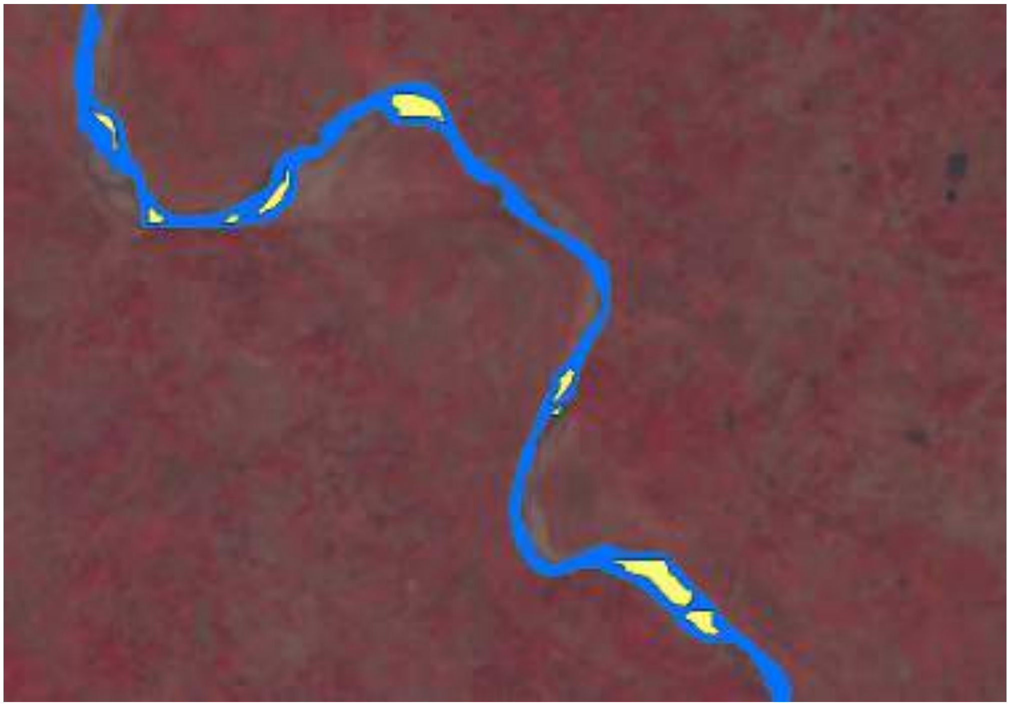
Final Report

# MORPHOLOGICAL STUDY OF BAGMATI RIVER



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# Executive Summary

Management, conservation, preservation, restoration and improvement of natural systems including river basins and other ecological assets is indeed an emerging concern. Towards this goal, amongst numerous other aspects, a scientific understanding of evolving plan forms & river channel morphology, river flow regimes and the overall dynamics of the river, as influenced by auto and allocyclic triggers, is imperative when planning the management and developmental protocol for the river basin and its water resources. Over the years, a diverse set of direct and indirect methods of observing and recording morphometric and other attributes of these rivers have been developed. Direct observation of river morphology includes physical recording of long- and short-term changes in channel cross sections and sediment transport mechanism. Though it is time consuming and expensive to record these morphological observations on ground, it helps in developing a sound physical understanding of the natural system. However, spatial and temporal scale of observation is limited for such observations. On the other hand, remote sensing technique provides observations on spatial and temporal scale depending on availability and recording of data through satellite. In both techniques, observations made are at a particular point and time but considering coverage, uniformity and high recurrence interval with advancement in remote sensing technology, indirect observations made about river morphology provide considerable amount of information about the areal extent of river functions, changes in river courses, seasonal variations in water line etc. This information can be used effectively to predict critical and stable reaches in particular system in a specified time frame, though ground survey-based observation is obligatory for detailed modelling exercises.

The present study evaluates channel bank retreat on account of erosion-deposition and river course dynamics of the Bagmati using satellite remote sensing data in GIS framework. For analyzing complete reach of Bagmati from its entrance in the Indian territory to its outfall into Kosi River features like channel area, active water area, sandbars and water bodies are extracted from satellite data (NRSC and USGS images) at an interval of about 10 years depending on availability of cloud free data. Five years identified for the comparative analysis are 1975, 1990, 2000, 2010 and 2016.

Transitions in channel area, bank lines, active water area, and sandbars have been measured for computation of channel bank retreat on account of erosion and deposition on grid scale of 10 km and results of each grid are analyzed. Analysis of river course dynamics in the form of movement of channel centerline on decadal time frame is carried out at 1 km interval and decision about critical and stable reaches are made accordingly. Some of the major findings drawn from the study are as follows:

- Chronologically incremental Land-Use changes in Bagmati River Basin have been studied and quantified using remote sensing imageries of various benchmarked years. The latter study suggests that a major part of the basin is covered with agriculture (based on land use of the year 2010), accounting for 36.19%, followed by Barren/Fallow land (31.5%), forest (24.376%), Snow/Glaciers (3.68%). Water bodies (2.6%), and Built-Up Land (0.341%). However, land-use changes reported in this study indicate that the built-up area has increased by 62.8%, whereas forest has shown a reduction of 1.12%. Considering the overlapping of scales, as discussed in Section 16.2 in Chapter 16, assessing the impact of land-use change on morphology cannot be achieved. However, based on changes in land use type, one may indirectly predict the pattern of erosion and deposition. Accordingly, it can be said that over the years, a decrease in forests and an increase in the urban area has been observed, which might have resulted in increased erosion in the basin.
- Hydrologic analysis of the observed streamflow data has been carried out and presented in detail in Chapter 9. However, and notwithstanding the analysis, it is noted that the observed Streamflow values at Benibad HO site are conspicuously lower than corresponding observations at the CWC HO site of Dheng Bridge. The latter site is an upstream site on Bagmati River and is located just 2.5 km downstream of Bhagmati River's crossover from Nepal into the North Bihar plains of India. It is noteworthy that the estimated long-term average annual flow at Benibad is significantly lower than the corresponding estimate derived for the HO site at Dheng Bridge. Estimate of Bhagmati bankull capacity has been reported to be around 560 cumecs (Rastogi et al, 2018).

  Understandably, therefore, higher than median sized flows would show a hydrodynamic tendency to spread out across the adjoining plains that, importantly, are also dotted with 'taals' and 'chaurs'. An accompanying consequence of the latter morpho-hydrodynamic reality being a reduced and sluggish hydrodynamic delivery of river floodflows at Benibad and marginally at Hayaghat as well. This is despite the commonly held understanding that the reach of Bhagmati between Dheng Bridge and Benibad should also be copiously supported by effluent base flow accretions. It is therefore only rational to expect that the Bhagmati riverflow at Benibad should be significantly higher than those observed at Dheng Bridge – hydrological necessity that is also aided by the increase in the drainage area of Bhagmati at Benibad. The aforementioned uncharacteristic observed diminishing hydrological responses may be attributable to a range of influences and are discussed in Chapter 9.

Given that the frequency analysis has been attempted based on observed but highly regulated streamflows, the derived inferences are not likely to be representative or even a realistic capture of the underlying Hydrological as well as the Hydro-morphological reality. Discretion is therefore advised, and the results of frequency analysis may be used only in the limited context of deriving gross morphological inferences and may not be extrapolated for applications such as design flood estimation.

- In order to promote a better understanding of Bhagmati River's morphological planform attributes such as sinuosity, radius of curvature, braiding and planform, conventional indices as are commonly available in published literature have been used for their quantification. Further, Improved Planform Indices (IPFI) and Modified Braiding Indices (MBI) as proposed by Parmar and Khosa, 2017, have also been used for comparison and objectivity.
- Study based on the conventional Indices suggests that the average sinuosity for the entire stretch of Bagmati River is 1.5, whereas the radius of curvature varied between 0 to 0.33 km. Similarly, numerical values obtained for the 'conventional' Braiding Index suggest that braiding in Bhagmati River is higher in those selected reaches that span from grid 12 to grid 44. Additionally, improvements over existing Plan Form Index and Braiding Index based on IPFI and MBI respectively have also been suggested.
- Understanding of River Course Dynamics has been carried out at 1 km interval and it has been seen that river has experienced changes in its course at a few locations. It has been seen that river has experienced changes in its course at a few locations. Those locations are concentrated in the middle stretch of the river (Near chainage 37-57).
- From the analysis of confluence points, confluence of Kosi River with Bhagmati is by and large observed to be stable without a significant shift being observed over the last 40 years.

An exception to this, however, is indeed observed over the interim 15 year period between 1975-1990.

- During the period 1975-1990, the river channel area shows significant influences of fluvial processes of erosion and deposition. During the latter period, significant level of areal retreat is observed. Specifically, the study shows the areal extent of erosion to be 33.97 sq. km larger than corresponding changes on account of deposition. Further, over the period 2000-2010, the deposition is markedly higher than erosion with net deposition being observed to extend across an area of 56.16 sq. km over the latter period. During the years from 2010-2016, in contrast, areas that have witnessed erosion and deposition seem to balance out with erosion exceeding deposition areas by a mere 3.43 sq. km.
- A few locations, distributed over the reach between Gaihati to Baheri, (chainage 100 km to chainage 161 km), have been identified where there is the likelihood of transition towards neck cut-off/ox-bow formation/reach abandonment in the foreseeable future. The coupled approaches of remote sensing based image analysis together with simulation studies have been used to identify morphologically active/critical reaches and emphasis is directed at reaches corresponding to chainage 20-24 (Near station Barahi), Chainage 101-106 (Near Benibad Station) and Chainage 129-134 (Near station Hayaghat) as being particularly vulnerable.
- Based on the physiography of River Bagmati, the entire stretch is divided into three zones and results of the morphological study are juxtaposed to discriminate between stable reaches and those that are indeed active.

The study confirms that observed rates of channel bank retreat on account of erosion and deposition are conspicuously significant at a few locations along Bagmati and movement of channel centerline is also significant. Detailed results have been presented in subsequent parts of the report. Most importantly, attempt has been made to define various terms such as channel centerline, shifting, river course dynamics, morphologically stable, active, and critical reaches which are commonly used in field of river morphology and have not been defined in a scientific manner in previously carried out morphological studies in Indian context.

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# Chapter 1 Introduction

## 1.1 General

Many natural sculptors shape the earth's surface by working together; among which, rivers, contributing to processes like weathering, erosion, transportation and deposition and moulding the contours of the earth much more than other natural factors, are of prolific importance (Marsh and Kaufman, 2013; Twidale and Campbell, 2005). River's shape is determined by these processes which are in turn functions of natural characteristics of river basin such as topography, geology, soil properties, climate as well as human-induced changes in land use and flow regimes of the river (Dominick and O 'neill, 1998). Other factors such as tectonic activities, lithology, glacial outbursts, landslides, vegetative factors are also responsible for the genesis of changes in river shape. River morphology; a special fluvial subsector of geomorphology (the science of landforms), deals with the shapes and forms of river channels and adjoining areas and changes in them on account of erosion, transportation and deposition of sediments by flowing water along with the origin and formational processes of the rivers (Garde, 2005).

River Morphology is the subject of great challenge as each river on the earth is unique (CWC, 2009) on account of unique combinations of the above-mentioned factors that are responsible for the shape of the river. Based on such combinations of contributing factors, different patterns and shapes of rivers (meandering, braided, straight, etc.), drainage basins (fern shaped, fan-shaped, etc.) and drainage networks (dendritic, parallel, rectangular, etc.) are commonly observed (Leopold and Wolman, 1957; Murthy, 2002; Matsuda, 2004). River channel behaviour often needs to be studied for its natural state and response to human-induced changes in such behaviour (Chang, 2008). While natural states are unique, human interactions with different rivers are also unique because of their geographical extents, hydrological enormousness and various demographic, socio-economic factors. This makes the morphological study of each river basin more critical and a meticulous requirement.

The study of morphological behaviours of the rivers is also essential from basin planning endeavours considering elevated risks from floods. Several types of research have linked floods with sediment transport process altered by hydraulic structures, which on the other hand, also threatens, destabilizes such hydraulic structures and disrupts their operations (Gharbi et al., 2016).

In alluvial rivers, cross-sections may face severe morphological changes during flood events due to sediment transport, log jam, rock jam, etc., which significantly alter the water levels. This implies the necessity of incorporation of calculated or estimated morphological changes to the flood risk assessment (Neuhold et al., 2009). The morphological study can provide information on the significant river processes and associated hazards and the river's response to past floods and control efforts (Field et al., 2014).

Challenges in a morphological study are conspicuous because of the need for knowledge of related sciences such as physics and geology, hydraulic engineering and hydrology, climatology and landscape ecology (Mangelsdorf et al., 1990). Special impulses of hydraulic engineering experiments obligate morphological studies. In recognition of the fact that every river engineering effort must be based on a proper understanding of the morphological features and their possible responses to the imposed changes (Chang, 2008); and that the morphological studies are a prerequisite of flood management issues; morphological studies are essential for sustainable river management and also for restoration and mitigation activities.

## 1.2 Remote Sensing and GIS for morphological study

Changes in river morphology can be studied using physical, analytical and numerical models (Cao et al., 2002; Chang, 2008); however, they can be complicated and time-consuming. Also, the solutions obtained from these traditional techniques are time and space-specific (NIH, 2013). Thus when the changes take place over considerable lengths and are slow, it is advantageous to use remote sensing techniques capable of providing information through time and space.

The remote sensing technique derives information about the earth's surface without physically coming in contact with it. It involves (i) making observations using sensors mounted on platforms; (ii) recording the observations on a suitable medium; (iii) transmission of data to the ground station; (iv) corrections to data to remove geometric and radiometric distortions (pre-processing); and (v) generation of output in the form of satellite imageries, the photographic enlargements with appropriate rectification (Garde, 2005)

These satellite imageries may be effectively used to evaluate the shifting characteristics of rivers quickly and cost-effectively, and they can also be used for an expedient and reliable demarcation of rivers at suitable time-space intervals to establish the stability or otherwise of their channels. As a special advantage, areas inaccessible for data collection can also be studied using remote sensing methods (Garde, 2005; NIH, 2013). Knowledge and hands-on experience of using image processing software and platforms like ERDAS and Arc-GIS is core for remote sensing data in morphological studies.

General Guidelines for Preparing River Morphological Reports, prepared in April 1991, have been revised to incorporate remote sensing as an advanced technology in morphological computations (CWC, 2009). Several river morphological studies incorporating satellite-based data have been reported in global literature in recent times. Davinroy et al., (2003) studied the morphology of the Kaskaskia River, a tributary of the Mississippi River, through aerial photography and USGS quadrangle maps. Mohammadi et al., (2008) determined the morphological changes of the Gorganrud River in Iran using satellite images of Landsat, ETM+. Legleiter (2010) studied the morphology of the Snake River in Wyoming, USA. Other case studies of different morphological aspects like coastal effects, aquatic habitat conditions, anthropogenic effects on the morphology of river etc., studied using remote sensing and GIS approach are also reported in the literature (Ghoshal et al., 2010; Legleiter et al., 2004; Seker et al., 2003; Tamminga et al., 2015). Morphological behaviour of the River Brahmaputra in Bangladesh has been studied in (Alam et al., 2007; Bhuiyan et al., 2015; Islam et al., 2017; Uddin et al., 2011)

A few studies for the morphological behaviour of Indian rivers are also based on a remote sensing approach. Manjusree et al. (2013) used remote sensing for morphological study of various reaches of River Brahmaputra and Ganga. Pan (2013) studied the morphology of various river courses in the Bankura District of West Bengal. Sarkar et al., (2012) studied the morphology of the Brahmaputra River in the Assam State of India using remote sensing techniques.

## 1.3 Objectives of the study

The present study aims at studying morphological aspects of the Bagmati River using remote sensing techniques. The broad objectives of the study are:

1. To study morphological behaviour of the River Bagmati
2. To estimate erosion and deposition (areal retreat) on a decadal time scale
3. To analyze the dynamics of the river course
4. To identify stable and critical reaches in the river.

# Chapter 2 Review of Literature

## 2.1 Overview

Several processes are responsible for complex and time-varying phenomena of river evolution which in turn drives the river morphology. Among these, processes such as sediment transport and erosion-deposition are predominant and carry much weightage than others. Multiple methods are available to assess the impact and rate of these processes. They can broadly be categorized into; i) field observation based and ii) remote sensing-based methods. Both methods have their advantages and disadvantages. The field observation-based methods involve field measurements for estimating linear rates and volumes of erosion/deposition and morphological cross-sections to track the changes in channel profile over a period (seasonal and annual scale). In contrast, remote sensing-based methods engage with analysis of the archival information available at various scales. The archival sources can be conventional survey maps (Toposheets), aerial photographs and/ or satellite images.

In the present era, remote sensing and GIS play a key role in geomorphological studies for various reasons. Availability of multitemporal and high-resolution data allows the user to analyze the river channel settings, shifting of courses, formation and abandonment of oxbow lakes, the pattern of erosion and deposition etc., which otherwise would require the deployment of significant resources. More importantly, coupling information drawn from remote sensing observations at a wider spatial scale with ground-based observations captured at the local scale is useful to arrive at a more rational outcome.

The literature review presented in this chapter includes the morphological indices that are commonly used to present a quantitative characterization of the underlying morphometrics as well as to present a qualitative characterization of the system's morphological behaviour. The review also touches upon a few case studies that highlight the use of remote sensing and GIS in river morphology and morphological studies focusing specifically on the Bagmati River System.

## 2.2 Morphological Indices

### 2.2.1 Meandering Parameter

A meandering river is the one which flows over a broad plain rather than just being confined to a narrow valley. The river turns its course on both sides of the bank following a looping and winding path along its way. Meandering starts when any river reaches its mature (old) stage, the lateral (sideways) erosion & deposition is greater than vertical erosion & deposition and thus a winding course develops due to the deposition of silt on one bank and erosion along the other bank. There are several indices that address the meandering behaviour of the river. Some of the notable contributions are discussed here.

1. Mueller's Sinuosity Index

   Mueller's sinuosity index quantifies the percentage of a stream channel's departure from a straight-line segment on account of hydraulic factors within the valley or topographic interference (Ezizshi, 1999). The index was redefined to incorporate hydraulic sinuosity and topographic sinuosity.

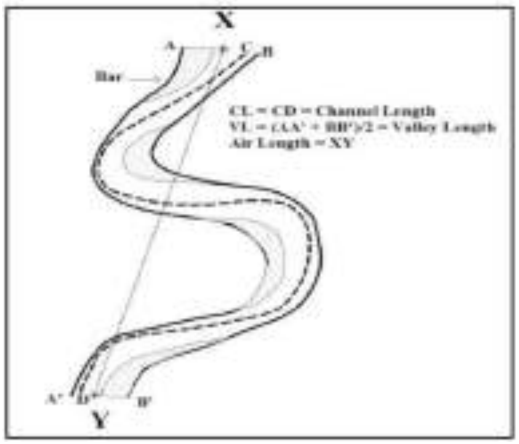



Figure 2-1: Mueller's Sinuosity Index

CL = the length of the channel (thalweg) in the stream understudy

VL = the valley length along a stream, the length of a line that is everywhere midway between the base of the valley walls.

Air Length = the shortest air distance between the source and mouth of the stream.

CI (Channel Index) = CL / Air

VI (Valley Index) = VL / Air

HSI (Hydraulic Sinuosity Index) = % equivalent of (CI – VI) / (CI – 1)

TSI (Topographic Sinuosity Index) = % equivalent of (VI – 1) / (CI – 1)

SSI (Standard Sinuosity Index) = CI / VI

2. Sinuosity Index (Friend and Sinha, 1993)

It is calculated as the length of the stream divided by the length of the valley. A perfectly straight river would have a meander ratio of 1 (it would be the same length as its valley), while the higher this ratio is above 1, the more the river meanders. According to Friend and Sinha (1993), the sinuosity parameter P is defined as,

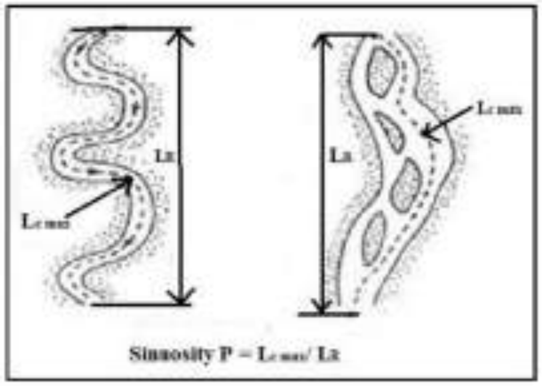



Figure 2-2: Friend and Sinha (1993) Sinuosity Index

$P = L_{cmax}/L_r$

Where $L_r$ = overall length of the channel belt and $L_{cmax}$ = mid-channel length for same reach or mid-channel length of the widest channel. It is possible to estimate this index using aerial photographs and satellite images.

### 2.2.2 Braiding and Planform Parameters

Rivers that have lots of channels that continually split and join are called braided rivers. These rivers are usually wide but shallow and characterized by steep slopes and riverbanks that accelerate erosion processes. According to Leopold and Wolman (1957), the braided river flows in two or more anastomosing channels around alluvial islands. Brice (1964) highlighted the significant impact arising from differences between mid-channel bars within braided rivers and regions of the floodplain exposed to channel diversions and avulsions. Schumm (1977) differentiated braided rivers at low stages with islands of sediment supporting temporary vegetation from the multiple-thread rivers that have branches with individual channel patterns. Bridge (1993) reviewed the existing definitions of the braided pattern and raised the concerns related to the difference between mid-channel bars and islands, the precise nature of the interaction between flow stage and bars or islands and the differences between the mechanisms of channel divergence that lead to two terms braiding and anastomosing.

There are several definitions and indices developed by researchers to characterize braiding phenomena in the past. A few of the important indices are discussed here

1. Braiding Index (Brice, 1964)

   Braiding index defined by Brice (1964), is

$$Braiding\ Index = 2 * \frac{\sum L_i}{L_r}$$

Where, $\sum L_i$ = length of all islands/bars in a reach

$L_r$ = length of reach measured midway between the banks

2. Braiding Index (Friend and Sinha, 1993)

   Braiding index is defined as the ratio of $L_{ctot}$ and $L_{cmax}$ where $L_{ctot}$ indicate the sum of mid-channel lengths of all the segments of the primary channel in a reach and $L_{cmax}$ indicate the mid-channel length of the widest channel through the reach.

$$Braiding\ Index = \frac{L_{ctot}}{L_{cmax}}$$

3. Plan Form Index (Sharma, 1995)

   Plan Form Index (PFI) developed by Sharma (1995) focusses on the degree of braiding in a highly braided river. Index values reflect the fluvial landform disposition at a specified water level. Lower values of the index indicate a higher degree of braiding.

   Planform Index (PFI) = $\frac{\frac{T}{B}}{N} \times 100$

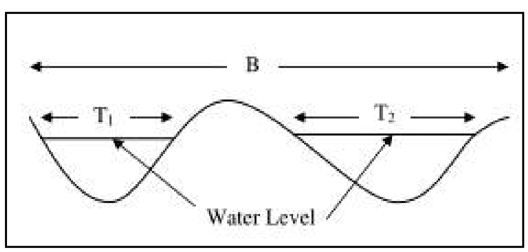



Figure 2-3: Planform Index (Sharma, 1995)

Where,

T= flow top width(T1+T2), and B = overall width of the channel,

N = number of braided channels

## 2.3 Remote Sensing and GIS in morphological studies

There are several studies which signify the importance of remote sensing and GIS techniques in the field of water resources management which can further be classified into various sub-themes such as water resources assessment, planning and impact analysis, monitoring and evaluation. Use of remote sensing images for land-use land cover mapping has also evolved in the last two decades. This land-use land cover mapping exercise when focused on the river and surrounding environment can also be used to draw inferences related to morphological changes/ evolution of river. Several studies have already been carried out in the Indian and global context. Some of these studies are discussed here.

A study carried out on the Subansiri River in Assam for investigating bank line migration by Goswami (1999) utilized topographic maps, aerial photographs, and satellite imageries of 50 years (1920-1970). It was reported that the high discharge of sediment load may have contributed to the formation of mid-channel bars which ultimately resulted in obstruction of the flow and associated bank erosion.

Karwan et al (2001) utilized aerial photographs and Landsat TM images for estimating land use changes and river channel morphology in the Venezuelan Andes, Jawra. It was observed that the rate of change in channel morphology was significantly high at the most deforested sites. Spatial variation in channel geometry expressed in the form of shape and channel were also important drivers of river morphology.

In Indian context, significant contribution has been made by a study from Kale et al (2002) which expresses the rich fluvial diversity of the Indian region. It also highlighted the gaps in the fluvial research focus on process dynamics. It argued for field-based studies for improving the understanding of the channel migration, avulsion and mechanisms of bank erosion, modes of meander development, and bedload transport. Another study by kale et al (2003) emphasized that the role of annual floods is more significant than occasional large floods in the Ganga-Brahmaputra Plains. Study also revealed that geomorphic effects of floods on peninsular rivers are modest.

Mani (2003) investigated the bank erosion and deposition pattern in Majuli island situated in the middle of the river Brahmaputra using satellite images from IRS satellites for the time frame of 1991-1998 and noticed that except for the 1997-1998 severe erosion was observed at the bank.

Chu et al (2006) used multi-temporal remote sensing data of Landsat MSS and TM for analyzing the patterns of erosion deposition of the modern Yellow River subaerial delta, China and juxtaposed with sediment discharge data. It was observed that cumulative increment in delta area is directly correlated with the cumulative Yellow River sediment discharge.

Evans et al (2007) analyzed the upstream channel changes after dam construction and its removal in Huron River, Ohio using remote sensing and GIS techniques. It was found out that dam construction resulted in reduction of the gradients and transport capacity upstream of the reservoir and ultimately resulting in no net downstream translation of the sediment wave.

Das (2007) analyzed morphological changes in the Barak River, India by utilizing the data of six different years from various sources such as toposheets, Landsat MSS, TM, and IRS LISS-II images. It was reported that overall trend indicates the intense shift of the river towards northward direction because of the uplift of the southern part of the river valley.

Surian et al (2009) examined the morphological effects of different channel-forming discharges in Tagliamento River, Italy by studying aerial photographs and ground truth information which include cross-section survey, grain-size analysis, and observation of painted sediments. It was found that bank erosion is a prominent process and accounts for tens of meters up to more than 100 m of erosion, associated with flood events with recurrence interval between 1 year and 12 years. Discharges equal to 20– 50% of the bankfull discharge are responsible for channel formation, whereas the bankfull discharge is a causal factor for the formation of low bars in Tagliamento River.

Ahmed & Fawzi (2011) assessed the meandering and bank erosion of the River Nile and its environmental impact on the area between Sohag and El-Minia using field observations, Landsat MSS (Multi-Spectral Scanner), Landsat Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) images. It was highlighted that presence of dam has resulted in significant change of sediment transport regime and system is moving towards new equilibrium which may result in deterioration of ecosystem on the downstream side of the dam.

Sarkar (2012) analyzed the bank erosion and deposition patterns along the Brahmaputra River for a period of 18 years (1990-2008) using remote sensing and GIS. It was noticed that both banks have experienced significant erosion whereas deposition was limited to few locations. The study also marked the critical reaches that had undergone maximum erosion.

Yousefi et al (2016) studied the morphometric parameters of Karoon River, Iran using remote sensing images, topographical and geological settings, etc. Sand Mining activity has significant role in decreasing the flow length by increasing the probability of cutoff events. The study also brought out that dam building and land use change have an important role in decreasing channel width in the study reach of the Karoon River.

## 2.4 Morphological studies on Bagmati River

Reviews on morphological studies on the Bagmati River is presented in this section.

Sinha and Friend (1994) have proposed the classification scheme for the rivers based on the source area characteristics. They have proposed four different river systems: (i) mountain-fed, (ii) foothills-fed, (iii) plains-fed and (iv) mixed-fed rivers. Among these classes, Bagmati fall in the foothills fed category, which means that it originates in the lower foothills, bordering the alluvial plains, and has smaller area and discharge, and with a much lower ratio of upland source area to alluvial area. They have found that the main channel belt of the Bagmati is braided in its upper two reaches and then becomes unbraided and of very variable sinuosity (1.0-2.41). Also, the mean annual flood estimates for both stations (Dheng Bridge and Hayaghat) are distinctly greater than the bank full estimates, and this implies that overbank flooding (spilling) is a frequent occurrence.

Jain and Sinha (2003) have prepared a historical record of channel relocation of the Bagmati river system from the year 1770 to 2000. The preparation of the drainage network is done with the help of maps and satellite data. The planform channel pattern has reflected the avulsion event, which includes eight major and several minor events. In general, Avulsions occur in the river due to channel slopes that are much less steep than the slope that the river could travel if it took a new course. The plausible reason behind the avulsion is listed as hydrological characteristics, sedimentological readjustments and neotectonics tilting.

Shrestha and Tamrakar (2012) have conducted a morphological analysis of Bagmati River reveals that meander wavelength, meander belt width, sinuosity and radius of curvature show the fluctuating trend of variation from upstream to downstream segments along the main stem river. There established a relationship (weak) between geological terrains and morphological parameters.

Overall, it can be said that very few studies focusing on the morphology of River Bagmati have been carried out in the recent past. However, hardly any of them address the basin-scale approach. In addition, the use of hydrological data in present form (highly altered flow regime) to lay down the foundation for such studies may not be appropriate.

## 2.5 Conclusion

The review of pertinent literature indicates that river morphology is studied and researched in both global and Indian context. Review of literature also highlights the role of remote sensing and GIS in morphological studies, outcomes, and its linkages with the ground observations. For Indian rivers, some of the studies emphasized on the usefulness of field-based observation data whereas studies based on remote sensing expressed the morphological attributes such as the bank erosion rate, eroded area, and deposition, if any, observed at spatial scale. The outcomes from remote sensing-based studies are generally expressed in areal form but miss out on volumetric analysis. Though few studies related to morphological understanding of Bagmati have been carried out, and even fewer for the Indian territory, it is difficult to utilize them for the present study. However, overall review of literature both in global and Indian context can be used as a basis to come up with more rational approach for understanding the morphological behavior of river at the basin scale.

# Chapter 3 Bagmati River: Salient Features

## 3.1 Physiography

The river Bagmati, one of the perennial rivers of North Bihar, originates in the Shivpuri range of hills in Nepal. It has several small tributaries such as Lalbakeya, Lakhandei, Darbhanga-Bagmati, old Kamla and Hasnpur Bagmati. The Bagmati river basin lies in the Gangetic plains, and this region is frequently flooded. The study area is shown in Figure 3-1. The salient feature of the study area is collected from the Source. Flood Management Improve Support Centre (FMIS), Bihar and presented in Table 3-1.

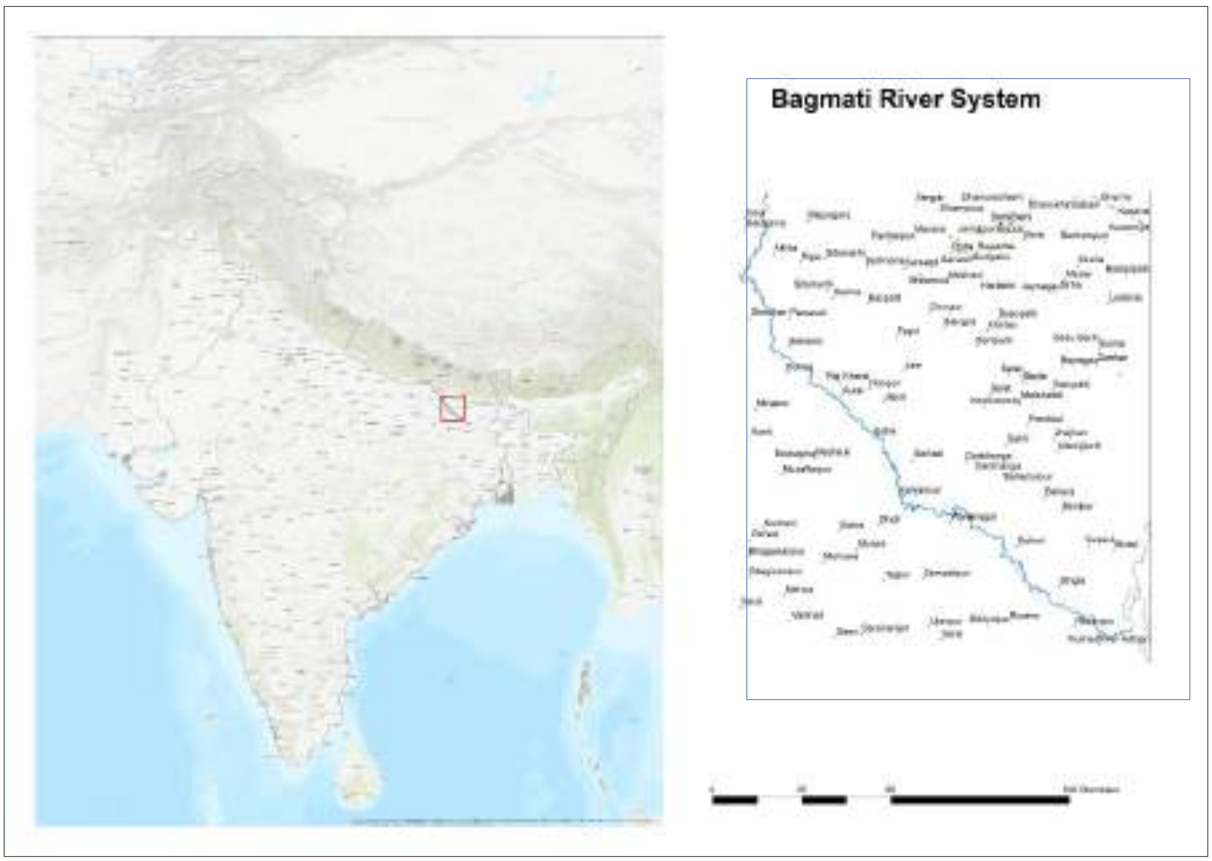



Figure 3-1: Location Map of Study area

River Bagmati originates at Shivpuri range of hills in Nepal at latitude $21^{o}47^{'}$ N and longitude $85^{o}17^{'}$ E, 16 km North-East of Kathmandu of 1500 m above MSL. It enters Indian Territory in Bihar in the village Showwatia in Sitamarhi district, nearly 2.5 km north of Dheng Railway Station. The main course of the river in its first reach inside Indian territory between Indo-Nepal border to

Khoripakar crosses Samastipur- Narkatiaganj railway line near Dheng Railway Station. Silting has taken place in this reach, and three channels have formed upstream of this railway bridge. These channels join to form the parent channel near village Joriahi at about 2.5 km south of the railway line. The Bagmati river in this reach flows towards the south for nearly 15 km, up to Khoripakar. River Lalbakeya outfalls into the mainstream from the right bank at this location.

Table 3-1. The salient feature of the basin

| S. No | Features | Details |
|---|---|---|
| **1** | Total Drainage Area | 14,384 Sq Km |
| **2** | Drainage Area in Bihar | 6500 Sq Km |
| **3** | Population in Bihar | 55.30 Lakh |
| **4** | Average annual Rainfall | 1255 mm |
| **5** | Total length of main river in Bihar | 394 Km |
| **6** | The cropped area in Bihar | 5362 sq Km |

## 3.2 Weather and Climate

The Bagmati drainage basin in India forms part of the Gangetic plains and situated in the direct path of the tropical depressions which form in the Bay of Bengal during the monsoon season and travel in a north-westerly direction. As such, nearly 85 per cent of the annual rainfall occurs in the monsoon period between June to October. Nepal's catchment contributes a significant portion of the runoff in the Bagmati and the Adhwara group of rivers. Rainfall in different districts of Bagmati river system is shown in Table 3-2.

Table 3-2. Average rainfall in the study area

| Sr. No. | Name of District | Average annual rainfall (mm) | Average monsoon rainfall (mm) (June to October) |
|---|---|---|---|
| 1 | Champaran | 1392 | 1193 |
| 2 | Muzaffarpur | 1184 | 1009 |
| 3 | Darbhanga | 1250 | 1044 |
| 4 | Sitamarhi | 1184 | 974 |

(Source. Comprehensive Plan of Flood Control of Bagmati prepared by GFCC in March 1991)

The hydrology of the rivers in this basin in the upper portion inside India up to Hayaghat is very complex on account of natural diversion of a substantial part of Bagmati flows into Burhi Gandak through Belwadhar and heavy spilling in other small rivers including rivers of the Adhwara group in the entire middle reach of this basin. The river regime above Hayaghat is complicated because of the high sediment load in the river flow and nearly flat terrain. The hydrology beyond Hayaghat station is relatively less complicated than the upstream because the flow is mostly confined between embankments on both sides up to Phuhia and later in joining the Kosi near Badalaghat,

## 3.3 Type of Soil in the Bagmati River Basin

The Bagmati River System and the Adhwara group of river systems are part of the Gangetic plain which occupies a structural trough of the earth's crust. Most of the rivers of this basin originate from Shivalik range of hills which is the southernmost range of the Himalayas. The rocks of this region consist of Pliocene, and Pleistocene deposits are the group (1 to 12 million years old) of incredibly fragile rocks. Therefore, the rivers deeply incised disintegrate fragile young rocks quickly and carry a considerable amount of sediment of the valley. The coarsest material, the boulders and gravels, are dropped off the Himalayas' foothills, and in the Terai region of Nepal, the vast quantities of coarse to excellent material are carried down into the plains in the Indian Territory. The terraces in the Terai comprise of the clay, sand and gravels. The hills at the flanks comprise conglomerates and thick beds of sand, rock and shoals.

There is a thick alluvial deposit, being a part of the Gangetic alluvial plain in the lower down in the Bagmati flood plain. The alluvial deposition is seen to be progressively finer-textured as one traverse from north to south. The soils along the northern boundary are light and absorb water quickly while soils in the south are comparatively heavier and retain water. This feature is modified by rivers, which carry coarse sediments, and deposits the same on both sides in their flood plain. Thus, at Phuhia deposits of medium sands are encountered on both sides of the river Kareh even though the neighbouring soil is quite fine. By and large, it can be said that the geology of the Bagmati catchment is unstable and susceptible to heavy wear and tear, bringing increased sediment loads, especially compared to the southern non-Himalayan rivers, which are relatively more stable, because of hard basaltic or granite formation of the concerned regions.

## 3.4 Socio-Economic Aspects

The population density in this basin is nearly 1551 person per square kilometers, whereas the density of the population for the Bihar is 1102 persons per square kilometers (Tiwary, 2015). According to Niti Aayog (2011), India, India's average population density is 382, which indicates that this basin is very densely populated despite the area prone to frequent flooding. About 90% population resides in the rural area and only 10% in the urban regions. Nearly 85 % of the people constitute the workforce engaged in agriculture, the presence of the alluvial soil, which is very fertile appears to be the reason for this high density of the population.

## 3.5 Water resources development on Bagmati River

The main tributaries of Bagmati River are Lalbhekya, Lakhandei and Adhwara group of rivers. An increasing amount of water supposed to flow through Hayaghat is spread in the surrounding region with a topography like a plate. In this region flood water of Bagmati intrudes in its tributaries and cause flood situation in their catchments. This typical topographic feature put villages located alongside Bagmati between Dheng to Hayaghat into dangerous flood situation. Without flooding the region in between, Bagmati cannot move ahead to Hayaghat. So, this area is prone to the flood.

The easiest way one can think to tackle flood situation is a construction of embankment along the channel. It protects alongside villages by establishing a safe zone. And that is what is being done since last 50 years under various irrigation and flood control schemes. The total length of the Bagmati river is 394 km in Bihar. Currently, embankment length of around 450 km has been constructed or is under construction on both the banks of Bagmati. Still, after spending thousands of crores, construction of embankment is a controversial issue. Barriers above Sitamarhi –Sheohar road crossing up to Indo-Nepal border were constructed in 1979-80 and are known as Bagmati afflux bund. The left afflux bund is around 50.5 km, right afflux bund is approximately 32.8 km, and Bargania ring bund is 7.2 km. Embankments below Sitamarhi –Sheohar road crossing and just upstream of Muzaffarpur-Sitamarhi road crossing have also been constructed. The left embankment from Hayaghat to Phuhia (around 73 km) and the right embankment from Surmarhat to Badlaghat (about 145 km) on river Kareh were constructed in 1956 for a design discharge of 1416 cumec. Later on, these embankments were strengthened in 1981 for a design discharge of 3695 cumecs. The embankments on the Bagmati river is shown in Figure 3-2.

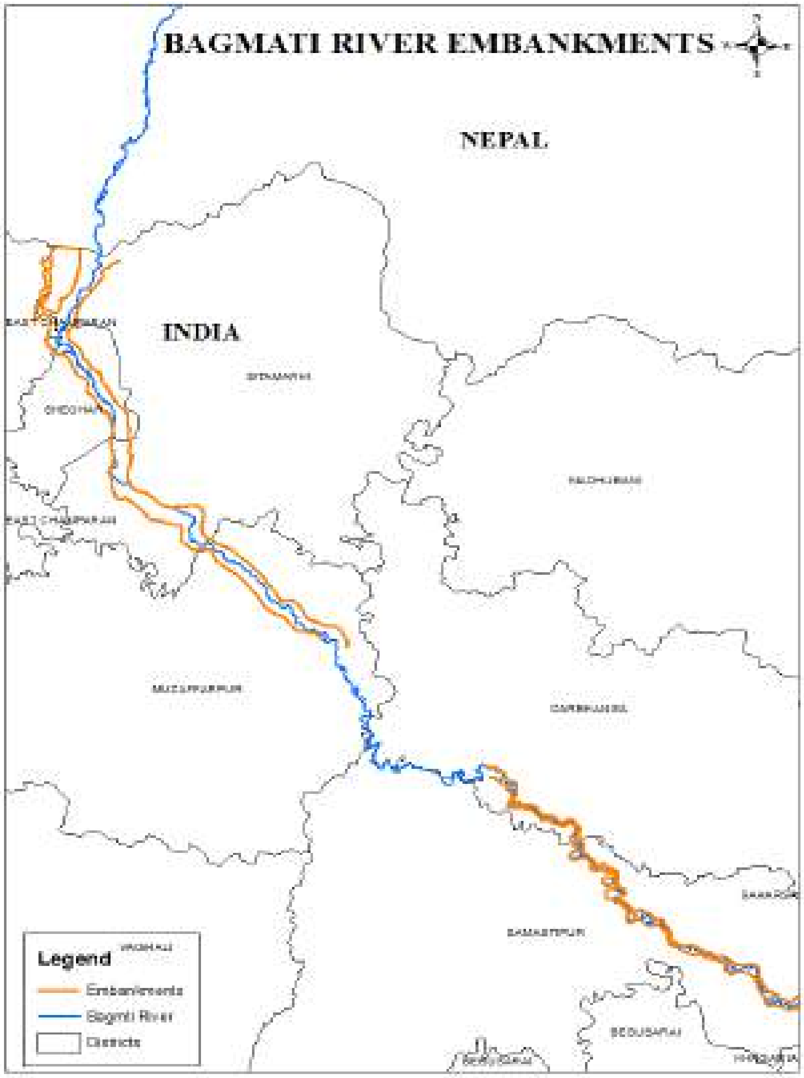



Figure 3-2. Existing Embankments along Bagmati River

## 3.6 Reported issues

Major issues reported in the Bagmati Basin is related to frequent flood and quality of water. The topography of the catchment in India is significantly flat. The huge sediment load carried by the river particularly in monsoon season is deposited by the river, thus raising the bed levels and flood plains of the river. This results in the spillage of floodwaters in large areas even in case of moderate floods due to the reduced capacity of the channel.

