PART-I

Chapter-1 Introduction

RIVERS are most widespread and dominant agent among all which shapes the earth's surface significantly at near global scale. With its combination of main channel, tributaries and distributaries, rivers carve out the uplifted surface of the earth and distributes and disperse the sediments and water throughout its course from source to the mouth. Owing such importance, riverine flood plains have always been teeming with all kinds of life (both flora and fauna). Man being the most intelligent and thus most powerful species among all fauna of Holocene period, found riverine floodplains most suitable for agriculture, settlement, industry and transport. It's not surprising therefore that all human civilizations be it ancient or modern have developed on banks of major rivers across the globe. One can say rivers have been always a part and parcel of human civilization and this significance manifests itself with the fact that rivers were the first to attract the human attention than any other agents of landscape evolution.

In literature we find the mention of River Nile's delta catching the attention of Greek historian, Herodotus. He observed the annual flooding of Nile and understood that this flooding is depositing fertile silt in the kingdom of Egypt and thus sustaining its prosperity. This made him call Egypt as "the gift of Nile". Rivers as landscape shaping physical entity, itself maintains or adjusts with the dynamics of its controlling factors like precipitation, base level change, tectonics etc. Now with the growth of human population globally, man has happened to overexploit the river and its resources leading to altered and disequilibrium condition of many rivers in different parts of the world. Therefore, river as a social entity is gaining significance since last one century. River is not being able to maintain equilibrium state in response to these human induced conditions and often causing damage to human settlements, agriculture and riverine engineering infrastructure. The natural vegetation also bears the brunt of such altered condition wherein damages the faunal population along with flora of the region happens thereby threatening ecological balance and biodiversity.

Now attention, focus and efforts are being taken to restore and manage the rivers to bring back to their natural equilibrium condition. However, this also has aroused a topic of furious debate whether man can really manage rivers? Some argue that current popular models and approaches of river management through damming, embankment construction, and concretization of flood plains are only worsening the problem. Opinions and advocacy for soft engineering in river management plans are getting vocal.

The scope of this study is not to get into this debate and take a stance; rather it has attempted to present a scenario of channel planform dynamics of the Chel River during last 62 years in the piedmont of Eastern Sub-Himalayan North Bengal. Channel dynamics is an inherent characteristic of rivers flowing in Terai and Dooars of Sub-Himalayan North Bengal plains and also beyond it southwards in the entire Barind tract of Ganga-Brahmaputra-Meghna system of Bengal basin. In fact, Chel basin falls under the Teesta Basin which is a part of Brahmaputra basin and thus forms a part of the upper Barind tract, an alluvial tract wherein river have been much dynamic and documented records of the same is available for about 250 years since the first maps of the region prepared by Rennell was published in 1780.

The Ganga and Brahmaputra River enters Bengal (Bengal here includes West Bengal in India and the Bangladesh together) through gap between the Rajmahal Hills (Deccan plateau) and the Meghalaya Horst. The interfluve between these two rivers is called Barind Tract and is drained by the major rivers of the Mahananda, the Teesta, the Jaldhaka and the Torsa and many small tributaries of these rivers (Fig.1.1). Along with Meghna system, they form Ganga-Brahmaputra –Meghna system which is again part of larger tectonic basin known as Bengal Basin. Rudra 2018 opines that river on this vast alluvial tract display two types of dynamics namely, gradual movement wherein rivers move to and fro (or oscillatory movement) like the pendulum of a cloak, within the meander belts and second type of dynamism is avulsion wherein rivers abruptly change their courses in different direction abandoning previous course for considerable time period or forever. The eastward avulsion of the Teesta in 1787, the southward detour of Damodar in mid-seventeenth century, the westward migration of the Brahmaputra (known as Jamuna in Bangladesh) in 1830, the eastward flight of the water of the Ganga through the Padma (name of the main distributary of the Ganga in Bangladesh) and recent westward diversion of the waters of the Mahananda through the Fulohar which takes off at Bagdob are five examples of avulsions in the Barind tract that Rudra documents in his book. Many palaeo-channels of the delta remind us the dynamics of the river during the historical period.

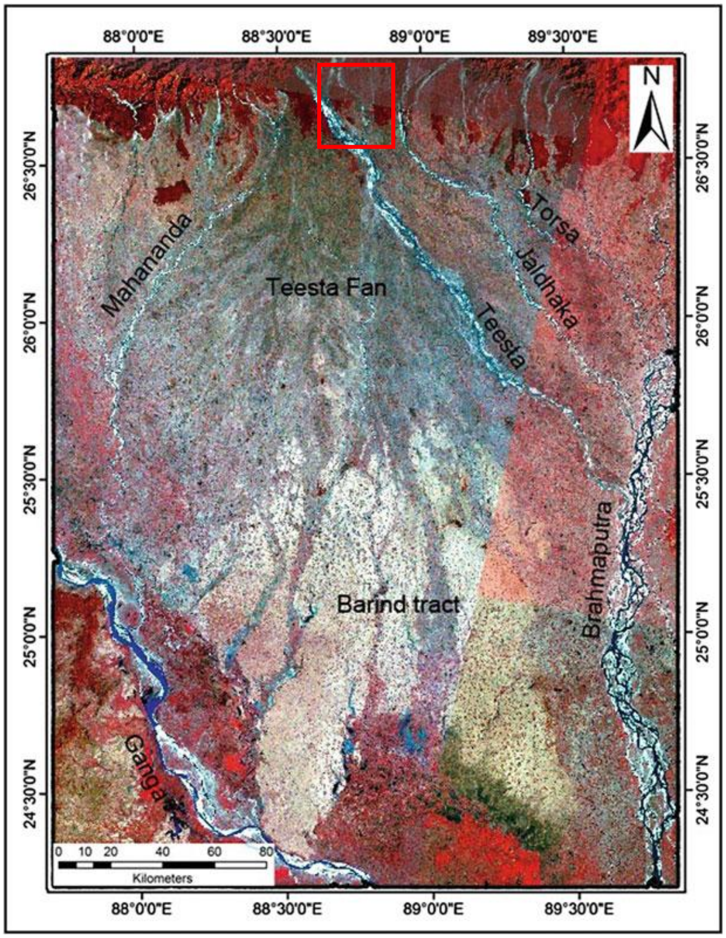

Figure 1.1 Barind tract, a large fan (Source- Rudra 2018.pp-21). The red rectangle shows the location of Chel River basin.

The 200km wide gap between the Deccan plateau and the Meghalaya plateau is known as Rajmahal- Meghalaya gap (Fig.1.2) and serves as a wide opening for the northward surge of monsoon winds which strikes the Himalaya and generates highest annual rainfall and most frequent heavy rains along the whole Himalayan front, values of both factors declining towards the west as well as towards the east (Dhar, Nandargi 2000; Starkel, Sarkar 2002; Baillie, Norbu 2004; Soja, Starkel 2007).

