units covers a complete gamut of environmental variability, which helps to develop a unique fluvial system in terms of hydrological, morphological and ecological aspects. These two main rivers of this study area i.e. Balason and Mahananda; originated from the lower Siwalik and started depositing its bedload just below their debouching points at Gulma and Dudhia respectively. The entire region is mostly dominated by the quaternary deposits (~ 50,000 years BP), containing sedimentary and metamorphosed rocks such as Darjeeling Gneisses, Dailing Schist, Sandstones and Quartzite (Wadia 1975). The entire Terai region of northern West Bengal has uniformity in terms of stratigraphic setting which can be distinguished as a separate geomorphic unit (Gansser 1964; Wadia 1975). These rivers are characterised by high fluctuating discharge, in case of Balason it ranged between 5.814 cumec in pre monsoon of 1989 to 61.579 cumec in post-monsoon, 1989, and in case of Mahananda it ranged between 1.804 cumec in pre monsoon of 1987 to 40.173 in post-monsoon of 1987

(De 1998; Sarkar 1989). Other than the sedimentary and hydrological environment, the climatic condition also displayed an unchanged scenario, since no significant temporal change has been observed in the precipitation pattern ( $R^2$  is 0.001) of Siliguri over time (Fig. 2). Since the flow of Balason and Mahananda are partially spared from any longitudinal barriers, and major channel forming factors (i.e. geological setting, sediment and precipitation) have remained constant; then it can be assumed that the discharge of these rivers has not varied significantly. However, the deteriorated conditions of these rivers indicate some other factors, which act as a major stressor on the fragile fluvial systems. It can be hypothesised that the anthropogenic actions have a notable amount of share in-channel modification.

Siliguri, the second largest urban agglomeration of West Bengal, being situated on the southern part of Darjeeling district, is getting tremendously urbanised at the expense of all its natural properties (Debnath et al. 2017). Since it is a gateway of North–Eastern India and acts as a major nodal point for international trades with China, Nepal and Bhutan; the immense economic potentiality of Siliguri and its surroundings attract a mass of the population from nearby states as well as countries as settlers. This Himalayan fore-deep consists of Quaternary alluvial sediment, experiencing a large scale transformation in landuses over the last three decades. This area has average elevation varying from 100 to 200 m, also characterised by large tea plantation, mono-specific forest lands, braided streams, largely urbanised patches and interspersed hamlets with dozens of settlers. The southern extent of the study region is mainly characterised by dense settlement patches with scattered fallow land on each side of the wide river beds. On the contrary, the northern part has higher elevation (200–300 m), embellished with tea plantation, forested areas and small patches of rural settlements.

### 2.2 Data Acquisition and Data Preparation

Three consecutive multispectral LANDSAT datasets with 30 m spatial resolution, acquired by Thematic Mapper (TM) sensor and Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) sensor, as well as a single-band panchromatic CORONA image of the year of 1968 with 2.5 m spatial resolution, downloaded from United State Geological Services (USGS) Earth Explorer (<https://earthexplorer.usgs.gov>), had been used for geospatial data exploration (Table 1). The post-monsoon season was considered at the time of data selection to obtain cloud-free images. A long 50 years' data had been assessed, after selecting the satellite datasets of the year 1968, 1987, 2002, and 2017. Along with these, the Census data of 1981, 1991, 2001 and 2011 of Darjiling and Jalpaiguri district were also taken into account for having a comprehensive outline regarding the demographic

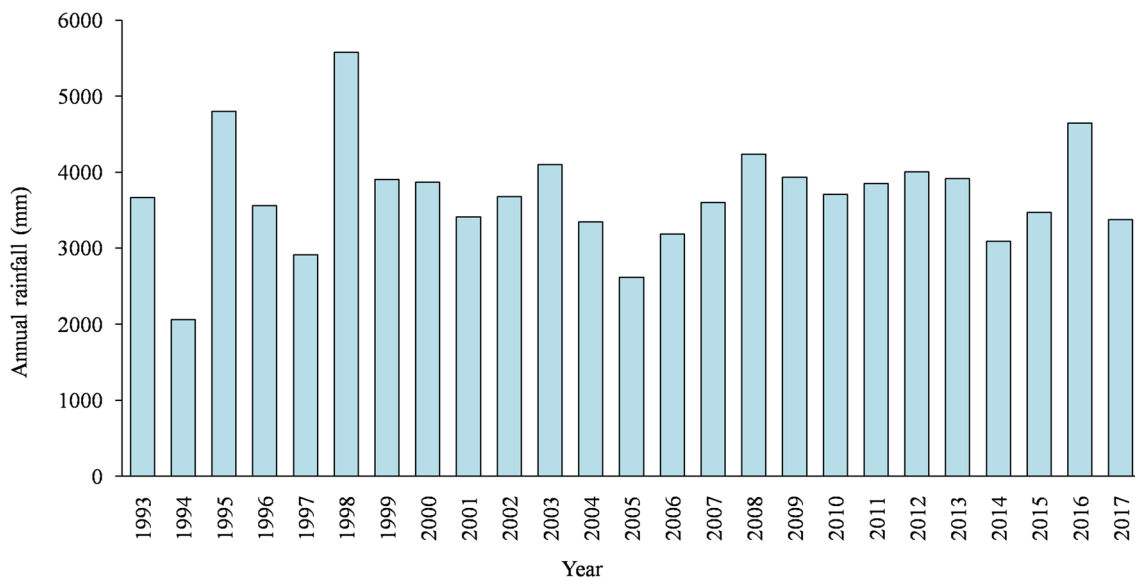


**Fig. 1** Geographical location and spatial distribution of the specific study sites; **a** Map indicating West Bengal along with border sharing neighbouring countries and states, the study area has been highlighted; **b** District wise division of northern part of West Bengal indicating the Balason Mahananda River system in the study area; **c** Map

strength of Siliguri Municipal Corporation (SMC) and its surroundings.

showing Balason Mahananda River system overlaid in digital elevation model with division of studied reaches, sections from where river LULC dynamicity and river widths are measured respectively, gauging stations where cross-profiles are measured, boundary of Siliguri Municipal Corporation (SMC) and various other places of interest

Image processing was primarily conducted using Erdas Imagine 2014 Version 14.01 software. The radiometric correction was performed on the three satellite datasets



**Fig. 2** Status of rainfall variability in Siliguri Municipality and its surroundings from 1993 to 2017 *Source:* Irrigation and Waterways Department, Siliguri Division; Government of West Bengal

**Table 1** Geospatial datasets used in the study

Date of acquisition	Satellite	Sensor	Path/row	Resolution (m)
22/12/1968	CORONA	–	–	2.5
31/12/1987	Landsat 5	TM	139/041	30
16/12/2002	Landsat 5	TM	139/041	30
01/12/2017	Landsat 8	OLI-TIRS	139/041	30

to convert the digital number (DN) values into top of atmosphere (TOA) radiance values and then it was again transformed into bottom of atmosphere (BOA) reflectance product. As the selected study region is mostly occupied with the urban built-ups, hence it can be assumed that the atmosphere of this region is filled with particulate matters. So, the dark matter subtraction method had been used to perform the necessary atmospheric correction (Campbell 1993; Chavez 1988). Usually, the greater amount of aerosol content in the air, higher will be the atmospheric scattering effect or irradiance recorded in the image. To get rid of this difficult atmospheric scattering, atmospheric correction using dark object subtraction was done (Campbell 1993; Liu et al. 2005; Chavez 1988). To reduce the geometric distortions, the process of Geometric correction was also performed on the geospatial data sets using the collected GCPs from the field survey. Firstly, the CORONA image of 1968 was rectified using the GCPs; then the other three images were co-registered using that pre-rectified image. Between two successive images, the root mean square error (RMSE) was kept as less than 0.5 pixel, which was considered as the

permissible range. CORONA image of 1968 was not used for supervised LULC classification due to its single-band availability; so except this, the images of 1987, 2002 and 2017 were classified based on the existing LULC's. The data derived from these classifications were further processed using the platform of Microsoft Excel. Data related to the channel width was obtained from repetitive field investigations and were also processed using Microsoft Excel.