The embankments further deteriorate the flood issues of the region. After construction of embankment water from local subsidiary streams cannot enter in the mainstream. It flows in a backward direction or moves parallel to the mainstream but outside the embankment, i.e., through the safe zone (Mishra 2010). In both the situation it submerges surrounding villages.

# Chapter 4 Geology of the Bagmati River Basin

## 4.1 Introduction

This chapter analyses the Bagmati/Kosi River basin's prominent topography, geomorphology, and geology features and their variations across the spatial domain. Physiography, rainfall and temperature patterns, geomorphology, and geology are essential characteristics of the basin that are crucial for addressing water resources-related issues and the type of habitation. These parameters are vital for watershed management, flood and drought estimation/management, waterlogging, erosion estimation/mitigation, identification of recharge zone, hydropower system, rainwater harvesting structure, and other structural development. This chapter provides a discussion on topographic characteristics, followed by discussions on geological and hydrogeological formations.

## 4.2 Topographic Characteristics

The Bagmati/Kosi basin's topography varies between the steep Himalayas to near flat in the middle and lower segments, but the area under the Indian territory is mostly flat. The river enters the Indian Territory in Bihar in the village Shorwatia in Sitamarhi district, nearly 2.5 km north of Dheng Railway Station. The Bagmati basin's topography is broadly classified into two groups, i.e., hilly region and plains and valleys. After the river exits Nepal and enters the Indian state of Bihar, the slope of Bagmati decreases to a drop of 0.87 meters per kilometer.

In contrast with the basin's upper reaches, where the river drops 10 meters in a 1-kilometre stretch, the lower basin's flatter gradients give the Bagmati a highly dynamic character. The elevation varies from 70 m at Dheng Bridge to 44 m at Hayaghat. The average topographical characteristics of the Bagmati River course are indicated in Table 4-1 and spatial variation of elevation in DEM, as shown in Figure 4-1.

Table 4-1. Topographical characteristics of the Kosi/Bagmati basin

| | |
|---|---:|
| Area ($km^2$) | 32166.39 |
| Minimum elevation (m) | 22 |
| Perimeter (km) | 1911.435811 |
| Mean slope (Degree) | 1.81 |
| Maximum elevation (m) | 2913 |

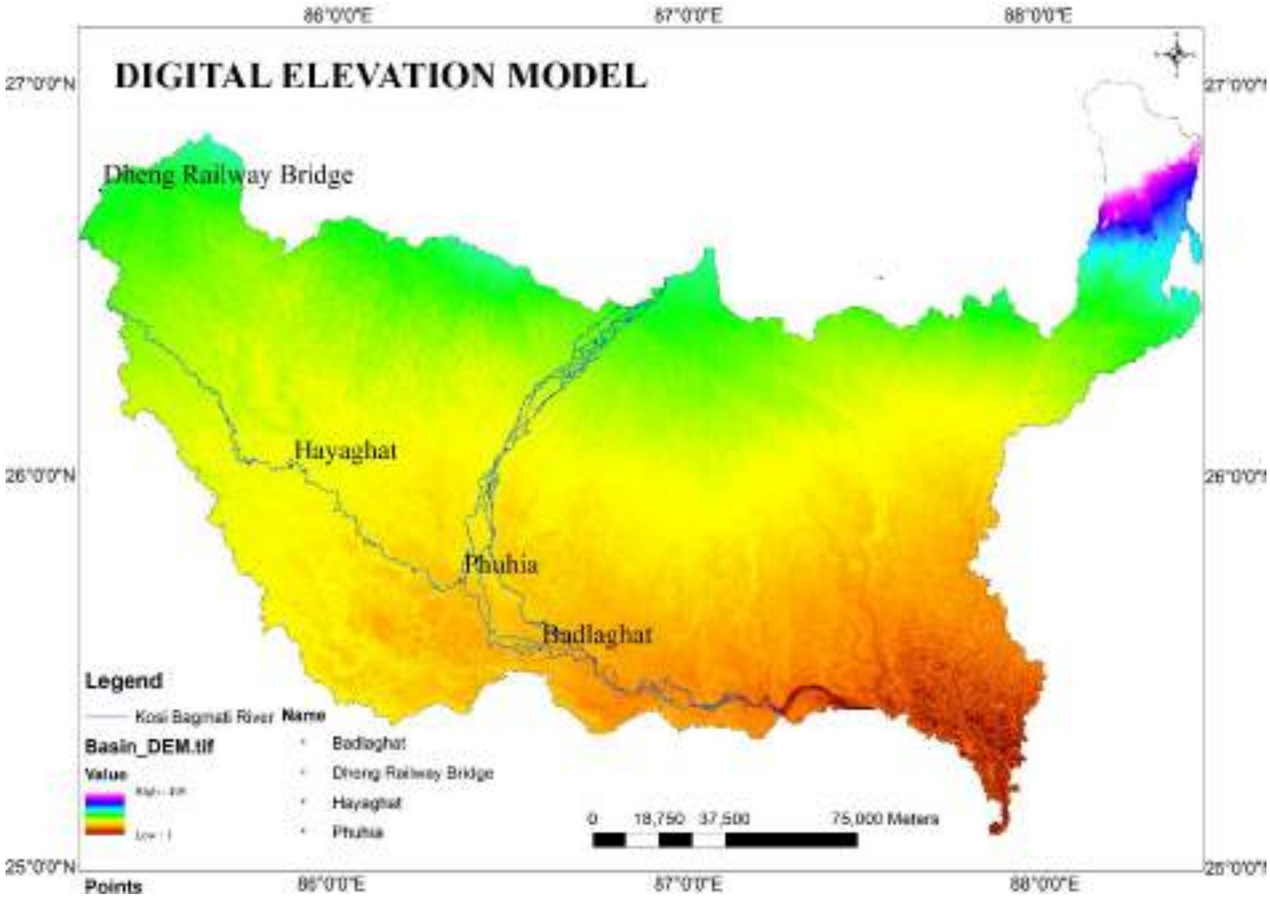



Figure 4-1: DEM of Bagmati River

The main river course's bed slope is almost flatter, 0.14m/km between Dheng railway bridge and Hayaghat, 0.4m/km between Hayaghat and Phuhia and 0.11m/km between Phuhia and Badlaghat. It also adds to the spilling of the river on both banks. The river course details and map are shown in Table 4-2 and Figure 4-2, respectively. The DEM data (SRTM 1 ARC) is obtained from the USGS platform, further used to prepare the slope map.

Table 4-2. Slope classification of River Bagmati

| S. no. | Stretch | Length of the river (km) | Rate of fall (m/km) |
|---|---|---|---|
| 1 | Dheng Railway Bridge to Hyayghat | 191 | 0.14 |
| 2 | Hayaghat to Phuhia | 96.39 | 0.4 |
| 3. | Phuhia and Badlaghat | 33.36 | 0.11 |

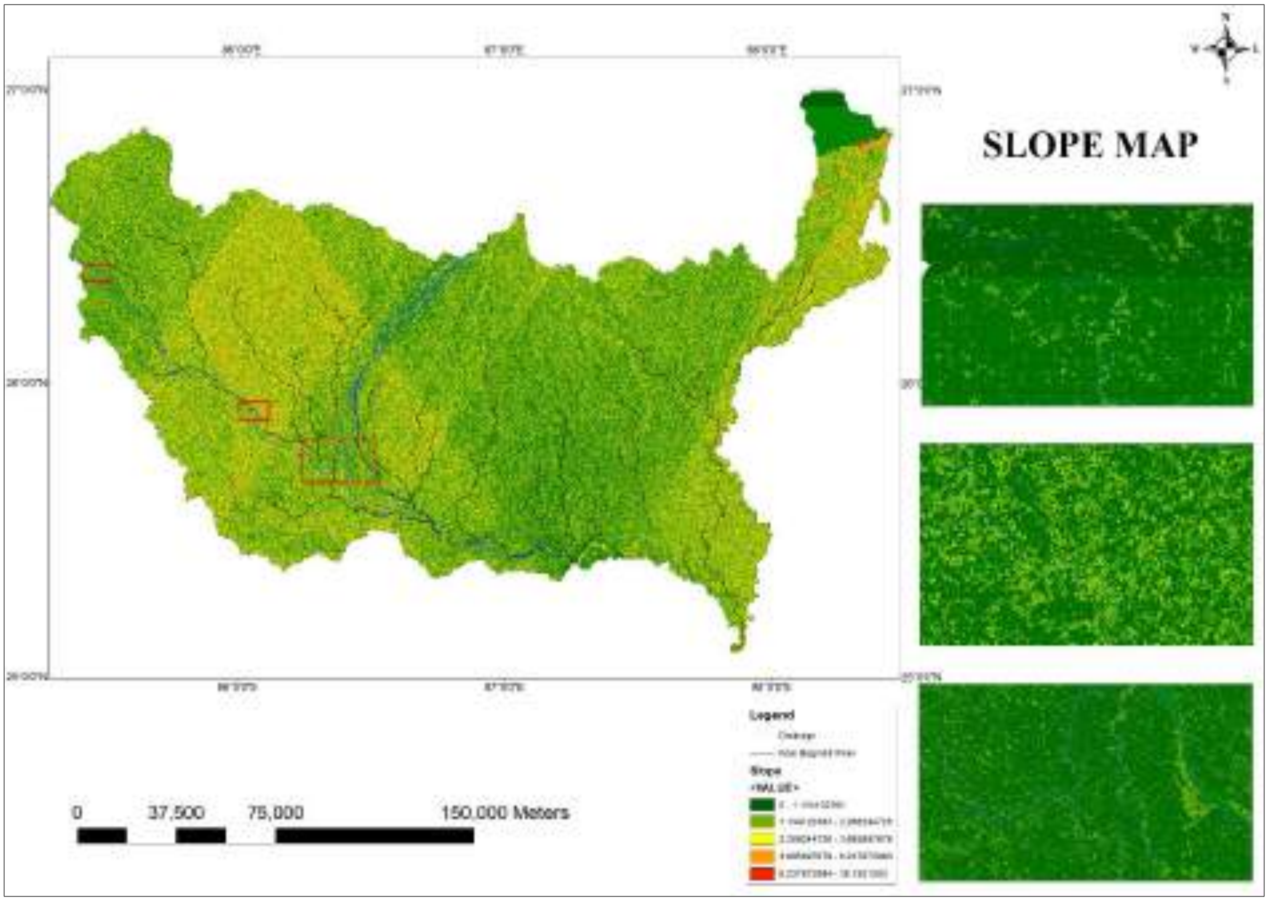



Figure 4-2: Slope Map of Bagmati River

## 4.3 Geomorphology

The Bagmati river course consists of different morphological features, including a small extent of highly and moderately dissected hilly and valleys regions, active and older flood plain, alluvial plains, lakes, ponds, and rivers as presented in Figure 4-3. The alluvial plain covers the vast area of the basin; there is a thick deposit that consists of silt, sand, clay, and gravel and often contains a good deal of organic matter. It, therefore, yields very fertile soils and encourages agricultural practices in the region. The alluvial deposition is seen to be progressively finer-textured as one traverse from north to south. The soils along the northern boundary are light and absorb water quickly, while soils in the south are comparatively heavier and retain moisture. This feature is modified by rivers, which carry coarse sediments and deposit the same on both sides in their flood plain. Thus, at Phuhia, deposits of medium sands are encountered on both sides of the river even though the neighbouring soil is quite fine in size. The geomorphology of the region help in understanding the reason for the frequent flood incidences in the basin: (1) Flat terrain (2) Alluvial cover, which can be easily carved by the river course (3) Dense drainage network (4) Flood plains.

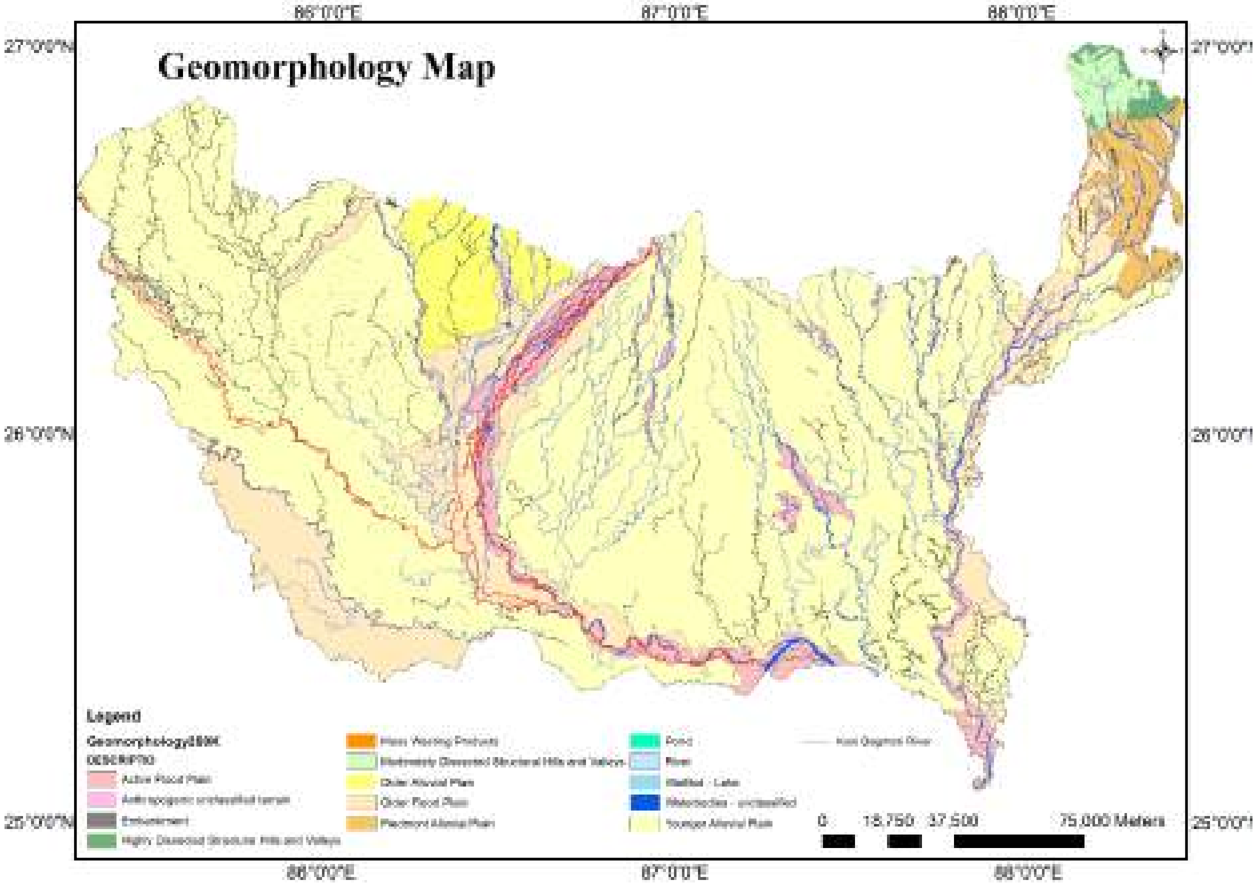



Figure 4-3: Geomorphology Map

## 4.4 Geological formations

The geological formation of the Kosi/Bagmati basin can be categorized into Proterozoic, Permian, Quaternary, and Pliocene-Pleistocene, shown in Figure 4-4. A significant portion of the region is Quaternary, the only hilly region with a different geological characteristic than the rest. The details of the formation are given below:

**Quaternary:** The Quaternary formation (unconsolidated material or sediments) of Kathmandu valley is classified as sal (recent alluvial soil), srs (residual soil), SCO (colluvial soil) and salf (alluvial fan deposit). Quaternary sediments of the Recent to Sub-Recent age cover about 89 per cent of the state's geographical area. They occupy the entire north Bihar plain and a vast stretch of land south of the river Ganga and the Chhotanagpur Plateau. Deep exploratory drilling by Central Ground Water Board has confirmed the thickness of sedimentary deposits in north Bihar plain as more than three hundred meters. In the south of the river Ganga, the alluvial thickness gradually decreases to as low as 50 m or even less towards the Jharkhand state. The sedimentary deposit consists of alternate sequences of sand and clay layers representing the multi-cyclic nature of sedimentation. The Quaternary alluvial deposit spread over south and north of the river Ganga is a part of Mid-Ganga Plain. The Terai belt, which is demarcated by auto-flow wells, occurs as a narrow strip in the bordering areas in Madhubani, Darbhanga, and West (GROUND WATER YEARBOOK, BIHAR (2015 - 2016)).

**Pliocene-Pleistocene:** Plio-Pleistocene formation (slightly consolidated sediment) is classified as tka (Tokha formation), gkr (Gokarna formation), cpg (Chapagaon formation), klm (Kalimati formation),kbg (Kobagaon formation), lkl (Lukundol formation) and bbd (Basal boulder bed).

**Proterozoic:** The Middle and Late Proterozoic, including the Eocambrian and Lower Cambrian sedimentary rocks, have been described in the Indian stratigraphy as the "Purana" (Purana meaning ancient). Practically the whole of the sedimentary pile of the Lesser Himalaya belongs to the Purana temporal range. The Proterozoic and Archean age rocks are granite, granitic-gneiss, quartzite, phyllites, slates, and meta basics.


Figure 4-4: Geological Map

The generalized stratigraphic succession of the state is presented in Table 4-3 ((GROUND WATER YEARBOOK, BIHAR (2015 - 2016)), and it is shown in Figure 4-5.

Table 4-3. A generalized geological succession of Bihar (Bagmati River course)

| Age | Formation | Broad Lithology |
|---|---|---|
| Quaternary | Alluvial Deposits Siwaliks | Sand, clay, silt and occasional gravel, sandstone, conglomerate, claystone, gravel |
| Proterozoic | Vindhyan Super Group | Sandstone, Limestone, Granite, gneiss, schist, phyllites, Dolomites, basic rocks |

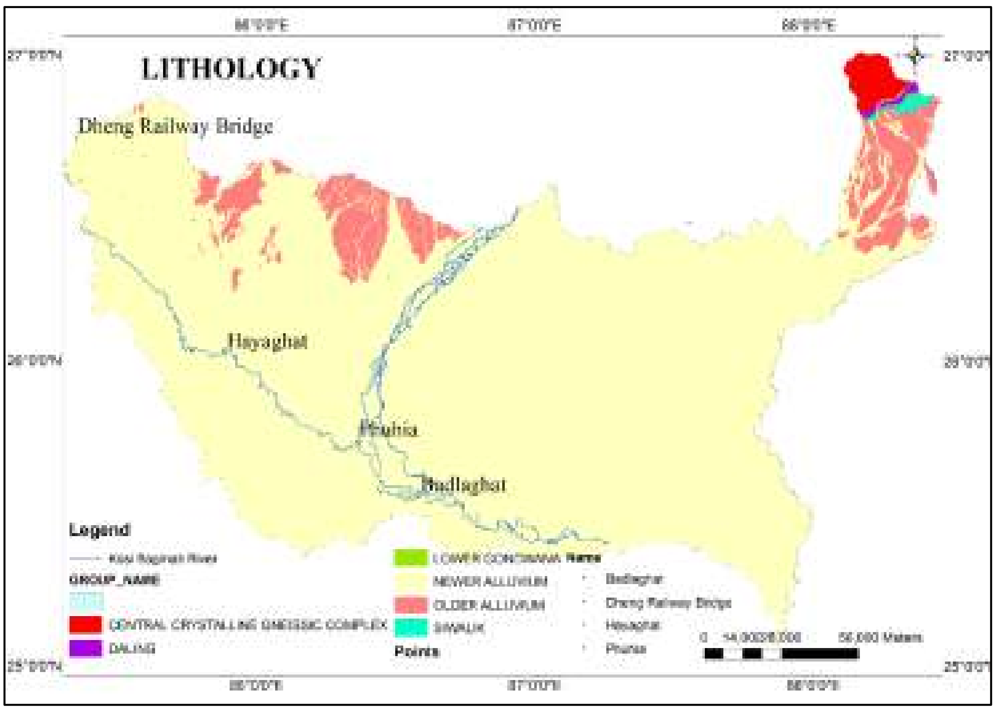



Figure 4-5: Lithology map

## 4.5 Lineaments

Bihar is located in the high seismic zone that falls on the tectonic plate boundary joining the Himalayan tectonic plate near the Bihar-Nepal Border, and has six sub-surface fault lines moving towards the Gangetic planes in four directions. The study area consists of several lineaments such as strike-slip faults, major lineaments and neo tectonic faults. The fault names are west Patna fault, east Patna fault, Munger Saharsa Ridge Fault, Purnia Everest Lineament and Malda Kishanganj fault (Figure 4-6(a): From left to right). East Patna fault is an active fault line among these fault lines (Figure 4-6(b).

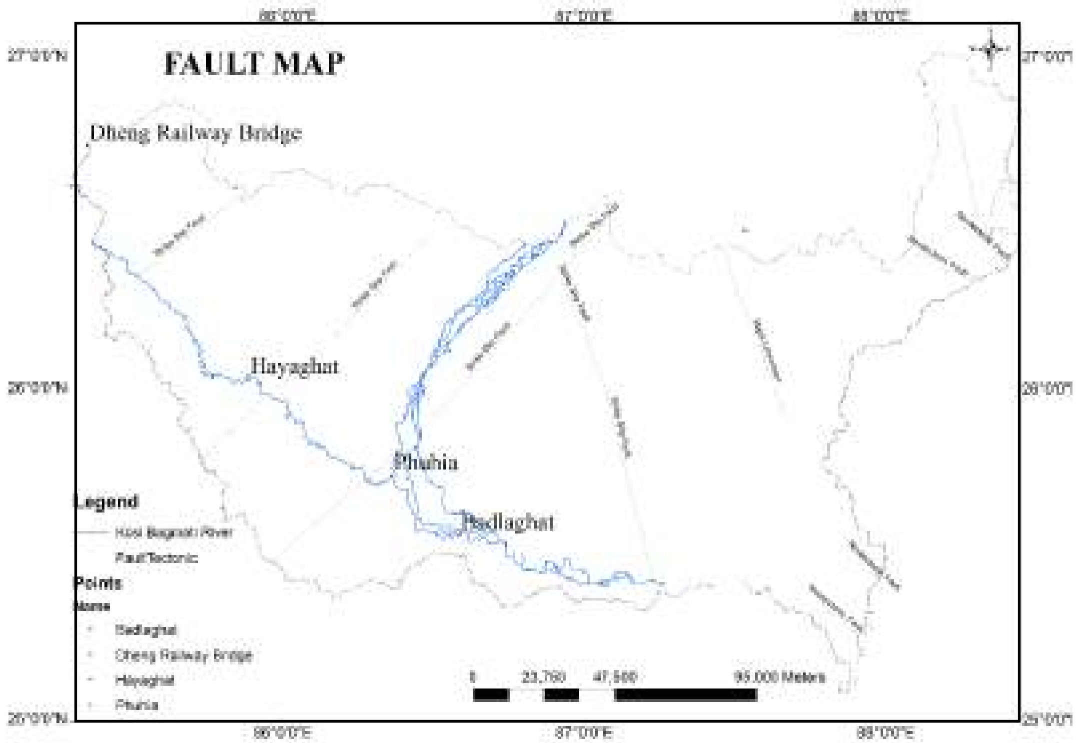



Figure 4-6 (a): Lineaments in the study area

The Himalayan tectonics influences the upstream part of the Bagmati River basin in the Kathmandu region. Besides the significant thrusts, i.e. Main Central Thrust (MCT) and Main Boundary Thrust (MBT). Most well-located epicenters reported after 1961 are concentrated in a 50 km wide zone, between MBT and MCT in the Lesser Himalaya, mainly south of MCT (Dasgupta et al., 1987). An earthquake's occurrence indicates the tectonic instability in the area and suggests that the faults are presently active. The study area's significant faults are West and East Patna faults in the East Ganga Basin that pass through Rajgir and Barauni towards the NE and the other from east of Bhagalpur N/NNW. These faults are known as transverse faults, as these faults are transverse to the trend of Himalayan faults (Dasgupta et al., 1987). Mohindra et al. (1992) inferred that the flood basin between the Burhi Gandak River and Kosi River is tectonically active and rapidly subsiding.

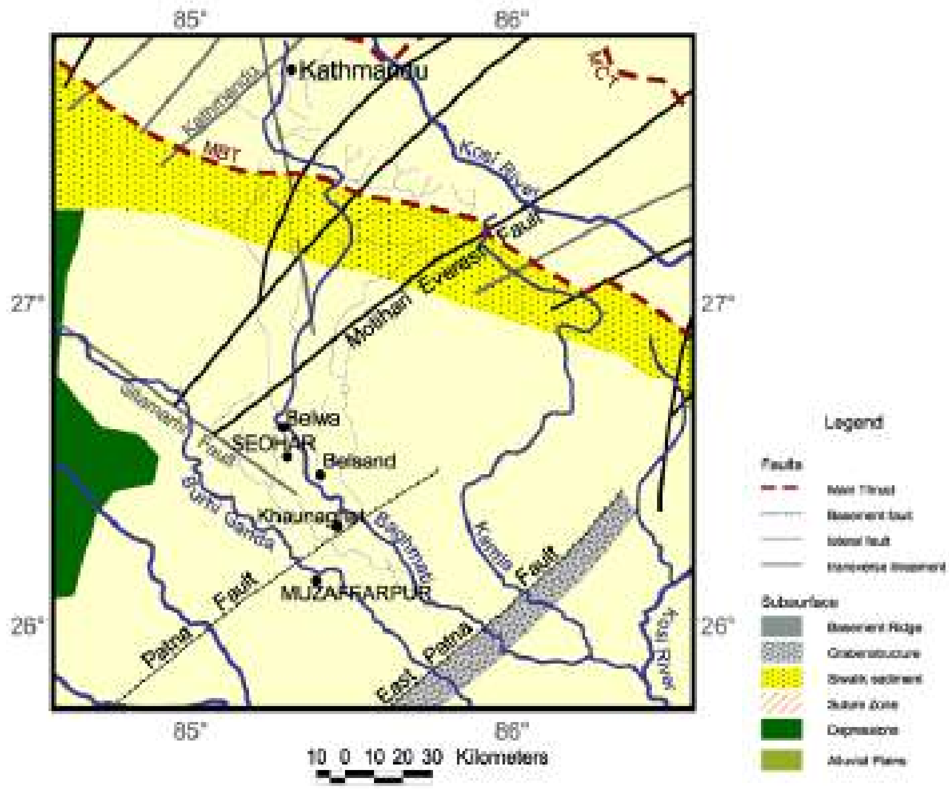



Figure 4-6 (b): Structural Map of the Bagmati river course (Reference: http://www.iitk.ac.in/gangetic/interfan/interfan_area_geol_neotect.htm)

# Chapter 5 Input Data

## 5.1 Hydrometeorological Data

The various hydrological observation sites on the Bagmati River were identified, and hydrological data in daily/ ten daily discharges were obtained from CWC. Hydrological data in daily discharges are obtained from CWC for following hydrological observation (HO) sites. Cross-sections of the Bagmati River are available at gauging stations. Dheng Bridge, Benibad and Hayaghat. The sites have been shown in the map, Figure 5-1.


Figure 5-1: HO sites for Bagmati River

## 5.2 Flow Probability Curves

Frequency analysis has been carried out using observed discharge data to estimate discharge corresponding to the 2-year return period. Higher return period flood peaks have also been estimated using frequency analysis to correlate with morphological parameters of the river. Details of frequency analysis are given below. The two main flood frequency analysis methods are analytical and graphical, with the IEA (Institution of Engineers Australia, 1987) recommending that both procedures be used in a complementary manner. The analytical method involves fitting a probability distribution function to model the observed peak flow data from which the probability of exceedance of discharge of a particular magnitude flood may then be estimated. Although this method is widely used, there is little theoretical basis in the choice of distribution (Cunnane, 1985; Kidson and Richards, 2005), and despite widespread research, no single distribution has appeared to be the best fitted across different sites (Adamowski et al., 1998). The probability distribution parameters are generally estimated through analysis of the selected data sample, which is assumed to represent its parent population. Methods such as L-moment diagrams and related goodness-of-fit measures have been encouraged for evaluating the suitability of various distributional alternatives for modelling flood flows on a regional scale (Vogel et al., 1993). However, the true distribution and parameters may differ significantly from the empirically fitted distribution, particularly in small samples (Singh and Strupczewski, 2002). In the present study, Gumbel extreme value, Log Pearson type III and Log-Normal distribution have been used, and best-fitted distribution has been used to estimate discharge for higher return periods. In the Graphical method, Weibull's plotting position has been used to determine discharge for a 2-year return period. Results of flood frequency analysis are discussed in detail in Chapter 9.

## 5.3 Satellite Data

Satellite data for five different years (1975-80, 1990, 2000, 2010 and 2016) are obtained from NRSC (National Remote Sensing Centre) and downloaded from USGS (the United States Geological Survey) website.

**National Remote Sensing Centre (NRSC):**

Satellite images are being used for feature extraction. Features extracted from these images are active water area, bank lines, stream centreline, channel area and islands. For 1990, 2000 and 2010, images from NRSC have been procured, and details regarding their usage are shown in Table 5-1.

Table 5-1: Details of NRSC data

| Year | Product and resolution | Issues | Solution |
|---|---|---|---|
| 2010 | LISS 3, 23.5m | Translation errors (lateral shifts in x and y-direction). | They are corrected for further utilization. |
| 2000 | LISS 3, 23.5m | Lateral shifts (~20-25 km) with geo-referencing errors.<br>Some of the scenes were missing. | USGS images of 2000 (30m multispectral and 15 m panchromatic) are used |
| 1990 | LISS 1, 72.5m | A few scenes are missing. Without Geo-referencing | USGS images of 1990 (30 m) are used |

**United States Geological Survey (USGS):**

In the absence of NRSC images, data from other satellites is being used to attain project objectives. Like NRSC image analysis, feature extraction is carried out on USGS satellite images (open sources data) and discussed in Table 5-2 and Table 5-3.

Table 5-2:Details of USGS data

| Year | Product and resolution | Issues | Solution |
|---|---|---|---|
| 2010 | LANDSAT 7 and LANDSAT 5, 30 m | Translation errors (lateral shifts in x and y-direction). | They are corrected for further utilization. |
| 2000 | LANDSAT 5, 30 m | Lateral shifts (~20-25 m) with geo-referencing errors. | Corrected for further utilization |
| 1990 | LANDSAT 5, 30 m | | Corrected for further utilization |
| 1977 | LANDSAT 1 and 2 MSS, 60 m | Resolution is coarse 60m and river is very thin, so it is challenging to delineate | Toposheets are used for rectification and digitization. |

Table 5-3:Description of USGS data

| Year | Product and resolution | Data Source | Path | Row | Date |
|---|---|---|---|---|---|
| 1 | LANDSAT 8, 30m multispectral | USGS Website | 140 | 41 | 2016-01-04 |
| | | | 140 | 42 | 2015-12-19 |
| | | | 141 | 41 | 2015-12-26 |
| | | | 141 | 42 | 2015-12-26 |
| 2 | LANDSAT 7 ETM+, 30m multispectral and 15m panchromatic and LANDSAT 5 TM, 30m multispectral | USGS Website | 104 | 52 | 2010-12-16 |
| | | | 104 | 53 | 2010-12-16 |
| | | | 105 | 53 | 2010-12-21 |
| | | | 106 | 53 | 2010-12-02 |
| | | | 106 | 54 | 2010-12-02 |
| 3 | LANDSAT 5 TM, 30m multispectral | USGS Website | 139 | 42 | 2000-12-10 |
| | | | 140 | 41 | 2001-01-18 |
| | | | 140 | 42 | 2000-12-01 |
| | | | 141 | 41 | 2000-11-22 |
| | | | 141 | 42 | 2001-01-25 |
| 4 | LANDSAT 5 TM, 30m multispectral | USGS Website | 139 | 42 | 1989-12-04 |
| | | | 140 | 41 | 1989-11-09 |
| | | | 140 | 42 | 1989-12-11 |
| | | | 141 | 41 | 1989-12-18 |
| | | | 141 | 42 | 1989-12-02 |
| 5 | LANDSAT 1 and 2 MSS, 60m multispectral | USGS Website | 150 | 42 | 1977-05-12 |
| | | | 151 | 42 | 1979-10-21 |

## 5.4 Toposheets

Survey of India (SoI) topo sheets have been used for digitizing features to prepare baseline data. However, the unavailability of topo-sheets of the entire stretch of the river reaches surveyed in the same year leads us to use satellite data from 1977 as a baseline year. Though features extraction activity is performed on the toposheets, it has not been used for the present study. Satellite imageries of the year 1977 and features extracted from those imageries are considered as baseline. Details of available topo sheets are given below in Figure 5-2 and Table 5-4.

Table 5-4:Toposheet details

| **Toposheet Details** |
|---|

| **Sr .No** | **Toposheets, Year** | **Source** | **Scale** |
|---|---|---|---|
| 1 | 72 $\frac{K}{1}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 2 | 72 $\frac{K}{10}$, 1970 | Survey of India, Dehradun | 1.50000 |
| 3 | 72 $\frac{K}{13}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 4 | 72 $\frac{K}{14}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 5 | 72 $\frac{K}{15}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 6 | 72 $\frac{K}{5}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 7 | 72 $\frac{K}{6}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 8 | 72 $\frac{O}{3}$, 1970 | Survey of India, Dehradun | 1.50000 |
| 9 | 72 $\frac{F}{7}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 10 | 72 $\frac{F}{8}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 11 | 72 $\frac{F}{9}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 12 | 72 $\frac{G}{13}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 13 | 72 $\frac{F}{3}$, 1970 | Survey of India, Dehradun | 1.50000 |
| 14 | 72 $\frac{F}{4}$, 1975 | Survey of India, Dehradun | 1.50000 |
| 15 | 72 $\frac{F}{5}$, 1960 | Survey of India, Dehradun | 1.50000 |
| 16 | 72 $\frac{F}{6}$, 1990 | Survey of India, Dehradun | 1.50000 |
| 17 | 72 $\frac{F}{1}$, 1953 | Survey of India, Dehradun | 1.50000 |
| 18 | 72 $\frac{F}{10}$, 1995 | Survey of India, Dehradun | 1.50000 |
| 19 | 72 $\frac{F}{12}$, 1970 | Survey of India, Dehradun | 1.50000 |
| 20 | 72 $\frac{F}{14}$, 1953 | Survey of India, Dehradun | 1.50000 |
| 21 | 72 $\frac{F}{15}$, 1975 | Survey of India, Dehradun | 1.50000 |

## 5.5 Software Used

The following software(s) are used for activities related to this project

a) Erdas Imagine: It has been used for satellite data processing

b) ArcGIS/ QGIS: Data digitisation and GIS operations

c) MS-Office: MS-Word and MS-Excel have been used for report writing and tabular analysis receptively.

## 5.6 Others

The following data are used for various analyses is presented in Table 5-5.

Table 5-5: Data and sources

| Sr .No. | Type of Data | Source |
|---|---|---|
| 1 | Geology | Geological Survey of India |
| 2 | Lineaments | Geological Survey of India |
| 3 | Roads | Geological Survey of India, Open Street Map |
| 4 | Railway Network | Geological Survey of India |
| 5 | Geomorphology | Geological Survey of India |
| 6 | Lithology | Geological Survey of India |

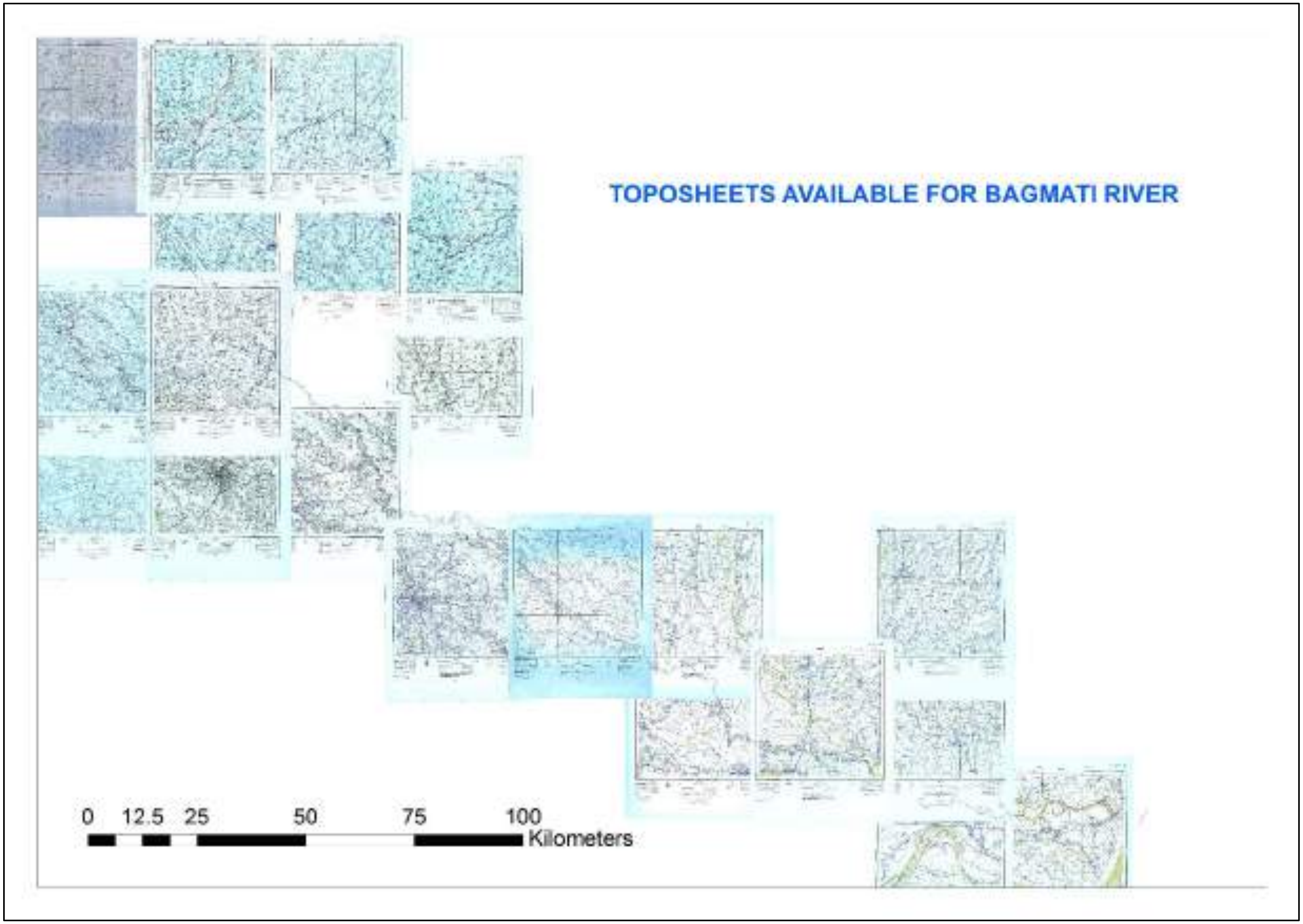



Figure 5-2: Available Toposheets for Bagmati River

# Chapter 6 Methodology

## 6.1 Defining terminologies

Terminologies related to river morphology in the present study are explained in the subsequent section and their adopted definitions.

### 6.1.1 Active water area

Active water area is that part of a river channel that represents actual flowing water at that time. Reasonably, the active water area in the monsoon season is different from the active water area in the lean season. Moreover, in some cases, the active water area is disconnected in the lean season because of other surface water and groundwater interactions at various locations. Figure 6-1 shows active water areas in the channel of the Bagmati River.

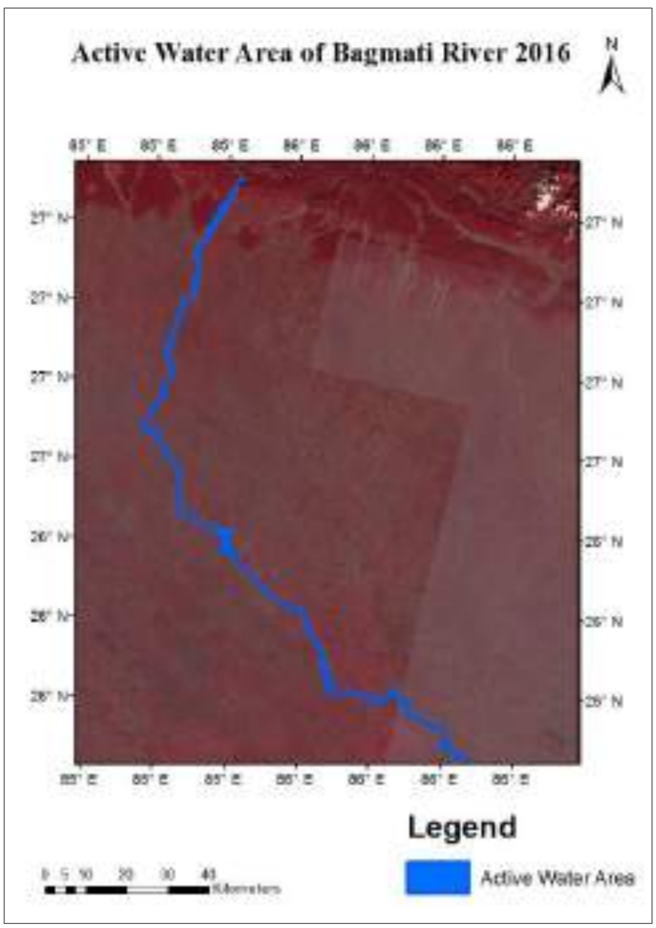



Figure 6-1:Active water areas in Bagmati River (Year 2016)

In the present study, active water areas at decadal time steps (1975, 1990, 2000, 2010 and 2016) have been marked using satellite images of the respective years. Considering seasonal characteristics of flow, lean season (months of December to February) imageries which occur immediately after the monsoon season is selected to mark active water area. Although, the river shows significant channel changes during monsoon period due to the occurrence of high flows. However, the imageries of the monsoon months have large discrepancies due to cloud cover. Hence, lean season month imageries have been used here.