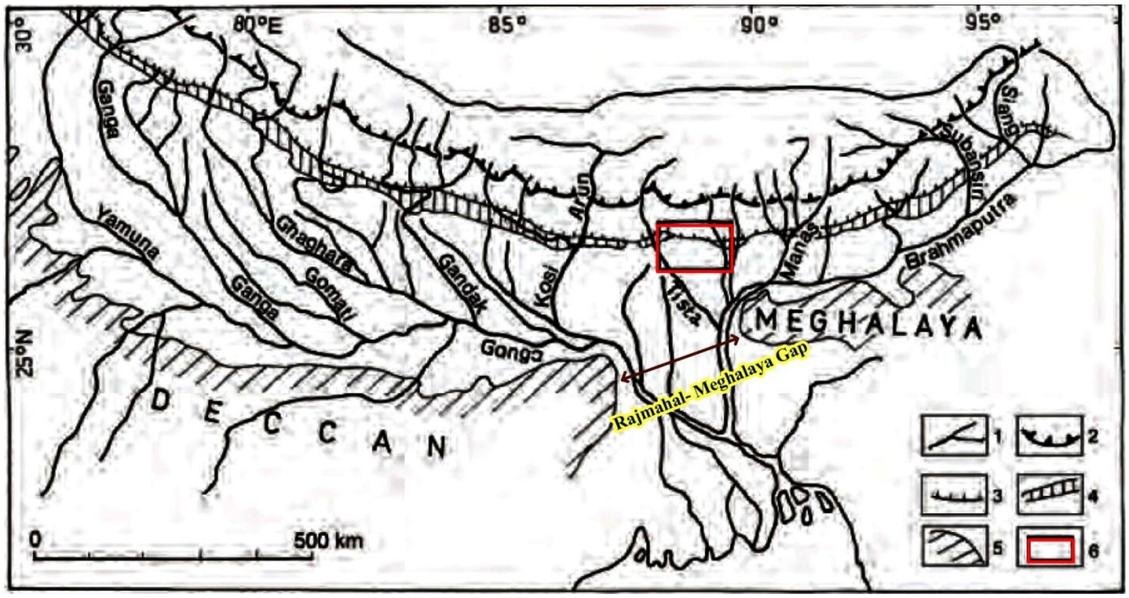

Figure 1.2 The Himalayan range and its foredeep. 1. Rivers, 2. Central Himalayan Thrust, 3. Main Boundary Thrust, 4. The Siwaliks, 5. Margin of Deccan and Meghalaya Plateaus, 6. Chel River Basin falls within this red rectangle. (Source- modified from Starkel et al. 2008. pp- 8).

Rivers from the Himalaya debouch on the north Bengal plains roughly at an elevation of 300m (Bagchi and Mukherjee 1983) and becomes sluggish and wide due to sudden loss of gradient. Here they experience huge amount of aggradation and consequently form triangular depositional landforms called Fans. The plains of Terai and Dooars have actually developed through the gradual coalescence of these alluvial fans and forms northern portion of the Barind Tract. The larger rivers like the Mahananda, the Teesta, the Jaldhaka and the Torsa have formed overlapping depositional lobes representing multi-dated sediment layers (Rudra 2018).

Rudra 2018 accounts that the rivers of North-Bengal faced three types and phases of human intervention. The first major human intervention altering the hydro-ecology of North Bengal was initiated from 1835 onwards when British created large tea plantations, destroying the dense virgin tropical forests of the region. The second structural intervention that changed the hydro-dynamics of rivers was the linear embankments which were built to control floods. But much like the southern Bengal this popular measure did not ensure total protection against floods; on the contrary, the sediment dispersal on the floodplain and deepening of channels by fast-flowing current were impaired. As usual, the sediment load was trapped between the embankment leading to decay of channels and resultant drainage congestion. The third intervention in the fluvial regime came in the form of narrow bridges and culverts. The road–railway networks in North Bengal is aligned in an east–west direction which cross the south-flowing rivers, and the bridges constructed for the purpose did not provide adequate passage for the floodwater. The subsequent impact of these bridges on the fluvial system was striking. In all cases, the channels became wide, both upstream and downstream, and the bridges acted as nodal points. This ultimately caused expansion of the flood contour (Ray 1932; Saha 1933).

Rudra 2018 opines that drainage map of North Bengal has changed since the eighteenth century. James Rennell was the first person to systematically survey the Ganga-Brahmaputra river system during 1764-1777 and come up with a compilation of thirteen maps entitled “A Bengal Atlas” in 1780, and in 1781 eight additional maps were added in the second edition. Comparison of Rennell’s maps with modern Satellite images shows that Teesta in North Bengal and the Jamunna or Brahmaputra in Bangladesh has altered their courses (Rudra 2018). All the major rivers of the North Bengal, namely Teesta, Jaldhaka, Torsa are flowing south-east, Mahananda River exceptionally flows in south-west direction, and perhaps this direction of Mahananda is guided by a subsidence along a line followed by Jamuna in Bangladesh (Morgan and McIntire 1959). Mahananda River which debouches from Darjeeling Himalaya near Siliguri flows south-westward into Bihar and bifurcates into two branches at Bagdob. The western branch is called Fulohar which joins the Ganga near Manikchak Ghat in Malda. The other branch is known as the Mahananda itself and is virtually disconnected from its feeder and doesnot receive any upstream flow except during high flood. Mahananda River basin earlier used to drain an area of 27,654 km^2 but now is bifurcated into two separate sub-basins which are called Fulohar and Mahananda. All these channel changes within Mahananda have gradually taken place during last three decades (Rudra 2018). Thus, the region is considered as few geomorphic hotspots in India which is famed for dynamic river systems.

Remote sensing is a very effective tool to identify planform changes (Gupta,2012). It can quantify planform changes, which can help in improving the understanding of drivers and conditions leading to these dynamics. Furthermore, as planform dynamics give rise to different channel patterns, this can possibly help to identify the controls of channel patterns too. But assessing the planform dynamics of a river system is always a multi-disciplinary task. It requires involvement of geologist, hydrologists, environmentalist, social scientists and engineers (Gupta, 2012). The scope of this thesis is limited to reconstruct the fluvial dynamics of the Chel River and understanding the factors controlling the planform dynamics on the foreland basin of Darjeeling-Sikkim Himalaya considering a time span of nearly 62 years using historical information and time series satellite sensor data complemented with extensive fieldwork. Geomorphic scale is significant parameter in the interpretation of landform development and landform characteristics of geomorphic system. Keeping this in mind the study has tried to explain and interpret the findings from regional scale, basin scale to channel and reach scale spanning last 62 years.