Intensive field investigation had been carried out to collect ground control points (GCPs) using handheld Geographic Positioning System (GPS) of Garmin E-Trex 20 for rectifying these images geometrically. During a pilot survey, various landuses were identified from 48 selected sites within the study region and geocoded by 170 collected GCPs. The results of that survey were further used for accuracy assessment of the classified raster images for the successive timeframes. The channel cross-sectional data of Balason and Mahananda River were procured from the previous research work of 1987 and 1989 respectively. Whereas the recent cross-sectional data were obtained through field-based total station survey using Leica TC-805 by the authors. It was measured during the non-monsoon period of 2018 (April 2018).

### 2.3 LULC Analysis

Having an accurate and detailed geospatial information regarding the changing scenario of landuse/landcovers (LULC's) throughout the study region, maximum likelihood classifier was chosen, which was found to be a most suitable and well established classification algorithm among

contemporary researchers (Shalaby and Tateishi 2007; Lillesand et al. 2008; Roy and Datta 2018). After adopting necessary pre-processing steps, all three selected raster images were classified into seven profound LULC classes (i.e. river, river deposit, natural vegetation, tea plantation, crop land and grass land, fallow land and built-up area) based on a priori knowledge of investigators regarding the study region and the classification scheme proposed by the National Remote Sensing Centre (Arveti et al. 2016). In these distinctively different LULC classes, the pixels under river class represented the perennial area within the river channel. Whereas; the wide river beds comprised of fluvial deposits, were represented by the class river deposit. Fallow lands mainly comprised of agricultural fields without any crops and bare arable lands, while, the built-up class included all types of impervious concretized features, such as buildings, concretized pavements, roads and other urban infrastructures. Only the crop land and grass land were considered as a single class as they can't be distinguishable for their homogenous spectral reflectance. Most importantly, the accuracy of this image classification was further assessed by the error matrices using the 170 pre-collected GCPs. These GCPs were allotted in a stratified random manner to the different LULC classes for checking the classification accuracy without any biases (Shalaby and Tateishi 2007).

## 2.4 Change Detection Analysis

Post-classification change detection had been performed to analyse the LULC dynamics of the study area. Primarily the spatial extent of each class was calculated into square kilometre (km<sup>2</sup>); thereafter those values were converted into percentage for standardization. The net areal change (NAC) for each LULC classes was also derived by comparing the areal coverage for two successive time frames (Coppin et al. 2004; Disperati and Viridis 2015). Through generation of transformation matrices, the pixel-to-pixel transformations of LULC's were detected over time within a space and quantified into km<sup>2</sup> for assessing the anthropogenic stress on nature. Recognition of the LULC conversion of every single pixel between two periods (i.e. 1987–2002 and 2002–2017) was the ultimate objective of these produced conversion matrices (Serra et al. 2003; Islam et al. 2016; Roy and Datta 2018; Sinha et al. 2016). 1987–2002 was termed as first half and 2002–2017 as the second half.

## 2.5 Measurements of the Channel Planform Attributes and River Profiling

In this study, bank to bank width of the entire channel was measured instead of channel passage or waterways; as those can be reshaped in quick successions, especially in the braided rivers (Bertoldi et al. 2009; Harrelson et al.

1994). Widths of the river channel (in between banks) were also measured sequentially from the selected satellite images used in this study i.e. 1968, 1987, 2002 and 2017. In the last 50 years, as the most destructive flood event of northern West Bengal was recorded in 1968; it can be stated that a new equilibrium was attained at that time by the channels, which has been quantified by measuring the channel width (Leopold and Wolman 1957). Floods, playing an important role in-channel forming; the highest magnitude (magnitude 5) flood in the recent history of northern West Bengal, the flood of 1968; subsequently lead to the planform attributes of 1968 to be taken as a benchmark for this study (Feio et al. 2014; Wang et al. 2008; Roy 2011).

Both of the rivers Balason and Mahananda were divided into 2 km long reaches and river widths were measured across the middle of every reach. They were divided into 10 and 11 reaches and were termed as A1, A2 to A10 and B1, B2 to B11; respectively. Image-based measurements of channel widths from recent times were further validated during field-based observations. But neither people's perception nor the channel relicts were found to be useful to validate the cross-sectional widths of 1968 for both the rivers. It happened chiefly due to the very low number of settlements located at the study sites then. A radical transformation of the adjoining floodplain has happened over the last 50 years (1968–2107), but due to its much higher resolution of 2.5 m, the bank lines were very easily detectable.

Like the channel planform, river cross-profiles being the function of its water and sediment flux, are one of the essential parameters to be assessed for detection of the effect of the channel forming process on river bed topography (Leopold and Wolman 1957; Harrelson et al. 1994; Tamang and Mandal 2015). Since both the rivers have been experiencing vigorous sediment mining activity for several decades, three-channel cross-profiles from each river were compared in this study to detect the fluctuations of the river bed topography during 1987–2017. On the stretch of Mahananda the profiles were situated at 250 m upstream of Central Water Commission (CWC) gauging station at Champasari Bridge (Mahananda Upper Gauge or U.G.) on NH-10/AH-2 (previously NH-31) and 50 m upstream of Champasari Bridge (Mahananda Central Gauge or C.G.) and 200 m downstream of Champasari Bridge (Mahananda Down Gauge or D.G.). On the other hand, for River Balason, the profiles were situated 425 m upstream (Balason U.G.) of CWC gauging station at Matigara Balason Bridge on NH-10/AH-2 (previously NH-31) and 25 m upstream (Balason C.G.) of Matigara Balason Bridge and 375 m downstream (Balason D.G.) of Matigara Balason Bridge. The measured river cross-profiles were compared with previous cross-profiles measured in 1987 and 1989 by superimposing them on a constant axis.