### 6.1.2 Channel Area

The Channel area of the river is considered a combination of areas in which the river flows in various seasons. While in monsoon season, the river is expected to flow with a larger top width of flow, in the lean season, the active water area is restricted to a smaller and deeper sub-section of river cross-section while the other sub-sections are not inundated. The Channel area includes both active water area and those non-inundated sandy and gravel beds in the river. Though floods of different return periods will have different inundation in flood plains, it is impossible to mark those extents based on remote sensing images. In the present study based on tonal variation and reflectance characteristics, an attempt has been made to analyze the most probable river course on the decadal time scale.

### 6.1.3 Sand Bars

Floods scour the sediments at the river bottom, and when floods recede, these sediments (such as sand or gravel) are deposited at different parts of the river channel in the form of sandbars. Sand Bar is an elevated region of sediments deposited by the river flow, which is not inundated at a certain flow depth.

Types of bars include mid-channel bars (also called braid bars and widespread in braided rivers), point bars (typical in meandering rivers), and mouth bars (standard in river deltas). The locations of bars are determined by the geometry of the river and the flow through it. Bars reflect sediment supply conditions and show where the sediment supply rate is higher than the transport capacity.

Sandbars play a crucial role in the maintenance of riverine ecosystems. They offer a small strip of riparian habitats for birds and insects, provide refuge to benthic invertebrates from abrasive and fluctuating flows, and places for their recolonization and create eddies where fish and other fauna feed (Hoeting, 1998; O'Neill and Thorp, 2011). Sandbars also serve as essential habitats for reptilians in the riverine environment for basking and nesting.

Only mid-channel bars (braid bars) altering active water area computations are considered (Figure 6-2). Point bars are regarded as part of the channel area. Variations in the areal retreat of sand bars are assessed on a decadal scale for estimating erosion and deposition.

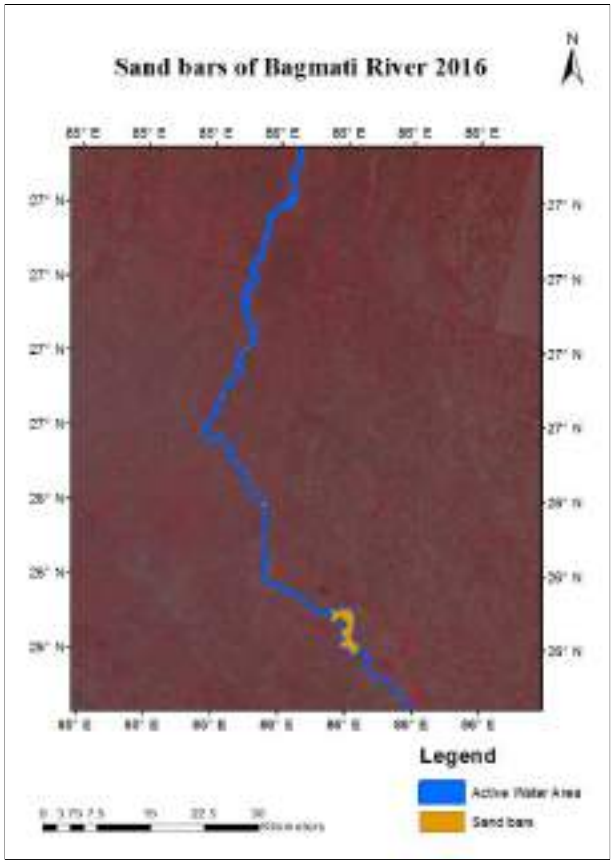



Figure 6-2**:**Sandbars in 1990 FCC image of Bagmati River

### 6.1.4 Water Bodies

Water bodies are identified in the present study as independent water areas not part of the channel area. Generally, water bodies are ox-bow features, swamps and small wetlands around the river course. Figure 6–3 shows representative water bodies near the Bagmati River.

### 6.1.5 Centre Line

There are diverse ways in which the wholly imaginary river centreline may be defined, and as a result, the concept of the river centreline is not amenable to a consistent and objective specification.

It can be defined as a line joining points of the lowest bed elevations along the thalweg channel. It can also be defined as the centreline of the active water area. The centreline is defined as a channel centreline in some modelling approaches, irrespective of depth variation within the channel.

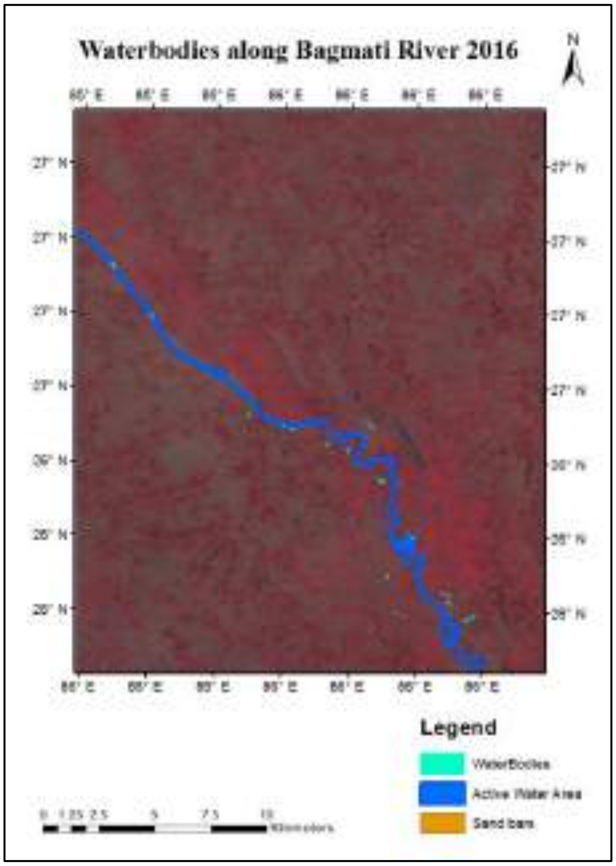



Figure 6-3:Representative water bodies near the Bagmati River

It is impossible to capture thalweg from remote sensing data because most remote sensing products are often based on reflectance from the ground surface, and only very few of them, e.g. InSAR and Lidar datasets, can capture the channel geometry. Though tonal variations in optical Remote Sensing data suggest the qualitative depth of water on broad-scale like shallow and deep water, generating exact information about the channel's deepest point is impossible. Parmar and Khosa, 2017, as part of the ongoing Doctoral study of the first author, present a comprehensive discussion on the concept of river centreline and for an in-depth discussion on this important morphological concept, reference may be made to the last report and the same is also annexed herewith as a separate memorandum.

Moreover, it is also important to note that the centreline based on active water area may vary from season to season. Figure 6-4 shows the channel centreline marked for a reach of Bagmati for different years.

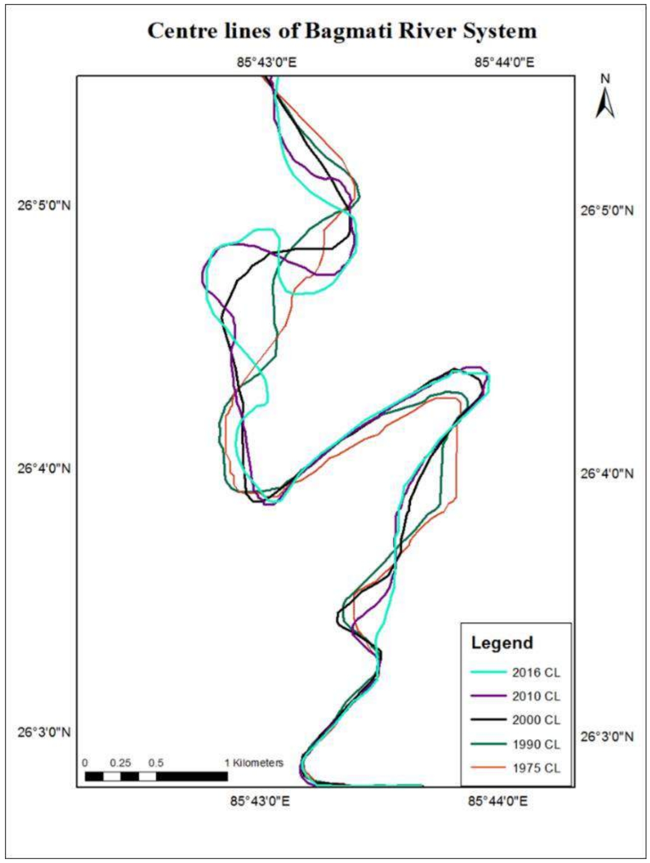



Figure 6-4**:**Channel centerlines marked for different years

### 6.1.6 Sinuosity Index (P)

Sinuosity index is a measure of the curvature of the channel. Leopold and Wolman (1957) defined the sinuosity index as a ratio of thalweg length and valley length. They also claimed that streams for which this ratio is equal to or greater than 1.5 are the true meandering streams.

Friend and Sinha (1993) modified the sinuosity index for Indian rivers with multi-channel situations. They defined sinuosity index as a ratio of $L_{cmax}$ and $L_R$, where; $L_{cmax}$ is the length of the primary channel in reach or length of the widest channel in the presence of more than one channel, and $L_R$ is the straight-line length of the channel for the same reach. The higher the sinuosity index (P), the higher is the meandering in the reach.

### 6.1.7 Braiding

Climate and geologic processes combine to control water discharge, sediment supply, and channel slope, dictating a river channel's pattern. Coarse sediments deposited during high flow become a barrier at low flow, and thus river starts flowing in multiple channels separated by these barriers. Such rivers are called braided rivers. Leopold and Wolman (1957) defined them as rivers that flow in two or more anastomosing channels around alluvial islands.

Braided channels are variable, dynamic systems with high fluvial activity rate and channel adjustment due to erosion and deposition processes. Braiding is typically referred to as splitting channels around bars or islands, which are contained within a dominant pair of floodplain banks.

Various types of braiding indices have been proposed in the literature. Notable among these are

- Leopold and Wolman (1957)
- Brice (1964)
- Rust (1978).
- Ashmore (1991)
- Cartoons and Ferguson (1993)
- Friend and Sinha (1993)
- Sharma (1995)

Parmar and Khosa (2017), as a constituent part of the first author's ongoing Doctoral study, have examined the latter indices, namely the indices by (i) Friend and Sinha (1993) and (ii) Sharma (1995 and 2004), for an objective perspective on them and have also suggested alternate forms which are summarized later in Chapter 11 and is a part of the annexed Memorandum enclosed herewith.

Friend and Sinha (1993); Lctot/Lcmax, has been adopted in the present study. Here, Lctot is the sum of the mid-channel lengths of all the segments of primary channels in a reach, and Lcmax is the mid-channel length of the widest channel through the reach.

The plan form index is also computed from the braiding index, and results are discussed in chapter 11, section 11-5.

## 6.2 Processing of Remote Sensing data

Data has been processed before feature extraction. Various operations have been performed on the data to make it usable for analysis.

### 6.2.1 Image processing and corrections

Image processing operation mainly involves georeferencing and mosaicking of data. While using the temporal satellite data, it is required to georeferenced the imageries of different dates. Some identifiable stable features like road crossings, railways, canals, bridges, barrages were selected as control points. Data prepared after image processing is checked for its consistency and error in georeferencing was estimated to be less than one pixel. After georeferencing, the scenes were combined to incorporate the entire reach of the river course. For this purpose, the Mosaic function in ArcGIS is used. The mosaic False Colour Composite (FCC) image of the Bagmati River system after correction for 2010 is shown for representation purpose (Figure 6-5).

Features obtained from the digitization of satellite imagery are Channel Area, Active Water Area, Sandbars, Water Bodies and Centre Line. All objects about these classes are obtained using the appropriate products for the desired years 1975-1979 (Landsat MSS data considered as baseline), 1990 (Landsat TM), 2000 (Landsat ETM+), 2010 (LISS III and Landsat 8) and 2016 (Landsat 8). Shapefiles of these features are available in the report's soft copy, accessed in ArcGIS (Version 10.2 and above). A representative reach of Bagmati with these features is shown in Figure 6-6. For this purpose, the Mosaic function in ArcGIS is used. Mosaic False Colour Composite (FCC) image of Bagmati River system after correction for the year 1990 is shown for representation purpose (Figure 6-5).

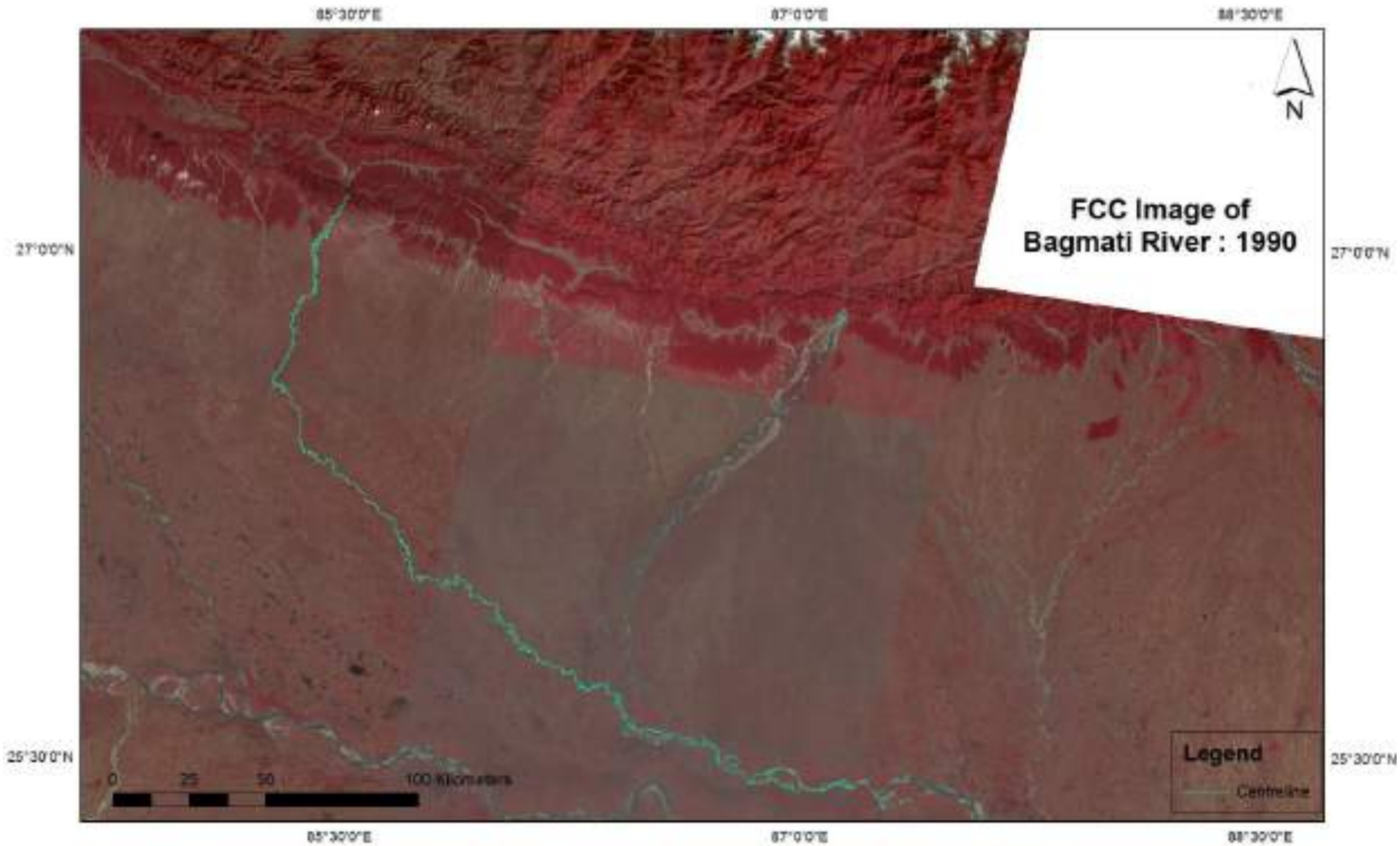



Figure 6-5: Mosaic False Colour Composite (FCC) image of Bagmati River

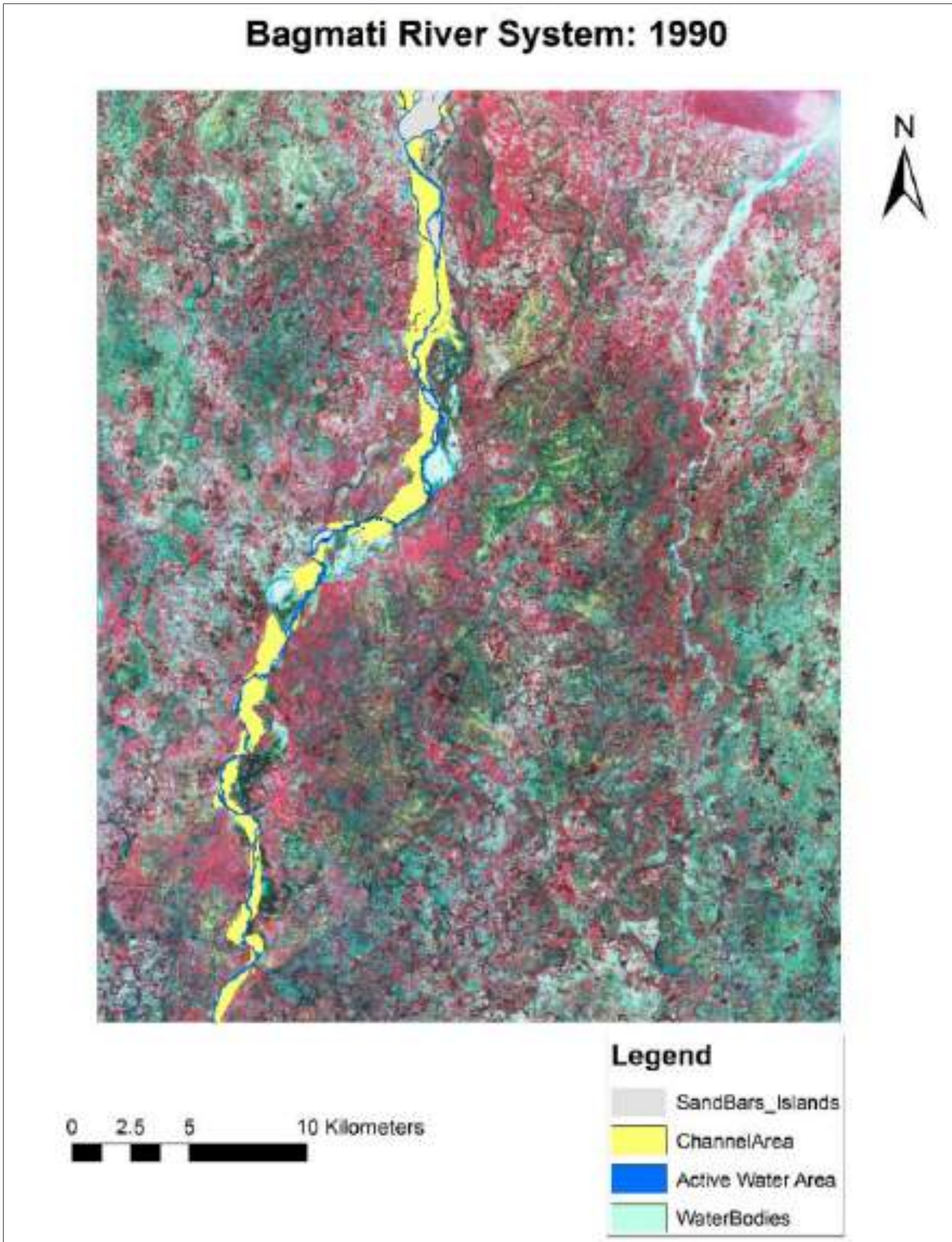



Figure 6-6: Morphological features extracted from 1990 FCC

## 6.3 The scale of the study

As per MoU, river stretch has to be studied at an interval of at least 50 km. However, an attempt has been made to analyze the river stretch at a more detailed scale. A grid size of 10 km is adopted for capturing finer details, and accordingly, the grid has been prepared for the entire Bagmati stretch under the study. For this, the total study area is divided into 234 grids (10 km size). The numbering of these grids, as shown in explanatory Figure 6–7 (A), starts from the origin at the top left corner (grid number one) and moves towards the right end of the row and moving similarly for all rows above numbering ends at the bottom right corner (at grid 234). Each row of the template contains 13 grids, and there are 18 rows in the template.

Figure 6-7 (B) shows the actual grid template used to analyze the Bagmati river system. Grids in which the river course falls are considered active grids and used in the present analysis to compute erosion and deposition.

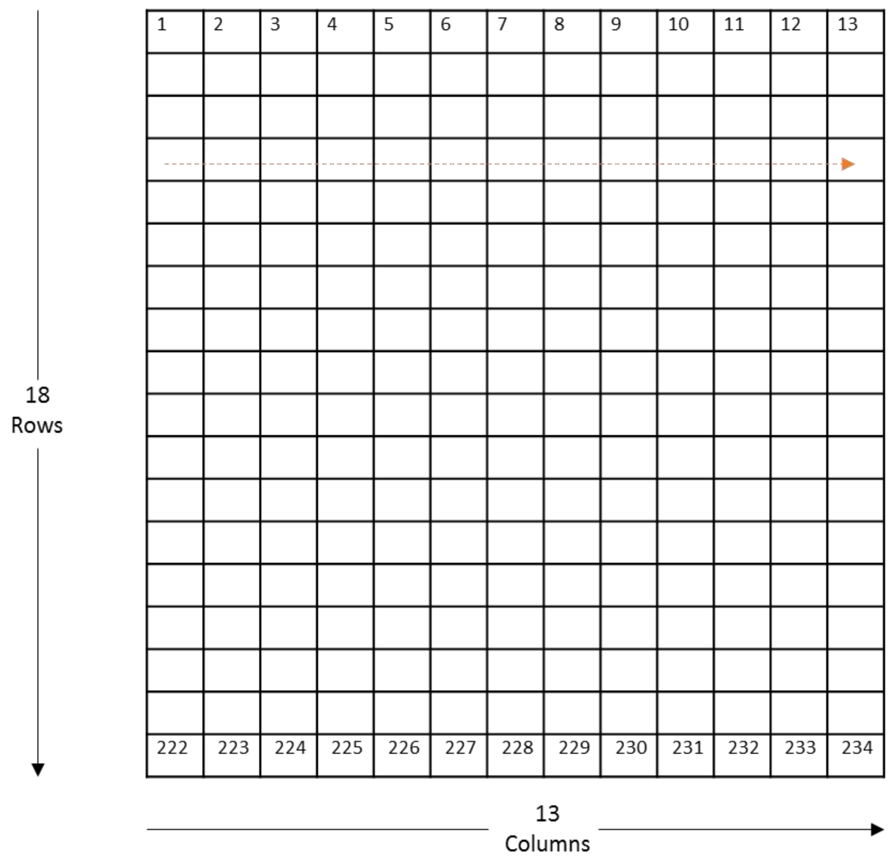



Figure 6-7:(A) Representation of numbering pattern of grids.

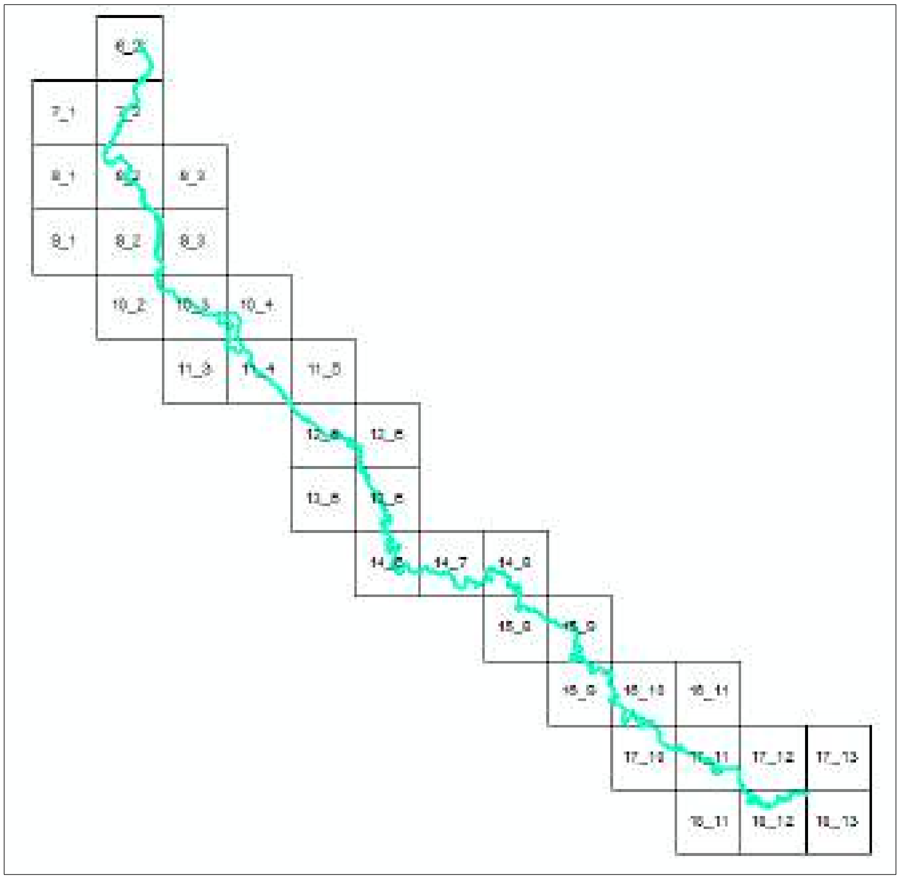


Figure 6-7: (B) Grid template used for the analysis of the Bagmati River

## 6.4 Estimation of Channel Bank Retreat on Account of Erosion and Deposition

Areal Retreat (area in $km^2$) of erosion and deposition is computed from digitized features. The difference in channel area, sandbars and water bodies based on their tonal variations observed in satellite images is considered to estimate erosion and deposition. Figure 6-8 shows grid wise erosion and deposition in a sample reach of the Bagmati River.

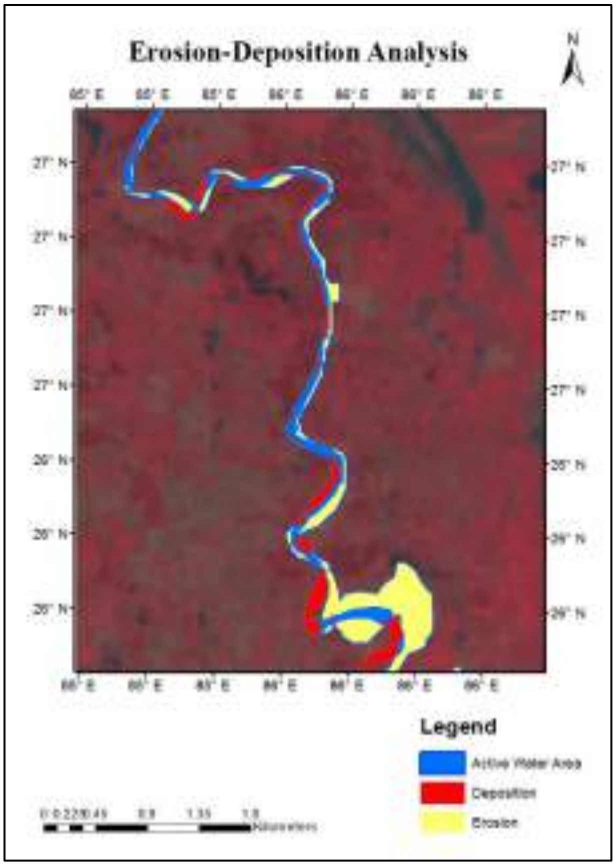



Figure 6-8: Estimation of channel bank retreat on account of erosion-deposition on a grid basis

## 6.5 Understanding of River Course Dynamics

River course dynamics is a highly complex phenomenon considering the river's inherent variability. Often, the term shifting is used to showcase river course dynamics. However, it is essential to note that the river may follow its historical path, and its movement may be limited to the paleochannels of the extent of its 'swing zone' or its designated river corridor, a concept proposed and so designated by Parmar and Khosa (2017). Therefore, when the river course dynamics is limited to the swing zone, shifting the river course should not be considered. Moreover, the term shifting has a specific meaning in the context of morphology. It indicates the movement of the river course, which is irreversible and significant. If the river swings and come back to its original position, it does not represent an actual shifting of the river course rather than possible flow paths within the channel area or extensions of the river course in the flood plain at a particular point in time.

In the present study, the river course's shifting is studied and analysed for all grids sequentially. For all the years (1975, 1990, 2000, 2010, and 2016), centrelines are considered for shift analysis. The procedure followed for shifting analysis has been explained hereunder.

1. Based on the centreline of the year 1975, the reference line is created by converting the centreline into a single straight line for each grid by removing vertices and retaining endpoints at the grid boundary (Figure 6-9 (A)).

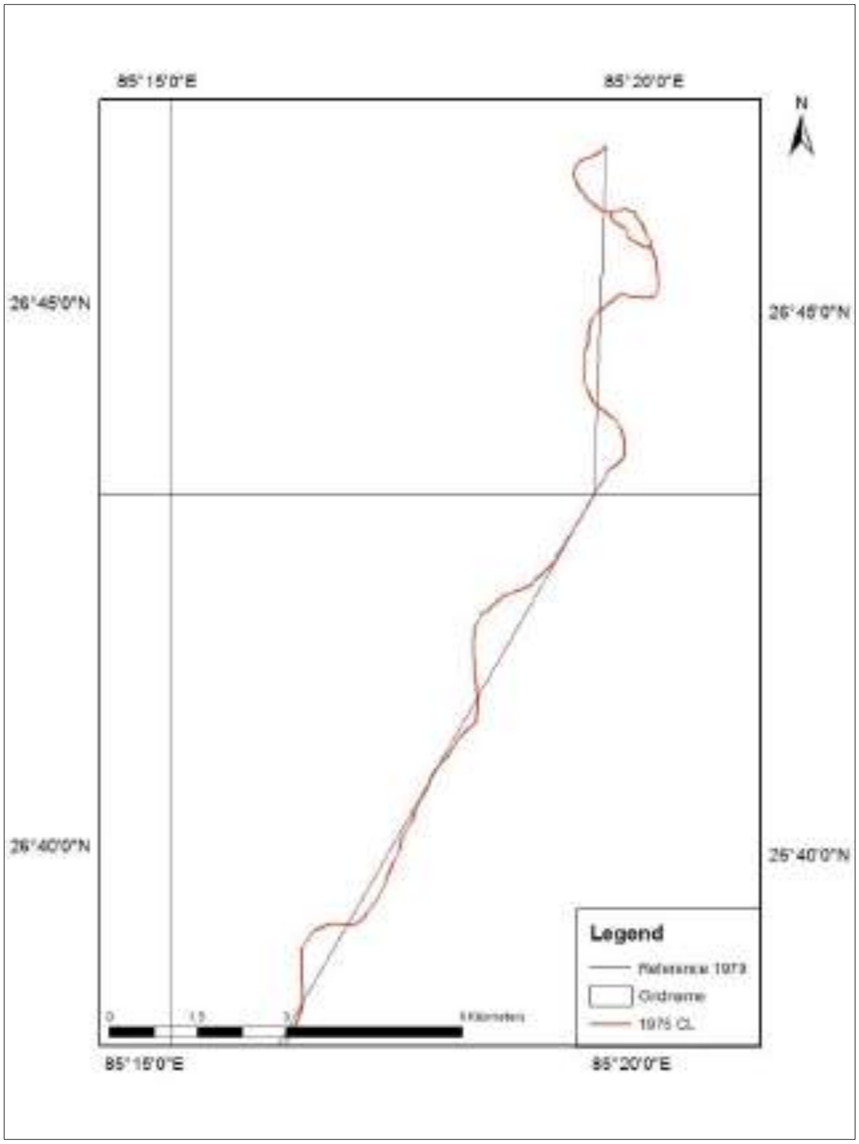



Figure 6-9:(A) Creation of Reference Line based on 1975 Centerline

2. Next, perpendiculars are drawn to the reference line from the centreline at an interval of 1 km. Intersection points of perpendiculars and reference line are referred to as chainage (Figure 6-

9 (B)). To specify exact locations of perpendicular lines, grid number, latitude and longitude of grid Centre and bearing of reference line are provided.

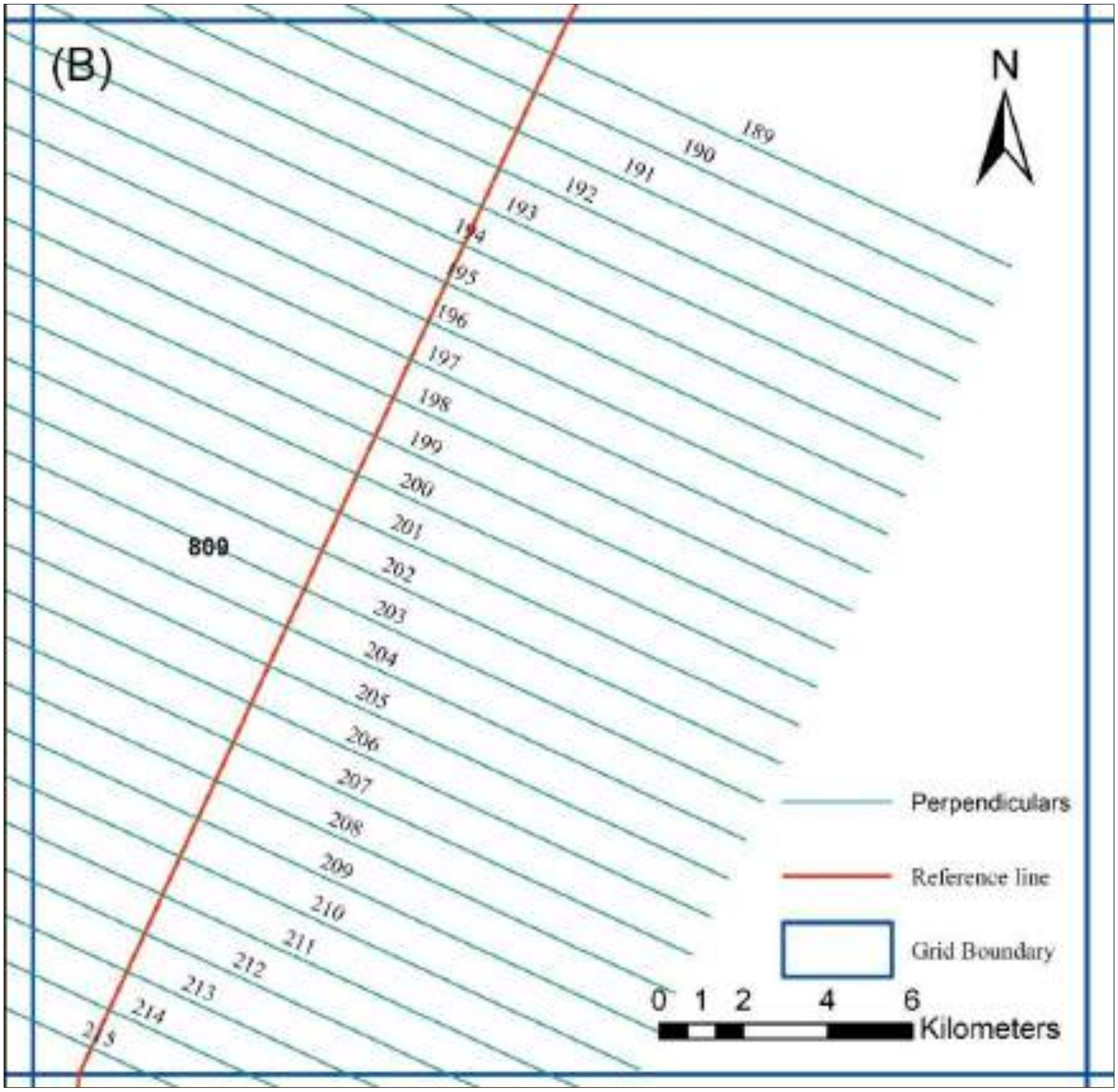



Figure 6-9: (B) Drawing Perpendiculars at 1 km interval on Reference Line

3. These perpendiculars are extended such that they intersect with the centrelines of other respective years and the distance between the centreline and the reference line is estimated for each time frame. The distance to the left of the reference line (in the direction of flow) is being shown by a negative sign (-), and the distance to the right side of the reference line is being shown by a positive sign (+) (Figure 6-9 (c)).

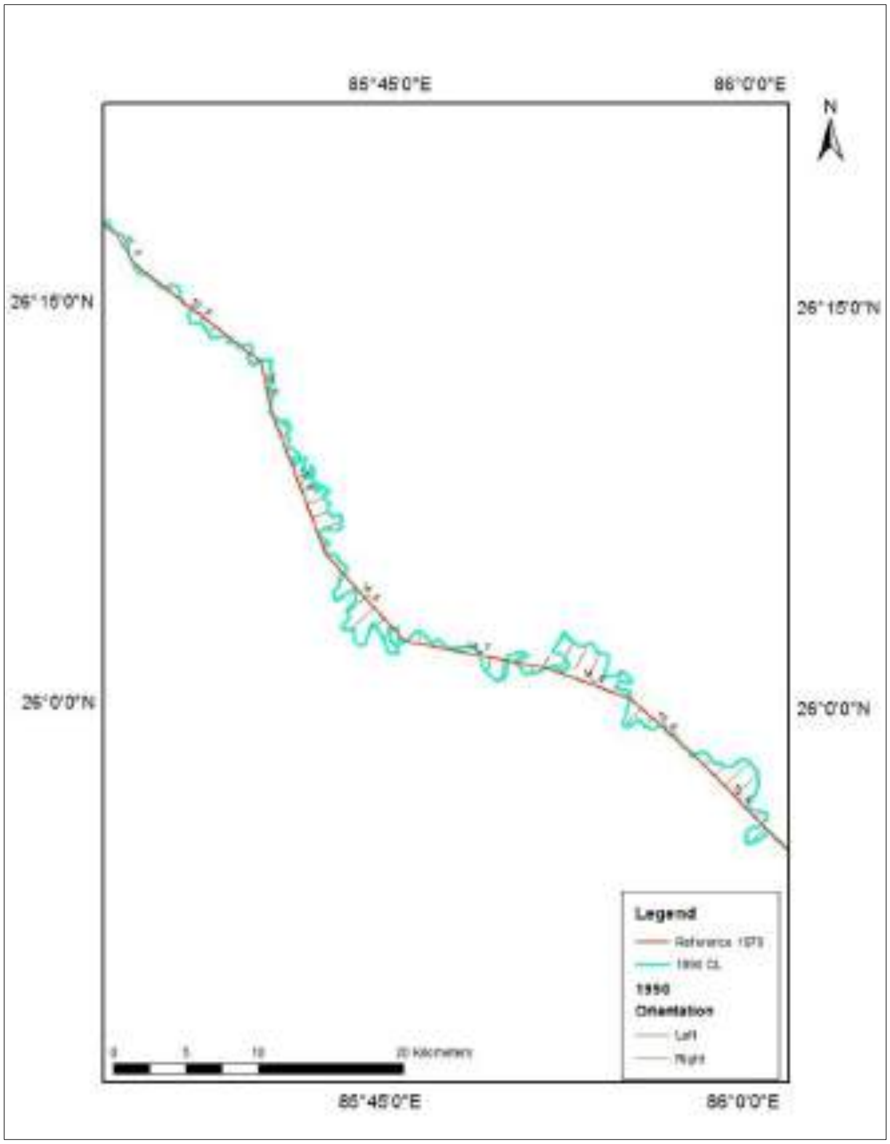



Figure 6-9: (C) Computation of distance between Reference Line and Centerlines

4. Differences between these distances obtained for two consecutive years of study are considered shifting of river course within that time frame. (Figure 6-9 (D) and Figure 6-9 (E)).

Zero chainage of the reference line represents the point at which River Bagmati enters the Indian Territory near Rajdevi. For reference on the ground, significant villages located on the river bank and the chainages nearby are noted, as shown in Table 6-1.