1.1 Conceptual Framework

River systems are essential by providing fresh water, transportation and important natural habitats. At the same time, they also pose risks. The river planform, or the river geometry as seen from above, is generally unstable and various landform dynamics take place. Examples are the migration of channels, the creation of new channels by avulsion and the formation of bars and islands (Rawee, 2020). These dynamics can have unwanted effects on the infrastructure, flood safety and shipping. Successful management is largely dependent on a good understanding of the processes leading to river dynamics (Ward, 1994).

To get an understanding of the existence of different planform geometries (or channel patterns) and their dynamics, classification schemes were proposed. A well-known classification of channel planforms is straight, meandering and braided (Leopold and

Wolman,1957). Furthermore, anabranching is often added, which is generally described as a large multithreaded river with stable vegetated islands (Latrubesse,2008). A common approach to classify different channel patterns is creating empirical models, which use parameters such as the bankfull discharge, channel slope and sediment size (eg. Leopold & Wolman,1957; Schumm,1985; Van den Berg,1995). These parameters can be used to get an understanding of the controls of planforms and their dynamics. Nevertheless, creating a thorough understanding of the controls of channel patterns and the planform dynamics remains difficult, as it depends on a large number of factors such as discharge variability, sediment transport, floodplain characteristics and the valley geometry (Harmer and Clifford,2006; Stowik,2018). The study of historical channel change is an important part of understanding fluvial systems. Only by understanding the past can we place recent and ongoing changes in channel form into perspective and thus begin to unravel the complex factors, which influence the nature of our rivers today (Winterbottom,2000).

Geomorphic processes especially the rivers work in a setup of boundary conditions. Dynamic behaviors of the rivers are often explained by the nature of these boundary conditions. Geology and climate constitute the imposed boundary conditions which do not change over a shorter time scale and so are taken to be semi-permanent. The flux boundary conditions such as discharge, sediment load and vegetation are generally attributed for the river dynamics. Sometimes, anthropogenic impacts are also made responsible for this. The Himalayan Rivers emerging at the piedmont register dynamic characters both in process and form (especially in planform characters). Chel River is a part of the Eastern Himalayan margin and foreland/piedmont region characterized by varied physiography, high seasonal discharge, influences of neo-tectonic activity and the young geological foundation with less consolidated cohesive and non-cohesive sediment coupled with human intervention in the form of massive sand-gravel mining, construction of short length bridges, extension of embankments, landuse changes which have left the Himalayan foreland basin a formidable ground, where silt-laden rivers tend to migrate frequently. From this conceptual perspective, it is logical to enquire whether dynamic characters of Himalayan piedmont rivers and consequent planform dynamics are sufficiently explained by the flux of discharge, load or vegetation or it is more linked to tectonic and human interventions. Inquiry into relative role of these factors is also important.

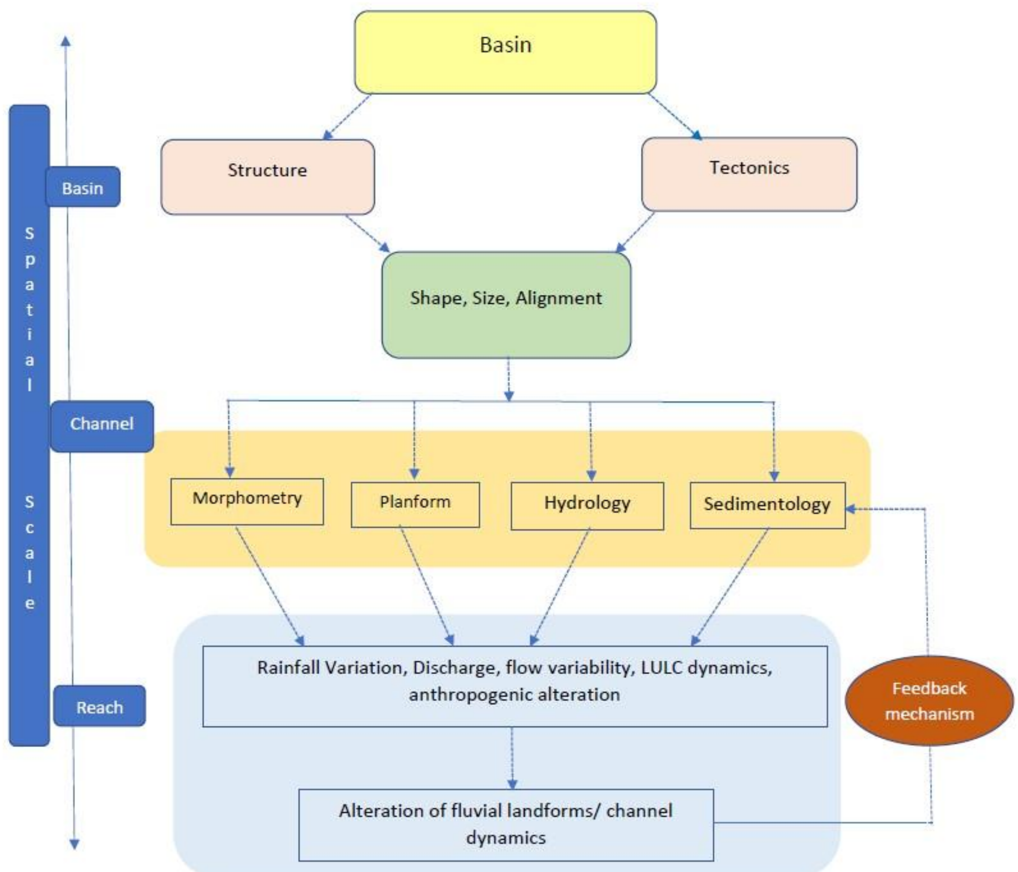

Fig.1.3 Conceptual workflow diagram

1.2 Study Area

1.2.1 Reason for selection of the study area

Channel dynamics studies in India have been mostly concentrated on the large alluvial rivers of Ganga and Brahmaputra. Huge volume of literature is available for upper and middle Ganga plain followed by literature upper and middle course of Brahmaputra. In Bengal the study till day is much focused on Lower Ganga plain. Studies on rivers of Terai and Dooars as such are very less and fragmentary too. Unlike rivers of south Bengal the rivers of north Bengal flow through transitional physiography between Himalayas and lower alluvial plains. Thus, though smaller in size and volume of water, they display great dynamics. Within the Terai and Dooars itself, we find disparity in the number of studies among the rivers. Much studies have been done on rivers like Mahananda, Balason, Teesta, Lish, Gish, Jaldhaka, Torsa whereas comparatively studies on Chel River are very less. During extensive literature review, the author came across few published research articles on Chel River but couldn't get any M.Phil and Ph.D dissertation on Chel River basin. Thus, the present work attempts to understand channel dynamics of a small river with 58 km length and 321 km^2 of total watershed area of a data scarce region and basin in particular.