## 2.6 Assessment of the Relationship Between Channel Planform and LULC Dynamics

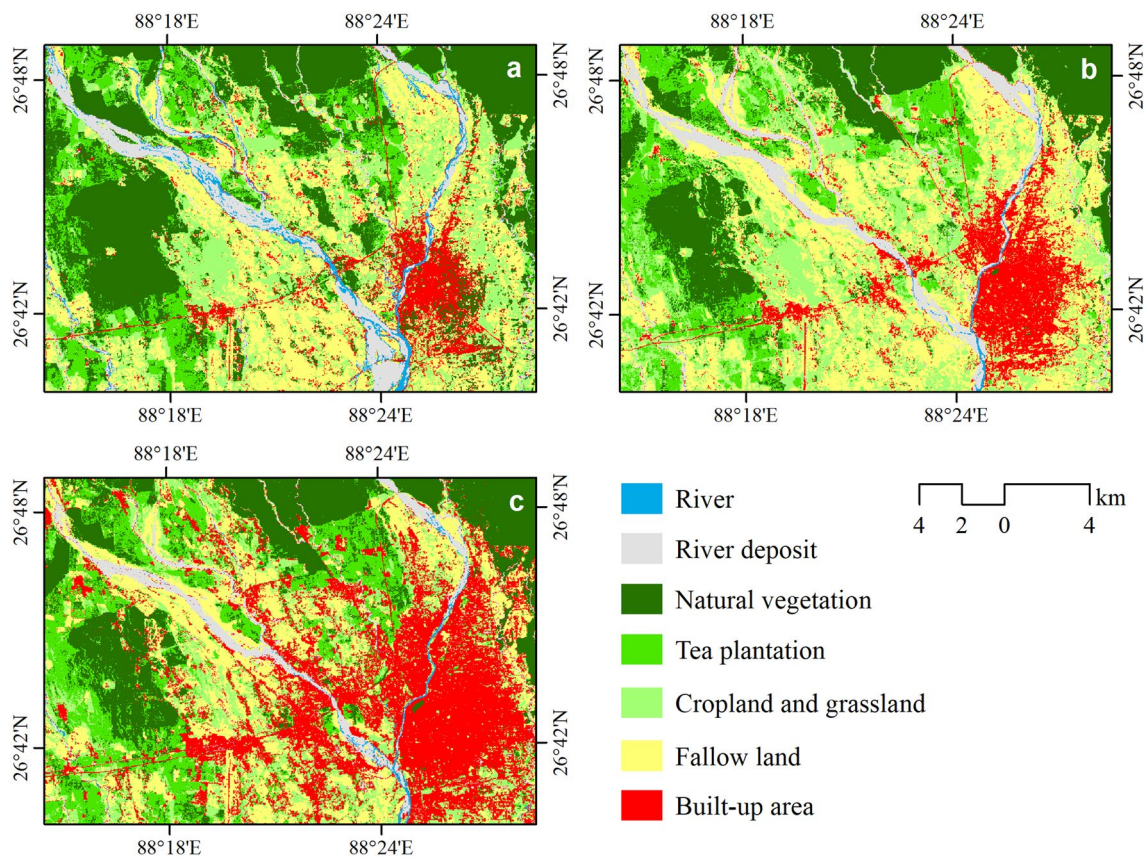
After measuring the channel widths of three successive years; i.e. 1987, 2002 and 2017 they were further compared with the dynamic areal coverage of the adjoining LULC classes within the buffer of 1 km. The buffer of 1 km is taken as the five times of average channel width. It was observed during the field survey that the area of influence of these reaches comes under this 1 km buffer area. These temporal areal data (km<sup>2</sup>) of different LULC's were further converted into a percentage (%) for standardising it into a more understandable than the absolute values. Channel widths of 1968 were also taken into account to portray the gradual change from the least disturbed scenario.

## 3 Results

### 3.1 Spatio-Temporal Pattern of LULC Transformation

As it could be seen from Fig. 3 and Table 2, an abrupt change with an overall increase of 76.17 km<sup>2</sup> (264.63%)

from 1987 to 2017 was experienced by the built-up coverage. It had increased from 28.78 km<sup>2</sup> in 1987 to 43.36 km<sup>2</sup> in 2002 and 104.95 km<sup>2</sup> in 2017 covering larger than one-fourth (26.69%) of the total area. However, the major expansion was observed in between 2002 and 2017 which was 61.59 km<sup>2</sup> (142.06%) as a consequence of major infrastructural development which took place during this period. Noticeably, this built-up expansion mainly occurred along the rivers and major roads of NH-10/AH-2 (previously NH-31). It has facilitated the increase of the number of census towns (C.T.) at the adjoining rural–urban continuum and as a result of that 10 new census towns emerged within the study area during 2001–2011. Tea plantation also portrayed an increasing trend throughout the study period, as in 1987 the land occupancy of this class was 41.56 km<sup>2</sup>, which increased to 50.48 and 59.49 km<sup>2</sup> in 2001 and 2017 respectively. It created an ambiguity, as in spite of losing profitability the area under tea plantation was increasing steadily. As per the local respondents, the reason of such surprising growth in tea plantation was reopening of some tea gardens through re-plantation at a larger extent and maintaining the gardens by wiping out threatened exotic shrubs and bushes. On another hand, after a rapid decline



**Fig. 3** Landuse and Landcover (LULC) classification map of the study area for the time frame of **a** 1987, **b** 2002, and **c** 2017

**Table 2** LULC change statistics of the study are from 1987 to 2017

LULC classes	Year 1987		Year 2002		Year 2017		% 1987–2002		% 2002–2017	
	Area (km <sup>2</sup> )	Area (%)	Area (km <sup>2</sup> )	Area (%)	Area (km <sup>2</sup> )	Area (%)	Area (km <sup>2</sup> )	Area (%)	Area (km <sup>2</sup> )	Area (%)
River	8.93	2.27	1.41	0.36	2.78	0.71	−7.52	−84.21	1.37	97.15
River deposit	22.45	5.71	23.68	6.02	16.65	4.24	1.23	5.50	−7.03	−29.67
Natural vegetation	117.51	29.89	76.18	19.37	77.96	19.83	−41.33	−35.17	1.78	2.33
Tea plantation	41.56	10.57	50.49	12.84	59.49	15.13	8.93	21.47	9.01	17.84
Crop land and grass land	76.45	19.44	83.18	21.15	57.32	14.58	6.73	8.80	−25.86	−31.09
Fallow land	97.50	24.80	114.89	29.22	74.03	18.83	17.38	17.83	−40.86	−35.56
Built-up area	28.78	7.32	43.36	11.03	104.96	26.69	14.58	50.64	61.60	142.06
Total	393.1849	100	393.1849	100	393.1849	100				

of 35.17% during 1987–2002, natural vegetation had arrested its declining trend during 2002–2017 with spatial coverage of 77.96 km<sup>2</sup>. Noticeably, except the built-up area and tea plantation, all other landuse classes have never followed a unidirectional trend towards increasing or decreasing.