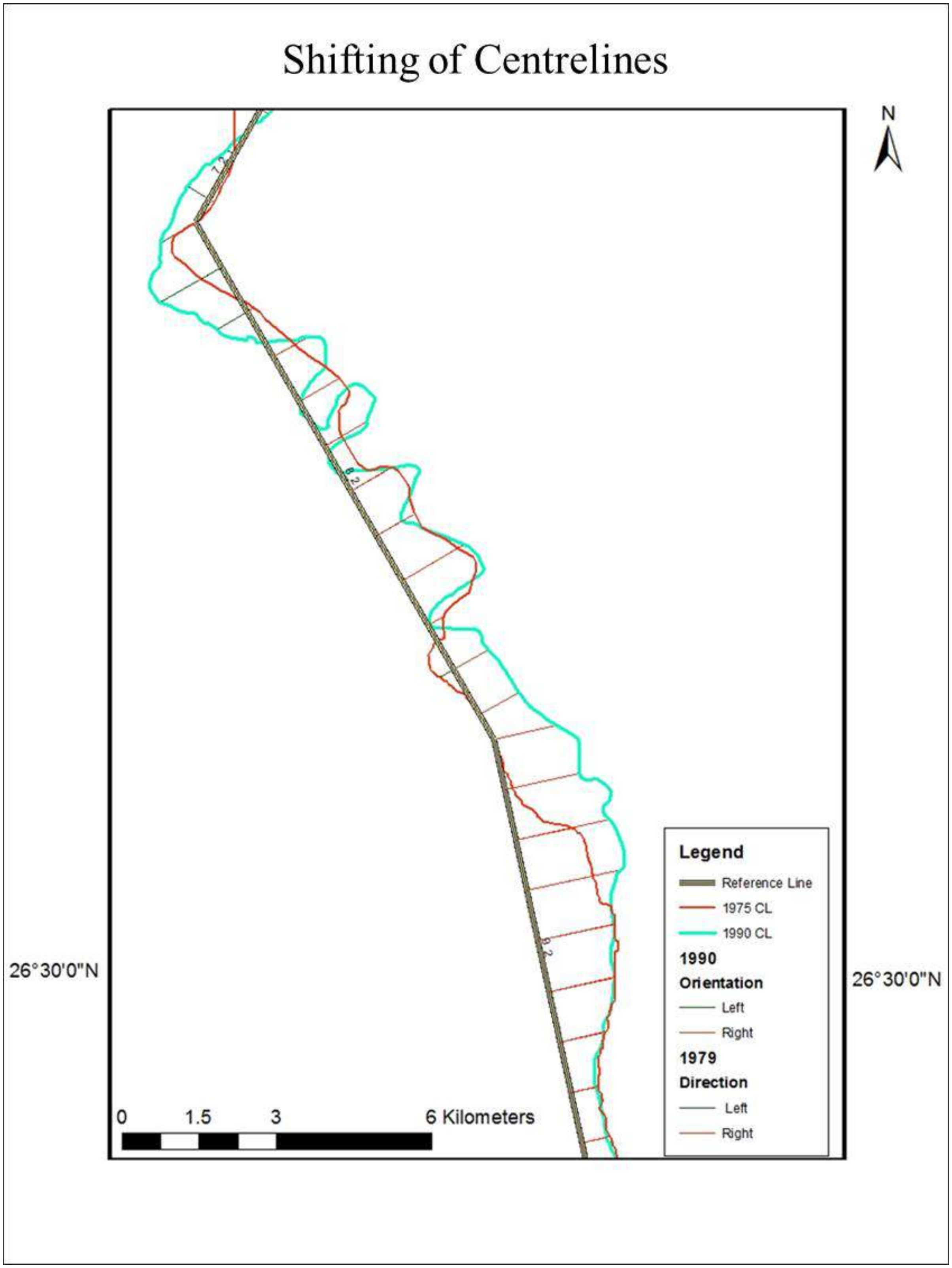



Figure 6-9 (D) Shifting of Centerlines for the years 1975 and 1990

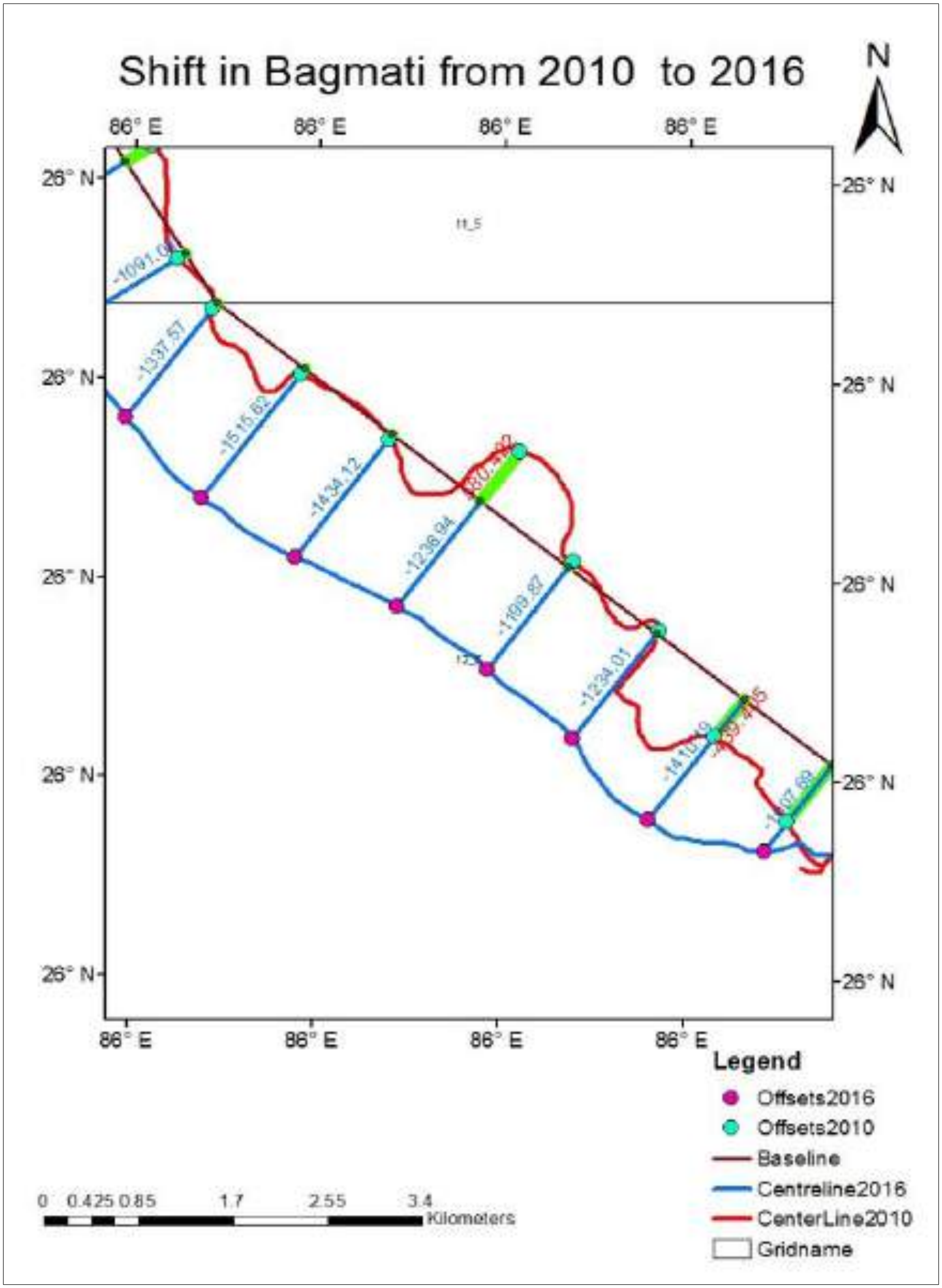



Figure 6-9: (E) Computation of Shifting of Centerlines

Table 6-1**.** Names of Villages/Cities along the river and nearby chainages

| Village Name | Chainage (km) |
|---|---|
| Rajdevi | 1 |
| Brahmapuri | 2 |
| Masha Naoratan | 5 |
| Dheng | 6 |
| Gamharia, Belganj | 8 |
| Joriahi Kothia, Bhataulia | 9 |
| Parsauni | 11 |
| Patahi | 13 |
| Marpa Tahir | 15 |
| Piprahi Sultanpur | 15 |
| Khori Pakar | 17 |
| Indarwa Khurd | 20 |
| Sengahi Indarwa | 21 |
| Dosti Mahamadpur | 21 |
| Piprarhi | 24 |
| Ratanpur Bishunpur Jagarn | 25 |
| Chamanpur | 27 |
| Parihara | 28 |
| Parsauni | 30 |
| Kamrauli Jangali | 31 |
| Harkarwa, Mohari | 32 |
| Az Rakba Kursahar | 33 |
| Surgahi | 35 |
| Ghorha | 36 |
| Jagdishpur | 37 |
| Madh Kaul | 39 |
| Panrahi | 40 |
| Mehthi | 41 |
| Pachnaur Murahi | 44 |
| Kharka | 45 |
| Baghauni | 46 |
| Pota urf Tajpur Phaksia Bharthi | 48 |
| Madhuban Partap | 57 |
| Chak Sarhanchia urf Dheki | 58 |
| Chainpur | 62 |
| Mathurapur Buzurg | 63 |

| Village Name | Chainage (km) |
|---|---|
| Basant | 65 |
| Katra | 69 |
| Madhopur | 71 |
| Gangia | 72 |
| Dumrawab | 75 |
| Kalyanpur | 76 |
| Pirauchha | 78 |
| Benibad | 79 |
| Paga | 83 |
| Gangaura | 86 |
| Haspanpur | 87 |
| Rajwara | 89 |
| Arazi Jadu Mahsi | 92 |
| Rajpa | 94 |
| Jatmalpur | 96 |
| East Bilaspur | 100 |
| Pauram | 101 |
| Sadhu | 106 |
| Benta | 108 |
| Dhobepur Bansara | 112 |
| Nankar | 114 |
| Partapatti | 115 |
| Boraj | 119 |
| Meghaulia | 120 |
| Chak Jari | 127 |
| Bhoraha Bahera | 128 |
| Bhatandi | 130 |
| Phulahra | 136 |
| Aura | 139 |
| Kundal | 145 |
| Manarwa Khaira | 153 |
| Khonta | 158 |
| Hathwan | 163 |
| Cherakhera | 167 |
| Supaul | 176 |

## 6.6 Critical and Stable Reach

Understanding the concept of critical and stable reach is important for identifying a certain river reach for its critical or stable status. Usually, reference conditions are obligatory to identify such reaches, and they can be based on expert judgement. No predefined methodology is available in the literature to identify critical or stable reaches applicable to different river systems of the world. Moreover, a wide range of parameters is available to analyse the stability of the systems. These parameters and impacts observed due to fluctuations of these parameters from reference conditions on hydrology, river hydraulics, associated ecology, environmental needs, and human demands can be used to define a particular reach as critical/stable reach. Hydrologist may suggest a particular reach of river as a critical reach where significant variations are observed in flow regime and its characteristics.

In contrast, ecologist may identify a particular fragment of the river as critical based on aquatic habitat conditions in that reach. For an administrator, river reach susceptible to flood risk is of highest priority and usually termed as critical reach with particular flag suggesting immediate actions to reduce damage and associated vulnerability. Mindset, an expert's background, and his/her judgement are the most important variables in declaring a reach as critical. It is important to note that a reach's stability or criticality is also a function of temporal and spatial scales of study. The scale on which observations are made also plays an important role in defining the reach under study's stability or criticality.

Our understanding of natural systems suggests that the river system in the unregulated flow scenario should be considered a reference to discover changes in the system over a temporal domain. In the present study, the system observed in 1975 is considered a reference condition. Various features, as explained above, are marked on the 1975 image, and used as a reference. Distance between bank lines (endpoints of channel area as observed in non-monsoon season) is used to obtain the centreline and channel width location. If swing displacement of the centreline between different years is more than the width of the channel in that particular stretch, it is analysed further to understand the dynamics of river functioning.

In the present study, the rate and scale of erosion-deposition and river course dynamics identify a critical reach. If the river's movement is limited to the swing zone, it is considered natural phenomena of river hydraulics, and it may not be attributed as a critical reach. More details about the identification of critical reaches and the genesis behind it provided in Chapter 16.

# Chapter 7 Land Use Changes

## 7.1 Introduction

Land-use changes the water and sediment supply to rivers, which, in response, alter channel geometry and composition towards conditions capable of passing the supplied sediment with the available water. Variations in water and sediment input can result from various land uses, including mining operations, timber harvesting, agriculture, urbanization or mixtures of these changes. Although the general cause and effect of the relationship between water and sediment supply on channel change are apparent, the possible channel response range is diverse. The rate and direction of changes in channel width, depth, or composition can vary with the relative magnitude of changes in water and sediment supply, as well as the quality of sediment supply. Adding to the complexity is the fact that land-use changes are spatiotemporal. Channel response may lag behind the land-use change and will often integrate the effects of a complex sequence of spatially and temporally variable land-use patterns. The result is that the channel response to any particular land use is difficult to isolate and most modern channels in developed regions exhibit an incomplete and spatially varying response to the suite of previous land-use changes.

Land use and land cover information are essential for many planning and management activities and are necessary for modelling and understanding the earth as a system. The term land cover narrates the feature present on the earth's surfaces, such as cornfields, lakes, trees. Land use relates to human activity or economic function associated with a specific piece of land, for example, built-up areas (Lillesand et al., 2008). For a hydrological study of rainfall-runoff characteristics, it would be essential to know the tract's amount and distribution of roofs, pavement, grass, and trees. Thus, both land use and land cover can be necessary for land planning and land management activities.

## 7.2 Land-use changes

The land use classification has been performed on satellite images obtained from various sources in the present case. While most of the images (1990, 2000, 2010 and 2015) have a resolution of 30 m (in multispectral bands), the image of 1975-1980 has a spatial resolution of 60 m. The classification process's motive is to categorize all pixels in a digital image into several land cover classes or "themes". The method used in the study is Object-Based Image Analysis.

## 7.3 Object-Based Image Analysis v/s Pixel Based Classification

A classification is an approach adopted to extract the information from the satellite imagery and transform the image into a reduced set of features; in this case, land use landcover map. Early attempts at land cover classification using remotely sensed imagery was dominated by pixel-based methods, where land cover classes are assigned to individual pixels (Aplin et al., 2008). A pixel-based classification analyses every pixel's spectral properties within the area of interest without taking the spatial or contextual information related to the pixel of interest into account. There are few limitations in the traditional classification approach, such as the spectral heterogeneity of land cover, which can cause the salt and pepper effect in the image (Whiteside et al., 2005). In addition to the limitations, the amplified application of higher resolution imagery is challenging as it is difficult to classify accurately using traditional pixel-based methods. The increased amount of spatial information often leads to an unreliable classification of pixels (Whiteside et al., 2005), and also sometimes pixel's spatial extent may not match the extent of the land cover feature of interest. The problem of mixed pixels is well known where a pixel represents more than a single type of land cover (Fisher et al., 1997), which often leads to misclassification, as 30-meter resolution satellite image is used for the preparation of land use landcover map, the situation of a mixed pixel is frequent especially nearby regions of the river. A solution to the difficulties associated with the pixel-based classification may be needed to operate at the spatial scale of the objects of interest themselves, then count on image pixels' extent (Platt and Rapoza, 2008). The development of object-oriented classification methods suitable for medium to high-resolution satellite imagery provides a valid alternative to traditional pixel-based methods (Baatz et al., 2004). Rather than dealing with individual pixels, the object-based approach segments the imagery into small homogeneous objects. Objects are a group of pixels having the same features; Object characteristics such as texture, shape, spatial relations and reflectance statistics can be used for classification. Image-based object analysis is generally approached in two ways, region growing and edge detection technique (Carleer et al., 2005). The object-oriented approach takes shape, textures and spectral information into account. Its classification phase starts with the segmentation, which can be handled in the later step of classification. The Multiresolution approach can do this segmentation; it allows to differentiate several levels of object categories.

OBIA is very useful in this case as **1)** Most of the built-up area falls into the category of the rural, and visually spectral properties of barren land and built-up area(rural) is too similar to distinguish; hence it is very difficult to extract the feature-based only on the brightness value of a pixel, hence applying a rule set such as NDVI can help to extract them separately. **2)** the basin includes several small tributaries, which is challenging to extract using the conventional method, but by applying geometrical rules such as length/width, the tributaries are extracted with much accuracy, as shown in Figure 7-4. **3)** Indices such as NDWI is used to extract the water bodies such as river and oxbow lakes 4)

## 7.4 Methodology

The framework of the methodology is shown in Figure 7-1. In the object-based approach, first segments imagery into small homogeneous objects, which serve as building blocks for subsequent classification.

### 7.4.1 Hierarchical Segmentation

For segmentation, various parameters were applied to the satellite imagery, such as scale, shape and compactness, given in Table 7-1. The rules were applied on the basis of the homogeneity, colour and shape criteria. This homogeneity criterion is a combination of spectral and shape characteristics of the features. Colour homogeneity is based on the standard deviation of the spectral values. The shape homogeneity is based on the deviation of a compact (or smooth) shape. Homogeneity criteria can be customized by weighting shape and compactness criteria. The shape and colour criterion can be given up to the value of 0.9. This ratio determines the degree shape influences the segmentation compared to colour—for example, a shape weighting of 0.6 results in a colour weighting of 0.4.

In the same way, the value the compactness gives it a relative weighting against smoothness. The scale parameter can also be modified ascending to a feature of interest—higher values for the scale parameter result in larger image objects and vice versa.

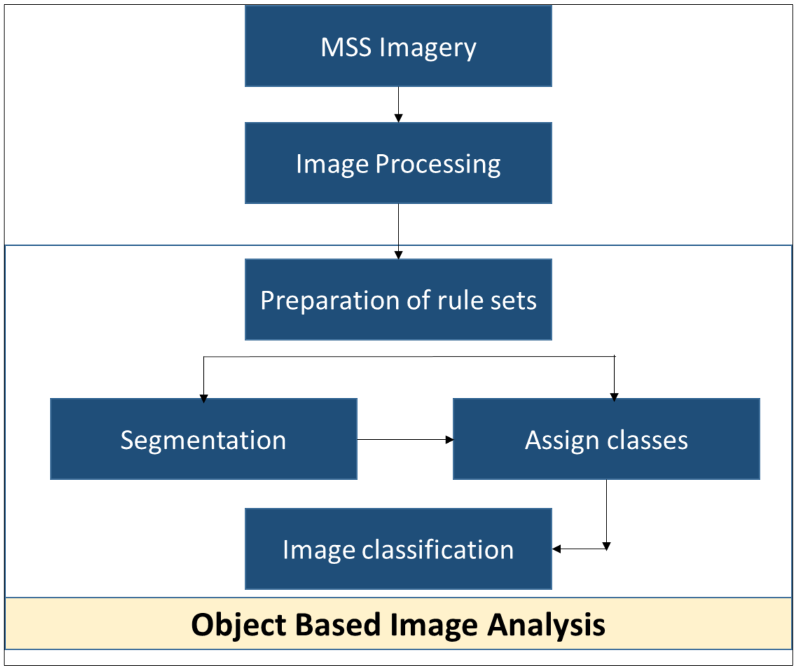



Figure 7-1: Framework of Methodology

Table 7-1: Segmentation parameters used in the analysis

| Segmentation level | Scale parameter | Shape | Compactness |
|---|---|---|---|
| Level 1 | 45 | 0.1 | 0.2 |

### 7.4.2 Classification

After creating a class hierarchy, different image objects are assigned by applying parameters and different rulesets. Table 7-2 shows the various spectral and geometrical characteristics the user decides to select to classify image objects into different classes. Thus, various statistics and algorithms applied for each image object in this study are mainly based on geometrical and spectral properties to evaluate image objects and classify them into various feature classes. The classes are created, namely Built-up, Snow and Glacier, Water Bodies, Barren Rocky, Fallow land, Forest and Vegetation. Indices such as NDWI and NDVI is used to extract water bodies and Green cover, respectively.

Table 7-2.Characteristics used in image analysis

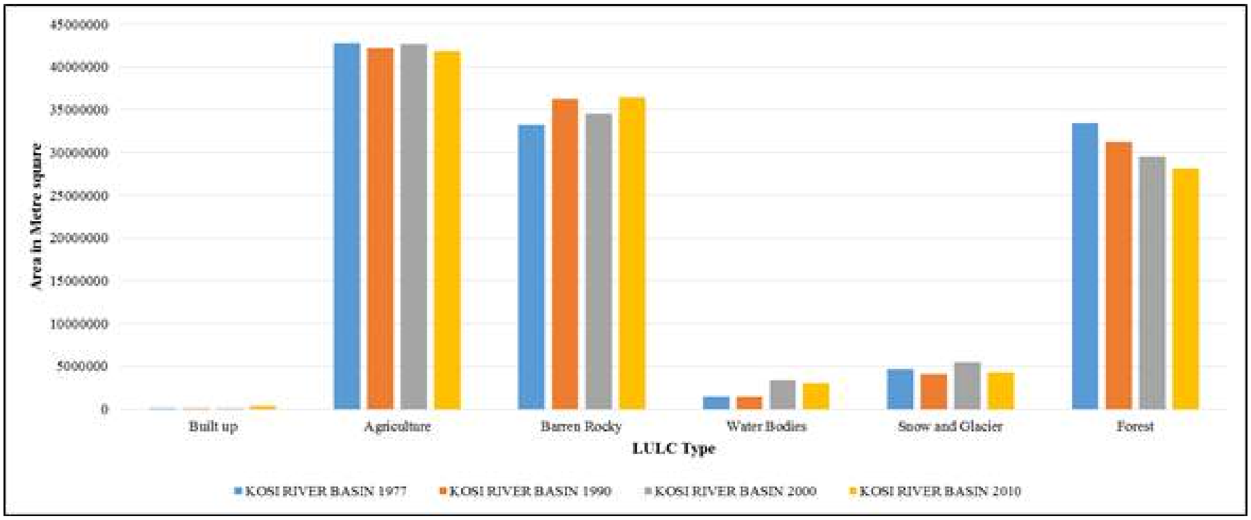
| | |
|---|---|
| **Spectral** | Mean, Brightness, Max. diff layer values |
| **Shape** | Area (sq.m), Length (m), Length/Width, rectangular fit, density, shape index, roundness |

| | |
|---|---|
| **Indices** | NDVI = $\frac{(NIR-Red)}{(NIR+Red)}$<br>NDWI = $\frac{(NIR-SWIR)}{(NIR+SWIR)}$ |

## 7.5 LULC pattern

The proportionate spatial coverage of each LULC is summarized and presented in Figure 7-2. The major LULC types identified include. Built-up, Snow and Glacier, Water Bodies, Barren Rocky, Fallow land, Forest and Vegetation (Figure 7-3 to 7-6). The maps indicated a drastic LULC change over 40 years of analysis. In the mid-1970s, the built-up area was the least dominant LULC type in the area. From the 1980s, arable land was gradually overtaken by built up and settlements mainly due to rapid population increase and demand for various products, forcing farmers to convert part of their land to other land-use types. However, the considerable increases in the built-up area were paralleled by rapid declines in the forest area. The area under vegetation showed a steady decrease between the 1977-2000 periods due to the population's outburst. The images belong to the post-monsoon and winter season (Nov, Dec and Jan). Between 1977 and 2000, Barren rock land remained unchanged due to its location and characteristics. It does not attract anthropogenic activities. LULC maps reflect an increase in water bodies, but an image taken for the analysis is different for a 1977 and 1980 year (Landsat MSS and Landsat TM), which includes only 4 and 5 bands, respectively reduces the accuracy of extraction. NDWI used to extract water bodies requires a SWIR band, and due to its unavailability, there is a difference in the outcome. There is a noteworthy increase in the population, but as more people reside in the rural areas, it is challenging to extract the rural area from coarse resolution imagery (30 m), so few cities were digitized from the google earth incorporated in the analysis.

A drastic increase in the built-up class can result from the mapping limitation (1) change of the image resolution. For 1977, the satellite image's resolution is 60 meters, while 30 meters for other years. (2) According to Niti Ayog, 90% of the basin population resides in rural areas. Hence, the material used to build the structures was not necessarily concrete, leading to a lower reflectance value, which led to difficulty in extraction of the feature (3) rural clusters are substantially smaller than the urban clusters, hence difficult to map accurately at coarse resolution. It has been seen that some of the classes have shown either a significant increase or decrease in these forty years. Specifically, the land-use class built up and forest shows trends as depicted below in Figure 7-3.



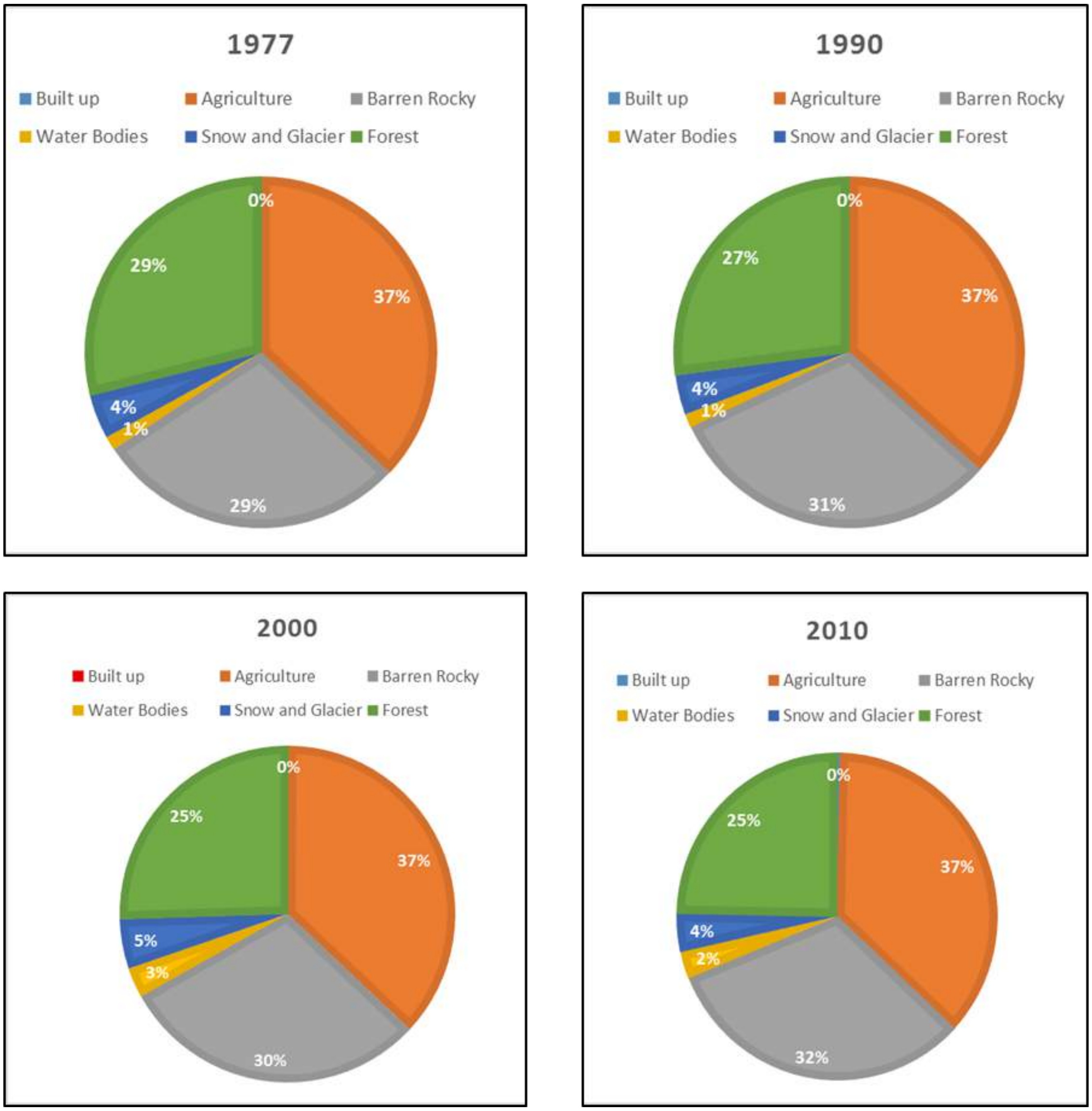



Figure 7-2: Change in LULC of Basin between the years 1977-2010

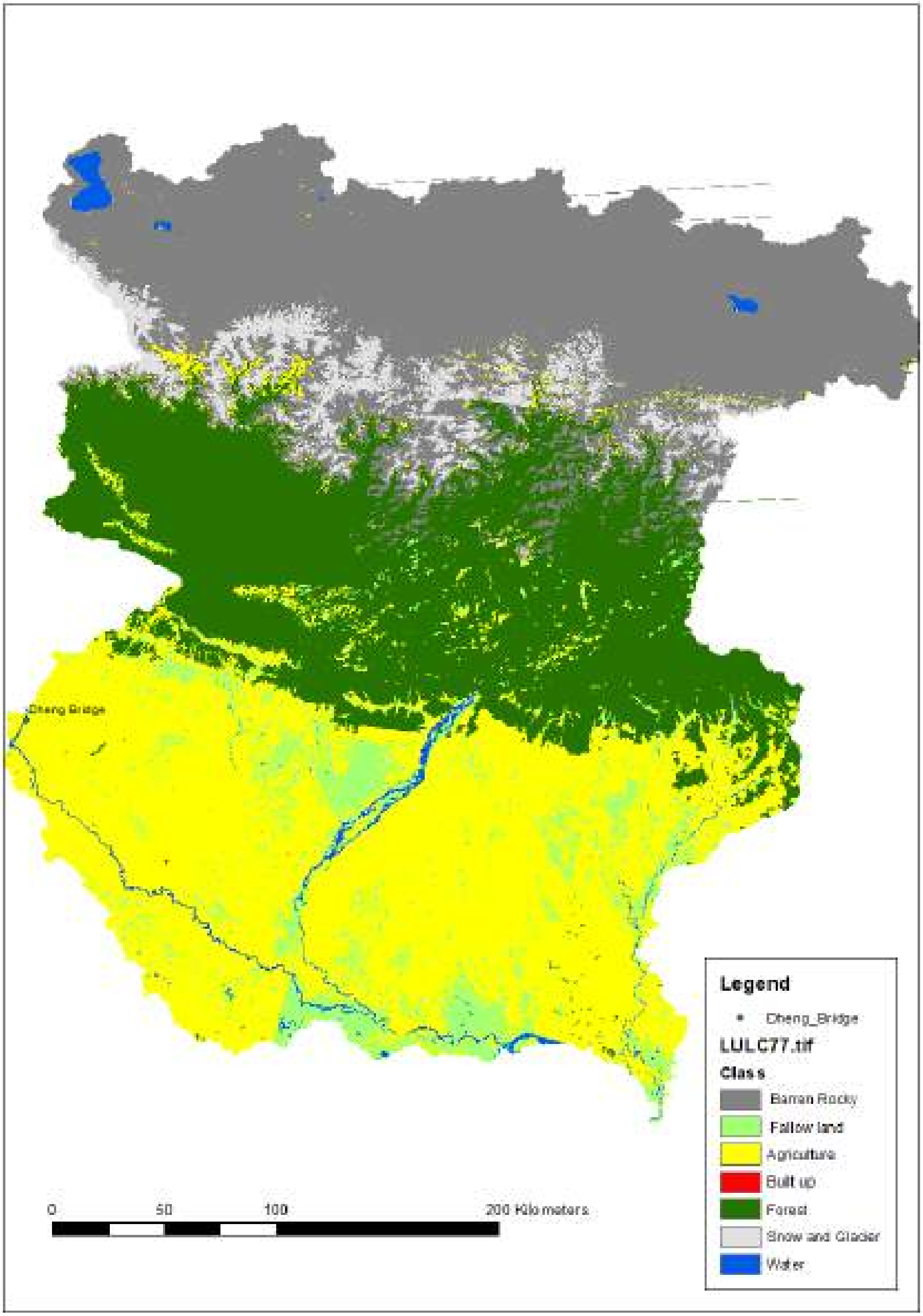



Figure 7-3:LULC map of basin for the year 1977

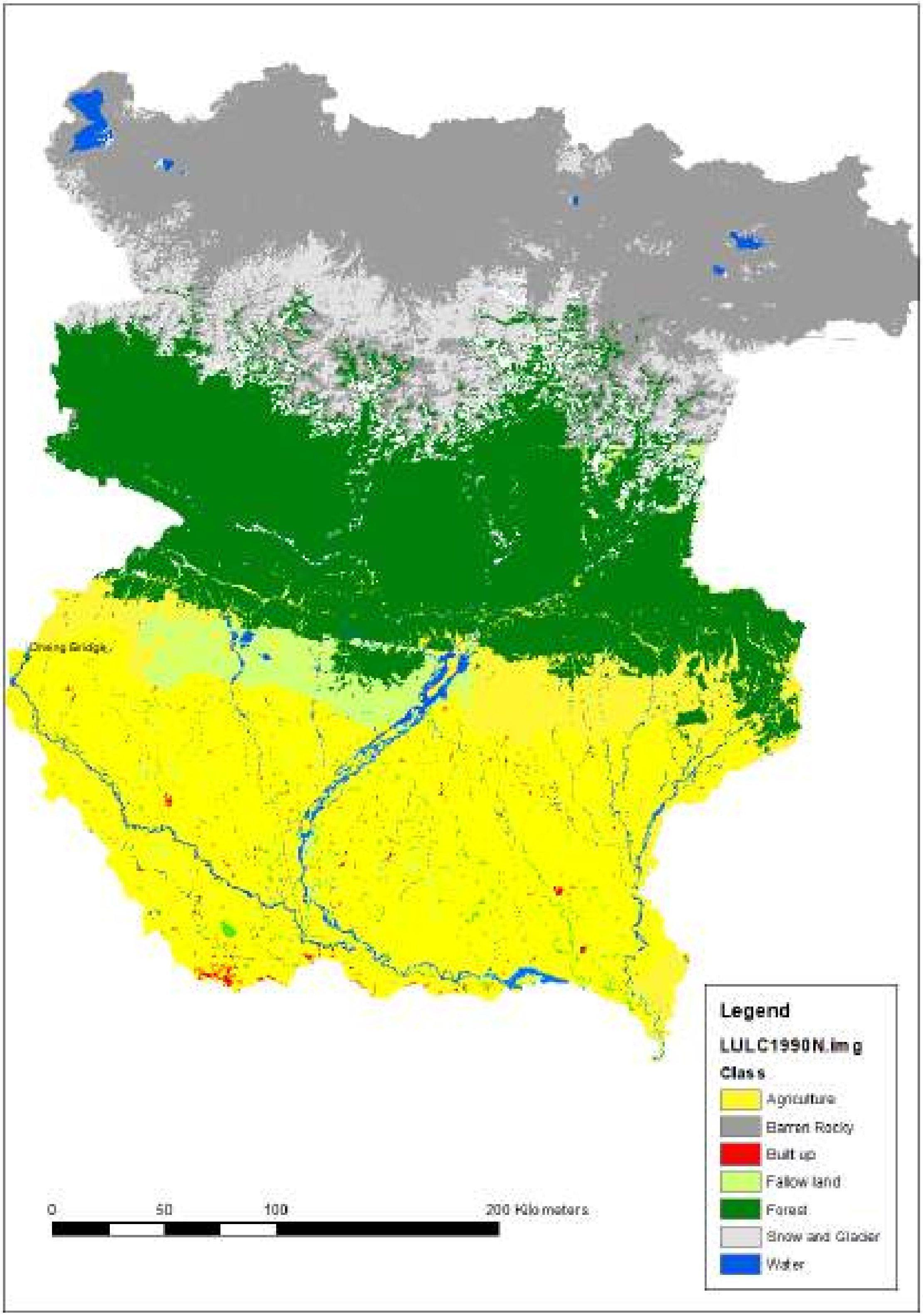



Figure 7-4: LULC map of basin for the year 1990

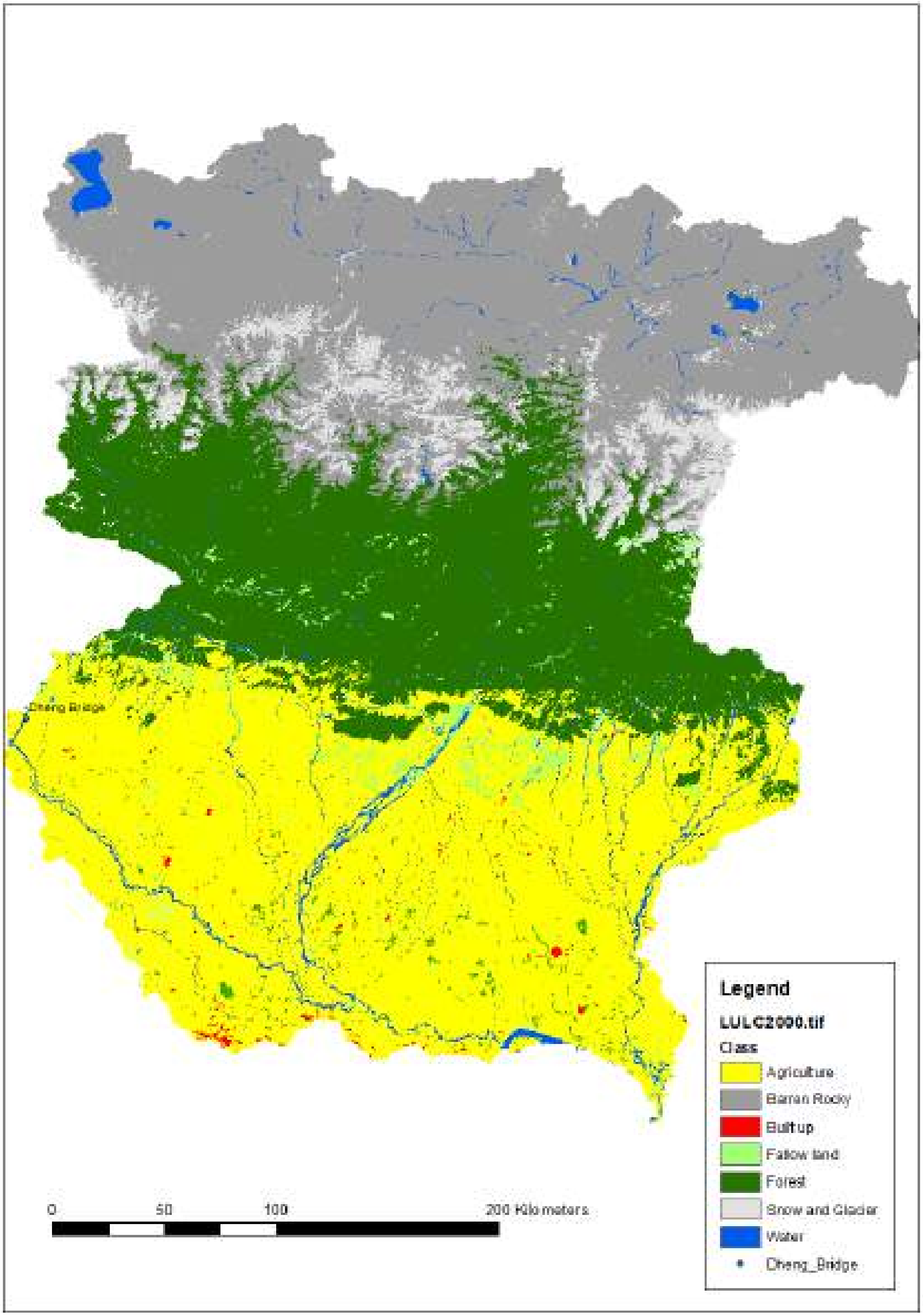



Figure 7-5: LULC map of basin for the year 2000

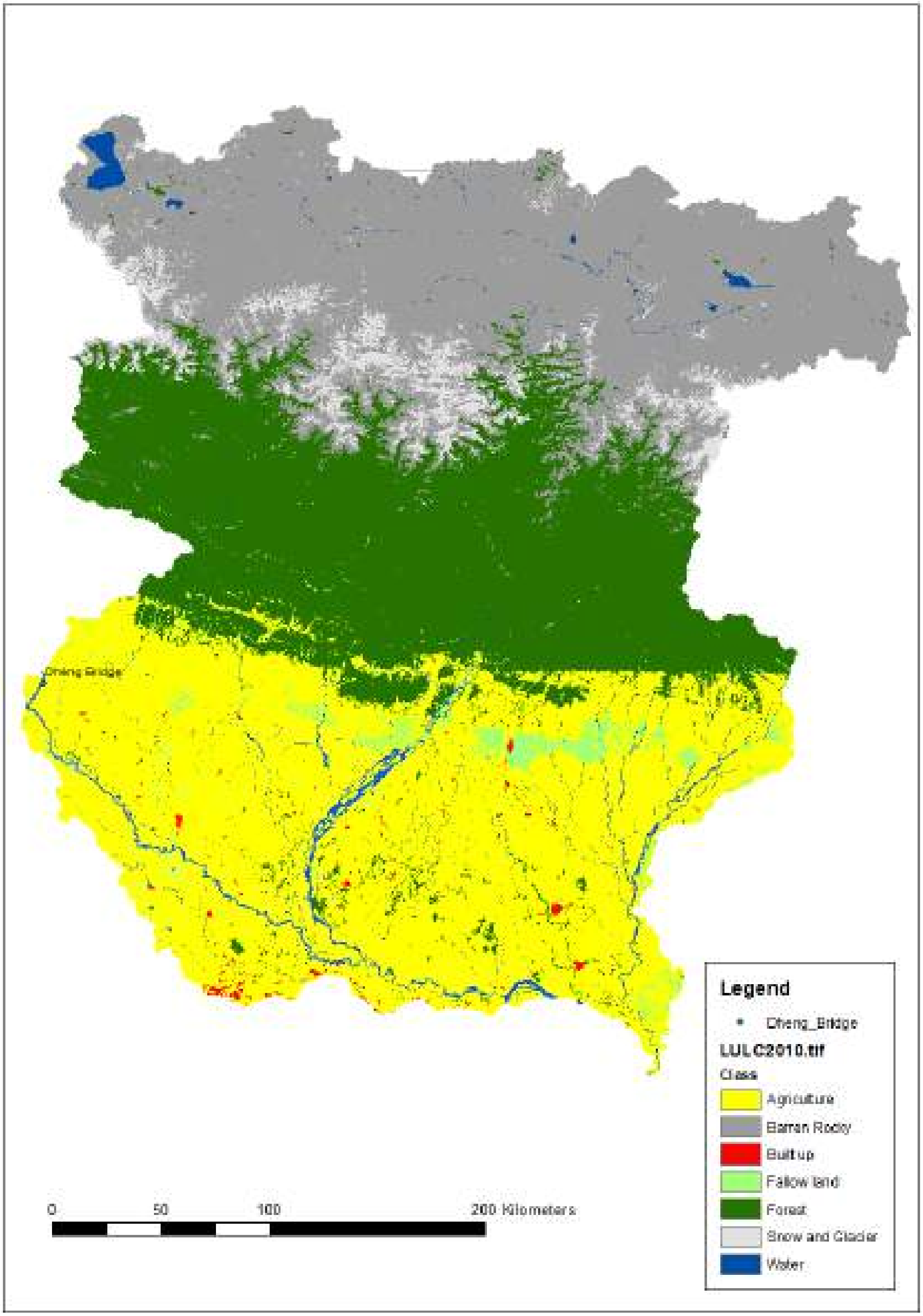



Figure 7-6: LULC map of basin for the year 2010

## 7.5 Effect of Land use change on Channel Morphology

This section presents few studies on the impact of the change in the LULC on the Bagmati river Morphology. Tuladhar et al. (2019) conducted a five decadal study on the effects of the land use land cover change on the upper catchment of the Bagmati basin and found that despite a positive contribution from urban area increase, decreasing river discharge from the upper catchment is mainly dependent on changes in rainfall. Analysis of correlation in conjunction with LULC changes also suggested that river discharge depends highly on rainfall in the urban area, and the correlation is weaker when the extent of human activities, especially urbanization. Lamichhane and Shakya (2019) have concluded that change in the Bagmati basin's water balance and the hydrological process was mainly due to the climatic variable (precipitation and temperature). The LULC change gave the counteractive role toward the urbanized section of the river basin area. The increase in rainfall and river discharge is a result of projected change in climate and LULC. Jha and Mishra (2007) have found that increase in the agricultural land and built-up land while the decrease in forest class has led to the rise in the surface runoff in the Bagmati basin between 1992-2001.