The selection of the Chel river for the present study was also prompted by the fact that the Chel river drains through the tectonically active Himalayan region and its foreland, thus gives an opportunity to test response of drainage lines and watershed to the neotectonics. Further, the entire course of the Chel is accessible to verify the results generated by remote sensing and GIS.

1.2.2 Location of the study area

Chel lies to the left of river Tista after Lish and Gish and joins Neora River at 88° 44' 13"E, 26° 41' 45.6"N near Kranti to become Dharala Nadi which ultimately merges with mighty Tista about 13kms downstream. The Chel River basin extends between 26° 41' 30" and 27° 5'15" north latitudes and longitudes 88° 37'00" and 88° 45' 15" east (Fig.1.4). The entire watershed covers an area of 321 km^2 with a watershed perimeter of 115.21 km. Administratively the Chel river basin spreads over parts of Gorubathan block of Darjeeling district (recently Darjeeling district was divided into Darjeeling and Kalimpong district. So now actually Gorubathan block falls under the Kalimpong district but in order to avoid confusion and convenience of data comparision Gorubathan is considered as part of undivided Darjeeling district only) and Malbazar block of Jalpaiguri district of West Bengal. Elevation ranges from 92 m to 2449 m within the basin. Geomorphologically the basin comprises of the alluvial plain, piedmont surface, terrace surfaces, lesser Himalayan surfaces etc. It dissects the lesser Himalaya. 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 – 100 km^2 and are located in the belt of higher precipitation and form large alluvial fans. Aggradations follow upstream into the hills, while farther downstream the braided channels change into meandering ones (Starkel and Sarkar, 2002).

1.3 Research Problem

Rudra 2018 states that heavy monsoon rainfalls, shallow cross-sectional area, declining slopes, huge sediment load are the major causes to make the North Bengal flood prone. The North Bengal Flood Control Commission and State Irrigation Department relied on embankments as the flood control measures, but those embankments failed to ensure protection during many devastating floods. The long-term effects of jacketing the river appear to be detrimental as it caused rapid deposition in the riverbed and diminution of the water-holding capacity (Mahalanobis 1927).

The east–west aligned railway and highways have an immense impact on hydro-geomorphology of North Bengal. The alignment of these communication lines with inadequate narrow culverts created serious problem of drainage congestion and has resulted in an expansion of the flood area. The devastating flood of 1922 was ascribed to the intense rain as well as expansion of road and railway with inadequate culverts (Saha 1933; Ray 1932). Since the passages of water are artificially constricted at the railway-road bridges, the rivers have the tendency to adjust with these structural interventions either by widening their valleys or by altering the courses in upstream and downstream sections (Rudra 2018).

Saha and Bhattacharya, 2019 on their work on the channel dynamics of one of the important rivers of Dooars namely, Torsa River states that rivers on the Himalayan foredeep are suffering from increasing bed elevation as a result of sedimentation. Consequently, this often leads to chocking of the active channel, and results in frequent changes in cross valley slope (Mukhopadhyay 2014; Sinha 1996; Jain and Sinha 2004;

Chakraborty and Ghosh 2010). Some works have linked avulsion or a certain change in river course with the super elevation of the existing channel and an inevitable change after a flood for rivers flowing through areas with topographic transition (Leopold et al. (1965), Aslan et al. (2005), Mukhopadhyay (2014), Perez-Arlucea and Smith (1999) and Sinha et al., 2014). A high rate of channel sedimentation and significant flood events often result in channel avulsion on the Himalayan foredeep plain.

In consistent with the kind of problems faced by north Bengal rivers, Chel River basin with two distinct physiographic units of upper catchments flanked over dissected outer Himalaya and middle and lower course passing through piedmont and alluvial plain section has varied geomorphologic problems. The hilly terrain in the north above the elevation 350m experience rapid overland flow, erosion and landslides whereas its piedmont in the intermediate and alluvial plain in the south is observing large scale sediment deposition, rise in valley floor and consequent shifting of channels (Lama and Maiti,2019a). Expansion of embankments, sediment mining and channel constriction due to twin bridges has altered the hydro-morphology of the river. Channel dynamism of river Chel is causing large scale erosion along its course and is damaging Tea Gardens, forests and agricultural lands. High variable discharge as a consequence of high but variable amount of rainfall coupled with active neotectonics and anthropogenic activities have a greater impact on the dynamism of Chel River.