This overall landuse transformation pattern observed from Table 3 portrays a pronounced landuse transformation pattern of a growing urban centre, from natural to quasi-natural or pseudo-natural to purely artificial

one. The landuse transformation matrices indicated that between 1987 and 2002; area coverage of 9.04, 6.95, and 26.60 km<sup>2</sup> of natural vegetation, river deposit and crop land and grass land had transformed into fallow land; as opposed to the second temporal span of 2002–2017. Large portions of crop land and grass land with an area of 18.24 km<sup>2</sup> areal coverage had transformed into fallow land during the second half. Though, earlier a noticeable amount of natural vegetation (14.54 km<sup>2</sup>) was altered into crop land and grass land, this transformation might

**Table 3** Landuse transformation matrix of the study area

(a) Landuse transformation matrix from 1987 to 2002

1987	2002						
	River	River deposit	Natural vegetation	Tea plantation	Crop land and grass land	Fallow land	Built-up area
River	0.57	4.29	0.03	0.03	0.47	2.72	0.83
River deposit	0.58	11.98	0.25	0.07	1.61	6.95	1.01
Natural vegetation	0.01	1.09	67.80	18.75	14.54	9.04	6.27
Tea Plantation	0.00	0.24	5.15	22.51	10.70	2.47	0.49
Crop land and grass land	0.02	1.23	1.80	6.57	34.53	26.60	5.69
Fallow land	0.11	3.79	0.62	2.16	19.30	60.38	11.14
Built-up area	0.12	1.07	0.53	0.39	2.03	6.73	17.92

(b) Landuse transformation matrix from 2002 to 2017

1987	2002						
	River	River deposit	Natural vegetation	Tea plantation	Crop land and grass land	Fallow land	Built-up area
River	0.51	0.45	0.00	0.01	0.09	0.09	0.26
River Deposit	1.33	10.85	0.33	0.22	1.38	5.99	3.58
Natural Vegetation	0.04	0.25	59.53	8.84	2.03	1.44	4.04
Tea Plantation	0.02	0.11	10.41	28.16	4.87	3.75	3.16
Crop land and grass land	0.17	0.85	4.47	16.05	24.26	18.24	19.13
Fallow land	0.48	3.34	2.24	5.39	23.03	43.10	37.30
Built-up area	0.24	0.81	0.96	0.82	1.64	1.40	37.4868



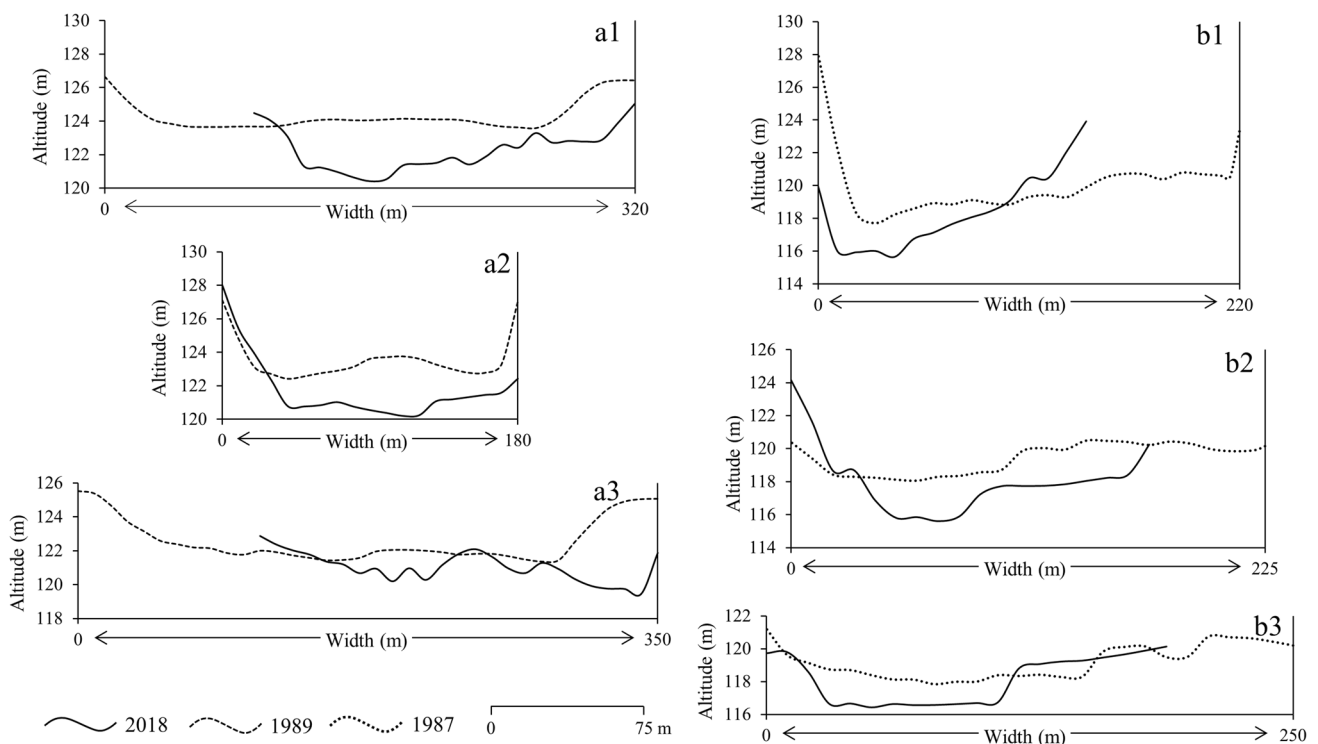
be happened due to the introduction of seasonal crops or change in cropping pattern. It was evidenced that the built-up area had been supplemented chiefly by fallow land with the transformation of 11.14 and 37.29 km<sup>2</sup> during first half and second half respectively in a process of altering the quasi-natural setting to a complete artificial concretized landcover. Along with this, a remarkable increase has been seen in the transformation of crop land and grass land into the built-up area covering 5.69 km<sup>2</sup> during 1987–2002 to 19.13 km<sup>2</sup> in 2002–2017. Some portions of tea plantation had also transformed directly into the built-up area (3.16 km<sup>2</sup>) between 2002 and 17. As a result of reclamation of aggradational landforms of both Balason and Mahananda River, some of the areas under river deposit had also transformed into crop land and grass land along with fallow land. Due to encroachments on point bars and mid-channel bars, 3.58 km<sup>2</sup> areas were directly transformed into the built-up area from the area covered with river deposit during the second half. Since the SMC was almost saturated with settlements, built-up areas had

sprayed rapidly in the adjoining rural areas at the expense of all above-mentioned LULC classes and as a result of that several C.T.'s, and large villages had also emerged.

Accuracy had been assessed for all three images using the 170 GCP's collected from the field during the survey procedure of 2017. Information gathered from residents regarding past landuses were also taken into account during the classification of multi-temporal satellite images. The overall classification accuracy was 82.35%, 83.53%, and 85.29% for the years of 1987, 2002 and 2017 respectively, whereas the derived Kappa statistics for all three classified images were 0.78, 0.80 and 0.82.

### 3.2 Characteristics of River Profiles

A detailed comparison of the six river cross-profiles measured at Balason and Mahananda portrayed a considerable change in terms of the width of the cross section as well as the depth of the river channel. Except for the profile situated at 25 m upstream of Matigara Balason Bridge i.e.