## 7.6 Conclusion

Following conclusions may be drawn from

1. The major part of the basin is covered with agriculture (based on land use of the year 2010), accounting for 36.19%, followed by Barren/Fellow land (31.5%), forest (24.376%), Snow/Glaciers (3.68%). Water bodies (2.6%), and Built-Up Land (0.341%).
2. The growing agriculture and deforestation in most areas of the Kosi-Bagmati basin may have led to soil erosion on the one hand and have accentuated flooding on the other. Most of the forest tracts within the basin are degraded because of overexploitation.
3. Though changes in land use have been observed, its direct impact on river morphology is difficult to predict because of several factors. Hydrological and meteorological factors, along with physiographic characteristics, have a significant bearing on the morphological behaviour of the river. Anthropogenic activities and development around the river corridor also affect morphological characteristics. As combining all these factors affects the river morphology, isolating land-use change from other factors is not possible. However, land-

use changes reported in this study indicate that the built-up area has increased by 62.8%, whereas forest has shown a reduction of 1.12%.

# Chapter 8 Reconnaissance

## 8.1 Introduction

This chapter presents the details of field visits undertaken to various locations of the Bagmati River Basin by the team of IIT Delhi. The observations made during the visits have been examined from the perspective of the outcomes of the morphological analysis carried out in this study. The observations are highlighted along with photographs.

## 8.2 Bank Erosion

Distinct signatures of bank erosion have been observed during the visit, and photographs indicating such occurrences are shown below. The area shown in the below pictures is around Phuhiya village in Darbhanga District. Significant agriculture activities have also been noticed in the active floodplain areas.

Figure 8-1:Bank erosion around the Phuhia Village (Photograph no:1)

Figure 8-2:Bank erosion (Photograph no:2)

Figure 8-3:Bank erosion (Photograph no:3)

Figure 8-4:Bank erosion (Photograph no:4)

Figure 8-5:Bank erosion (Photograph no:5)

From the observation, it can also be said that sediment depositions observed in lower reaches of Bagmati constitute mainly of fine silt and sand and boulders are very rare.

Figure 8-6:Fine Silt and sand deposition at the bank

## 8.3 Condition of the embankments

A team of IIT Delhi visited some of the embankments in the area around Kamla-Bagmati confluence. From the observation it is found that embankments have suffered considerable damage and need regular maintenance. The conditions of the embankments are shown in below images. On both sides of embankments, other activities such as use of immediate adjacent land for agricultural activities and as temporary road etc. may have resulted in the damage of embankment.

Figure 8-7 :Conditions of embankments

## 8.4 Accumulation of water in channels outside the traditional network

By traditional network we mean well-defined channel network of river and its tributaries for a selected stream order. On the contrary to it, channels formed around the roads, railway bridges and to some extent on account of oxbows are considered here as active water channel outside the traditional network. During the visit, such water accumulation or saturated areas are observed in non-monsoon season at various places. This can be justified on two fronts; one is shallow water table levels coupled with the soil characteristics and geologic formations. Secondly flat topography coupled with comparatively high rainfall might result in the formation of channels in the area where soil is loosened on account of agriculture and construction activities. This may result in deterioration of road conditions in the region (Figure 8-2 and Figure 8-3).

Figure 8-8 :Accumulation of water along roadside

Figure 8-9 :Road conditions

## 8.5 Significant activities in floodplains

It was noticed that significant agricultural activities are being carried out in the active floodplain areas on both the banks. It often results in loosening of soil. When such land is exposed to flood events it faces loss of soil in one area and deposition of the same in other area. The following figures are indicative of agriculture activities carried out in active floodplain area.

Figure 8-10 :Agriculture activities in active floodplain (photograph no:1)

Figure 8-11 :Agriculture activities in active floodplain (photograph no:2)

Figure 8-12 :Agriculture activities in active floodplain (photograph no:3)

Figure 8-13 :Agriculture activities in active floodplain (photograph no:4)


Figure 8-14 :Agriculture activities in active floodplain (photograph no:5)


Figure 8-15 :Agriculture activities in active floodplain (photograph no:6)

## 8.6 Other issues related to risk to life and property

### 8.6.1 Use of boats without standardized protocol

On most occasions, small boats and wooden raft are used for connecting islands/ bars with mainland. Two-wheelers, goods, food items, LPG cylinders etc are transported together with people in a crowded and probably overloaded situation. In case of boat capsize, chances of loss of lives and property are quite high. Following photographs indicate the crowded boats that are used to connect islands/bars to mainland.

Figure 8-16 :Crowded boat used for movement

Figure 8-17 :Crowd waiting at the bank for boat ride

### 8.6.2 Infrastructure activities in floodplain areas

Infrastructure activities such establishment of electric transmission tower and Brick-kiln within or around the active floodplain have also been observed. It may be difficult to comment on the exact distance of the such establishments from the riverbank, but prima facie it looks that they are located and in operation in the active floodplain area. Extreme flood events may result in damage to these infrastructure projects and may cause loss of lives.

Figure 8-18 : Brick Kiln in active floodplain area

Figure 8-19 : Power Transmission Tower

## 8.7 Conclusion

The following conclusions are drawn from the field visit of Bagmati River Basin

1. Bank erosion is dominant characteristic of Bagmati river system and signatures of such erosion and cut-off were clearly visible during the visit.
2. Embankments need regular maintenance. A protocol should be developed and followed at ground level for uses of embankments apart from flood control so that longevity of structure can be attained.
3. Channels formed or constructed along roadside should be connected to natural drainage system so that saturation conditions along the roadsides can be prevented. To accomplish this, a comprehensive hydrological study of the system is imperative.
4. Activities in active floodplain should be restricted and plantation of trees should be promoted. This may help is reducing soil erosion and also the economic loses from flood affected agriculture.
5. Infrastructure activities should be planned and designed considering the extreme events. Moreover, activities such as brick kiln should not be allowed in the active floodplain area.

Table 11-1. Grid wise average sinuosity index calculations for 1975,1990,2000,2010, and 2016

| **Sinuous length and Straight length are in km** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Grid** | **1975** | | **1990** | | **2000** | | **2010** | | **2016** | |
| | **Straight length** | **Sinuous length** | **Straight length** | **Sinuous length** | **Straight length** | **Sinuous length** | **Straight length** | **Sinuous length** | **Straight length** | **Sinuous length** |
| **216** | 9.73 | 18.63 | 9.74 | 18.51 | 9.69 | 18.56 | 9.66 | 18.77 | 9.68 | 18.96 |
| **204** | 0.96 | 0.99 | 1 | 1.02 | 1.02 | 1.03 | 1.06 | 1.08 | 1.03 | 1.04 |
| **187** | 11.23 | 17.82 | 11.3 | 17.74 | 11.32 | 17.61 | 11.33 | 17.79 | 11.35 | 17.84 |
| **170** | 5.48 | 6.42 | 5.32 | 6.15 | 5.29 | 6.12 | 5.24 | 6.13 | 5.24 | 6.1 |
| **144** | 5.64 | 11.94 | 5.63 | 11.94 | 5.66 | 11.92 | 5.65 | 9.22 | 5.69 | 9.22 |
| **160** | 8.64 | 18.07 | 8.69 | 18.35 | 8.67 | 18.42 | 8.68 | 18.05 | 8.65 | 17.9 |
| **135** | 8.56 | 15.34 | 8.59 | 15.37 | 8.56 | 15.38 | 8.55 | 15.44 | 8.54 | 15.37 |
| **120** | 5.88 | 8.72 | 5.87 | 8.5 | 5.88 | 8.49 | 5.86 | 8.55 | 5.87 | 8.63 |
| **112** | 6 | 17.97 | 5.98 | 15.58 | 5.98 | 16.54 | 6.02 | 15.66 | 6.01 | 15.96 |
| **98** | 10.18 | 16.46 | 10.17 | 16.2 | 10.15 | 16.54 | 10.15 | 15.48 | 10.16 | 14.85 |
| **84** | 8.11 | 20.71 | 8.14 | 21.16 | 8.25 | 19.97 | 8.32 | 22.97 | 8.27 | 18.65 |
| **78** | 10.7 | 22.45 | 10.68 | 21.18 | 10.65 | 19.37 | 10.63 | 20.15 | 10.62 | 19.93 |
| **72** | 3.37 | 4.7 | 3.39 | 4.69 | 3.44 | 4.76 | 3.44 | 4.97 | 3.47 | 5.05 |
| **60** | 10.95 | 15.09 | 11.01 | 15.28 | 10.97 | 15.48 | 10.93 | 16.38 | 11.98 | 15.05 |
| **55** | 2.54 | 3.04 | 2.56 | 2.83 | 2.53 | 2.79 | 2.53 | 2.92 | | |
| **44** | 12.21 | 16.27 | 12.17 | 15.67 | 12.53 | 16.1 | 12.28 | 17.76 | 13.72 | 17.25 |
| **40** | 3.09 | 5.51 | 2.8 | 5.22 | 2.73 | 4.74 | 2.65 | 3.77 | 2.8 | 3.75 |
| **30** | 11.51 | 19.91 | 11.8 | 21.21 | 11.3 | 11.95 | 11.2 | 12.84 | 11.03 | 13.23 |
| **20** | 1.41 | 1.59 | 1.15 | 2.07 | 2.02 | 2.68 | 2.39 | 2.81 | 2.68 | 3.02 |
| **18** | 10.23 | 11.64 | 10.02 | 11 | 10.14 | 11.32 | 10.08 | 11.31 | 10.04 | 11.73 |
| **16** | 11.55 | 14.57 | 12.73 | 21.03 | 11.82 | 16.78 | 12.05 | 16.94 | 11.87 | 17.35 |
| **14** | 11.53 | 12.43 | 11.61 | 12.97 | 11.22 | 13.02 | 11.25 | 13.67 | 11.03 | 12.95 |
| **12** | 5.94 | 8.37 | 5.98 | 7.05 | 5.94 | 7.75 | 5.95 | 7.78 | 5.95 | 7.7 |

As mentioned above, Sinuosity on grid-scale in different years is indicated in the table below, where different colour indicates channel pattern in terms of Sinuosity.

| Straight | **Sinuous** | Meandering |
|---|---|---|

Table 11-2. Sinuosity ratio

| Sinuous length and Straight length are in km | | | | | |
|---|---|---|---|---|---|
| **Grid** | **1975** | **1990** | **2000** | **2010** | **2016** |
| | **Sinuosity Index** | **Sinuosity Index** | **Sinuosity Index** | **Sinuosity Index** | **Sinuosity Index** |
| **216** | 1.91 | 1.9 | 1.92 | 1.94 | 1.96 |
| **204** | 1.03 | 1.02 | 1.01 | 1.02 | 1.02 |
| **187** | 1.59 | 1.57 | 1.56 | 1.57 | 1.57 |
| **170** | 1.17 | 1.16 | 1.16 | 1.17 | 1.16 |
| **144** | 2.12 | 2.12 | 2.1 | 1.63 | 1.62 |
| **160** | 2.09 | 2.11 | 2.13 | 2.08 | 2.07 |
| **135** | 1.79 | 1.79 | 1.8 | 1.81 | 1.8 |
| **120** | 1.48 | 1.45 | 1.44 | 1.46 | 1.47 |
| **112** | 3 | 2.6 | 2.77 | 2.6 | 2.66 |
| **98** | 1.62 | 1.59 | 1.63 | 1.52 | 1.46 |
| **84** | 2.55 | 2.6 | 2.42 | 2.76 | 2.26 |
| **78** | 2.1 | 1.98 | 1.82 | 1.9 | 1.88 |
| **72** | 1.39 | 1.38 | 1.38 | 1.45 | 1.46 |
| **60** | 1.38 | 1.39 | 1.41 | 1.5 | 1.26 |
| **55** | 1.2 | 1.1 | 1.1 | 1.15 | NA |
| **44** | 1.33 | 1.29 | 1.28 | 1.45 | 1.26 |
| **40** | 1.79 | 1.86 | 1.74 | 1.42 | 1.34 |
| **30** | 1.73 | 1.8 | 1.06 | 1.15 | 1.2 |
| **20** | 1.13 | 1.8 | 1.33 | 1.18 | 1.13 |
| **18** | 1.14 | 1.1 | 1.12 | 1.12 | 1.17 |
| **16** | 1.26 | 1.65 | 1.42 | 1.41 | 1.46 |
| **14** | 1.08 | 1.12 | 1.16 | 1.22 | 1.17 |
| **12** | 1.41 | 1.18 | 1.3 | 1.31 | 1.29 |

The following conclusions may be drawn from calculated values of sinuosity ratio of Bagmati River

1. In the entire reach of the Bagmati River, for the years 1975, 1990, 2000, 2010 and 2016, the maximum and average sinuosity ratio values are 3 and 1.5, respectively.
2. As the average value is around 1.5, Bagmati may be considered the sinuous/meandering river as per Leopold and Wolman (1957).

3. Sinuosity ratios for the grids 216, 187, 160, 144, 135, 112, 98, 84, 72 and 40 are relatively higher than other grids (with an average of 2). Sinuosity of the river is higher in its upper reaches.
4. No significant change is observed in the Sinuosity over time from the period of 1975 to 2016.

## 11.3 Radius of Curvature

To determine geometrical parameters associated with Sinuosity, the radius of curvature for the different years has been worked out. The following table indicates the average radius of curvature calculated for each grid.

Table 11-3. Grid Wise Average Radius of curvature for 1975, 1990, 2000, 2010 and 2016

| Grid | 1975 | 1990 | 2000 | 2010 | 2016 |
|---|---|---|---|---|---|
| **216** | 0.2 | 0.19 | 0.27 | 0.19 | 0.18 |
| **187** | 0.27 | 0.15 | 0.2 | 0.26 | 0.15 |
| **170** | 0.31 | 0.2 | 0.24 | 0.23 | 0.27 |
| **160** | 0.29 | 0.19 | 0.24 | 0.29 | 0.2 |
| **144** | 0.33 | 0.23 | 0.26 | 0.2 | 0.22 |
| **135** | 0.3 | 0.21 | 0.2 | 0.26 | 0.25 |
| **120** | 0.16 | 0.2 | 0.28 | 0.27 | 0.2 |
| **112** | 0.18 | 0.23 | 0.18 | 0.23 | 0.22 |
| **98** | 0.14 | 0.23 | 0.19 | 0.19 | 0.17 |
| **84** | 0.21 | 0.19 | 0.31 | 0.24 | 0.21 |
| **78** | 0.16 | 0.21 | 0.2 | 0.18 | 0.17 |
| **72** | 0.23 | 0.17 | 0.16 | 0.18 | 0.2 |
| **60** | 0.22 | 0.16 | 0.27 | 0.17 | 0.22 |
| **55** | 0.2 | 0.17 | 0.18 | 0.17 | 0.2 |
| **44** | 0.19 | 0.19 | 0.22 | 0.21 | 0.23 |
| **40** | 0.13 | 0.23 | 0.15 | 0.24 | 0.24 |
| **20/27*** | 0* | 0.27 | 0.18 | 0.17/0.32* | 0.28/0.22* |
| **30** | 0.25 | 0.22 | 0.26 | 0.26 | 0.27 |
| **18** | 0 | 0.23 | 0.22 | 0.25 | 0.18 |

| Grid | 1975 | 1990 | 2000 | 2010 | 2016 |
|---|---|---|---|---|---|
| **16** | 0.22 | 0.21 | 0.2 | 0.26 | 0.26 |
| **14** | 0.31 | 0.23 | 0.2 | 0.29 | 0.2 |
| **12** | 0.3 | 0.17 | 0.18 | 0.24 | 0.26 |

The above table 3 indicates that the average radius of curvature (grid wise) varies from 0 to 0.33 km. It is important to note that only a moderate value of the radius of curvature estimated for few segments indicates a comparatively straight channel, and the associated segment cannot be considered a meandering segment. Analysis of the average radius of curvature suggests that no significant trend is observed over the past 40 years (1975 to 2016).

## 11.4 Braiding Index

In the present study, the braiding index, as suggested by Friend and Sinha (1993); $L_{ctot}$ / $L_{cmax}$, has been adopted. Here, $L_{ctot}$ is the sum of the mid-channel lengths of all the segments of primary channels in a reach, and $L_{cmax}$ is the mid-channel length of the widest channel through the reach.

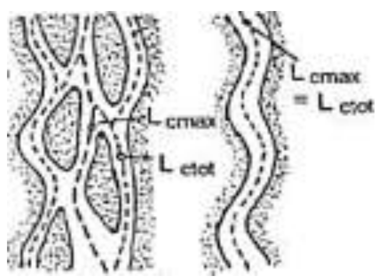



Figure 11-2: Braiding Index suggested by Friend and Sinha (1993)

Gird wise length of total channel and length of wider channel based on digitised data of different years is indicated in Table 11-4, and decadal variation of Braiding Index is shown in Table 11-5.

Table 11-4. Gird Wise total length and length of the wider channel (in km)

| Total length and length of wider channel are in km | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Grid** | **1979** | | **1990** | | **2000** | | **2010** | | **2016** | |
| | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** |
| 216 | 18.63 | 18.63 | 18.84 | 18.51 | 18.86 | 18.56 | 19.03 | 18.77 | 19.21 | 18.96 |
| 204 | 0.99 | 0.99 | 1.02 | 1.02 | 1.03 | 1.03 | 1.08 | 1.08 | 1.04 | 1.04 |
| 187 | 17.82 | 17.82 | 17.74 | 17.74 | 17.61 | 17.61 | 17.79 | 17.79 | 17.84 | 17.84 |
| 170 | 6.42 | 6.42 | 6.15 | 6.15 | 6.12 | 6.12 | 6.13 | 6.13 | 6.1 | 6.1 |
| 144 | 11.94 | 11.94 | 11.94 | 11.94 | 11.92 | 11.92 | 9.22 | 9.22 | 9.22 | 9.22 |
| 160 | 18.07 | 18.07 | 18.35 | 18.35 | 18.42 | 18.42 | 18.33 | 18.05 | 17.9 | 17.9 |
| 135 | 15.34 | 15.34 | 15.37 | 15.37 | 15.38 | 15.38 | 15.44 | 15.44 | 15.37 | 15.37 |
| 120 | 8.72 | 8.72 | 8.5 | 8.5 | 8.49 | 8.49 | 8.55 | 8.55 | 8.63 | 8.63 |
| 112 | 17.97 | 17.97 | 15.58 | 15.58 | 16.54 | 16.54 | 15.66 | 15.66 | 15.96 | 15.96 |
| 98 | 16.46 | 16.46 | 16.2 | 16.2 | 16.54 | 16.54 | 15.48 | 15.48 | 14.85 | 14.85 |
| 84 | 20.71 | 20.71 | 21.16 | 21.16 | 19.97 | 19.97 | 22.97 | 22.97 | 18.65 | 18.65 |
| 78 | 22.45 | 22.45 | 21.18 | 21.18 | 19.37 | 19.37 | 20.15 | 20.15 | 19.93 | 19.93 |
| 60 | 15.67 | 15.09 | 15.28 | 15.28 | 15.48 | 15.48 | 16.38 | 16.38 | 15.30 | 15.05 |
| 55 | 3.04 | 3.04 | 2.83 | 2.83 | 2.79 | 2.79 | 2.92 | 2.92 | | |
| 44 | 16.66 | 16.27 | 15.67 | 15.67 | 16.10 | 16.10 | 17.97 | 17.76 | 20.07 | 17.25 |
| 40 | 5.51 | 5.51 | 5.22 | 5.22 | 4.74 | 4.74 | 4.08 | 3.77 | 9.43 | 3.75 |
| 30 | 19.91 | 19.91 | 21.21 | 21.21 | 11.95 | 11.95 | 13.44 | 12.84 | 15.87 | 13.23 |

| Total length and length of wider channel are in km | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Grid** | **1979** | | **1990** | | **2000** | | **2010** | | **2016** | |
| | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** | **Total Length** | **Length of widest Channel** |
| 20 | 1.59 | 1.59 | 2.07 | 2.07 | 2.68 | 2.68 | 3.49 | 2.81 | 3.47 | 3.02 |
| 18 | 11.64 | 11.64 | 11.35 | 11.00 | 15.83 | 11.32 | 15.95 | 11.31 | 15.03 | 11.73 |
| 16 | 14.57 | 14.57 | 22.03 | 21.03 | 26.90 | 16.78 | 24.74 | 16.94 | 23.39 | 17.35 |
| 14 | 12.43 | 12.43 | 18.87 | 12.97 | 15.06 | 13.02 | 23.14 | 13.67 | 18.03 | 12.95 |
| 12 | 9.37 | 8.37 | 8.62 | 7.05 | 7.84 | 7.75 | 9.17 | 7.78 | 9.21 | 7.70 |

Table 11-5. Braiding Index of Bagmati River

| **The total length and length of the wider channel are in km** | | | | | |
|---|---|---|---|---|---|
| **Grid Name** | **1979** | **1990** | **2000** | **2010** | **2016** |
| | **Braiding Index** | **Braiding Index** | **Braiding Index** | **Braiding Index** | **Braiding Index** |
| 216 | 1.02 | 1.02 | 1.02 | 1.01 | 1.01 |
| 204 | 1 | 1 | 1 | 1 | 1 |
| 187 | 1 | 1 | 1 | 1 | 1 |
| 170 | 1 | 1 | 1 | 1 | 1 |
| 144 | 1 | 1 | 1 | 1 | 1 |
| 160 | 1 | 1 | 1 | 1.02 | 1 |
| 135 | 1 | 1 | 1 | 1 | 1 |
| 120 | 1 | 1 | 1 | 1 | 1 |
| 112 | 1 | 1 | 1 | 1 | 1 |
| 98 | 1 | 1 | 1 | 1 | 1 |
| 84 | 1 | 1 | 1 | 1 | 1 |
| 78 | 1 | 1 | 1 | 1 | 1 |
| 60 | 1.04 | 1 | 1 | 1 | 1.02 |
| 55 | 1 | 1 | 1 | 1 | |
| 44 | 1.02 | 1 | 1 | 1.01 | 1.16 |
| 40 | 1 | 1 | 1 | 1.08 | 2.51 |
| 30 | 1 | 1 | 1 | 1.05 | 1.20 |
| 20 | 1 | 1 | 1 | 1.24 | 1.15 |
| 18 | 1 | 1.03 | 1.40 | 1.41 | 1.28 |
| 16 | 1 | 1.05 | 1.60 | 1.46 | 1.35 |
| 14 | 1 | 1.45 | 1.16 | 1.69 | 1.39 |
| 12 | 1.12 | 1.22 | 1.01 | 1.18 | 1.20 |

The braiding index of the Baghmati River varies in the range from 1 to 2.15, with an average value of 1.07. However, it is important to note that in past imageries the braiding is observed in only selected reaches of the Bagmati River, for example, grid 40 (2016), grid 216 (for all years) and grid 160 (2010). In 2016, a significant higher Braiding index was observed in Grid 40 in the Sitamarhi district, where the river bifurcated at chainage 57 and merged into one at chainage 68. It is important to note that braiding is observed in only selected reaches of the Bagmati River. In order to understand the associated plan form in a detailed manner, the planform index is computed and discussed in Section 11.5.

## 11.5 Plan Form Index (PFI)

The PFI of Bagmati River is calculated using the approach given by Sharma (2004). The PFI is calculated as reach specific; hence the total reach of the river is subdivided according to their respective geometric characteristics to compute the bed width, river width and the number of channels, and average into 0-4 km chainage long segments. Each Chainage, PFI (%) is calculated for 1975, 1990, 2000, 2010 and 2016. Calculated values are shown in Table 11-5.

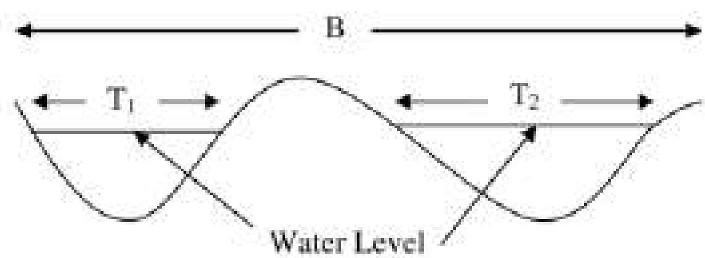
The PFI of Bagmati River is calculated using the approach given by Sharma (1995). The following equation has been used to find out plan form index.

$$Plan\ Form\ Index = \frac{\frac{T}{B} * 100}{N}$$

where, T = T1+T2 = Flow top width

B = Overall flow width

N = Number of braided channels




The total reach of the river is subdivided into segments, and the bed width, river width and the number of channels is computed for each segment. At each Chainage, PFI (%) is calculated for 1975, 1990, 2000, 2010 and 2016. Calculated PFI are shown in Table 11-6, and the graphical representations are shown in Figure 11-3 to 11-12.

The Chainage is measured from at the Dheng Bridge. To better understand the geographical location of braiding patterns, various villages are depicted in the remarks section along with their corresponding chainages.

Table 11-6. Plan Form Index at 4 km Chainage (in %)

| Highly Braided | Moderately Braided | Less Braided |
|---|---|---|
| PFI < 4 | 4< PFI < 19 | PFI > 19 |

| Chainage range (km) | 1975 | 1990 | 2000 | 2010 | 2016 | Remarks |
|---|---|---|---|---|---|---|
| **0-4** | 46 | 24 | 23 | 47 | 42.5 | |
| **4-8** | 100 | 43 | 31 | 39 | 48 | |
| **8-12** | 40 | 17 | 14 | 14 | 28 | Akhta (Sitamarhi) |
| **12-16** | 100 | 27 | 47 | 26 | 28.5 | |
| **16-20** | 34 | 39.5 | 17 | 32 | 49.5 | |
| **20-24** | 75 | 29.75 | 10 | 36 | 30 | |
| **24-28** | 66 | 62 | 71 | 25 | 31.33 | |
| **28-32** | 32 | 74.5 | 40 | 71 | 67.5 | |
| **32-36** | 30 | 100 | 42 | 35 | 16 | |
| **36-40** | 25 | 100 | 39 | 42 | 28.5 | |
| **40-44** | 45 | 100 | 46 | 39 | 70.5 | |
| **44-48** | 34 | 100 | 79 | 76 | 77 | |
| **48-52** | 90 | 93.67 | 100 | 71 | 75.5 | |
| **52-56** | 41 | 83.33 | 100 | 68 | 82 | |
| **56-60** | 41 | 100 | 29 | 7 | 52 | Sitamarhi |
| **60-64** | 38 | 85.5 | 74 | 4 | 4 | Sitamarhi |
| **64-68** | - | 63 | 91 | 53 | 5 | Muzaffarpur |
| **68-72** | 100 | 84 | 100 | 100 | 80.5 | |
| **72-76** | 68 | 65.5 | 100 | 100 | 47 | |
| **76-80** | 76 | 100 | 100 | 100 | 83 | |
| **80-84** | 100 | 100 | 93 | 45 | 88 | |
| **84-88** | 100 | 76.67 | 99 | 100 | 90.5 | |
| **88-92** | 100 | 85 | 75 | 100 | 68 | |
| **92-96** | 100 | 100 | 94 | 100 | 96.5 | |
| **96-100** | 100 | 66 | 68 | 92 | 71.5 | |
| **100-104** | 100 | 38.33 | 100 | 88 | 52 | |
| **104-108** | 100 | 91.67 | 95 | 86 | 97 | |
| **108-112** | 100 | 100 | 98 | 100 | 98.33 | |
| **112-116** | 100 | 65.2 | 94 | 95 | 98.2 | |
| **116-120** | 100 | 61.5 | 100 | 97 | 97.4 | |
| **120-124** | 100 | 20 | 90 | 65 | 100 | |
| **124-128** | 100 | 100 | 88 | 100 | 98 | |
| **128-132** | 100 | 59.33 | 92 | 84 | 76.33 | |
| **132-136** | 100 | 68 | 88 | 87 | 85 | |
| **136-140** | 100 | 73 | 58 | 73 | 68.67 | |
| **140-144** | 100 | 94.5 | 72 | 87 | 97 | |
| **144-148** | 100 | 100 | 58 | 100 | 85 | |
| **148-152** | 100 | 76 | 69 | 53 | 90.8 | Benipur |
| **152-156** | 93.5 | 46.33 | 52 | 78 | 92.67 | |

| Chainage range (km) | 1975 | 1990 | 2000 | 2010 | 2016 | Remarks |
|---|---|---|---|---|---|---|
| **156-160** | 85.5 | 57.67 | 61 | 82 | 98.67 | |
| **160-164** | 100 | 100 | 71 | 100 | 99 | |
| **164-168** | 100 | 100 | 90 | 92 | 98.8 | |
| **168-172** | 100 | 100 | 78 | 100 | 96.33 | |
| **172-176** | 100 | 100 | 88 | 60 | 99 | |
| **176-180** | 100 | 100 | 89 | 100 | 97.5 | |
| **180-184** | 100 | 100 | 96 | 100 | 98.75 | |
| **184-188** | 100 | 100 | 100 | 100 | 97 | |
| **188-192** | 100 | 100 | 100 | 100 | 96 | |
| **192-196** | 100 | 98.33 | 97 | 100 | 97 | |
| **196-200** | 100 | 69 | 100 | 100 | 95.5 | |

Examination of the above table leads to the following conclusions:

- In the river 8-12 km chainage segment, which is upstream of the confluence of Bagmati and Lalbekya river, significant braiding is observed. From Chainage 16-24 km, moderate braiding is observed due to the confluence of the Bagmati and Lalbekya river, and the braiding may have increased due to the addition in the sediment load. A significantly higher braiding is observed from 56 to 68 chainage as at chainage 57 (Sitamarhi district,) the river bifurcates and remain bifurcated till chainage 68.

- In the lower segment of the reach, low braiding is observed. The satellite images have revealed that the river is on a straight course with less to no braiding. After this point, the river assumes an insignificant braiding pattern and flows as a single braid up to its confluence with the Kosi River

For more visual clarity, various PFI charts have been plotted (Figure 11-3 to Figure 11-12) for every 20 km chainage from the upstream point of Dheng Bridge to the confluence of the Kosi river for the years 1975, 1990, 2000, 2010 and 2016.

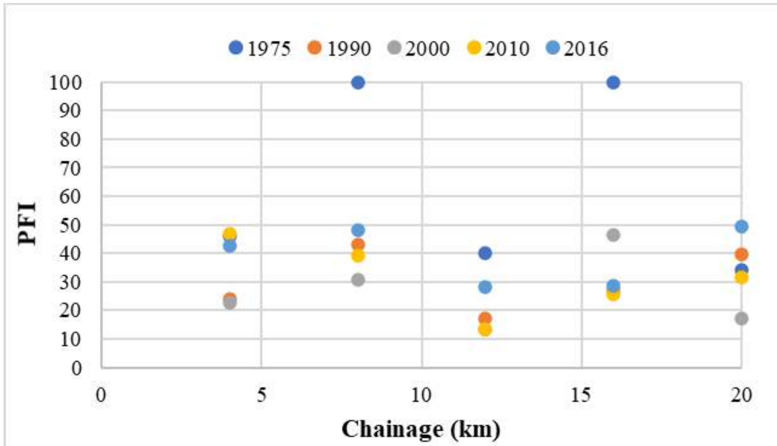



Figure 11-3: Plan Form Index of Bagmati river (Chainage 0-20 km)

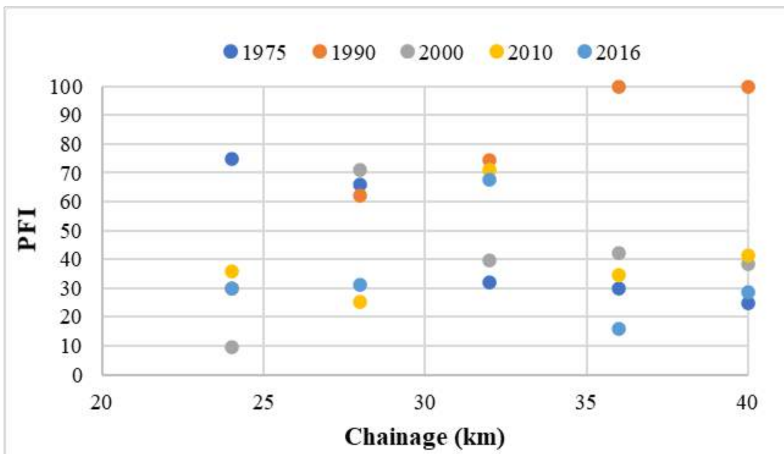



Figure 11-4: Plan Form Index of Bagmati river (chainage 20-40km)

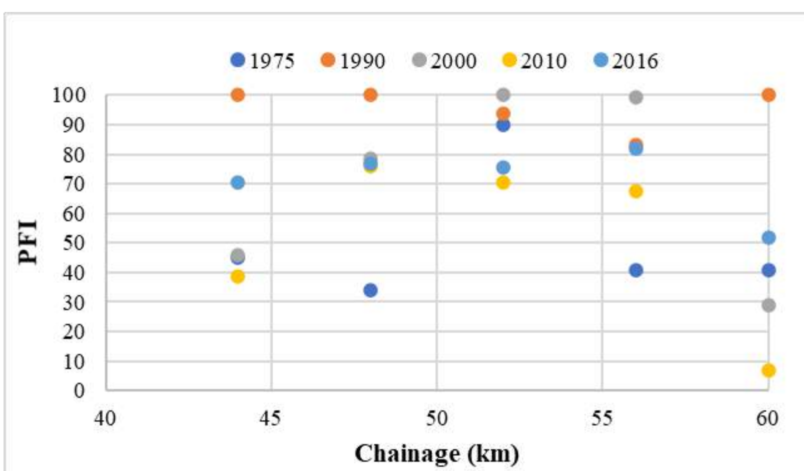



Figure 11-5: Plan Form Index of Bagmati river (chainage 40-60 km)

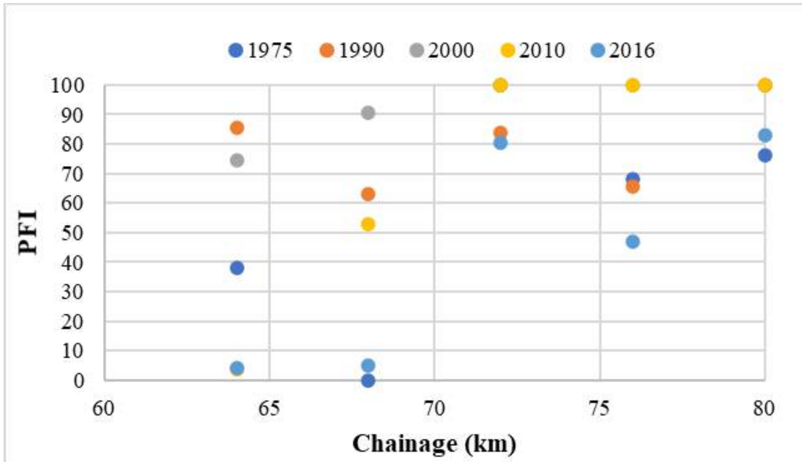



Figure 11-6: Plan Form Index of Bagmati river (chainage 60-80 km)

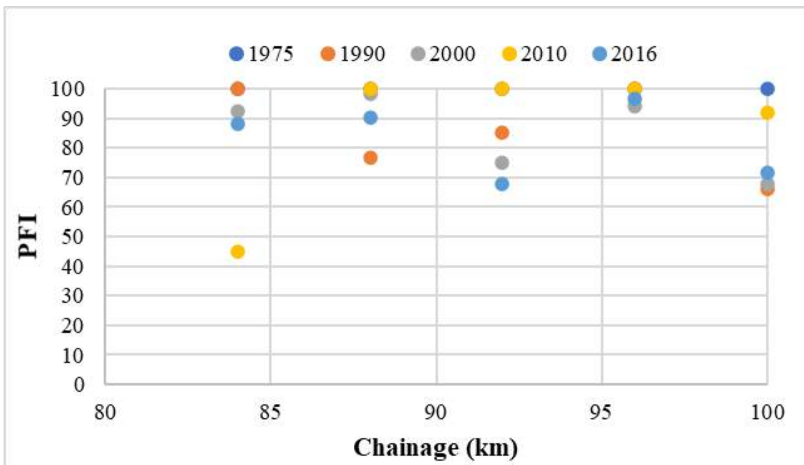



Figure 11-7: Plan Form Index of Bagmati river (chainage 80-100 km)

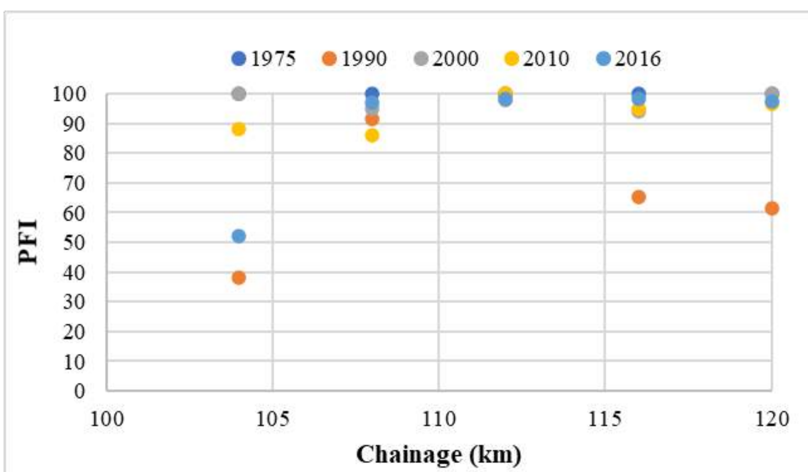



Figure 11-8: Plan Form Index of Bagmati river (chainage 100-120 km)

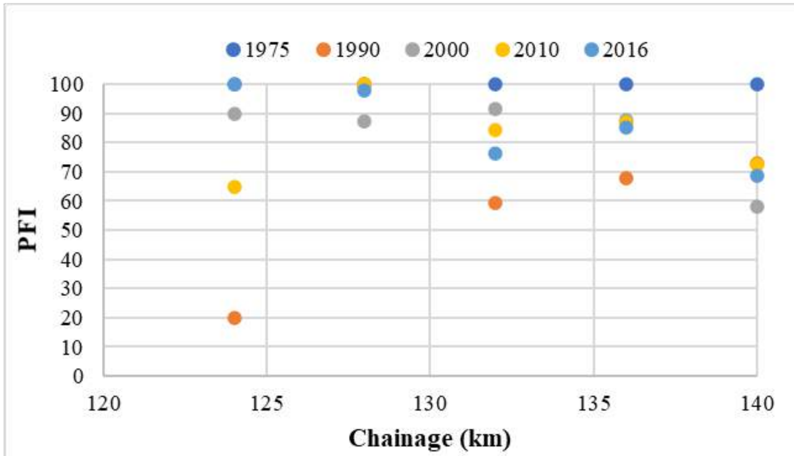



Figure 11-9: Plan Form Index of Bagmati river (chainage 120-140 km)

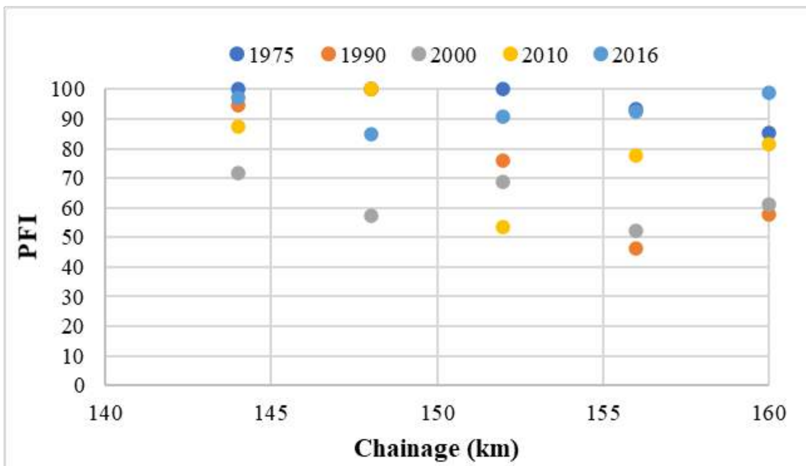



Figure 11-10: Plan Form Index of Bagmati river (chainage 140-160 km)

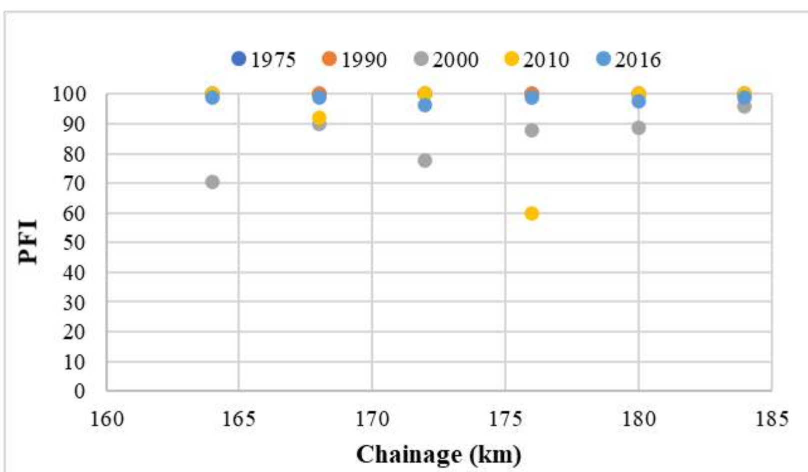



Figure 11-11:Plan Form Index of Bagmati river (chainage 160-185 km)

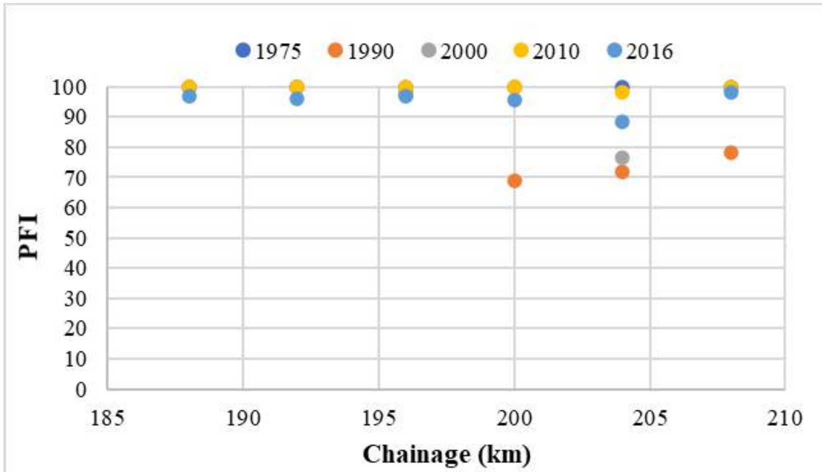



Figure 11-12: Plan Form Index of Bagmati river (chainage 185-210 km)

## 11.6 Understanding of River Course Dynamics

In the present study, river course dynamics has been analysed by recording the movement of the channel centreline. The latter movement is recorded on a grid-based template for an objective base reference proposed by Parmar and Khosa (2017). Difference between the distance of centrelines of two specific years (such as 1975-1990, 1990-2000, 2000-2010 and 2010-2016) from a predefined reference line and assessing change at an interval of every 1 km. The reference line is drawn based on the channel centreline of 1975. The difference in centreline is considered as the swing displacement in the river channel during the specified period.