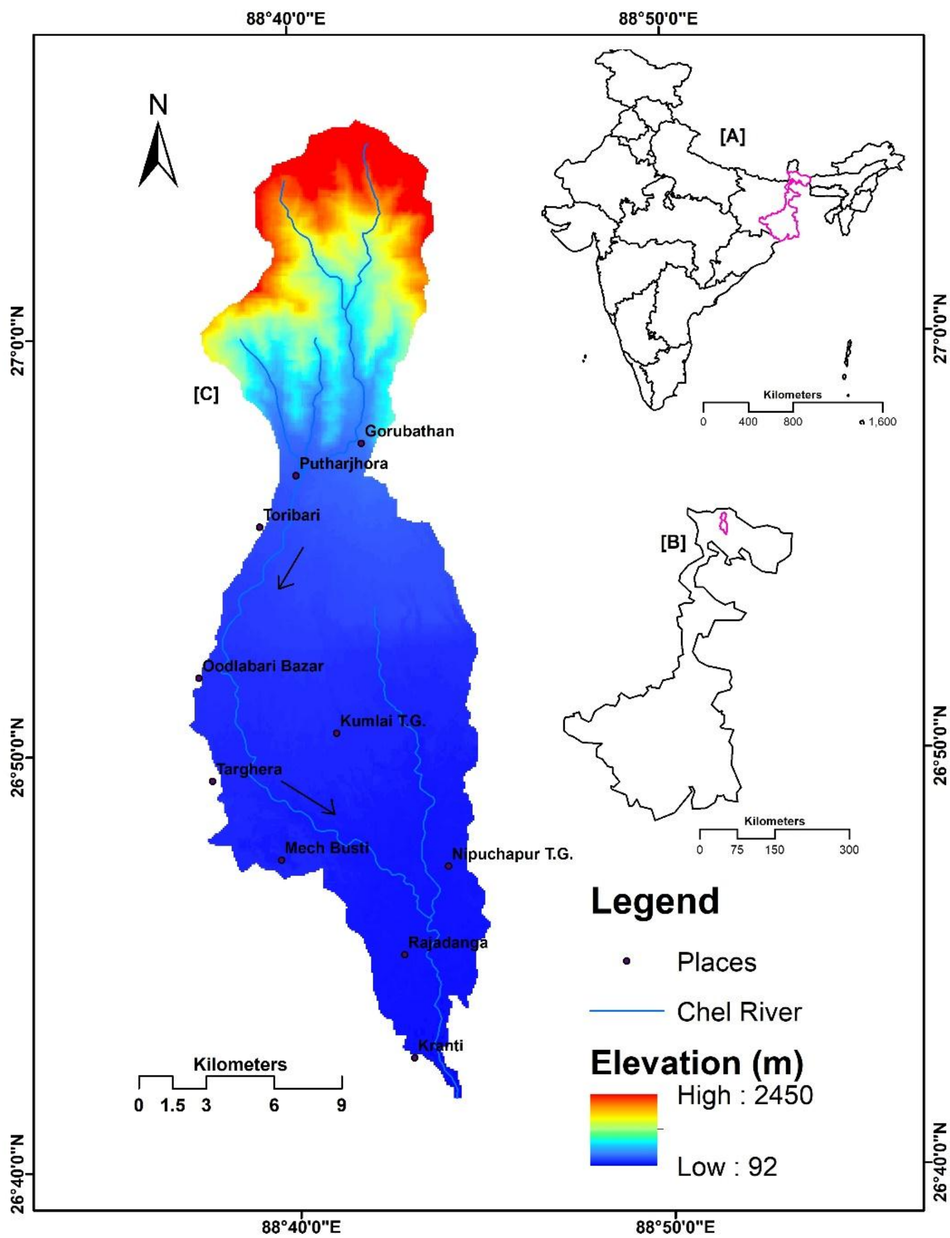

Figure 1.4 (A) India with the state of West Bengal, (B) West Bengal with location of Chel river Basin and (C) Chel River Basin (Study Area).

In the context of above problems, research questions for the present study can conclude as- How does channel respond to climatic, tectonic and anthropogenic impulses? And what are the impacts of channel dynamics?

1.4 Objectives of the study

Major objectives of this research are-

- to document and analyze the spatial and temporal variation in channel for understanding the nature and process of channel planform dynamics in the study area.
- to understand the impacts of channel dynamism.

Detail objectives of the present research are as following:

- to understand the pattern of channel planform change
- to identify the locations of erosion and aggradations and associated bank line migration.
- Role of neotectonics
- Role of Human interventions.
- Role of climate induced catastrophies

1.5 Methodology

To accomplish the undertaken objectives of the present study various scientific techniques and methods have been used. The details of the methodologies adopted are discussed below.

1.5.1 Collection of Secondary data and maps

The study has extensively used information, data and maps from reliable published and unpublished sources. Reports and online materials from various government and non-governmental organizations and offices have also been referred and incorporated in the present study (Table 1.1)

1.5.2 Field survey and monitoring

- Repeated pre-monsoon and post-monsoon field surveys were conducted to measure the channel cross profiles at 2km interval.

- Repeated pre-monsoon and post-monsoon field surveys were done to measure the hydrological parameters like water depth, width, wetted perimeter, velocity, etc across each channel cross profiles at 2km interval.
- Repeated pre-monsoon and post-monsoon field surveys were conducted to conduct coarse sediment analysis across each channel cross profiles at 2km interval

1.5.3 Data analysis in GIS Platform and Statistical software

- Morphometric analysis of the Chel River basin has been achieved by using extensive use of Arc hydro and spatial analyst tools in ArcGIS 10.1 software using topographical maps and SRTM DEM. The perspective view of the basin has been prepared using Golden Surfer V.15.
- Estimation of discharge and sediment yield was achieved by running ArcSWAT model for the Chel River Basin with the input of Landuse, soil and meteorological data.
- Channel banklines and centerlines were delineated from multi-temporal toposheets and Landsat images largely using Spatial analyst tools in ArcGIS 10.1 software.
- Movements of two confluence points namely, Chel-Kumlai confluence and Chel-Neora confluence in the lower Chel-Neora river system has been analyzed using multi- temporal Landsat Images and topographical sheets in ArcGIS 10.1 software.
- Overlay analysis method was deployed for the computation of areas affected by erosion and accretion using georeferenced topographic maps and Landsat images spanning over 62 years (from 1955 to 2017) ArcGIS 10.1 software.
- SRTM DEM 1 Arcsec was used for extraction of geomorphic indices in ArcGIS 10.1 software to access the implications of neotectonics in the Chel river basin.

- Google Earth images have been used to show wet-pit sediment mining scars and sediment processing units of Odlabari and Toribari.
- SRTM DEM and Aster GDEM of 2000 and 2001 with 30m resolution has been used to show the bed elevation changes upstream and downstream induced by the twin bridges of Odlabari.
- Arc GIS10.1, ERDAS IMAGINE 9.0, Microsoft Excel 2007, Microsoft Word 2007, Microsoft Access 2007 has been used extensively for preparation, processing, tabulation, analysis, modeling, mapping and graphical representation of the data.

1.5.4 Synthesis and analysis

The huge amount of data and information thus generated from secondary sources, field works, modeling and indices in software were carefully attempted to be interpreted and synthesized to understand the overall channel planform dynamism of the Chel River. The causative factors of such channel dynamism observed, has been given due attention while interpreting the results.

1.6 Data sources

Huge amount of primary data (field observation) was collected during filed surveys and qualitative secondary data were collected from reliable sources. The details of data used in the study and their sources are given in table 1.1.

Table 1.1 Details of data used and their sources.

Data used	Sources
SRTM DEM	http://earthexplorer.usgs.gov/
Geological maps	Geological and Mineral map of West Bengal, GOI,1999 and Mitra et al. 2010
Topographical Maps: 1:50000, 1:250000	Survey Of India(SOI), http://www.lib.utexas.edu/maps/ams/india
Soil Map	NBSS & LUP Maps
Rainfall data	Tea Garden records
Census Data	Census of India
Landuse	Toposheets, Google Earth and fieldwork.
Satellite Images (MSS,TM,ETM,OLI/TIRS)	http://earthexplorer.usgs.gov/
Cadastral map and other land record	DLLRO of districts

1.7 Review of the literature

Owing to its great significance, Channel dynamics studies have been undertaken worldwide by geographers, hydraulic engineers, planners and environmental managers. Present study went through various existing literatures on channel dynamics of international, national and regional importance to have an insight into the process and response of channel dynamics. Among all the following are worth mentioning here.