**Fig. 4** Comparison of river cross-profiles; **a1** Balason upper gauge (U.G.) situated 425 m upstream of Balason River gauging station at Matigara; **a2** Balason central gauge (C.G.) situated 25 m upstream of gauging station and (**a3**). Balason down gauge (D.G.) situated 375 m downstream of gauging station. **b1** Mahananda upper gauge (U.G.) situated 250 m upstream of Mahananda gauging station at Champasari; **b2** Mahananda central gauge (C.G.) situated 50 m upstream of gauging station and **b3** Mahananda down gauge (D.G.) situated 200 m downstream of gauging station. For Balason River cross-pro-

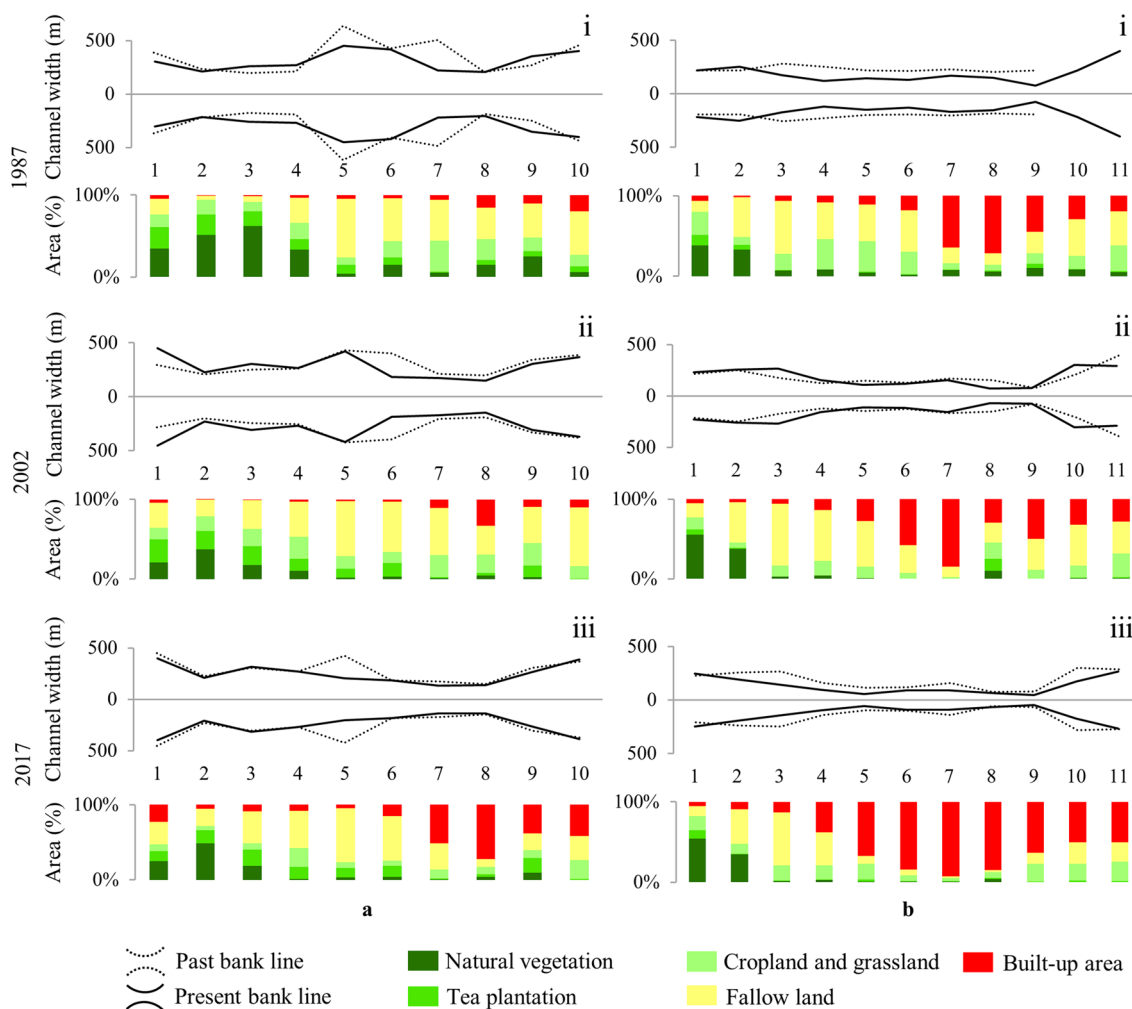
files are compared between 1989 and 2018 and for Mahananda it is 1987 and 2018 *Data source*: Cross-section data of 2018 were measured at field by the authors, cross-section data for Balason of 1989 was procured from unpublished PhD thesis of Prof. Sunil Kumar De; Department of Geography, North-Eastern Hill University, Shilong and cross-section data for Mahananda of 1987 was procured from unpublished PhD thesis of Prof. Subir Sarkar; Department of Geography and Applied Geography, University of North Bengal, Siliguri

Balason C.G. (a2 in Fig. 4) all other profiles surveyed at both rivers showed a remarkable decrease in the width of the river channel. Balason U.G. (a1 in Fig. 4) and Balason D.G. (a3 in Fig. 4) lost its width by 80 m and 100 m in just 29 years. In case of Mahananda River, a similar trend was observed as Mahananda U.G., C.G. and D.G. (b1, b2 and b3 in Fig. 4) were narrowed by 70, 45 and 50 m respectively in just 31 years. Concerning decreasing channel width, all these six profiles have also portrayed substantial down cutting at an average rate of  $> 2$  m in less than thirty years. In the case of Balason U.G, the vertical difference between the past and present thalweg point was 3.15 m and for Balason C.G. and D.G. it was 2.58 m and 1.9 m respectively. On the contrary in the case of Mahananda U.G., C.G. and D.G., rates of down cutting were 2.06 m,

2.45 m and 1.43 m respectively. It was a bit on the slower side than that of Balason.

### 3.3 Relationship Between LULC Dynamics and Channel Planform Attributes

The whole channel regime of Balason River, except reaches like a3 and a4, showed tendencies of channel narrowing from 1968 to 2017. Only these two reaches, a3 and a4 had widened to some extent at an average rate of 4.84 m and 2.31 m per year. Being a braided river, Balason had shown enough dynamicity from a1 to a4, but the majority of the rest of the channel was under vigorous negative change from section a5 to a7. The highest registered narrowing was observed at section a5, where the channel narrowed at an average of 18.8 m per year. On the contrary a8, a9 and a10



**Fig. 5** Relationship between LULC dynamics and channel width for the rivers Balason (a) and Mahananda (b); have portrayed here. **a<sub>i</sub>** and **b<sub>i</sub>** are showing LULC dynamics of 1987 and comparison of river channel width between 1968 and 1987. In case of **a<sub>ii</sub>** and **b<sub>ii</sub>**; LULC

dynamics for 2002 and river channel width for 1987 and 2002 are shown; **a<sub>iii</sub>** and **b<sub>iii</sub>** portray the situation prevailed in 2017 in terms of LULC and comparison of channel width between 2002 and 2017

experienced very lesser narrowing rate compared to a5, a6 and a7 because at these reaches the river was laterally disconnected by embankments for many years so the stretch had adjusted anyway. From the data provided by Irrigation and Waterways Department, Siliguri Division, Government of West Bengal and from the field survey the past condition of the embankments were revealed. The dominant LULC associated with the sections from a5 to a10 were characterised by rapidly increasing built-ups with encroached point bars and continuous stretch of concrete embankments. The upper reaches from a1 to a4 had still maintained their natural channel regime; with larger areas covered by natural vegetation and tea plantation and few small patches of built-ups. At these upper reaches i.e. a1 to a4; no such features that disconnect the rivers with its floodplains or hillslopes were observed (Fig. 5).