Figure 11-13 and Figure 11-14 indicates river course dynamics in the complete length of the river Bagmati from its origin to its confluence with the river Kosi. Detailed presentation of various segments is rearranged in separate graphs (Figure 11-15 to Figure 11-26) depicting only 15-20 km reach of the river at a time, and information is presented in tabular form in Table 11-7. The analysis reveal that the Baghmati River is highly dynamic especially in its upper reach.

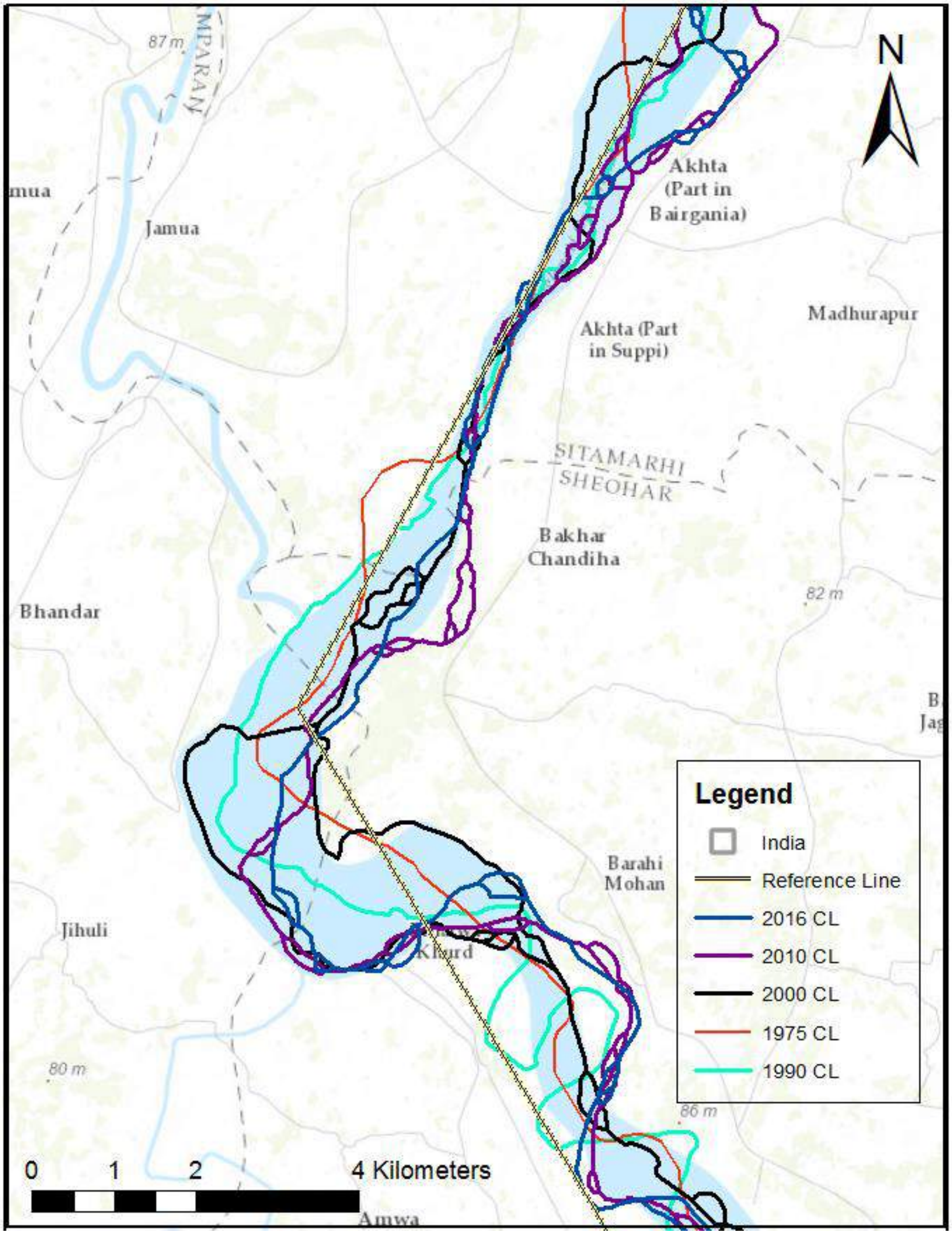



Figure 11-13: Map of River Course Dynamics (Background map Source. ESRI, MapmyIndia, Delrome, ME TI/NASA)