Gurnell (1997) have studied the channel change on the River Dee meanders, for 50 years (1946-1992) using air photographs and is actually a continuation of Gurnell et al. 1994 work wherein they have worked on the same river reach showing channel change over 115-year period (1987–1992) by overlaying information primarily derived from historical maps within GIS platform. The biggest contribution of Gurnell (1997) work is to come up with a non-morphological approach in defining the channel bank limit. Gurnell (1997) illustrates that a simple morphological definition (water-soil limit) which was used in the interpretation of bank positions by Gurnell et al. (1994) is not entirely correct because of the problem posed by variable morphology of the channel cross-sections across the fluvial- tidal transition. Therefore, a non-morphological approach (soil-vegetation limit) that can be clearly identified from photographs was adopted for the interpretation of the six sets of air photographs maintaining the consistency. Gurnell (1997) further adds that the only problem with non-morphological approach is faced when large trees overhang and obscures the actual soil-vegetation limit. In such locations, the position of the limit was identified wherever possible gaps in between the trees and was then interpolated using the assumption of a similar proportion of overhanging tree canopy at intermediate points. This non-morphological approach of defining channel banklines is simple and non-confusing and therefore grew much popular and was widely adopted by the subsequent scientists (Yang et al.1999, Winterbottom 2000, Tiegs and Pohl, 2005, Gupta et al.2013, Dewan et al. 2017.etc.).

Yang et al. (1999) have used a series of time-sequential Landsat images spanning a period of 19 years in GIS to study the channel migration of the active Yellow River Delta, China. Channel banks were defined using a non-morphological variable, namely soil-vegetation limit (Gurnell, 1997). The spatio-temporal changes of banklines and centerline were systematically examined, and the computation results of these analyses were related with appropriate natural and human processes affecting the delta. The study revealed a spatial pattern of highly mobile upstream and downstream stretches and of a relatively stable middle reach. They found a temporal decreasing trend during 1976-1987, followed by increasing magnitude of change in the active Yellow River Delta. They attributed these changes to the modifications in the proportions of water discharge and sediment load brought by the complicated interaction between humans and the environment throughout the Yellow River drainage basin and particularly in the deltaic lowland. The study demonstrates the huge utility of satellite remote sensing coupled with GIS in investigating channel migration.

Tiegs and Pohl (2005) have examined the planform channel response of the upper Colorado River Delta (lilitrophe reach) to the recently human altered hydrology from regulation using time series aerial photography and GIS. The study provides significant insight into how floods affect the channel system which provides the very foundation for aquatic and riparian biodiversity. It highlights that the issue is growing relevance since the idea of rehabilitating the riparian and aquatic ecosystems of the Colorado River delta through intentional flood flow is gathering international interest. Thus, the study made assessment of the response of the Colorado River's planform to the fluctuations in hydrology during the period 1976-2000 and thereby assisted land managers in figuring out an appropriate flow regime for proposed rehabilitation of native riparian vegetation

Stevaux et al., (2009) describes channel confluences as sites of drainage systems with complex hydraulic interactions provided by the integration of two different flows which constitutes an environment of "competition and interaction" with gradual dynamism in flow velocity, river discharge and structure, physical and chemical properties of water and channel morphology.

Ollero (2010) assessed the channel dynamics and consequent floodplains changes in the middle Ebro River, Spain over 80 years and proposed feasible floodplain management solutions.

Dewan et al. (2017) have used Landsat images and hydrological data to quantify the channel changes in the upper (Ganga) and lower (Padma) reaches of the Ganges system in Bangladesh over 38 years (1973-2011). A soil-vegetation limit method was used to manually digitize the channel boundary from multi-temporal Landsat images. Alongwith bankline movement and computation of erosion and deposition, channel pattern was mapped by calculating channel width, area, sinuosity and Braiding index in GIS. Long term discharge data of both Ganga and Padma was analysed to determine the role of floods and mean discharge in bank erosion and accretion. Channel planform maps of the Ganges over 38 years of assessment reveal the fact that the river has experienced contraction and expansion as well as adjustment to its planform. 57km^2 of land was eroded along the right bank whereas 59km^2 of land was gained along the left bank, suggesting near balanced pattern of erosion and accretion during the assessment period. The relationship between bank curvature and erosion and accretion along the river banks seems to contradict the establish meander theory. The linear correlation between the mean flood discharge and the annual rate of bank erosion of the Ganges was found to be significant. They further state that the Padma switches its course more frequently and lateral migration is higher to accommodate excess massive flow that it receives from Brahmaputra. Unlike the Ganges, the Padma has experienced considerable erosion along both banks and the combined loss of land totals 163km^2. Further annual average discharge played greater role than floods in bank erosion.

Yao et al. (2011) have quantified areas of erosion and accretion along the Ningxia-Inner Mongolia reaches of the Yellow River from 1958 to 2008. They have used a time series of georeferenced data using a combination of digital topographic maps and Landsat TM images. Soil- Vegetation limit approach was used to delineate the channel boundaries and thus created continuous polygons representing the stream channel in each year using the image data in GIS. By overlaying the recent year river polygons over the older ones, areas of erosion and accretion were mapped and calculated. The study also evaluated the role of flow discharge, Plate tectonic movements and anthropogenic activities in bank erosion and accretion. The study revealed great spatial and temporal variability in the areas of erosion and accretion along the study reach. The Bayan Gol-Hekouzen section of the river sustained the most intensive erosion distribution, whereas the Shizuishan-Bayan section has sustained the least bank erosion.

Within India too there is a large literature on Channel change studies. The important among them which were referred during this study are the following.

Roy and Sinha (2007) have studied the confluence dynamics in the Ganga–Ramganga valley in the western Ganga plains using multi-date remote sensing images and topographic sheets for a period spanning nearly 100 years (1911–2000). The study found that new confluences have been created during this period and that the confluence points have moved both upstream and downstream on a historical time scale. Avulsions, river capture, neck cut-offs and aggradations in the confluence area have determined the confluence movements.

Midha and Mathur, (2014) have assessed the planform dynamics along a 6o km reach of Sharda River during 1977 and 2001 in the Terai region of Northern India and established that the altered dynamics is threatening the future of critical wildlife habitats in Kishanpur Wildlife Sanctuary and North Kheri Forest Division in the state of Uttar Pradesh. Thus, an improved understanding of river channel change processes is imperative for improving river engineering and environmental management as well.