Among the eleven reaches on Mahananda, only the uppermost reach, i.e. b1, experienced continuous channel widening at an average rate of 1.33 m per year, whereas all other reaches, from b2 to b11 was characterised by the tendencies of intensified channel narrowing. The lower reaches of Mahananda showed continuous narrowing trend with the highest narrowing of 334 m for section b9 during 1968–2017 at an average rate of 6.82 m per year. The lower reaches, i.e. b10 and b11, has not been fully assessed due to less areal coverage of the CORONA image of 1968. Interestingly, at b10, channel width had increased at an average rate of 11.5 m per year from 1987 to 2002 but largely decreased at an average rate of 17.5 m per year from 2002 to 2017. The 11 sections along the Mahananda River can be divided into three broader groups concerning the pattern of landuses observed at the associated areas. Areas under the reaches of b5, b6, b7, b8 and b9 were featured by a continuous progression of built-up areas with the almost destruction of natural vegetation. Reaches such as b3, b4 and b9, b10 was characterised by dense built-up areas with a complete absence of natural LULC features; i.e. crop land and grass land, fallow land, and natural vegetation etc. In contrast with all the other cross sections, areas associated with uppermost sections, b1 and b2 still had large patches of natural vegetation cover with almost no impervious surface (Fig. 5).

## 4 Discussion

### 4.1 Understanding the Drivers of LULC Change

Since the time of British rule in India, Siliguri had experienced an immense burden of immigration of large numbers of tribal people, who were forced to settle in Siliguri and its surrounding hilly areas to run the tea plantation sector. Initially the majority of immigrants came from Nepal but after the geopolitical setback of 1947 and 1971 and Bangladeshi

migrants came in large numbers into this region (Datta 1998, 2003). People from the neighbouring states such as Bihar, Jharkhand, Assam and Sikkim also participated in the event of population growth throughout this exclusive region of Himalayan foothills (Chatterjee 2001; Debnath et al. 2017; Ghosh 2018; Datta 2003). Eventually, a stage-wise pattern of LULC alteration was identified from the analysis of geo-spatial data, which was the outcome of the above-mentioned multi-sequential migration streams. In the early nineteenth century, through massive deforestation, forested lands were converted into farmland; and tea plantation was begun under the supervision of former British rulers. However, when this tea industry and agricultural practices were proven to be unprofitable for the stakeholders, they were pushed to sell these lands or left it as fallow and got engaged in more profitable economic practices mostly in the sediment mining from river bed (Prokop 2018; Khawas 2002; Tirkey 2005; Tirkey and Gardner 2006). Thus, within just a few decades, the morphology of extensive fluvial landscape had changed dramatically and reached the verge of problematic urbanisation practices as one-fourth of the study area was transformed into the impervious surface.

LULC transformation of an area is primarily regulated by the aspiration for better living and developmental approach towards the economic prosperity of an area (Senanayake et al. 2013, Pradhan 2004). Being the main urban centre of northern West Bengal, Siliguri has immense economic potential as it acts as a major node of connectivity with north-eastern states of India and other neighbouring countries such as Nepal, Bhutan, Bangladesh and China. In terms of locational importance, Siliguri remains the connection with eight North–East Indian states of high strategic importance with the other parts of the country. Siliguri Municipal Corporation (SMC) or former Siliguri Municipality, established in 1967, had extensively sprawled out after the 1990s. This areal expansion of urban built-ups was just an after effect of population growth in SMC with a decadal growth of 40.53%, 76.70% and 33.88% for 1981–1991, 1991–2001 and 2001–2011 respectively. The areal extent of SMC had also increased accordingly from 15.59 km<sup>2</sup> in 1981, 26.37 km<sup>2</sup> in 1994 (after getting the status of Municipal Corporation in 1994) and 41.9 km<sup>2</sup> in 2001 which remains constant in 2011 also. (Bureau of Applied Economics and Statistics 1986, 1996–97, Census of India 2006: Darjiling district; Census of India 2014: Darjiling district; Census of India 2006: Jalpaiguri district; Census of India 2014: Jalpaiguri district).

The result of LULC transformation depicted that the built-up area had stretched towards Dabgram, situated in the north-eastern part of the SMC. This newly grown area had also been absorbed within the administrative setup of SMC in 2001. During 2001–2011, in just one decade, 10 new C.T.'s had emerged in addition to 2 previous Notified Municipalities in the adjoining rural areas of Matigara and

Naxalbari C.D. blocks of Darjeeling district. It was observed that a huge number of people, immigrated in Siliguri mainly to have a better livelihood, were settled in adjacent rural areas of SMC as the living cost was relatively low there comparing to the main city and consequently, a rapid LULC transformation took place on that area. An interesting demographic lag was observed as, in spite of having a greater population growth rate in the first half, (1987–2002) built-up area was not much expanded lower comparing to the second half (2002–2017). The second half was characterised by much lower population growth than that of the first half. From 1991 to 2001 the population growth was 76.7% within the SMC area and the growth in the built-up area from 1987 to 2002 was 50.6%. Whereas from 2001 to 2011 the population growth was only 33.9% (SMC area) and the growth of the built-up area was nearly 142% from 2002 to 2017. It was affirmed from the community response that this trend of built-up expansion could be considered as the general trend for this region.

#### 4.2 Site-specific Effects of LULC Transformation on Channel Planform and Topography

According to the results of multi-temporal classified maps, the entire study area can be divided into three LULC segments considering the stages of LULC transformation. The northernmost part was characterised by dense natural vegetation patches with lowest built-up cover hence low anthropogenic activities. While the middle portion of the study area was becoming the most urbanised, with almost two-thirds of this region under built-up cover; the southernmost part was distinguished by a quasi-natural landuse setting with patches of built-ups along with agricultural land and barren lands. This area was reclaimed a long time before but mainly used for agricultural practices. However, present trends portrayed that this area also was getting covered by impervious surface. In case of Mahananda, the adjoining floodplain and point bars were reclaimed a long time before, mostly during the time of massive urbanization in SMC during the 1990s, whereas, the floodplain of Balason, comprised of rural areas, got in touch with such urbanisation process in very recent time. The expansive river bed of Balason dissected by large point bars, mid-channel bars and vast floodplains; were reclaimed in a slipshod manner as these adjacent rural areas were starting to transform into built-up spaces rapidly. While river reaches such as a1, a2, a3 and b1, b2, b3 (Fig. 5); lying in the northernmost part, were distinguished by wide and expansive river channel; middle part of the study area from section a7 to a9 and b5 to b9 had recorded a major channel narrowing; where the landuse adjacent to the channel was rapidly transforming or already transformed into impervious urbanised areas. However, reaches in the southernmost part i.e. reach a10 and

b10, b11 (Fig. 5); were marked transforming very slowly into built-ups, which was directly reflected into the relatively wider channel width in this segment for both of the river. Hence it could be stated that urbanised landcover was inversely proportionate to channel width as with increasing urbanisation in the adjoining floodplain the river channel might lose its width largely (Yousefi et al. 2017; Vanacker et al. 2005; Hollis and Luckett 1976).