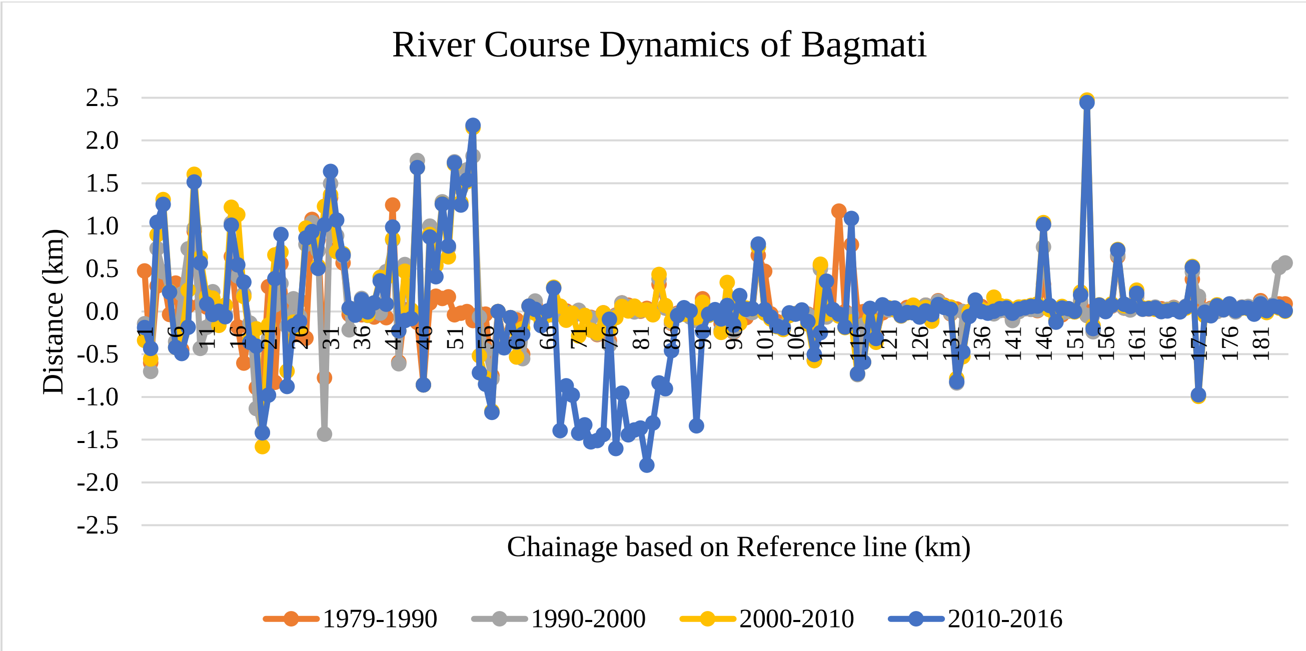



Figure 11-14: River Course Dynamics of complete reach of Bagmati River

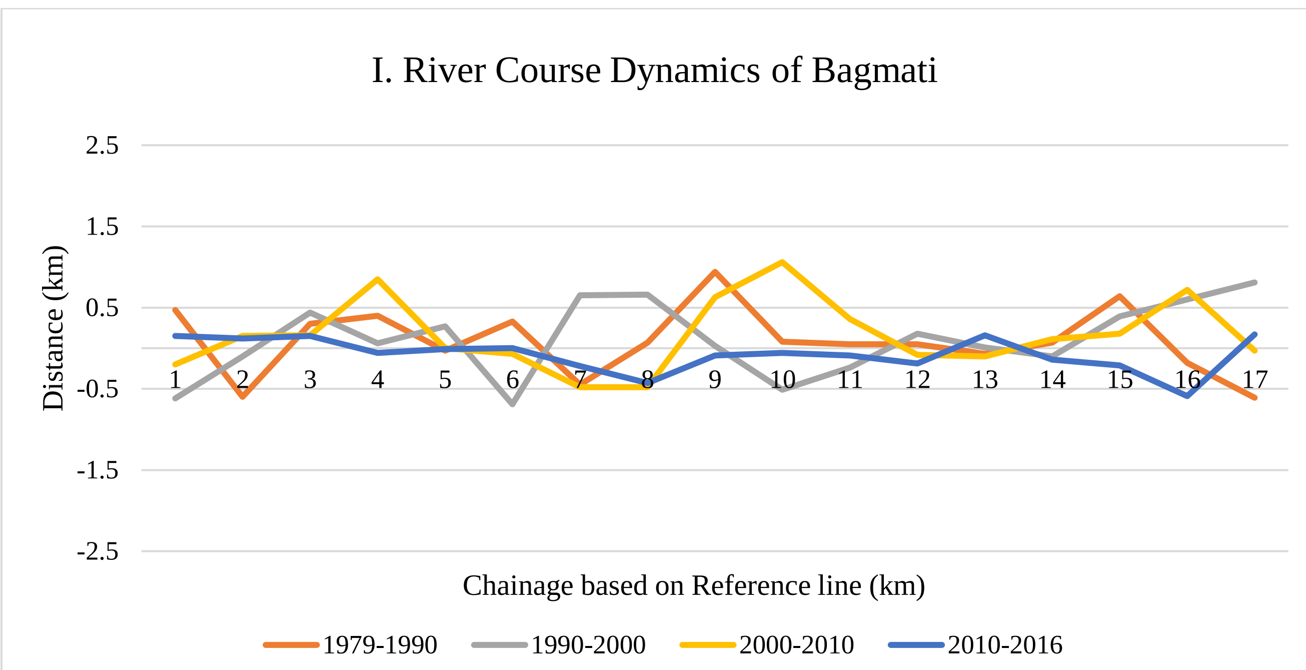



Figure 11-15a: River Course Dynamics of Bagmati River from Chainage 1-17 km

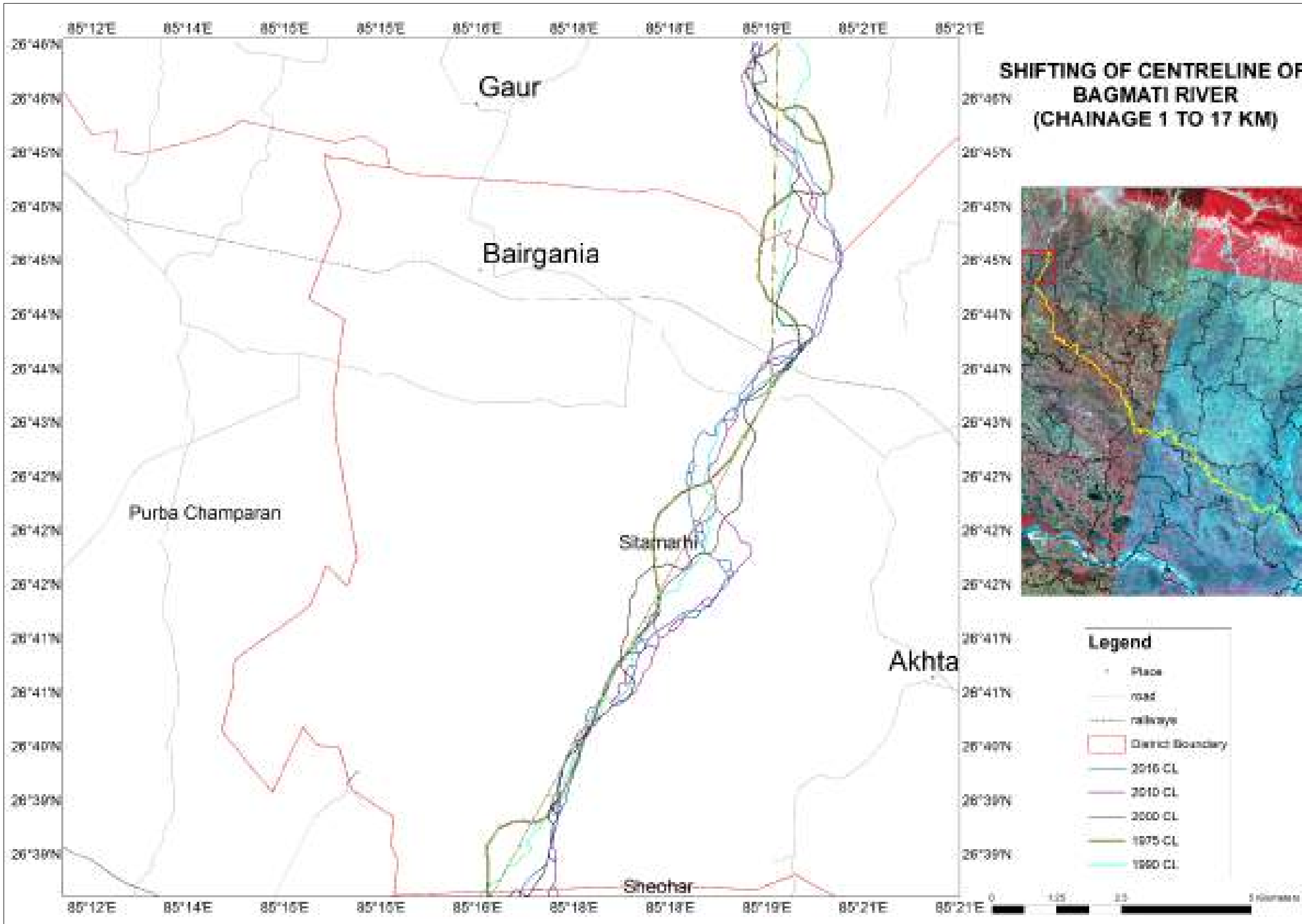



Figure 11-15b: River Course Dynamics of Bagmati River from Chainage 1-17 km

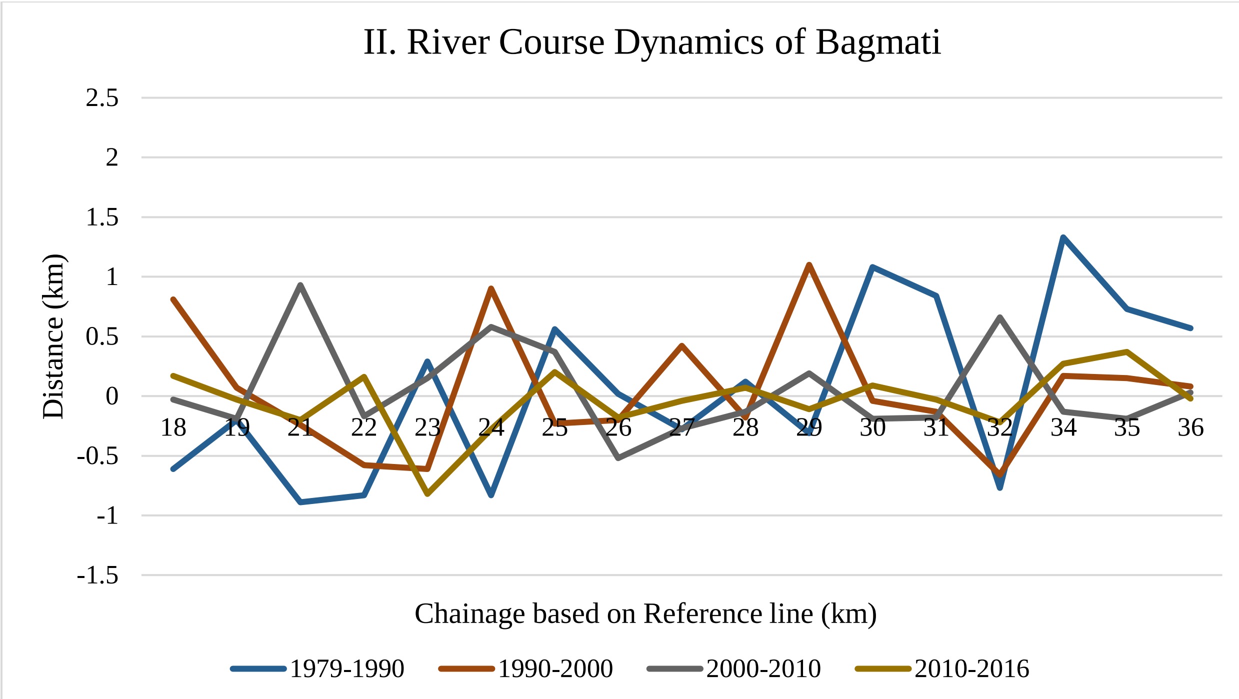



Figure 11-16a: River Course Dynamics of Bagmati River from Chainage 18-36 km

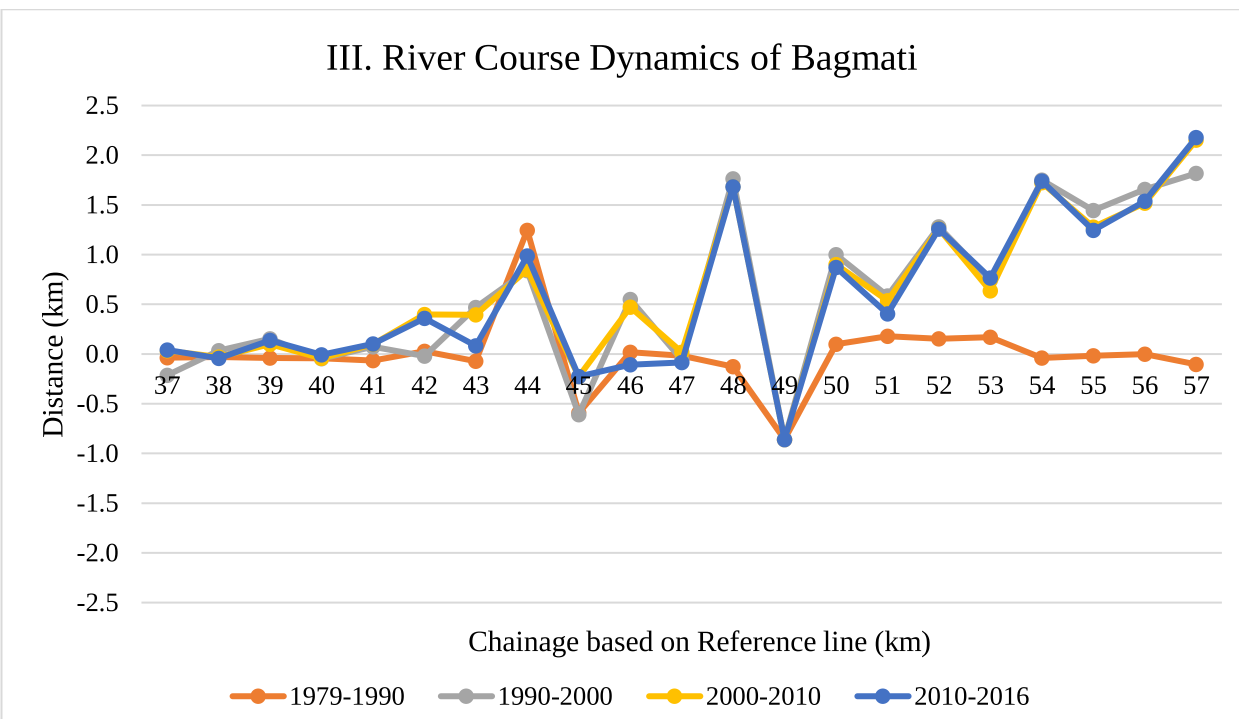



Figure 11-17a. River Course Dynamics of Bagmati River from Chainage 37-57 km

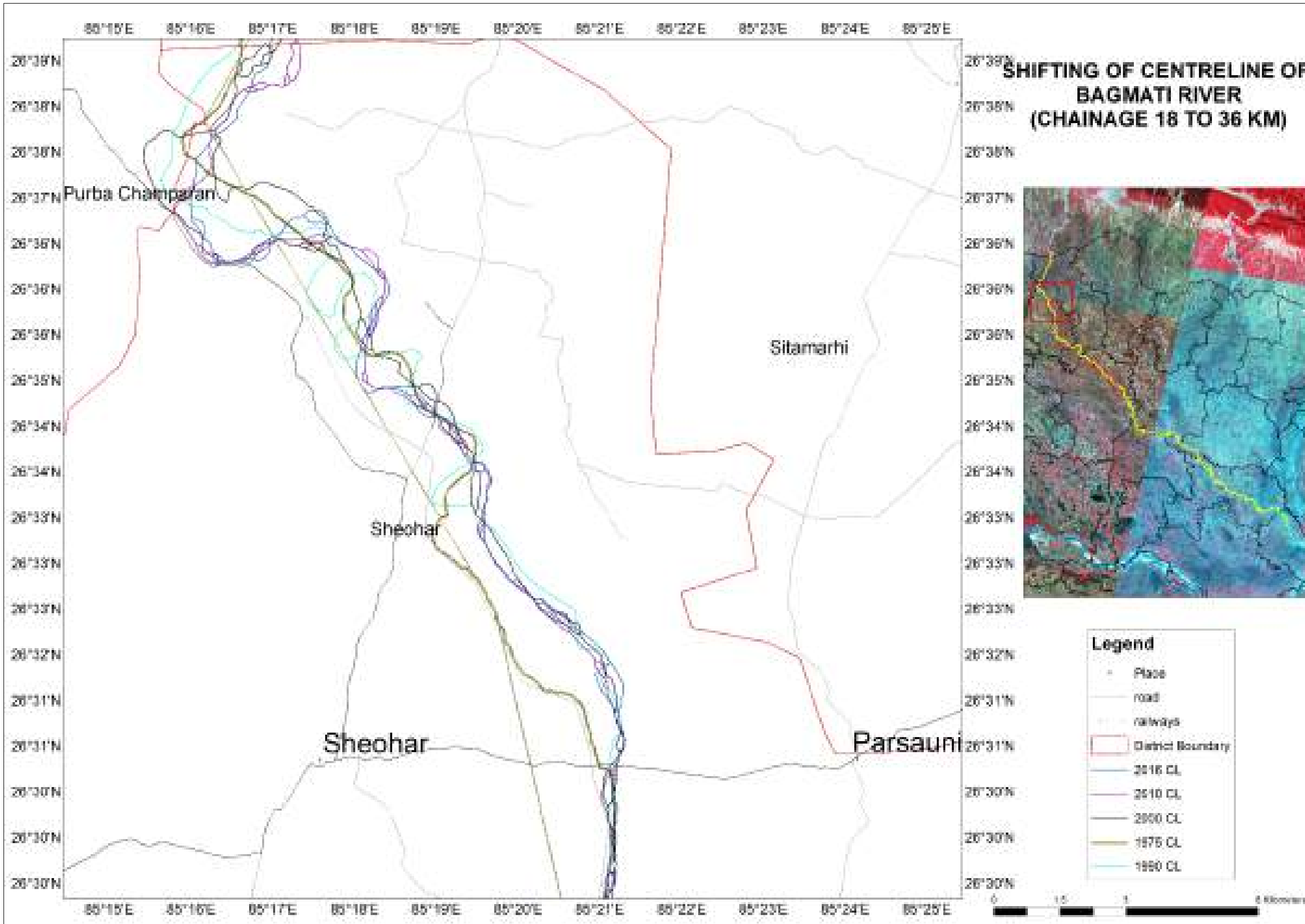



Figure11-16b: River Course Dynamics of Bagmati River from Chainage 18-36 km

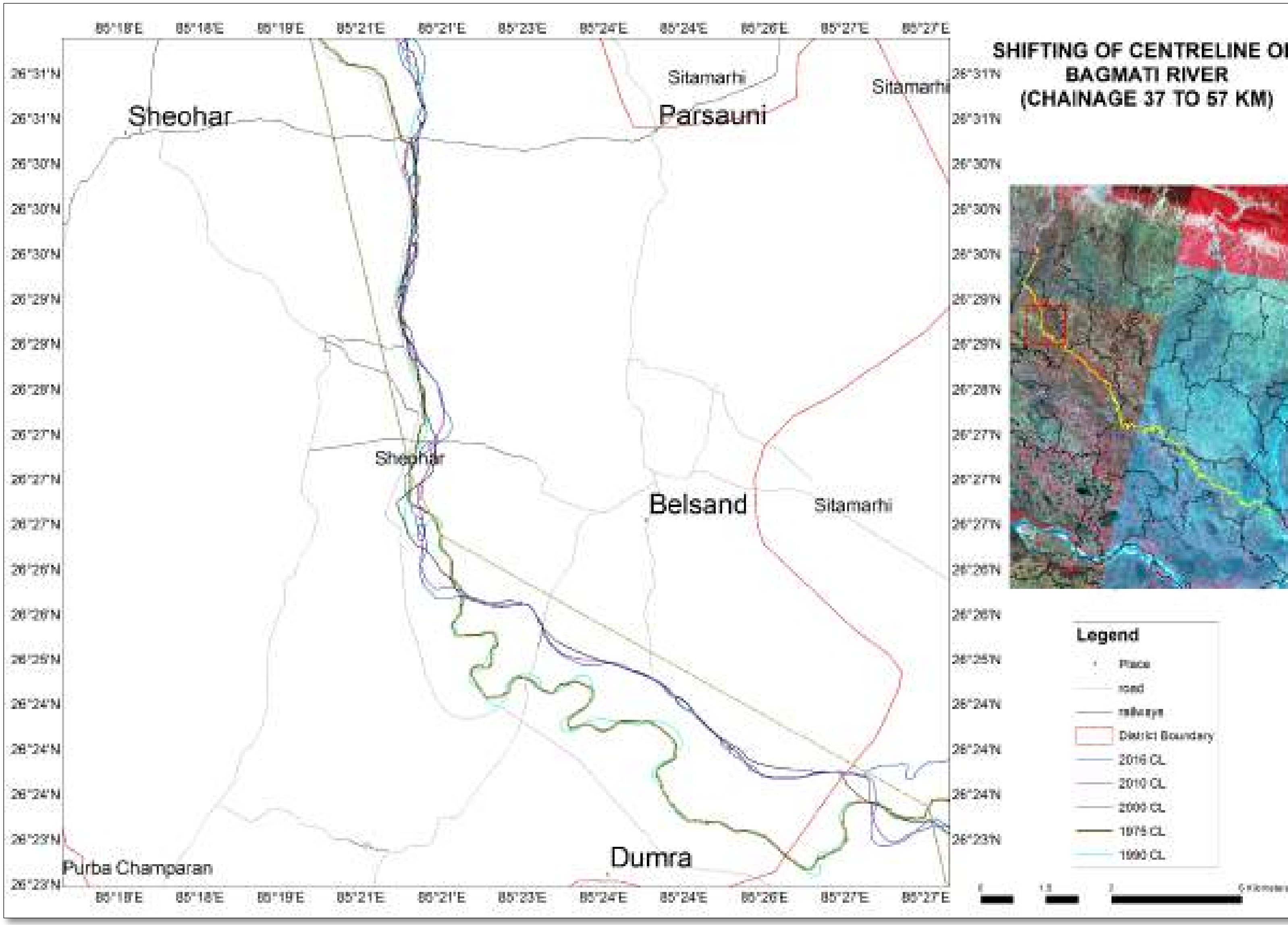



Figure 11-17b: River Course Dynamics of Bagmati River from Chainage 37-57 km

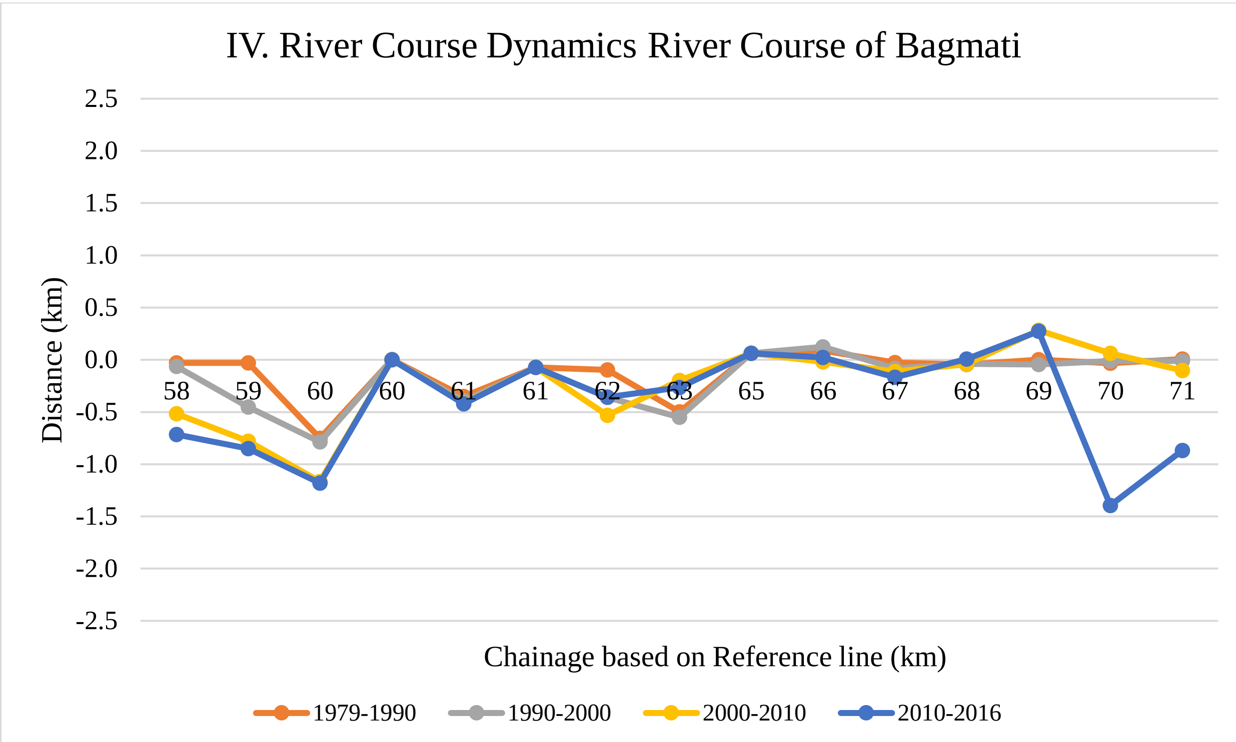



Figure 11-18a: River Course Dynamics of Bagmati River from Chainage 58-71 km

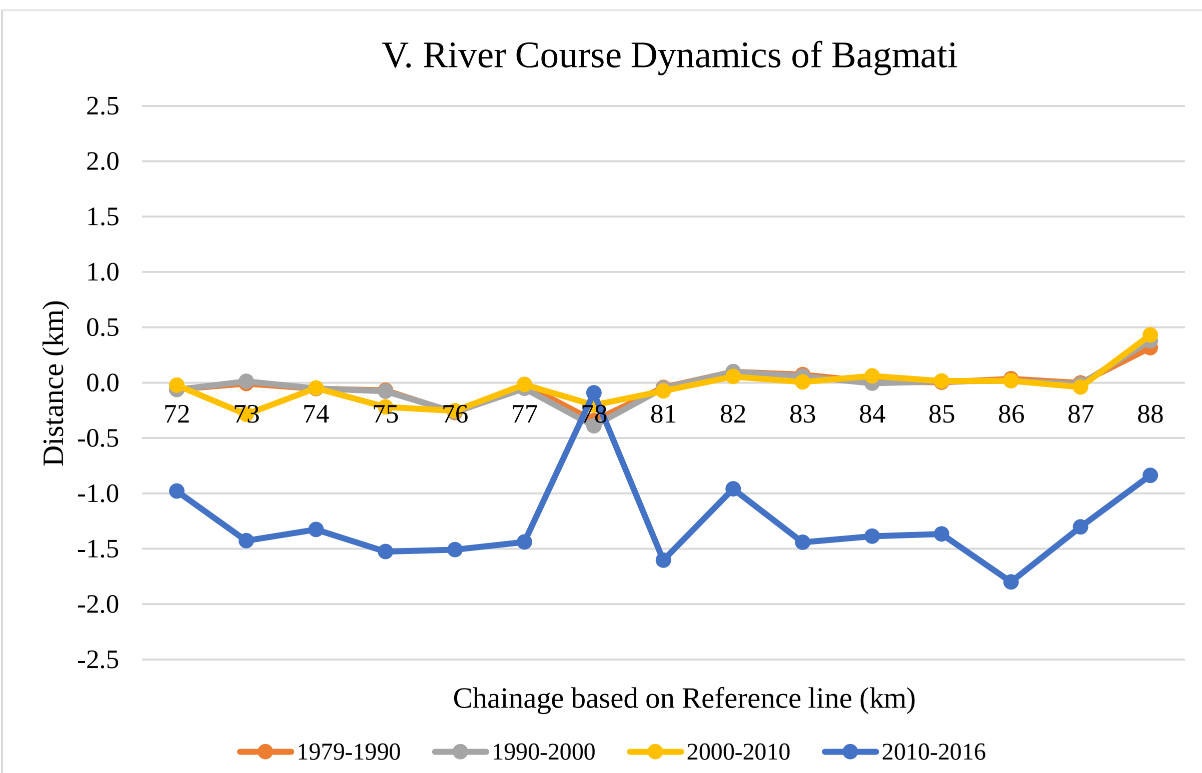



Figure 11-19a: River Course Dynamics of Bagmati River from Chainage 72-88 km

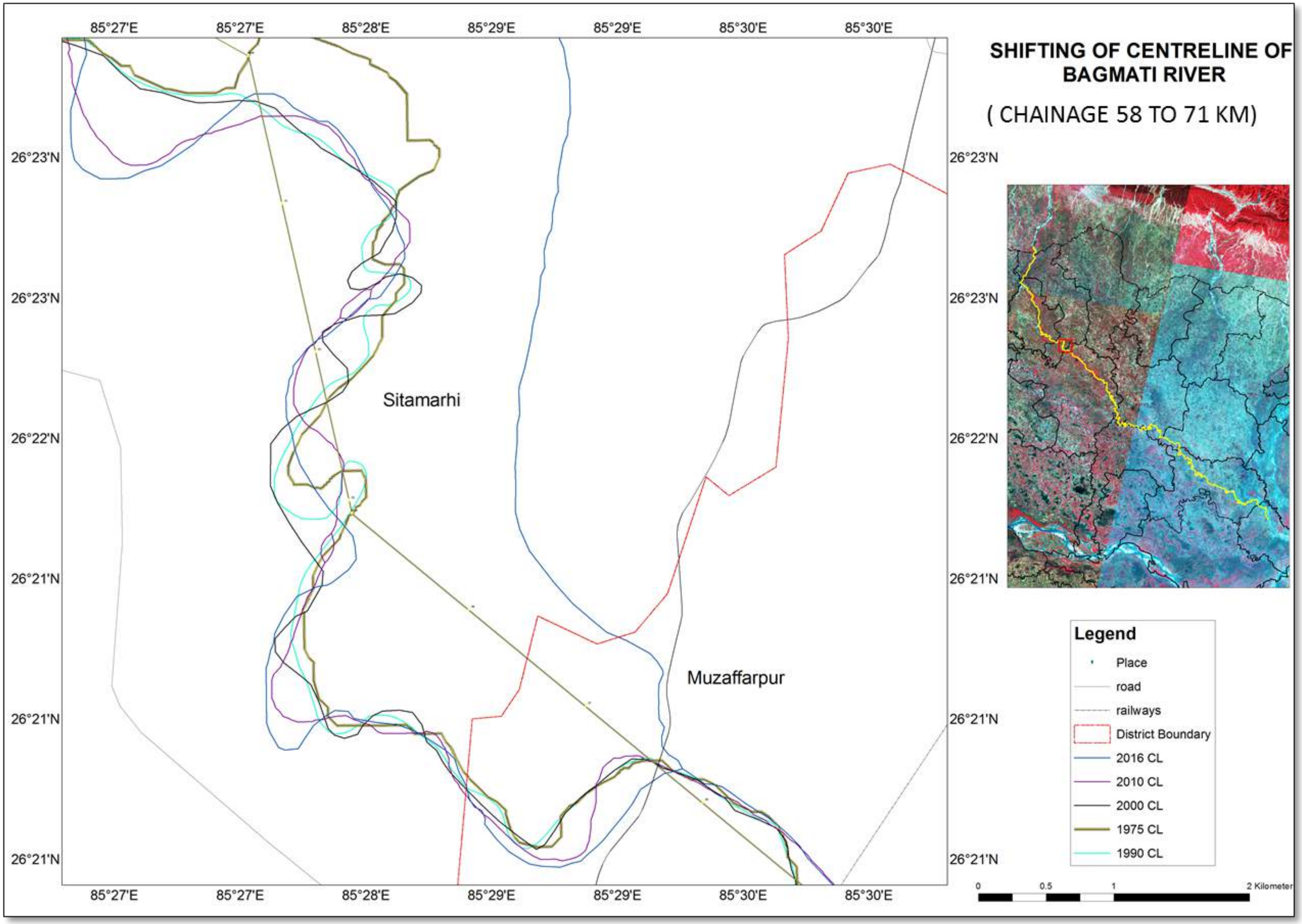



Figure 11-18b. River Course Dynamics of Bagmati River from Chainage 58-71 km

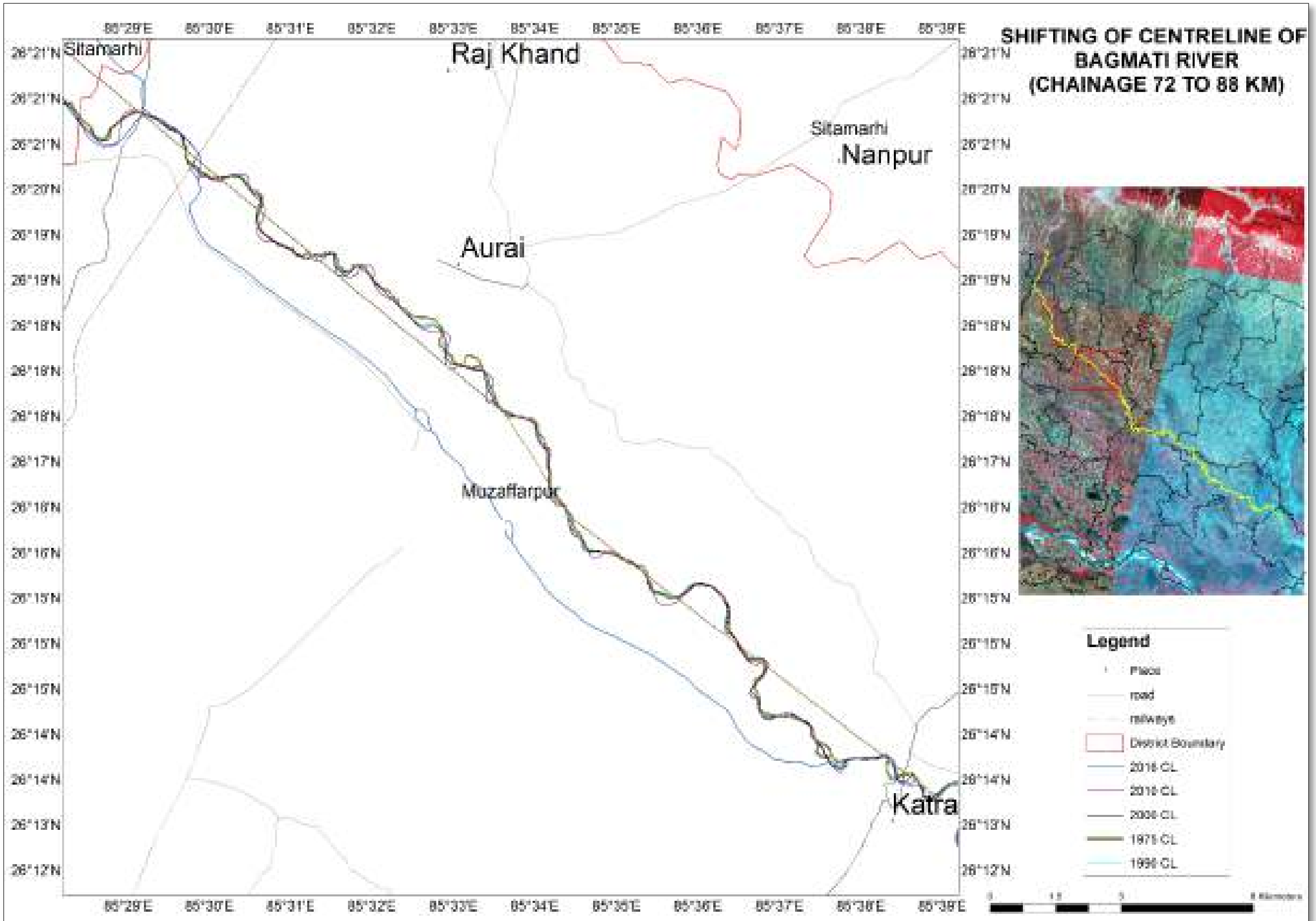



Figure 11-19b. River Course Dynamics of Bagmati River from Chainage 72-88 km

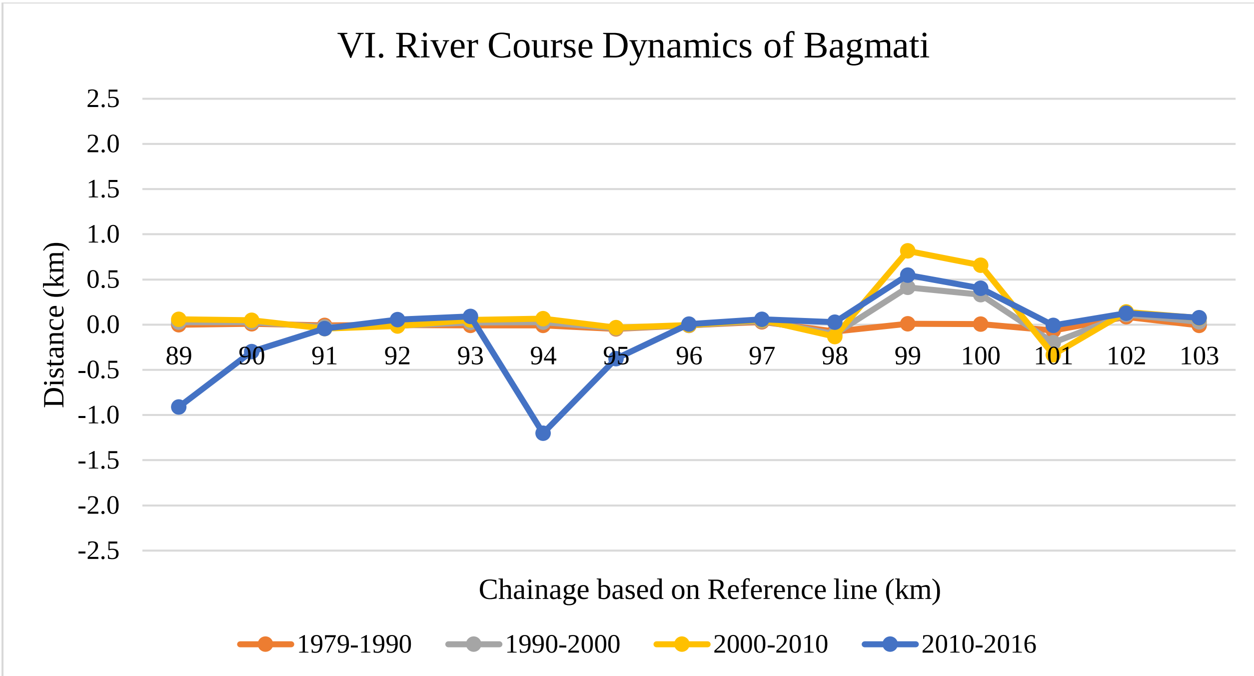



Figure 11-20a: River Course Dynamics of Bagmati River from Chainage 89-103 km

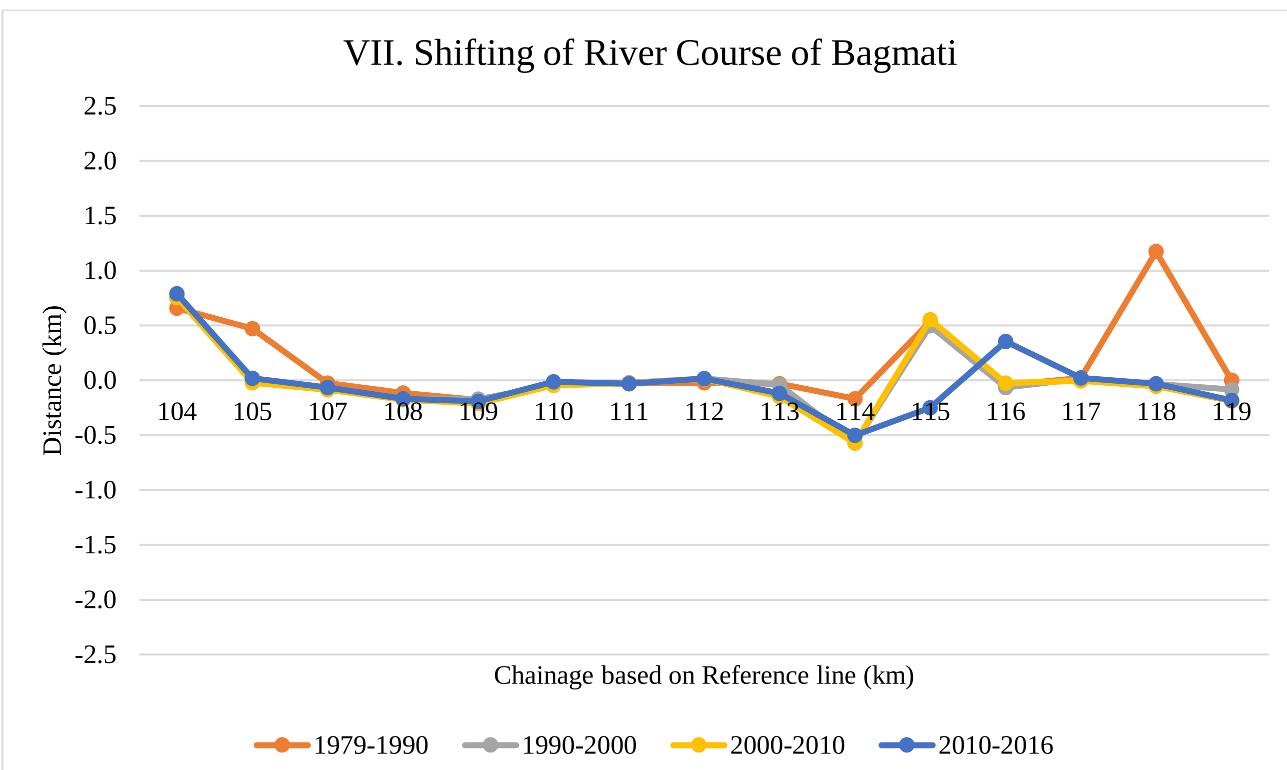



Figure 11-21a: River Course Dynamics of Bagmati River from Chainage 104-119 km

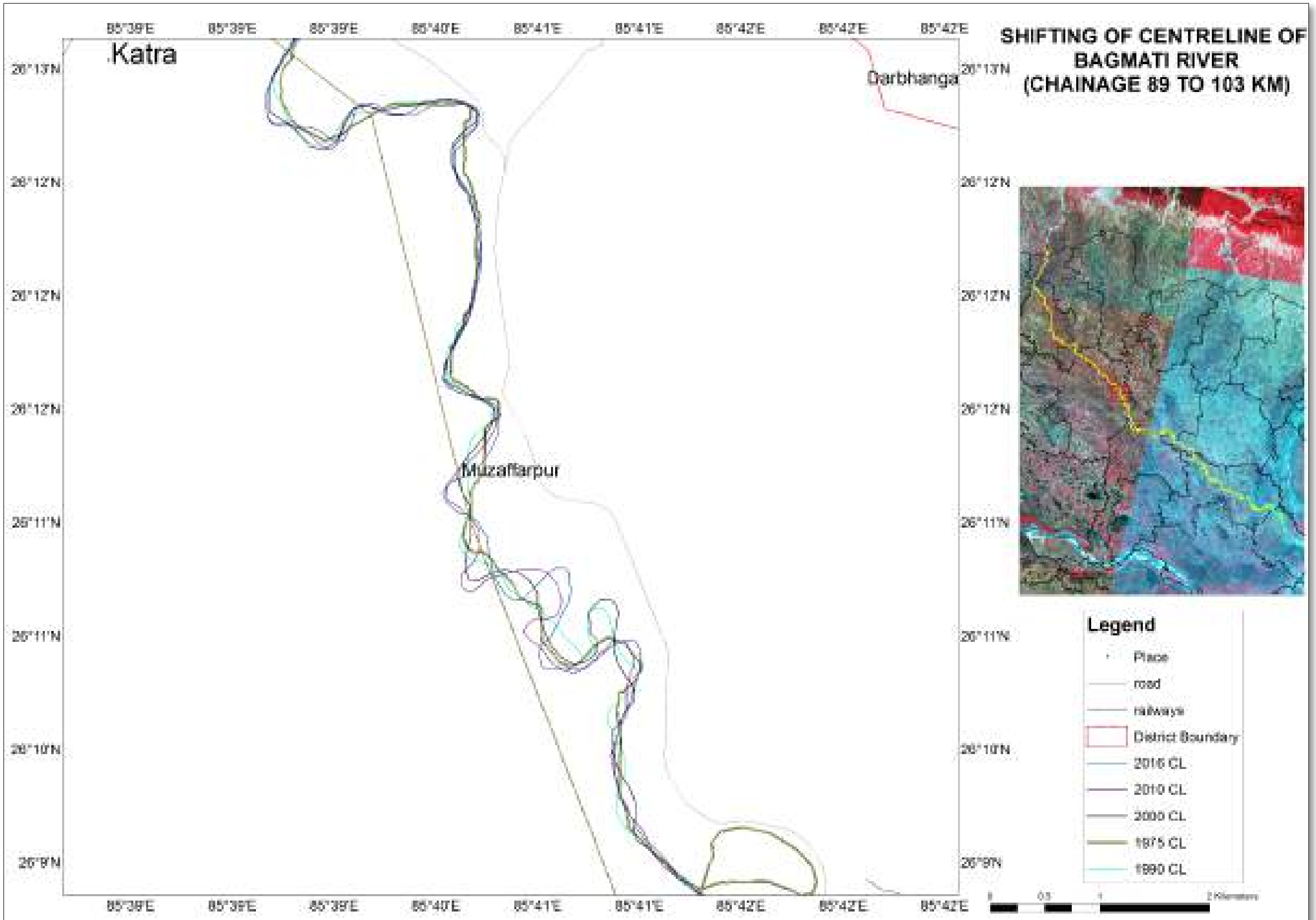



Figure 11-20b. River Course Dynamics of Bagmati River from Chainage 89-103 km

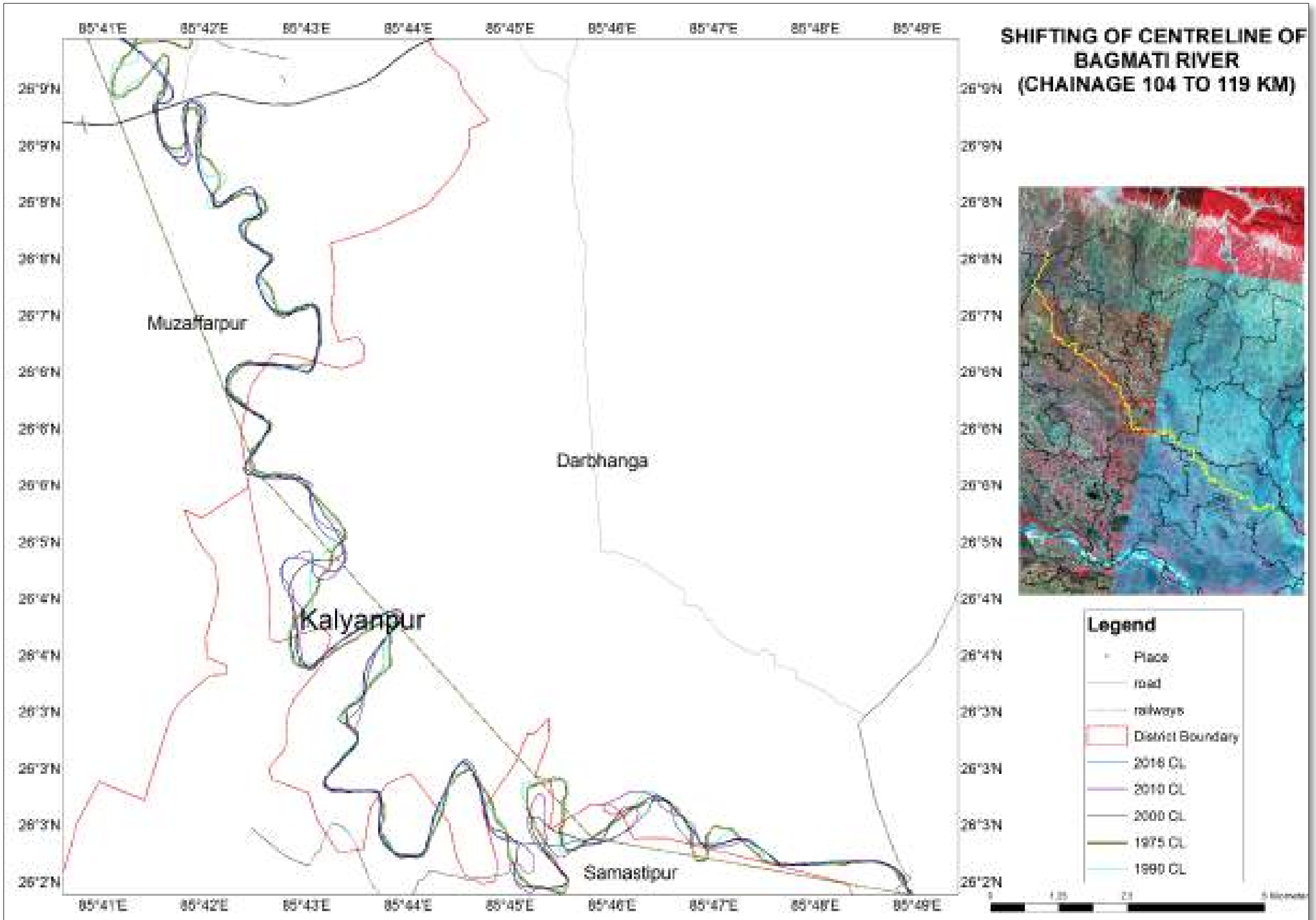



Figure 11-21b. River Course Dynamics of Bagmati River from Chainage 104-119 km

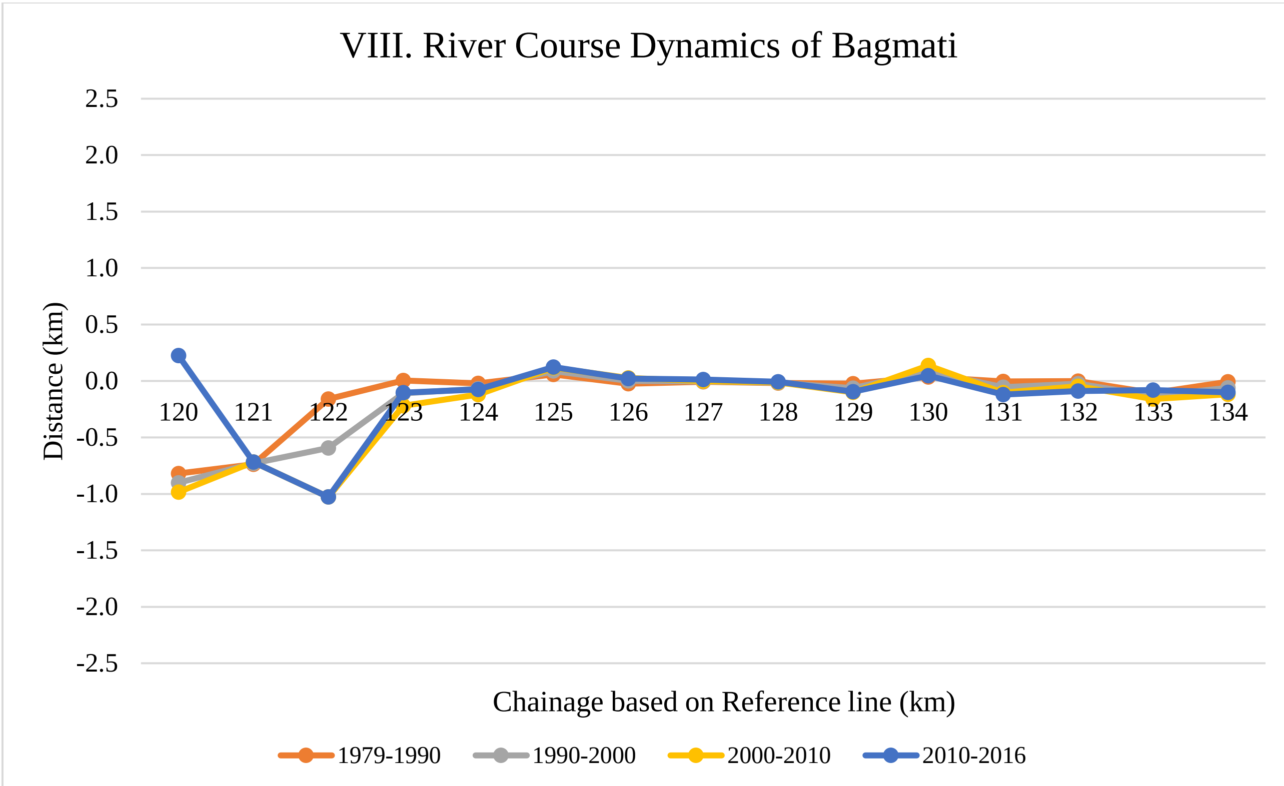



Figure 11-22a: River Course Dynamics of Bagmati River from Chainage 120-134 km

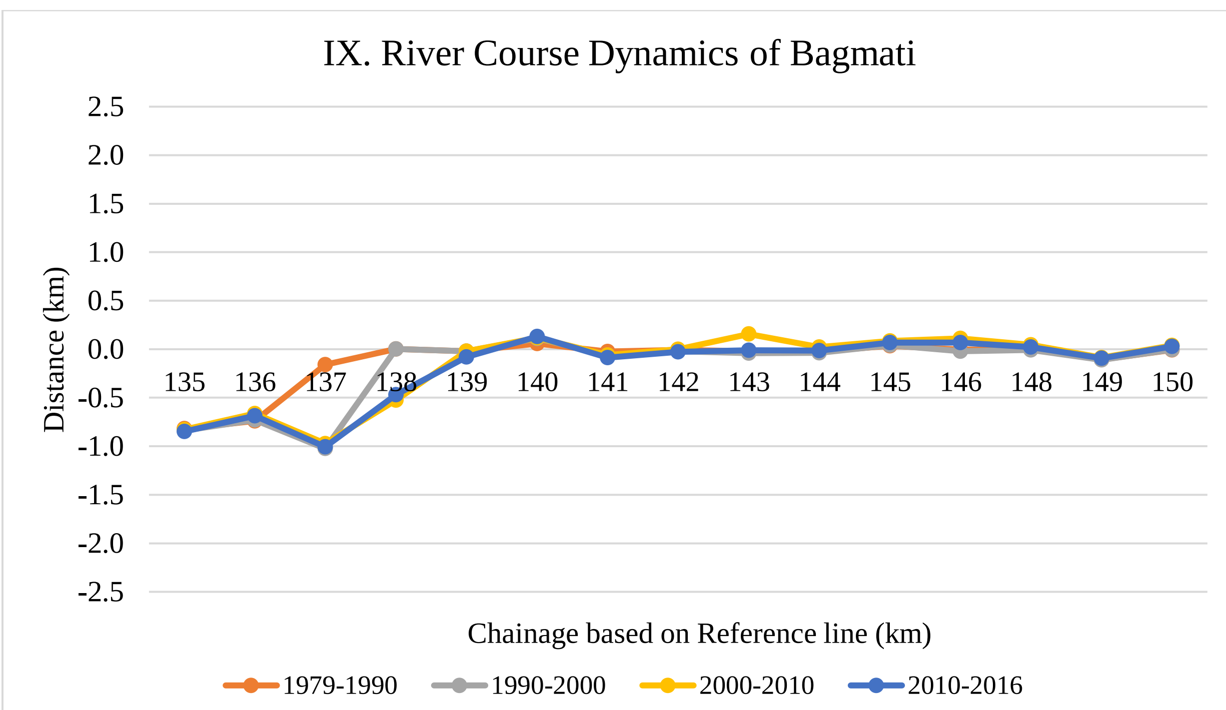



Figure 11-23a: River Course Dynamics of Bagmati River from Chainage 135-150 km

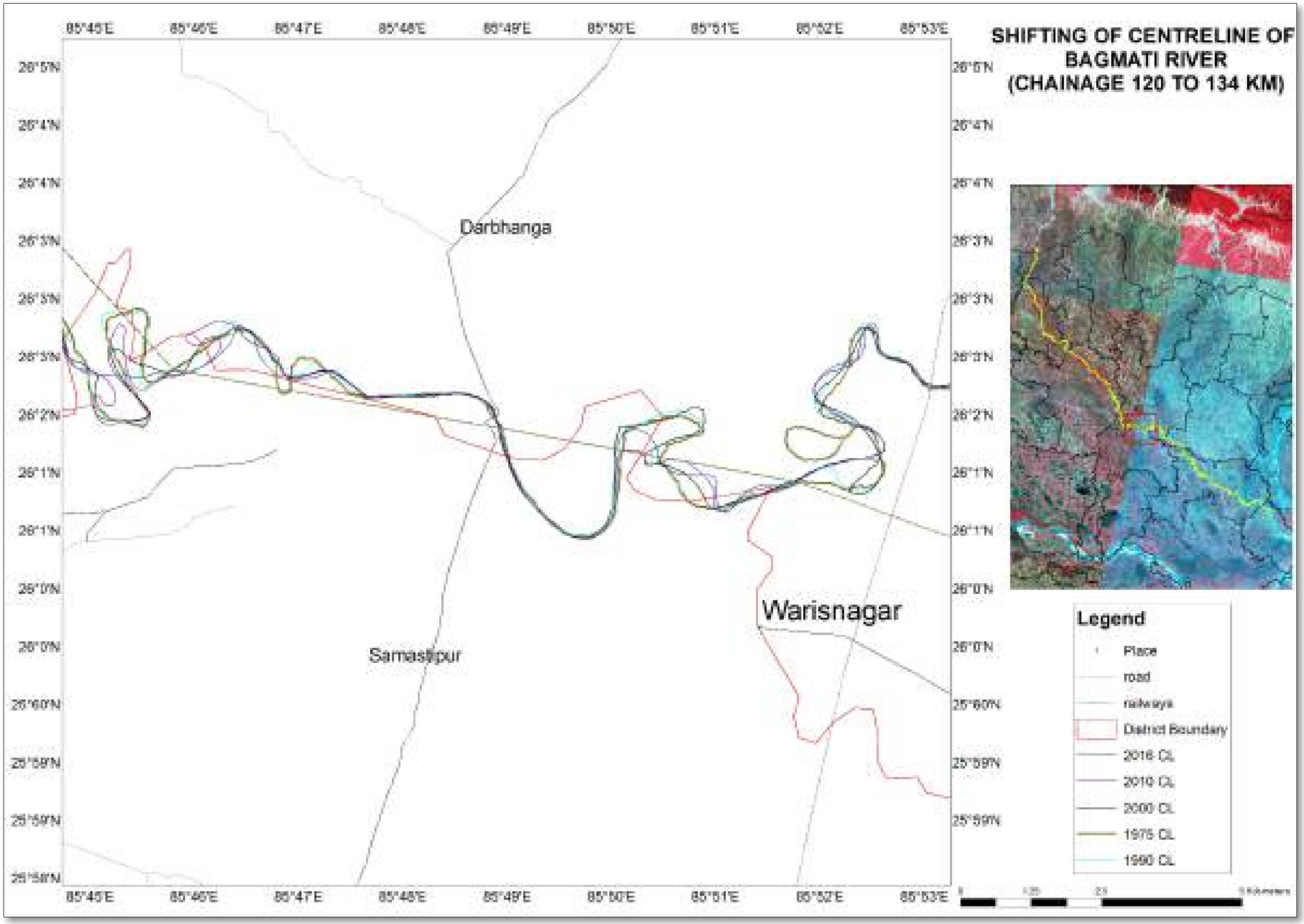



Figure 11-22b. River Course Dynamics of Bagmati River from Chainage 120-134 km

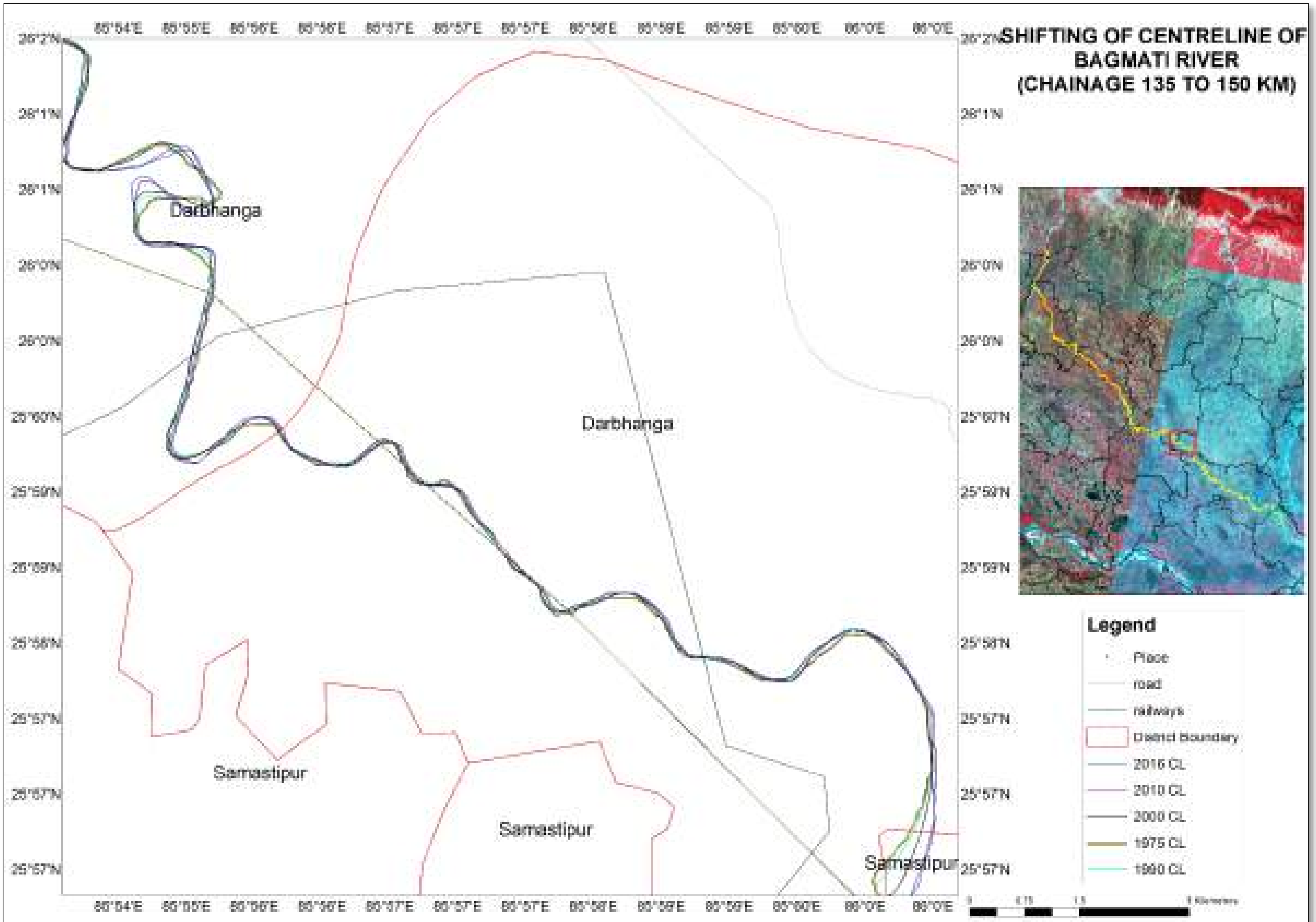



Figure 11-23b. River Course Dynamics of Bagmati River from Chainage 135-150 km

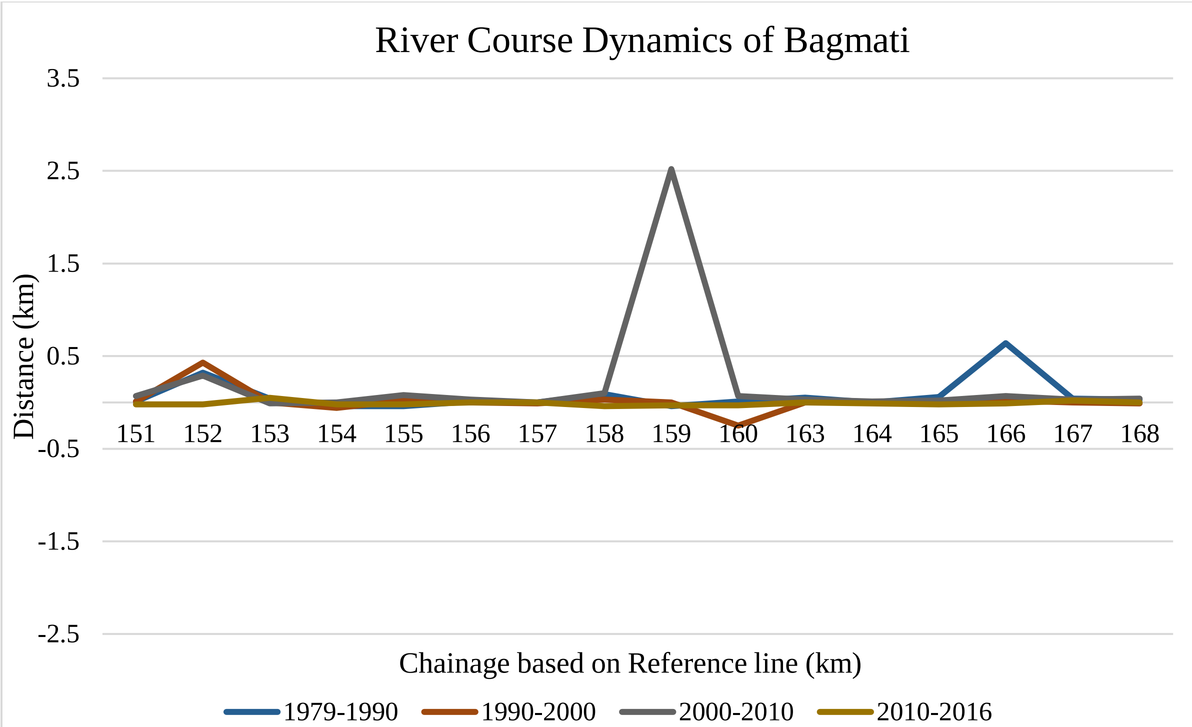



Figure 11-24a: River Course Dynamics of Bagmati River from Chainage 151-168 km

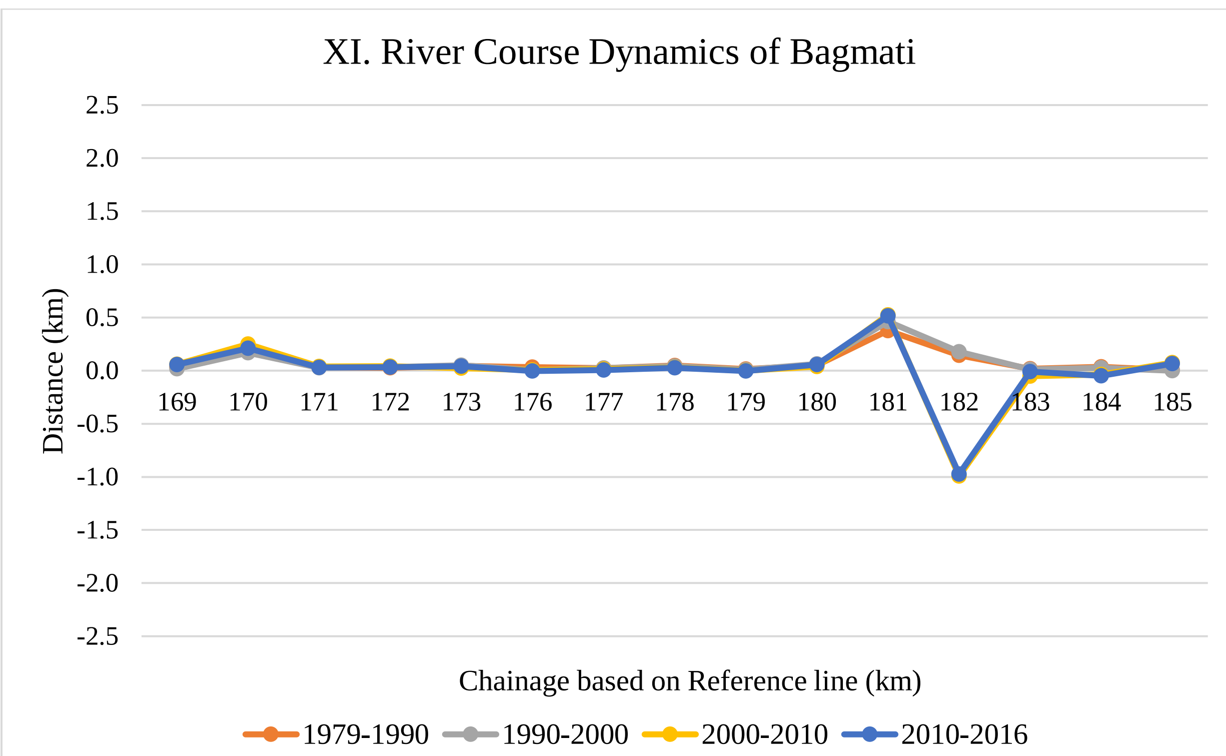



Figure 11-25a: River Course Dynamics of Bagmati River from Chainage 169-185 km

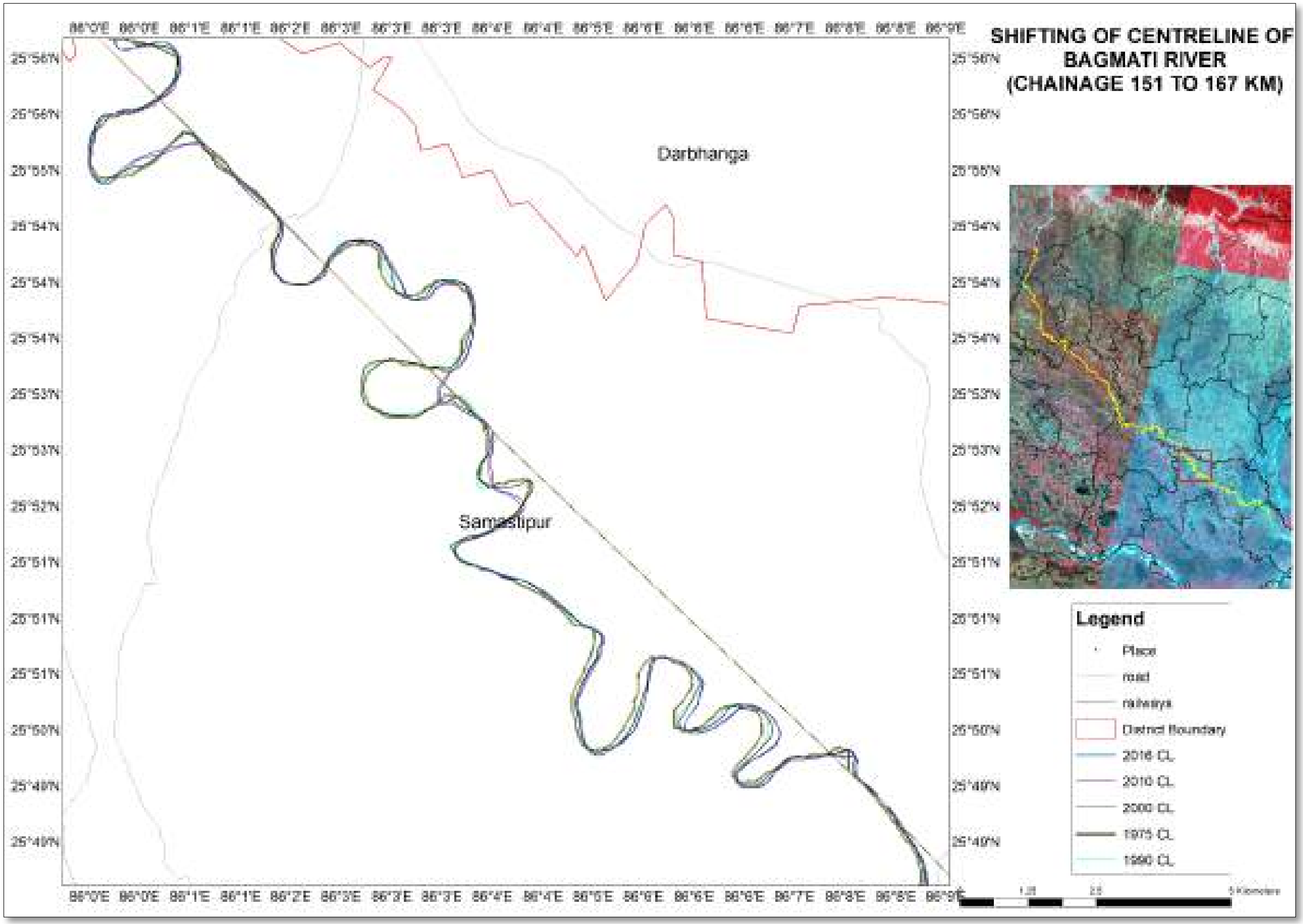



Figure 11-24a. River Course Dynamics of Bagmati River from Chainage 150-167 km

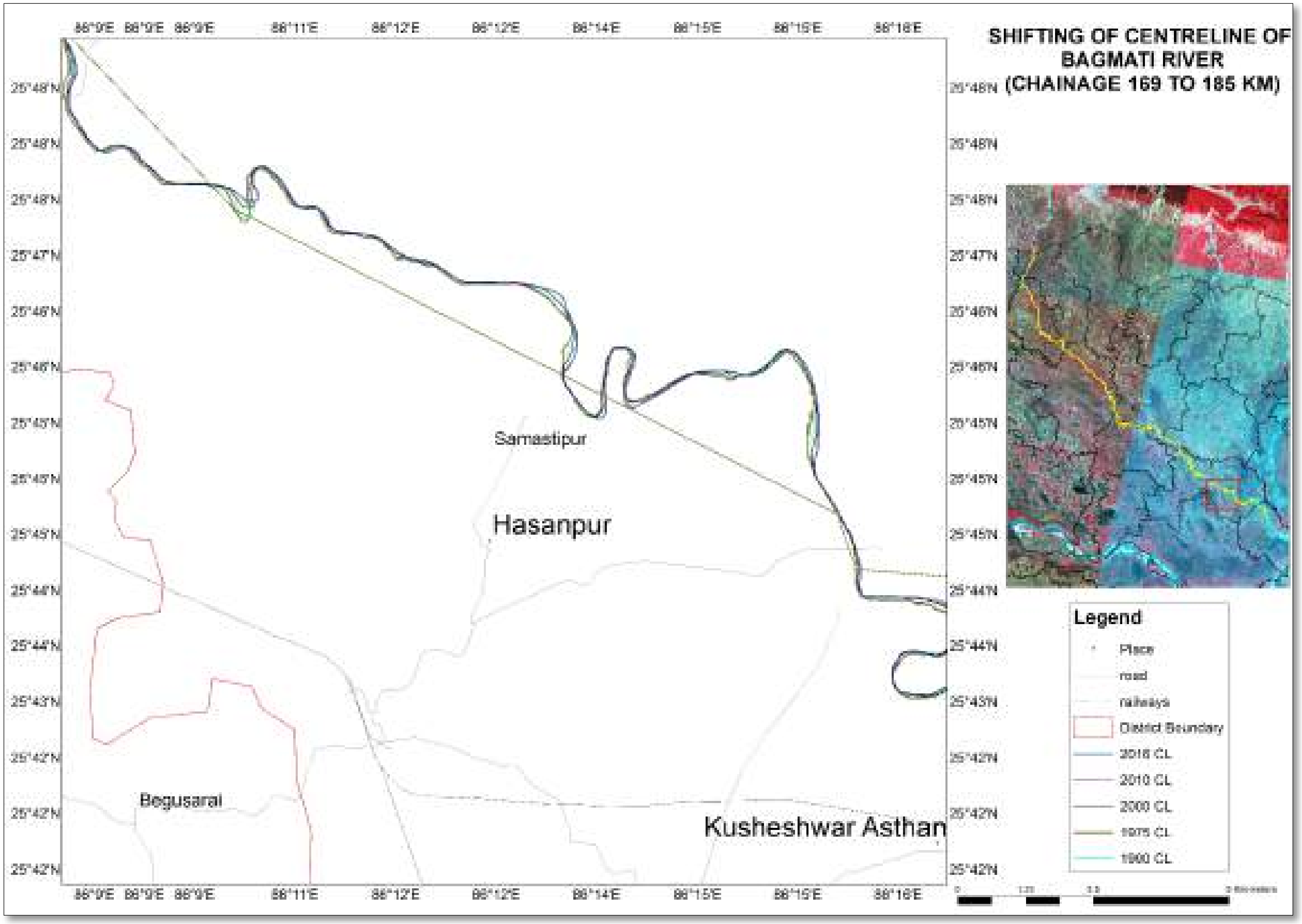



Figure 11-25b. River Course Dynamics of Bagmati River from Chainage 169-185 km

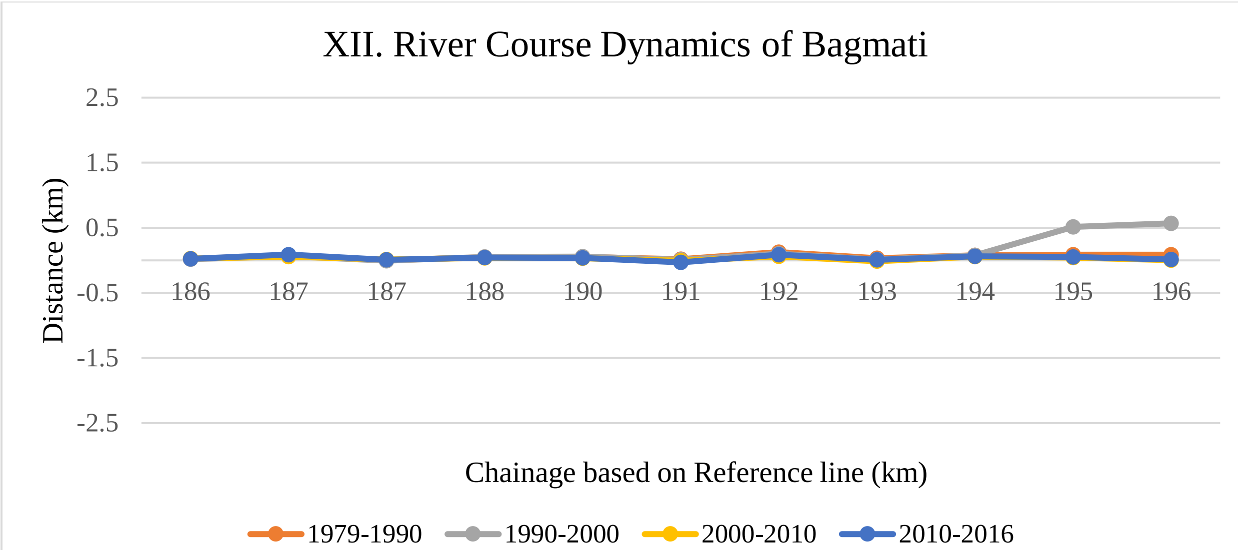



Figure 11-26a: River Course Dynamics of Bagmati River from Chainage 186-196 km

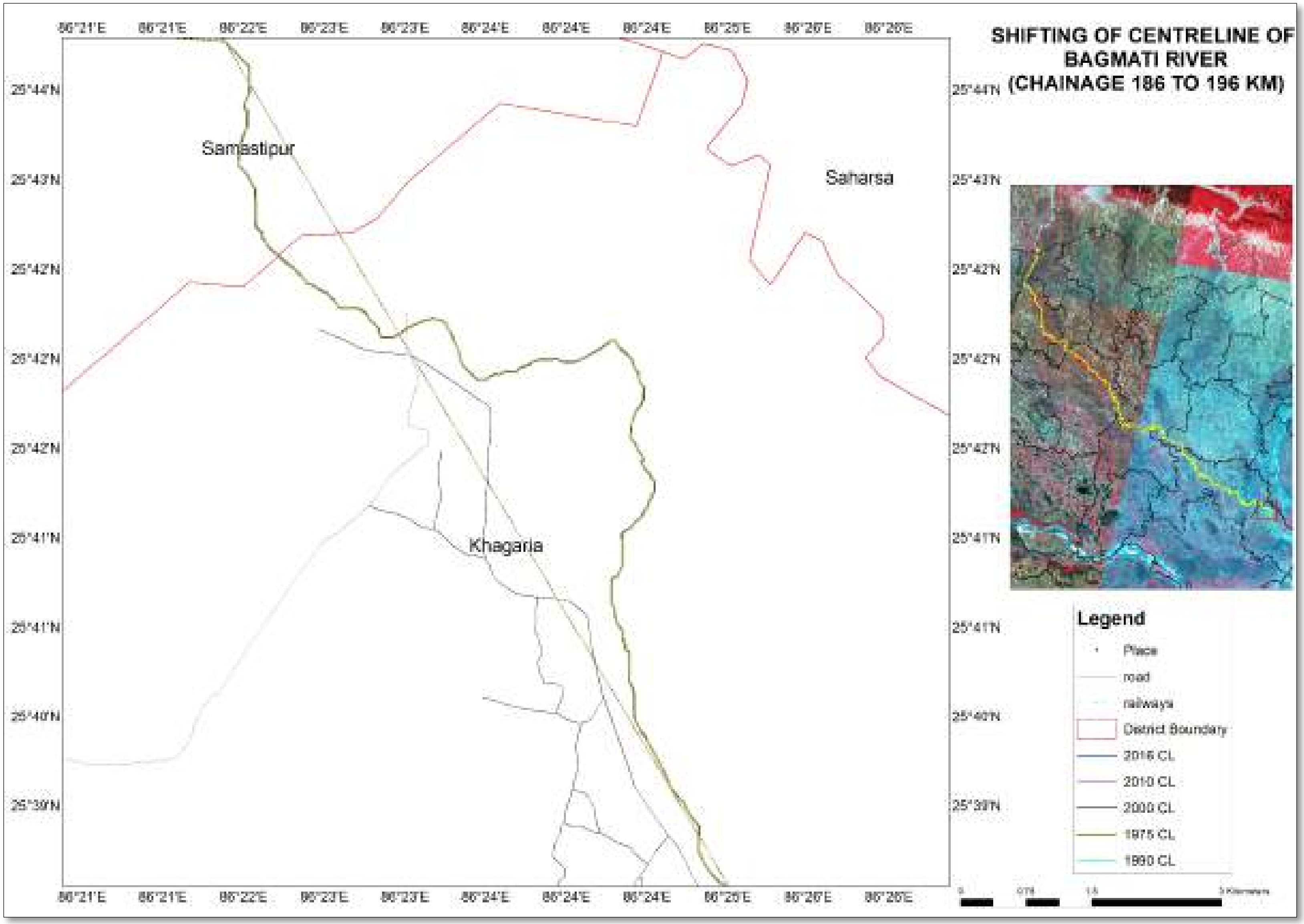



Figure 11-26b. River Course Dynamics of Bagmati River from Chainage 186-196 km

Table 11-7. Grid-wise analysis of River Course Dynamics

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline(-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| **Grid Number** | **Latitude** | **Longitude** | **Length of Baseline** | **Chainage** | **1979** | **1990** | **2000** | **2010** | **2016** | **1979-1990** | **1990-2000** | **2000-2010** | **2010-2016** |
| 12 | 26.7665 | 85.3030 | 5.9362 | 2 | -0.17 | 0.30 | -0.32 | -0.51 | -0.36 | 0.47 | -0.62 | -0.20 | 0.15 |
| | | | | 3 | 0.91 | 0.31 | 0.21 | 0.36 | 0.48 | -0.60 | -0.10 | 0.15 | 0.12 |
| | | | | 4 | -0.16 | 0.14 | 0.58 | 0.74 | 0.89 | 0.30 | 0.44 | 0.16 | 0.15 |
| | | | | 5 | -0.24 | 0.16 | 0.22 | 1.07 | 1.01 | 0.40 | 0.06 | 0.85 | -0.06 |
| | | | | 6 | 0.48 | 0.44 | 0.71 | 0.71 | 0.70 | -0.03 | 0.27 | 0.00 | -0.01 |
| | | | | 7 | 0.00 | 0.33 | -0.35 | -0.42 | -0.42 | 0.33 | -0.69 | -0.07 | 0.00 |
| 14 | 26.6763 | 85.3043 | 11.5272 | 8 | -0.03 | -0.48 | 0.17 | -0.30 | -0.52 | -0.45 | 0.65 | -0.48 | -0.22 |
| | | | | 9 | -0.25 | -0.18 | 0.48 | 0.00 | -0.43 | 0.07 | 0.66 | -0.48 | -0.43 |
| | | | | 10 | -0.62 | 0.32 | 0.35 | 0.99 | 0.89 | 0.94 | 0.03 | 0.63 | -0.09 |
| | | | | 11 | 0.01 | 0.09 | -0.42 | 0.64 | 0.58 | 0.08 | -0.51 | 1.06 | -0.06 |
| | | | | 12 | 0.06 | 0.11 | -0.13 | 0.23 | 0.14 | 0.05 | -0.24 | 0.36 | -0.09 |
| | | | | 13 | 0.03 | 0.09 | 0.27 | 0.19 | 0.00 | 0.05 | 0.18 | -0.08 | -0.19 |
| | | | | 14 | 0.14 | 0.07 | 0.07 | -0.02 | 0.14 | -0.07 | 0.01 | -0.10 | 0.16 |
| | | | | 15 | 0.20 | 0.27 | 0.16 | 0.27 | 0.13 | 0.07 | -0.10 | 0.11 | -0.14 |
| | | | | 16 | -0.46 | 0.19 | 0.58 | 0.76 | 0.55 | 0.64 | 0.39 | 0.18 | -0.21 |
| | | | | 17 | 0.01 | -0.17 | 0.43 | 1.14 | 0.56 | -0.18 | 0.60 | 0.72 | -0.59 |
| | | | | 18 | 0.12 | -0.48 | 0.33 | 0.30 | 0.47 | -0.61 | 0.81 | -0.03 | 0.17 |
| | | | | 19 | 0.00 | -0.20 | -0.13 | -0.33 | -0.36 | -0.20 | 0.07 | -0.19 | -0.03 |

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline (-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| Grid Number | Latitude | Longitude | Length of Baseline | Chainage | 1979 | 1990 | 2000 | 2010 | 2016 | 1979-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
| 16 | 26.5860 | 85.3056 | 11.5467 | 21 | -0.46 | -1.35 | -1.60 | -0.66 | -0.87 | -0.89 | -0.24 | 0.93 | -0.20 |
| | | | | 22 | 0.16 | -0.68 | -1.26 | -1.42 | -1.26 | -0.83 | -0.58 | -0.17 | 0.16 |
| | | | | 23 | 0.49 | 0.78 | 0.17 | 0.33 | -0.49 | 0.29 | -0.61 | 0.15 | -0.82 |
| | | | | 24 | 0.90 | 0.07 | 0.97 | 1.56 | 1.28 | -0.83 | 0.90 | 0.58 | -0.28 |
| | | | | 25 | 0.39 | 0.95 | 0.72 | 1.08 | 1.29 | 0.56 | -0.23 | 0.37 | 0.20 |
| | | | | 26 | 0.90 | 0.93 | 0.73 | 0.21 | 0.03 | 0.02 | -0.20 | -0.52 | -0.18 |
| | | | | 27 | 0.85 | 0.58 | 1.00 | 0.73 | 0.69 | -0.28 | 0.42 | -0.27 | -0.04 |
| | | | | 28 | 1.26 | 1.38 | 1.20 | 1.06 | 1.14 | 0.12 | -0.18 | -0.13 | 0.07 |
| | | | | 29 | 0.36 | 0.05 | 1.14 | 1.33 | 1.22 | -0.31 | 1.10 | 0.19 | -0.11 |
| | | | | 30 | -0.29 | 0.79 | 0.75 | 0.56 | 0.65 | 1.08 | -0.04 | -0.19 | 0.09 |
| | | | | 31 | 0.03 | 0.87 | 0.74 | 0.56 | 0.54 | 0.84 | -0.13 | -0.18 | -0.03 |
| | | | | 32 | 0.00 | -0.77 | -1.44 | 1.23 | 1.01 | -0.77 | -0.66 | 2.66 | -0.22 |
| 18 | 26.4958 | 85.3070 | 10.2340 | 34 | 0.16 | 1.49 | 1.65 | 1.52 | 1.80 | 1.33 | 0.17 | -0.13 | 0.27 |
| | | | | 35 | 1.13 | 1.86 | 2.01 | 1.82 | 2.20 | 0.73 | 0.15 | -0.19 | 0.37 |
| | | | | 36 | 1.31 | 1.88 | 1.96 | 1.98 | 1.97 | 0.57 | 0.08 | 0.03 | -0.02 |
| | | | | 37 | 1.54 | 1.51 | 1.33 | 1.58 | 1.58 | -0.04 | -0.18 | 0.25 | 0.01 |
| | | | | 38 | 1.32 | 1.29 | 1.36 | 1.29 | 1.28 | -0.03 | 0.06 | -0.06 | -0.01 |
| | | | | 39 | 0.92 | 0.88 | 1.07 | 1.02 | 1.05 | -0.04 | 0.19 | -0.05 | 0.04 |
| | | | | 40 | 0.55 | 0.51 | 0.50 | 0.51 | 0.55 | -0.04 | 0.00 | 0.00 | 0.04 |
| | | | | 41 | 0.56 | 0.50 | 0.64 | 0.66 | 0.66 | -0.06 | 0.14 | 0.03 | 0.00 |
| | | | | 42 | 0.58 | 0.60 | 0.55 | 0.97 | 0.93 | 0.03 | -0.05 | 0.42 | -0.04 |
| | | | | 43 | 0.11 | 0.04 | 0.58 | 0.51 | 0.20 | -0.07 | 0.54 | -0.07 | -0.31 |
| | | | | 44 | 0.00 | 1.25 | 0.84 | 0.85 | 0.99 | 1.25 | -0.41 | 0.01 | 0.14 |

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline(-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| Grid Number | Latitude | Longitude | Length of Baseline | Chainage | 1979 | 1990 | 2000 | 2010 | 2016 | 1979-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
| 20 | 26.4055 | 85.3083 | 1.4118 | 45 | 0.03 | -0.56 | -0.58 | -0.20 | -0.20 | -0.59 | -0.02 | 0.39 | 0.00 |
| | | | | 46 | 0.00 | 0.02 | 0.55 | 0.47 | -0.11 | 0.02 | 0.53 | -0.08 | -0.58 |
| 30 | 26.4067 | 85.4085 | 11.5120 | 47 | -0.81 | -0.83 | -0.87 | -0.80 | -0.90 | -0.02 | -0.04 | 0.08 | -0.10 |
| | | | | 48 | -2.22 | -2.35 | -0.46 | -0.54 | -0.54 | -0.13 | 1.89 | -0.08 | 0.00 |
| | | | | 49 | -1.25 | -2.11 | | | | -0.86 | | | |
| | | | | 50 | -1.71 | -1.61 | -0.71 | -0.81 | -0.84 | 0.10 | 0.90 | -0.10 | -0.03 |
| | | | | 51 | -1.26 | -1.08 | -0.67 | -0.72 | -0.85 | 0.18 | 0.41 | -0.05 | -0.13 |
| | | | | 52 | -1.75 | -1.60 | -0.47 | -0.49 | -0.50 | 0.15 | 1.13 | -0.02 | 0.00 |
| | | | | 53 | -1.30 | -1.13 | -0.55 | -0.66 | -0.53 | 0.17 | 0.57 | -0.11 | 0.13 |
| | | | | 54 | -2.58 | -2.62 | -0.83 | -0.85 | -0.84 | -0.04 | 1.79 | -0.02 | 0.02 |
| | | | | 55 | -2.36 | -2.38 | -0.92 | -1.09 | -1.12 | -0.02 | 1.46 | -0.17 | -0.03 |
| | | | | 56 | -2.20 | -2.21 | -0.55 | -0.69 | -0.67 | 0.00 | 1.66 | -0.14 | 0.02 |
| | | | | 57 | -2.28 | -2.38 | -0.46 | -0.13 | -0.10 | -0.10 | 1.92 | 0.33 | 0.03 |
| | | | | 58 | -0.47 | -0.50 | -0.53 | -0.98 | -1.18 | -0.03 | -0.04 | -0.45 | -0.20 |
| | | | | 59 | 0.00 | -0.03 | -0.45 | -0.78 | -0.85 | -0.03 | -0.42 | -0.33 | -0.07 |
| 40 | 26.4078 | 85.5088 | 3.0870 | 60 | 0.00 | -0.75 | -0.79 | -1.17 | -1.18 | -0.75 | -0.04 | -0.38 | -0.02 |
| | | | | 60 | 0.48 | | | | 0.00 | | | | 0.00 |
| | | | | 61 | 1.03 | 0.68 | 0.63 | 0.61 | 0.60 | -0.35 | -0.04 | -0.02 | -0.01 |
| | | | | 61 | | -0.07 | | | | -0.07 | | | |
| | | | | 62 | 0.45 | 0.36 | 0.09 | -0.08 | 0.09 | -0.10 | -0.26 | -0.17 | 0.17 |
| | | | | 63 | 0.12 | -0.38 | -0.44 | -0.08 | -0.15 | -0.50 | -0.05 | 0.35 | -0.07 |
| | | | | 65 | | 0.06 | | | | 0.06 | | | |

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline(-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| Grid Number | Latitude | Longitude | Length of Baseline | Chainage | 1979 | 1990 | 2000 | 2010 | 2016 | 1979-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
| 44 | 26.3175 | 85.5099 | 12.2113 | 66 | -0.98 | -0.89 | -0.86 | -1.00 | -0.96 | 0.09 | 0.04 | -0.14 | 0.04 |
| | | | | 67 | -0.86 | -0.89 | -0.95 | -0.98 | -1.03 | -0.03 | -0.06 | -0.03 | -0.05 |
| | | | | 68 | 0.14 | 0.10 | 0.10 | 0.10 | 0.15 | -0.04 | 0.00 | 0.00 | 0.05 |
| | | | | 69 | -0.14 | -0.14 | -0.19 | 0.14 | 0.13 | 0.00 | -0.04 | 0.33 | -0.01 |
| | | | | 70 | 0.29 | 0.26 | 0.28 | 0.35 | -1.10 | -0.03 | 0.02 | 0.07 | -1.46 |
| | | | | 71 | -0.28 | -0.28 | -0.29 | -0.39 | -1.15 | 0.01 | -0.02 | -0.09 | -0.77 |
| | | | | 72 | -0.12 | -0.18 | -0.18 | -0.14 | -1.10 | -0.06 | 0.00 | 0.04 | -0.96 |
| | | | | 73 | 0.39 | 0.39 | 0.41 | 0.11 | -1.03 | -0.01 | 0.02 | -0.30 | -1.14 |
| | | | | 74 | 0.38 | 0.33 | 0.33 | 0.33 | -0.94 | -0.05 | 0.00 | 0.00 | -1.28 |
| | | | | 75 | 0.55 | 0.48 | 0.47 | 0.33 | -0.98 | -0.07 | -0.01 | -0.14 | -1.31 |
| | | | | 76 | 0.48 | 0.21 | 0.22 | 0.23 | -1.03 | -0.27 | 0.00 | 0.01 | -1.26 |
| | | | | 77 | 0.06 | 0.04 | 0.01 | 0.04 | -1.38 | -0.01 | -0.04 | 0.04 | -1.42 |
| | | | | 78 | 0.00 | -0.34 | -0.39 | -0.20 | -0.09 | -0.34 | -0.05 | 0.19 | 0.11 |
| 55 | 26.3185 | 85.6101 | 2.5389 | 81 | 0.36 | 0.32 | 0.31 | 0.29 | -1.24 | -0.04 | -0.01 | -0.03 | -1.53 |
| | | | | 82 | -0.13 | -0.03 | -0.03 | -0.08 | -1.09 | 0.10 | 0.00 | -0.04 | -1.01 |
| | | | | 83 | 0.00 | 0.07 | 0.06 | 0.01 | -1.44 | 0.07 | -0.01 | -0.05 | -1.45 |
| 60 | 26.2282 | 85.6111 | 10.9476 | 84 | -0.13 | -0.12 | -0.13 | -0.07 | -1.52 | 0.01 | -0.01 | 0.07 | -1.45 |
| | | | | 85 | -0.07 | -0.07 | -0.06 | -0.05 | -1.43 | 0.00 | 0.01 | 0.01 | -1.38 |
| | | | | 86 | 0.56 | 0.60 | 0.58 | 0.58 | -1.24 | 0.04 | -0.02 | 0.00 | -1.82 |
| | | | | 87 | 0.10 | 0.10 | 0.09 | 0.06 | -1.20 | 0.00 | -0.01 | -0.03 | -1.26 |
| | | | | 88 | -0.40 | -0.08 | -0.02 | 0.03 | -1.23 | 0.32 | 0.06 | 0.05 | -1.27 |
| | | | | 89 | -0.51 | -0.47 | -0.47 | -0.44 | -1.41 | 0.04 | 0.00 | 0.03 | -0.97 |
| | | | | 90 | -0.55 | -0.69 | -0.68 | -0.66 | -1.01 | -0.14 | 0.01 | 0.02 | -0.35 |
| | | | | 91 | 0.02 | 0.00 | -0.01 | -0.03 | -0.03 | -0.02 | -0.01 | -0.02 | 0.00 |
| | | | | 92 | -0.03 | -0.05 | -0.06 | -0.06 | 0.01 | -0.02 | 0.00 | -0.01 | 0.07 |
| | | | | 93 | 0.40 | 0.34 | 0.34 | 0.37 | 0.41 | -0.06 | -0.01 | 0.03 | 0.04 |
| | | | | 94 | 0.00 | -0.10 | -0.11 | -0.07 | -1.34 | -0.10 | -0.01 | 0.04 | -1.27 |

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline(-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| Grid Number | Latitude | Longitude | Length of Baseline | Chainage | 1979 | 1990 | 2000 | 2010 | 2016 | 1979-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
| 72 | 26.2292 | 85.7112 | 3.3729 | 95 | 0.36 | 0.51 | 0.46 | 0.47 | 0.13 | 0.15 | -0.05 | 0.01 | -0.34 |
| | | | | 96 | 0.66 | 0.63 | 0.62 | 0.62 | 0.63 | -0.04 | -0.01 | 0.00 | 0.01 |
| | | | | 97 | 0.18 | 0.16 | 0.19 | 0.20 | 0.20 | -0.03 | 0.03 | 0.01 | 0.01 |
| | | | | 98 | 0.22 | 0.08 | 0.00 | -0.02 | 0.14 | -0.14 | -0.08 | -0.03 | 0.16 |
| | | | | 99 | -0.55 | -0.62 | -0.61 | -0.21 | -0.48 | -0.07 | 0.01 | 0.40 | -0.27 |
| | | | | 100 | 0.00 | -0.24 | -0.23 | 0.09 | -0.16 | -0.24 | 0.01 | 0.33 | -0.25 |
| 78 | 26.1389 | 85.7122 | 10.6999 | 101 | 0.25 | 0.31 | 0.24 | 0.11 | 0.43 | 0.06 | -0.07 | -0.13 | 0.33 |
| | | | | 102 | 0.53 | 0.46 | 0.54 | 0.57 | 0.55 | -0.07 | 0.09 | 0.03 | -0.02 |
| | | | | 103 | 0.38 | 0.37 | 0.36 | 0.40 | 0.41 | 0.00 | -0.01 | 0.04 | 0.00 |
| | | | | 104 | 0.11 | 0.77 | 0.87 | 0.87 | 0.90 | 0.66 | 0.10 | 0.00 | 0.03 |
| | | | | 105 | 0.54 | 1.01 | 0.52 | 0.52 | 0.56 | 0.47 | -0.49 | 0.00 | 0.04 |
| | | | | 107 | 1.25 | 1.23 | 1.19 | 1.17 | 1.19 | -0.03 | -0.04 | -0.02 | 0.02 |
| | | | | 108 | 1.31 | 1.19 | 1.14 | 1.13 | 1.14 | -0.12 | -0.05 | -0.01 | 0.01 |
| | | | | 109 | 0.47 | 0.30 | 0.30 | 0.26 | 0.28 | -0.18 | 0.01 | -0.04 | 0.02 |
| | | | | 110 | 1.79 | 1.76 | 1.75 | 1.75 | 1.78 | -0.04 | -0.01 | 0.00 | 0.03 |
| | | | | 111 | 0.47 | 0.44 | 0.45 | 0.44 | 0.44 | -0.03 | 0.01 | -0.01 | 0.00 |
| | | | | 112 | 0.00 | -0.02 | 0.02 | 0.01 | 0.02 | -0.02 | 0.04 | 0.00 | 0.00 |
| 84 | 26.0486 | 85.7132 | 8.1109 | 113 | 0.43 | 0.40 | 0.39 | 0.28 | 0.31 | -0.03 | -0.01 | -0.11 | 0.03 |