Gupta et al. (2013) highlights the immense possibilities and capabilities of continuous monitoring of Earth surface and processes occurring in it with the launch of Landsat programme in 1972. Free availability of Landsat archieve from mid-2008 has immensely helped and enabled the scientists to reconstruct the Earth's changing surface and, in particular, to reconstruct the planform dynamics of world's largest rivers. In this study, they have reconstructed the planform changes in the lower reaches (particularly upstream and downstream of Farakka Barrage) of Ganga River using Landsat archives. The study revealed the fact that the river exhibits a self-organising behavior in which it periodically reaches a critical value of sinuosity at which point one or more chute cut-offs are triggered. This periodically repeating pattern is fixed locally by hard point in the geology, and the Farakka Barrage, and therefore it is much likely that this pattern will persist at least for short-term in the future. Unlike the popular local concern of potential lateral migration of the river Ganga and consequent erosion and loss of productive land, the study found that the Ganga is experiencing periodic repeating pattern in which the river is constrained to reworking old material.

Sinha and Ghosh (2012) in their study of the lower Ganga plains puts their concluding remarks as that large scale dynamics of Ganga has increased land disputes between India and Bangladesh but a long-term solution incorporating geomorphic understanding of the river have been lacking in the river management strategy. They emphasize on the significance to realize that river dynamics is a natural behavior of the river and it is crucial for us to accurately map the extent of migration and reaches prone to migration. This migration extent must be defined as the "Space" for the river and the concept of floodplain zoning must be perused seriously. They advocated that this is very crucial for not only saving large human population from the misery accompanied with river dynamics but is also important for improving the river health.

Dhanya (2014) has used Asymmetry Factor (AF) and Transverse Topography Symmetry Factor (TTSF) for different segments and sub watersheds of Anchankovil river basin of Kerela considering the course orientation to decipher the role of active tectonics in modifying the basin symmetry. It is found that basin have experienced differential tilting. SE migration of river course in upper segment and NW migration of river course in the down segment is observed. Geologic events like Western Ghats uplift, base level changes and strike slip movements have influenced the drainage development and modified the basin asymmetry.

Vijith et al. (2015) have investigated the implications of neotectonic activities in landform development and stream characteristics of the Mahe River basin through analysis of ASTER DEM based geomorphic indices. The irregular concave hypsometric curves and low integral values, derived for the whole basin indicate the old age stage of the river basin which is in the end phase of evolution. The influence of tectonic processes over the basin evolution is reflected by the undulations in the hypsometric curves. The basin is not symmetric and tilted towards the SSE direction, as evidenced by the drainage basin asymmetry factor and the transverse topographic symmetric factor (T). The abrupt changes in the SL gradient index are a proxy of the differential upliftment of the drainage basin in response to the neotectonics of the region. The geomorphic indices altogether suggest that different parts of the basin have undergone tectonic activity of varying severities with a general increasing trend towards the southern parts.

Ghosh et al. (2016) have assessed the geomorphic impacts of sand mining on an alluvial reach of Damodar River. They have identified Thalweg dynamics, bank erosion, instability of channel bars; channel bifurcation and pool-riffle sequence change as few major geomorphic impacts of sand mining. Segment and yearwise detailed morphological characteristics of the channels before and after sand mining was investigated through computation of sinousity Index, braiding index and braid-channel ratio using Friend and

Sinha;s method(1993). As measures of precaution, they recommend that mining at active flood plains, active channel especially wet pit mining and the concave side of the river channel should be avoided to prevent bank erosion. They further add that accurate geomorphic study of the nature and behavior of the area under investigation is urgently needed to develop a process-based understanding of rivers for better management of rivers and its environment.

At the regional level, our knowledge on the piedmont of Darjeeling-Sikkim Himalaya is less, general and fragmentary (Chakraborty and Datta, 2013). But being a fragile terrestrial system Darjeeling Himalaya and its surroundings have pulled the attention of scholars as earlier as the Hooker (1854). One of the first attempts of scientific study in this region was made by J.D. Hooker, (1854). During his two years of long travel (1848-1849), he traced the regional domal picture of gneisses and observed the overlying sedimentary bedding. According to him, these formations originating from glacial or glacio-fluviatile processes are cut into flat topped terraces, flanking the spurs of the mountains. He studied such stratified sand and gravel terraces, flanking the Balason River. Mallet (1874), Gansser (1964) and Bose (1990) also made detailed investigations on the geological and mineral characteristics of the region. The work of Geological Survey of India in this region began with the studies of the metamorphism of the rocks of Darjeeling area by Roy (1947) and also detail geological mapping by Ghosh (1950) and Dutta (1951) in their studies on landslips in Darjeeling observed that except the ridge top no portion of the Darjeeling town is absolutely stable. Nakata (1972) made detail survey of terraces and alluvial fans between Balason and Chel River while studying the geomorphic evolution of the mountain front of the Darjeeling Himalaya and crustal movements. Since 1950s alluvial fans of Dooars received some attention due to damage to tea gardens, railways and roadways by floods. Dutt (1966) provided one of the earliest and valuable works of the region wherein first annual records of river discharges and sediment loads in the Lish, Gish and Neora rivers were computed. Basu, Ghatowar and Ghosh studied landslides and alluvial fans in the catchments of two left-bank tributaries of the Tista, called the Lish and Gish during 1980s (Basu SR, Ghatowar L, 1986; Basu SR, Ghatowar L, 1988; Basu SR, Ghatowar L, 1990; Basu SR, Ghsh L, 1993). Chattopadhyay and Das (1992) ; Das and Chattopadhyay (1993) from the Geological

Survey of India published a general sketch of the margin of the piedmont zone, and later surveyed the Quaternary sediments of the Himalayan foreland in West Bengal to distinguish several formations in the piedmont zone.

Region east of Tista received still more attention at the end of 20th century. A preliminary concept was devised as regards the great role played by clusters of floods much higher than in the Darjeeling Himalaya in the transformation of this part of the piedmont zone (Starkel L, Sarkar S (2002), Starkel L (2004), Sarkar S (2004, . Soja R, Starkel L (2007), Sarkar S (2008). During same period Guha et al. (2006) studied the complex of high elevated terraces in the Jaldhaka river catchment. The detailed study by Starkel et al.(2008) has attempted to show the role of different factors in the present-day evolution of the Sikkimese-Bhutanese Himalayan piedmont.

Many researchers have carried out their Ph.D dissertations on the changing geomorphic and fluvial nature of the region. Among them, Sarkar (1983) conducted detailed study on Geo environmental appraisal of the upper Mahananda basin of the Darjeeling Himalaya, Ghatowar (1986) studied the fluvial dynamics of the twin basins of the river Lish and Gish, Bhattacharya (1993) carried out a comprehensive study on the problem of management of the Rakti basin, De (1998) made detail study of the fluvial dynamics of Balason river and Lama (2003) also studied the environmental geomorphology in the Balason Basin. Tamang (2013) has studied effects of boulder lifting activities on the fluvial characteristics of the lower Balason River.