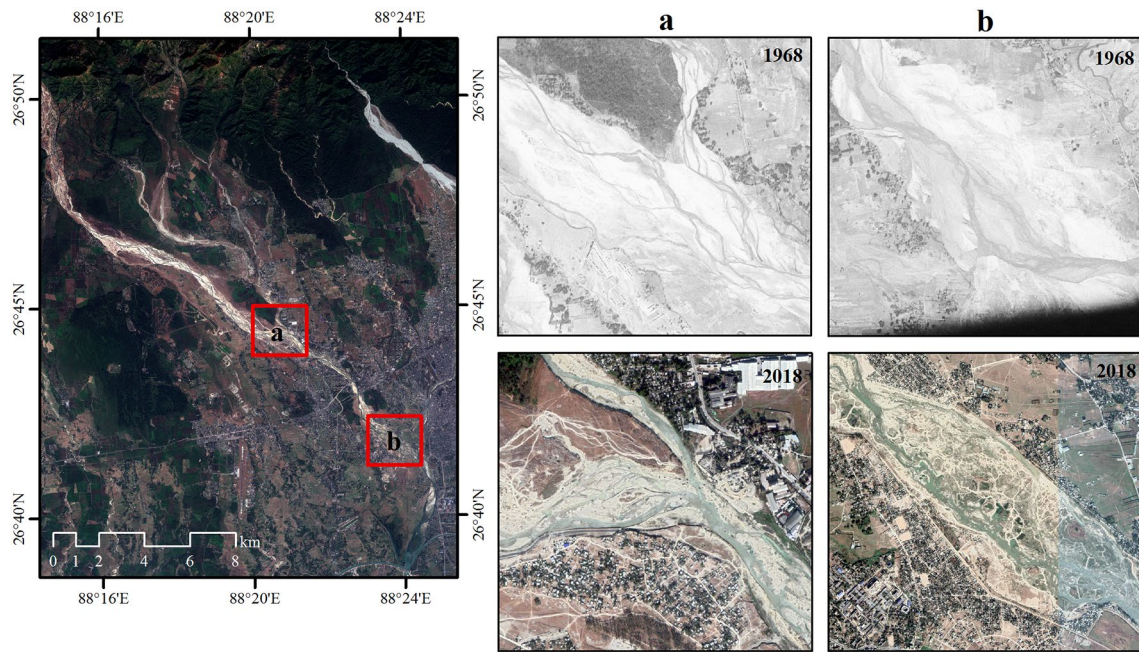
Large concrete embankments and bed stabilizing structures had been introduced in Mahananda a long time back to protect people from bank failures and floods. Areas adjoining the major bridges like Champasari bridge or Hill cart road bridge were embanked at the time of earliest establishment and as Siliguri grew up by its side Mahananda got embanked. Concrete embankments were introduced to Balason recently as Siliguri started absorbing its contiguous rural areas. At present, almost half of the Balason River had embanked with large concrete embankments and bed stabilization structures and the process was ongoing at a rapid rate (Table 4).

Compared to Mahananda, Balason has relatively large catchment area (size of the Balason catchment is 255.27 sq. km compared to Mahananda which is only 78.42 sq. km) and is characterised by a relatively higher volume of water and sediment flux in the flood season of June to October. Due to that high sediment yield Balason is getting heavily mined compare to Mahananda River which is always narrower compared to Balason, due to lesser amount of water and sediment flux. Mahananda also was heavily mined but the mining pits were only constrained to some reaches; on the other hand, in case of Balason, the entire stretch of Balason flowing through the study area was heavily mined (Tamang and Mandal 2015) (Fig. 6).

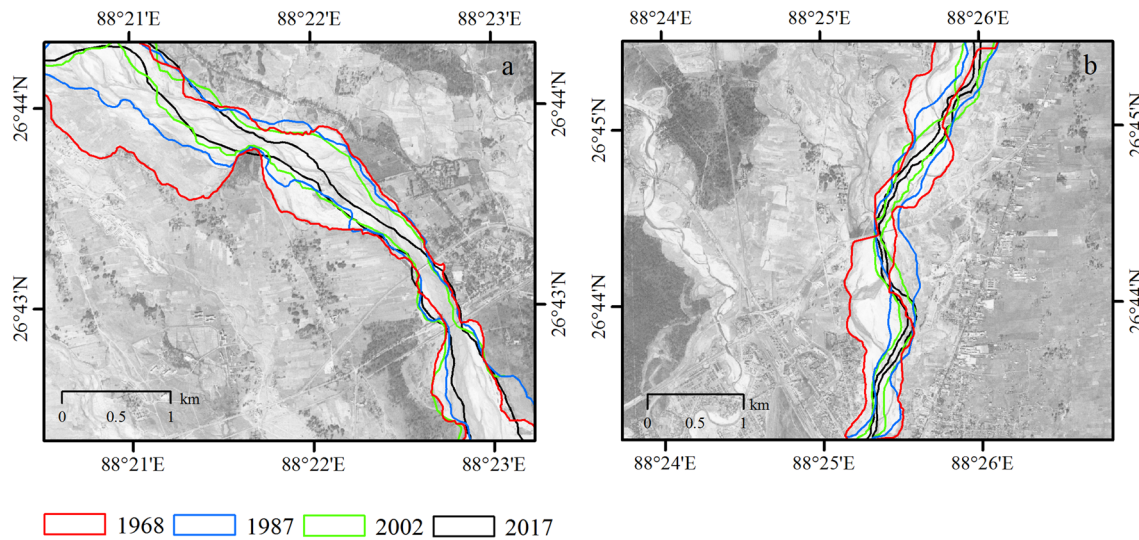
Though the responses of these two fluvial systems i.e. narrowing and deepening and change in channel pattern (Fig. 7); were same, but the nature of anthropogenic pressure was not similar in every case. While Balason was deteriorating from heavy sediment mining, Mahananda was experiencing the adverse impacts of getting laterally disconnected due to embankments and increased imperviousness in its floodplain. The effect of sediment mining was on the lower side for Mahananda and, on the contrary, floodplain of Balason was less urbanised than that of Mahananda. Hence, down cutting and narrowing of both these channels could not be linked with just any single causative factor. Changes

**Table 4** Increase in percentage of river banks protected by concrete embankments (1968–2018) *Source:* Satellite image, Irrigation and Waterways Department, Siliguri Division, Government of West Bengal and Field Survey

Year	Balason	Mahananda
1968	1	2
1987	5	7
2002	36	42
2018	46	77



**Fig. 6** Changes in planform of Balason due to extensive gravel mining in the channel bed; **a** is at Khaprail bazar and **b** is at Naukaghat, confluence of Balason with Mahananda



**Fig. 7** Gradual change in channel width of Balason and Mahananda River from 1968 to 2017

in the channel pattern also had come as an inevitable effect of these factors (Fig. 7). In order to justify this kind of channel narrowing and down cutting it could be said that since there was no longitudinal disconnectivity found in both of the rivers, the rainfall did not show any significant change during the studied years. Moreover, since the entire river stretch is lying on similar kinds of Stratigraphic settings, then it could be perceived that the rapid down cutting and narrowing only happened due to the cumulative action of

intense anthropogenic activities such as urbanisation of the adjoining floodplains, sediment mining, encroachment on river planform etc.