Chakraborty and Datta (2013) analysed the confluence dynamics scenario of Jaldhaka-Diana River system spanning nearly 80 years (1930-2011). During this span the confluence point has moved and re-oriented both upstream and downstream on a historical time scale and new confluence points have been created by repeated shifting and migration of channels. No definite trend is observed in the movement of the confluence points.

Chakraborty and Mukhopadhyay (2014) has assessed the channel dynamics of the Diana River of this concerned region for an 85-year spanning period to unveil the nature of channel migration in terms of changes in historical bankline and centerline positions and alterations in meander geometries through numeric and graphical methods coupled with field observations to define the overall zone of channel migration for three subsequent reaches of the Diana River.

Mandal and Sarkar (2016) reveal the imprints of neotectonics on the topography, drainage and sediments along the course of River Chel in the Darjeeling- Jalpaiguri districts of North Bengal. The study gathers geomorphic signatures induced by neotectonics from both hilly terrain and alluvial fan region of the Chel basin. A semi-circular ridge delineates the cathchment of Chel River and within this structural confinement; composite drainage pattern has developed being convergent along the periphery and divergent on a butte inside. Ramp and flat structures and mylonitization of rocks were found alongwith the geomorphic neotectonic signatures. The course of River Chel as a whole has shifted westward during 1962-2007 in response to neotectonism. They add that the alluvial fan system of Chel is composed of five morphogenetic fans stacked one above another with a tendency to shrink and shift progressively upslope. All five fans differ from each other in terms of tilt, axial orientation, primary depositional surface gradient and convexity in transverse section and thus represent adjustment of fans with ongoing tectonics.

Biswas and Bannerjee (2018) have studied the effects of Odlabari Rail and Road Bridge on the channel morphology of Chel River. With the help of topographical maps, DEM (Aster and SRTM), LISS images, field-based measurement of hydrological parameters and sediment size analysis, the study reveals distinct changes in the channel planform and alteration of sediment size regime in response to channel constriction imposed by twin bridges. Simulation of the hydraulic modeling in HEC-RAS specifies the extent of flood water both with and without the bridges. The surface elevation in the upstream of the bridges is increasing in response to sedimentation whereas the surface downstream to twin bridges is experiencing erosion of floodplains induced by twin bridges is evident from the comparison of DEM images of 2005 and 2015. Higher water depth and velocity due to precipitous reversal mechanism of the Stream Energy is considered to be scouring at the foot of the bridge piers. The ends with the concluding remarks that bottleneck condition so developed has enormously increased flood probability in both upstream and downstream of the twin bridges with bank erosion and noticeable impacts on the surrounding LULC.

Very recently Saha and Bhattacharya (2019) have done a study on reconstruction of channel shifting pattern of the Torsa River on the Himalayan Foreland Basin over the last 250 years from 1764 to 2017. The study suggests that Torsa River is experiencing Channel migration of oscillatory nature rather that unidirectional of varying nature during different time spans. Channel migration of Torsa since 1964 has strewn topographic markers of beheaded old distributaries, a misfit channel system and the presence of abandoned segments all across its course. Morphometric changes in the old courses and neotectonic activity guided the gradual migration of channels whereas the mechanism of avulsion was completely driven by sedimentation-induced channel morphometric changes and occasional high discharge.

1.8 Significance of the present Research

Study on channel dynamics and its historical reconstruction holds immense significance in understanding fluvial systems. The significance of historical channel change studies lies in the fact that by understanding the past changes in river, we can compare the recent and ongoing changes in the river which helps in unraveling the factors that alter today's fluvial systems (Winterbottom, 2000). Channel instability cause damages to riverine infrastructure and also alteration of aquatic and riparian ecosystems. It also influences the site selection, design, and maintenance of structures such as highways, railways, bridges, pipelines, transmission lines, flood control works, buildings, dams, navigation channels.

Understanding the planform dynamics of river channels has important implications for maintaining biodiversity (Naiman *et al.,* 1993; Hughes, 1997; Ward *et al.,* 1999) and minimizing flood damage too (Holburt, 1984). Investigations of historical channel change provide insight into how stream channels respond to flood events. With this information, land and resource managers are able to make decisions that minimize social costs (*e.g.*, flood damage to property) and maximize the ecological benefits of flooding (*e.g.*, rehabilitating riparian vegetation and deterring the proliferation of exotic species) (Tiegs and Pohl, 2005). Thus, channel dynamism poses challenges for engineers, scientists, and managers on how to best accommodate societal needs maintaining the health of river at the same time.

Channel dynamism also bears hydro-political aspect along international borders. The highly dynamic lower reach of Ganga has become a source of land dispute between the India and Bangladesh. Thus, an improved understanding of river channel change processes is imperative for improving river engineering, environmental management and relations among the neighboring countries as well.

The present study makes an elaborate analysis of historial channel dynamics of Chel River covering topics ranging from basin morphometry,channel forms, hydraulics and pattern,channel dynamics, channel confluence dynamics, consequent erosion and accretion and then also examines the role of climate, tectonics and human activities in channel dynamism. It generates a huge geomorphological data relating to channel dynamics of an otherwise data scarce region in general and basin in particular.

1.9 Limitations.

The study suffers from limitations in assessing the overall channel dynamics scenario of the Chel River due to lack and limitation of relevant data which is common across the Dooars region. Being a border region, Survey of India topographical maps covering the area also are restricted in use and not available in public domain. The SOI toposheet covering upper catchment of Chel (78A/12) and Neora River (78 B/13) could not be assessed for the same reason. Two CWC gauging stations located along NH-31C Road Bridge on Chel River at Odlabari and Diana River at Red Bank Tea Garden records only the gauge height and data relating to that too CWC didn't provided. Therefore, quality long historical data relating to daily precipitation, discharge, sediment load and flood history could not be procured relating to selected rivers for this study.

1.10 Arrangement of the Thesis

The whole thesis has been categorized into three (3) broad parts. **Part-I** (Chapters-1,2 and 3) of the thesis consists of chapters **on Introduction, Study area and Basin Morphometry**. This part basically gives a preliminary ideas and concepts on planform dynamics, conceptual framework, related literature review, methodology applied, about the study area and morphometry of the basin. **Part-II** (Chapter-4) is titled as **Analysis** and consists of all the analysis done on Channel dynamics of River Chel based on temporal satellite maps, topographical maps, other historical records and extensive fieldworks. Relative role of neotectonics and anthropogenic interventions have also been analyzed. This chapter is the longest and thus has been presented as sub-chapters which are numbered as 4.1, 4.2,4.3,4.4,4.5 and 4.6). **Part-III** (Chapter- 5) is the **Major findings and Conclusion** chapter of the thesis. It consists of major or overall findings of the study and concluding remarks.

Summary of the study and references cited are given at the end of the thesis.