### 4.3 Possible Future Patterns of Channel Planform and Topography

Channel narrowing, channel incision and changes in channel pattern were found to be highly interlinked in the study

area. With respect to the study area, when the natural channel forming variables remained constant, and development of concrete embankments, sediment mining and urbanisation proved to be the main reasons of channel narrowing, and then reconfiguration of the river topography becomes inescapable. If channel narrowing process continues in this way, then as an immediate response to that river channels of Balason and Mahananda would be deeply incised and consequently, several structures such as railway and roadway

bridges will collapse (Kondolf 1997; Kondolf et al. 2002; Khaleghi and Surian 2019; Wishart et al. 2008). Furthermore, as a consequence of channel incision, groundwater can seep into the river channel and the piezometric level will go down, which may create a crisis of potable water for the local inhabitants. Usually, groundwater gets recharged by river water during flood season. Whereas in the lean months, the river channel maintains its flow by getting recharged from aquifers. In this situation, if the channel incised deeper



**Fig. 8** Evidences of anthropogenic stresses and its impact on Balason and Mahananda River; **a** Encroachments of a point bar found on Mahananda River bank at Champasari; **b** Large amount of sediment is getting withdrawn from Balason River bed at Matigara; **c** Ground water is getting discharged from exposed water carrying layer as a result of bed lowering on Balason River at Tarabari; **d** Heavily

embanked Mahananda River bank with bed stabilizing structures; **e** and **f** Exposed piers of a railway bridge at Matigara and unstable pillars of a roadway bridge at Champasai on National Highway 10 over Balason and Mahananda respectively as a consequence of bed lowering. Photographs are taken by authors

than the level of acquirers, then the local groundwater table cannot maintain its hydrological budget with fluvial system, which may prove to be undesirable for the locals, who reside at the adjacent riparian zones and floodplains, and directly depend on groundwater for their daily water requirements (Khaleghi and Surian 2019; Rinaldi et al. 2005). During the field survey, the above-mentioned phenomena were evidenced very prominently in the form of displaced bridge pillars (Fig. 8) on both the river and severe water crisis for 6–8 months of a year, specifically manifested at the Tarabari village situated on the right bank of Balason river (Biswas 2016). Eventually, the groundwater level of their wells went down, immediately after the offset of monsoon rainfall of October and it cannot regain its former level until the onset of monsoonal rainfall in June. In a broader dimension, the nexus between uncontrolled in-channel gravel mining and channel narrowing can damage the natural cycle of the entire fluvial system, natural sediment sorting, river bed morphology as well as the inherent ecological properties, which were subsequently capable of altering the channel pattern of the river. Some of the above-mentioned problems have already started to condense and being considered as an intimidation for the stakeholders to be alert and responsive to the changes taking place in the fluvial system; otherwise those may get intensified in the eminent years, and can be detrimental for the river system (Gregory 2006; Paul and Meyer 2001).

## 5 Conclusion

This study can be conceived as the pioneering work on analysing the effects of anthropogenic activities on channel morphology in the lower Darjiling Himalaya using a combined methodology of geospatial data analysis, field investigations, along with community responses. Community responses helped immensely to understand not only the past landuse scenario but also the past geomorphic setting. This study has shown that rapid landuse transformation took place adjacent to the river channels. Along with this, intense anthropogenic activities are getting operated in-channel; which is significantly altering the river planform as well as river bed topography causing severe eco-hydrological as well as socio-hydrological hazards. Amplification of the magnitude of storm water flux, disturbed sediment budget, is fuelling the incision process which can be destructive to bridge pillars, bed stabilization structures and groundwater interactions. Increased down cutting fuelled by sediment mining, lateral disconnection of the river channel and increase in impervious area can result in disconnection of river-ground water interchange, and initial tendencies are directing towards this. It may lead to ground water scarcity which can be detrimental for a huge population living on the floodplains and prove to be an enormous social hazard. On

the eco-hydrological perspective, it would simply destruct the natural habitat condition which may lead to mass extinction of living inherent biota. So, further studies on this area can be directed towards these problems and on replicating this methodology to find out the nature, degree, impact of anthropogenic intervention on other major rivers of Terai region.

Restoration of the channel form or habitat condition of these channels is a timely need. Most importantly the restoration programme must include the scheme of giving better job opportunities to the locals instead of sediment mining. On the other hand, for the sake of infrastructural developmental activities, construction aggregates sourced by sediment mining are highly needed. So to have this supply and demand evenly balanced, there should be a two-way approach of channel restoration projects; firstly, estimate the sediment budget and upon that try to regulate demand and supply rates and secondly, implementation of a plan for sustainable withdrawal of sediments as well as of aquatic resources leaving the channels as a continuous source of resources. Riverbanks and bars must be free from any encroachments and no further concrete embankments shall be built in the upstreams. There shall be regulation imposed by local authorities on future urbanisation processes, which shall give dividends to the prevailing hydrological systems of this region. New settlements or urban amenities should have enough open unpaved surfaces for groundwater recharge and along with that; the riparian zone must be free from any such concretization and should be left in its natural stage. Hence future urbanization as well as restoration management policy should have the inherent resilience to combat further difficulties to come.

**Acknowledgements** This study received financial support (Fellowship Reference No. 3128/NET-JUNE 2014) extended by the University Grants Commission, India to the first author. Authors are thankful to Prof. Subir Sarkar, Professor, Department of Geography and Applied Geography, University of North Bengal; Prof. Sunil Kumar De, Professor, Department of Geography, North-Eastern Hill University; for permitting us to use data from their unpublished PhD thesis. Authors are also grateful to Dr. Debajit Datta, Assistant Professor, Department of Geography, Jadavpur University; for his valuable support during the preparation of the manuscript. We also express our gratitude towards those who provided their logistic support during fieldwork.

**Funding** This study had received financial support (Fellowship Reference No. 3128/NET-JUNE 2014) extended by the University Grants Commission, India to the first author.

## Compliance with Ethical Standards

**Conflicts of interest** The authors declare that they have no conflict of interest.

**Availability of Data and Material** The data or materials used in this article are part of the ongoing Ph.D. research work of the first author, hence not to be shared until its completion. Satellite images used here

are freely available, however, the data extracted from these, and used in this article, can't be shared.

**Code Availability** Not applicable for this article.

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