| | | | | 114 | -0.46 | -0.63 | -1.03 | -1.03 | -0.96 | -0.17 | -0.40 | 0.00 | 0.07 |
| | | | | 115 | -1.23 | -0.70 | -0.73 | -0.68 | -1.48 | 0.54 | -0.04 | 0.05 | -0.80 |
| | | | | 116 | -1.66 | -1.71 | -1.73 | -1.69 | -1.31 | -0.05 | -0.02 | 0.04 | 0.38 |
| | | | | 117 | -2.27 | -2.25 | -2.25 | -2.27 | -2.25 | 0.02 | 0.00 | -0.02 | 0.02 |
| | | | | 118 | -2.52 | -1.35 | -2.56 | -2.57 | -2.55 | 1.17 | -1.21 | -0.02 | 0.02 |
| | | | | 119 | -0.95 | -0.95 | -1.03 | -1.14 | -1.13 | 0.00 | -0.09 | -0.10 | 0.01 |
| | | | | 120 | -1.27 | -0.49 | -1.31 | -1.39 | -0.19 | 0.78 | -0.82 | -0.08 | 1.21 |
| | | | | 121 | | | -0.74 | -0.73 | | | -0.74 | 0.01 | |
| | | | | 122 | | | -0.16 | -0.59 | -0.09 | | -0.16 | -0.43 | 0.00 |

| West of Baseline (-)/ East of Baseline(+) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| Grid Number | Latitude | Longitude | Length of Baseline | Chainage | 1979 | 1990 | 2000 | 2010 | 2016 | 1979-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
| 98 | 26.0495 | 85.8132 | 10.1760 | 123 | 0.81 | 0.84 | 0.84 | 0.73 | 0.85 | 0.03 | 0.00 | -0.11 | 0.12 |
| | | | | 124 | 0.55 | 0.26 | 0.24 | 0.19 | 0.24 | -0.29 | -0.02 | -0.05 | 0.05 |
| | | | | 125 | 0.12 | 0.10 | 0.16 | 0.19 | 0.19 | -0.02 | 0.06 | 0.03 | 0.00 |
| | | | | 126 | 0.28 | 0.32 | 0.30 | 0.32 | 0.32 | 0.04 | -0.02 | 0.03 | -0.01 |
| | | | | 127 | 0.34 | 0.37 | 0.36 | 0.37 | 0.38 | 0.03 | -0.01 | 0.00 | 0.02 |
| | | | | 128 | -1.03 | -1.06 | -1.08 | -1.08 | -1.07 | -0.03 | -0.02 | 0.00 | 0.01 |
| | | | | 129 | -1.47 | -1.42 | -1.45 | -1.49 | -1.48 | 0.05 | -0.02 | -0.04 | 0.01 |
| | | | | 130 | -0.12 | -0.14 | -0.10 | -0.05 | -0.14 | -0.01 | 0.04 | 0.05 | -0.09 |
| | | | | 131 | -0.61 | -0.61 | -0.61 | -0.66 | -0.68 | 0.00 | 0.00 | -0.05 | -0.02 |
| | | | | 132 | -0.11 | -0.04 | -0.04 | -0.06 | -0.10 | 0.07 | 0.00 | -0.02 | -0.04 |
| | | | | 133 | 0.00 | 0.02 | -0.09 | -0.11 | -0.04 | 0.02 | -0.11 | -0.03 | 0.08 |
| 112 | 26.0503 | 85.9131 | 6.3550 | 134 | 1.81 | 1.94 | 1.93 | 1.87 | 1.89 | 0.13 | -0.01 | -0.05 | 0.02 |
| | | | | 135 | 1.76 | 1.83 | 1.81 | 1.82 | 1.80 | 0.07 | -0.02 | 0.01 | -0.02 |
| | | | | 136 | 0.62 | 0.59 | 0.60 | 0.67 | 0.64 | -0.03 | 0.01 | 0.07 | -0.03 |
| | | | | 137 | 1.35 | 1.38 | 0.52 | 0.57 | 0.53 | 0.03 | -0.86 | 0.05 | -0.03 |
| | | | | 138 | | | 1.38 | 0.85 | 0.91 | | | -0.53 | 0.06 |
| | | | | 139 | | | | 1.20 | 1.14 | | | | -0.06 |
| | | | | 140 | 0.34 | 0.40 | 0.45 | 0.46 | 0.47 | 0.06 | 0.05 | 0.00 | 0.01 |
| 120 | 25.9600 | 85.9139 | 5.8846 | 141 | -1.79 | -1.73 | -1.76 | -1.76 | -1.79 | 0.06 | -0.03 | 0.00 | -0.02 |
| | | | | 142 | -0.76 | -0.76 | -0.77 | -0.75 | -0.78 | 0.00 | -0.01 | 0.02 | -0.03 |
| | | | | 143 | 0.09 | 0.09 | 0.07 | 0.26 | 0.10 | -0.01 | -0.02 | 0.20 | -0.17 |
| | | | | 144 | 0.15 | 0.18 | 0.16 | 0.22 | 0.19 | 0.02 | -0.01 | 0.06 | -0.04 |
| | | | | 145 | -0.06 | -0.05 | -0.04 | 0.00 | -0.02 | 0.01 | 0.01 | 0.04 | -0.02 |
| | | | | 146 | 0.00 | -0.09 | -0.11 | 0.02 | -0.02 | -0.09 | -0.02 | 0.13 | -0.04 |

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline(-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| Grid Number | Latitude | Longitude | Length of Baseline | Chainage | 1979 | 1990 | 2000 | 2010 | 2016 | 1979-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
| 135 | 25.9607 | 86.0138 | 8.5594 | 148 | 0.69 | 0.69 | 0.68 | 0.74 | 0.71 | 0.00 | -0.01 | 0.05 | -0.02 |
| | | | | 149 | 0.99 | 1.02 | 1.02 | 1.04 | 1.03 | 0.03 | 0.00 | 0.02 | -0.01 |
| | | | | 150 | 2.41 | 2.43 | 2.44 | 2.48 | 2.47 | 0.02 | 0.00 | 0.05 | -0.01 |
| | | | | 151 | 2.20 | 2.21 | 2.22 | 2.29 | 2.27 | 0.01 | 0.01 | 0.07 | -0.02 |
| | | | | 152 | 0.27 | 0.59 | 1.02 | 1.31 | 1.29 | 0.32 | 0.43 | 0.29 | -0.02 |
| | | | | 153 | 0.50 | 0.54 | 0.54 | 0.53 | 0.58 | 0.04 | 0.00 | -0.01 | 0.05 |
| | | | | 154 | -1.56 | -1.59 | -1.66 | -1.66 | -1.68 | -0.04 | -0.06 | 0.00 | -0.02 |
| | | | | 155 | -0.04 | -0.08 | -0.06 | 0.02 | 0.00 | -0.04 | 0.02 | 0.08 | -0.02 |
| 144 | 25.8704 | 86.0146 | 5.6424 | 156 | -0.02 | -0.02 | -0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.03 | 0.00 |
| | | | | 157 | -0.48 | -0.48 | -0.49 | -0.49 | -0.48 | 0.00 | -0.01 | 0.00 | 0.00 |
| | | | | 158 | 0.51 | 0.60 | 0.63 | 0.73 | 0.70 | 0.09 | 0.03 | 0.10 | -0.04 |
| | | | | 159 | -1.04 | -1.09 | -1.09 | 1.43 | 1.40 | -0.04 | 0.00 | 2.52 | -0.03 |
| | | | | 160 | -0.08 | -0.07 | -0.32 | -0.25 | -0.28 | 0.01 | -0.25 | 0.07 | -0.03 |
| 160 | 25.8711 | 86.1144 | 5.5084 | 163 | 0.30 | 0.35 | 0.34 | 0.38 | 0.37 | 0.05 | 0.00 | 0.03 | 0.00 |
| | | | | 164 | 0.38 | 0.39 | 0.39 | 0.40 | 0.38 | 0.00 | 0.00 | 0.01 | -0.01 |
| | | | | 165 | -1.09 | -1.03 | -1.02 | -1.00 | -1.02 | 0.06 | 0.01 | 0.02 | -0.02 |
| | | | | 166 | 0.19 | 0.84 | 0.85 | 0.92 | 0.91 | 0.64 | 0.02 | 0.07 | -0.01 |
| | | | | 167 | 1.06 | 1.10 | 1.10 | 1.12 | 1.14 | 0.04 | 0.00 | 0.03 | 0.02 |
| 170 | 25.7808 | 86.1150 | 5.4805 | 169 | -0.04 | -0.01 | -0.03 | 0.01 | 0.01 | 0.03 | -0.01 | 0.04 | 0.00 |
| | | | | 170 | -0.54 | -0.37 | -0.38 | -0.30 | -0.33 | 0.18 | -0.01 | 0.08 | -0.04 |
| | | | | 171 | -0.98 | -0.95 | -0.96 | -0.94 | -0.95 | 0.03 | 0.00 | 0.01 | -0.01 |
| | | | | 172 | -0.58 | -0.55 | -0.54 | -0.54 | -0.54 | 0.03 | 0.01 | 0.01 | -0.01 |
| | | | | 173 | 0.03 | 0.07 | 0.08 | 0.05 | 0.07 | 0.04 | 0.01 | -0.03 | 0.02 |

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline(-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| **Grid Number** | **Latitude** | **Longitude** | **Length of Baseline** | **Chainage** | **1979** | **1990** | **2000** | **2010** | **2016** | **1979-1990** | **1990-2000** | **2000-2010** | **2010-2016** |
| 187 | 25.7813 | 86.2148 | 11.2281 | 169 | -0.04 | -0.01 | -0.03 | 0.01 | 0.01 | 0.03 | -0.01 | 0.04 | 0.00 |
| | | | | 170 | -0.54 | -0.37 | -0.38 | -0.30 | -0.33 | 0.18 | -0.01 | 0.08 | -0.04 |
| | | | | 171 | -0.98 | -0.95 | -0.96 | -0.94 | -0.95 | 0.03 | 0.00 | 0.01 | -0.01 |
| | | | | 172 | -0.58 | -0.55 | -0.54 | -0.54 | -0.54 | 0.03 | 0.01 | 0.01 | -0.01 |
| | | | | 173 | 0.03 | 0.07 | 0.08 | 0.05 | 0.07 | 0.04 | 0.01 | -0.03 | 0.02 |
| | | | | 176 | 0.52 | 0.55 | 0.53 | 0.53 | 0.52 | 0.03 | -0.03 | 0.00 | -0.01 |
| | | | | 177 | 0.54 | 0.56 | 0.56 | 0.55 | 0.54 | 0.02 | 0.00 | -0.01 | -0.01 |
| | | | | 178 | 0.55 | 0.59 | 0.59 | 0.58 | 0.57 | 0.05 | 0.00 | -0.01 | 0.00 |
| | | | | 179 | 0.64 | 0.65 | 0.65 | 0.64 | 0.63 | 0.01 | -0.01 | -0.01 | 0.00 |
| | | | | 180 | 1.04 | 1.09 | 1.10 | 1.07 | 1.09 | 0.05 | 0.01 | -0.03 | 0.02 |
| | | | | 181 | 0.21 | 0.59 | 0.67 | 0.74 | 0.73 | 0.38 | 0.08 | 0.06 | -0.01 |
| | | | | 182 | 0.64 | 0.78 | 0.81 | -0.36 | -0.34 | 0.14 | 0.03 | -1.17 | 0.02 |
| | | | | 183 | 0.96 | 0.98 | 0.97 | 0.91 | 0.95 | 0.02 | -0.01 | -0.06 | 0.04 |
| | | | | 184 | 1.52 | 1.55 | 1.54 | 1.48 | 1.47 | 0.04 | -0.01 | -0.06 | -0.01 |
| | | | | 185 | 1.55 | 1.56 | 1.55 | 1.63 | 1.61 | 0.01 | -0.01 | 0.08 | -0.01 |
| | | | | 186 | 0.15 | 0.17 | 0.17 | 0.18 | 0.17 | 0.02 | 0.00 | 0.01 | -0.01 |
| 204 | 25.7818 | 86.3145 | 0.9623 | 187 | 173 | 0.03 | 0.07 | 0.08 | 0.05 | 0.07 | 0.04 | 0.01 | -0.03 |
| 216 | 25.6915 | 86.3150 | 9.7323 | 188 | -1.33 | -1.28 | -1.28 | -1.29 | -1.29 | 0.05 | 0.00 | -0.01 | 0.01 |
| | | | | 190 | -2.25 | -2.20 | -2.19 | -2.21 | -2.21 | 0.05 | 0.01 | -0.03 | 0.01 |
| | | | | 191 | -2.55 | -2.53 | -2.53 | -2.55 | -2.58 | 0.02 | -0.01 | -0.02 | -0.02 |
| | | | | 192 | -1.92 | -1.79 | -1.82 | -1.86 | -1.83 | 0.13 | -0.02 | -0.04 | 0.03 |

| All units in Kilometres | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West of Baseline(-)/ East of Baseline(+) | | | | | | | | | | | | | |
| All Indices measured perpendicular to the Baseline | | | | | | | | | | | | | |
| | In Decimal Degree | | | | Distance from reference Line (km) | | | | | River Course Dynamics (km) | | | |
| Grid Number | Latitude | Longitude | Length of Baseline | Chainage | 1979 | 1990 | 2000 | 2010 | 2016 | 1979-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
| | | | | 193 | -0.88 | -0.85 | -0.87 | -0.89 | -0.87 | 0.03 | -0.02 | -0.02 | 0.02 |
| | | | | 194 | -0.94 | -0.86 | -0.86 | -0.88 | -0.88 | 0.07 | 0.00 | -0.02 | 0.01 |
| | | | | 195 | 0.16 | 0.25 | 0.67 | 0.20 | 0.21 | 0.09 | 0.43 | -0.47 | 0.01 |
| | | | | 196 | 0.19 | 0.28 | 0.76 | 0.19 | 0.20 | 0.09 | 0.48 | -0.56 | 0.01 |

## 11.7 Confluence Points

Channel confluence is a vital element of the river systems as they influence the geomorphology and hydrology of both upstream and downstream reaches. The dynamics of the confluence points affects the availability of water in different reaches and the pattern of sediment distribution in the confluence zone. A major implication of such movements is scouring or aggradation, which affects the system's stability under consideration and raises issues related to its management.

Variations in channel position, as well as confluence points, were analysed at a decadal scale for the last forty years using satellite images from Landsat MSS (spatial resolution 60 m), Landsat 5 TM (spatial resolution 30 m), Landsat 7 ETM+ and Landsat 8 (spatial resolution 30m and 15m for multispectral and panchromatic respectively), and Indian Remote Sensing Satellite (spatial resolution 23.5 m). Visual interpretation and digital image processing techniques such as contrast stretching, edge enhancement, image filtering, false colour composites, principal component analysis, image ratio, and image subtraction were applied to the digital data to map the channel and confluences.

Various parameters affect the dynamics of confluences. Those parameters can broadly be categorised into two categories, allocyclic and auto cyclic. In the narrow context of the remote sensing-based morphological study of the Bagmati River system, the effect of auto cyclic and allocyclic behaviour cannot be explored in detail. However, channel characteristics such as channel position, top width, slope and junction angle, which have indirect consideration for some of the auto cyclic processes, are obtained using satellite imageries for understanding the system behaviour at the confluence. The terminology used for confluence analysis is explained in the template form, as shown in Figure 11-27.

1. Confluence Points

Parmar and Khosa, 2017, have argued that the confluence points can be captured more objectively and with a relatively higher level of assurance if the approach based on intersections between bank lines is followed. However, in this study, confluence points are generated from the centre line of the channel area of the main channel and tributary channel. Point P represents the confluence point (Fig 11-27). Confluence points are represented by labels of numeric values 1, 2, …, …, n. where 1 represents confluence for the first year of analysis which in this study is 1975. For the next target year of analysis, if the confluence changes from its original position, it is denoted by the next successive number, i.e., 2. If its geographical position does not change, it is represented by the same number as in the previous analysis year. For the first year, i.e., 1975, the Confluence point is considered a reference point for measuring upstream and downstream channel sections from the confluence.

2. Area of confluence/ confluence zone

Confluence area (yellow shaded area in Fig. 11-27) is polygon, which is made up of four points. Two points are the endpoints of the tributary channel when it joins the mainstream whereas other two points are deduced by drawing perpendicular lines from these points to the channel flow in the mainstream. The intersection of these lines at the other bank of the main channel give the other two points for the polygon. Polygon formed by joining all these points is termed as area of confluence/ confluence zone in the present study.

3. Channel top width analysis

Channel area is determined by segregating channel from adjacent land features using satellite image analysis. Channel area obtained for the erosion/ deposition analysis as explained in Chapter 6 (Section 6.1) is used to determine the channel top width at the confluence. As shown in Figure 11-27, cross-sections at upstream of confluence point in the main channel (AA' and BB'), upstream of confluence point in the tributary channel (XX' and YY') and downstream of confluence in the combined flow channel (ZZ' and CC') have been drawn for analysing top width. It is important to note that, based on catchment characteristics and physical settings of different tributaries, the interval between the cross sections ranges from a few meters to a few kms (300m to 3.3 km).

4. Junction Angle

It is measured as the angle between the tributary channel and the main channel at confluence point. Preferably, it should be the angle between the tangents on the curved thalweg from the confluence point of the two channels. However, with multispectral satellite data in the study that only provides surface reflectance, it is not possible to identify thalweg (or the depth of channel). Therefore, channel centrelines are considered for determining the junction angle between tributary and main channel. In Figure 11-27, this angle is represented by the red lines meeting at point P.

5. Slope

The slope is considered in the tributary and main channel upstream of the confluence and downstream of confluence. The average slope for a channel section is measured between cross sections, both upstream and downstream of confluence.

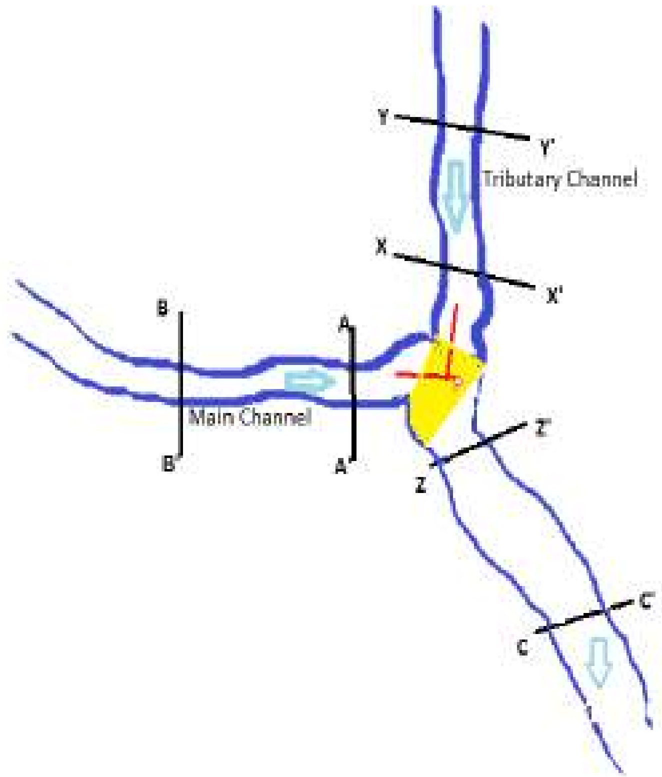



Figure 11-27: Parameters used confluence analysis.

1. **Lalbakeya-Bagmati (Near Khoripakar village)**

The confluence points for 1975 and 1990 are labelled as point 1 (85.26E, 26.64 N) & 2, respectively (85.27 E, 26.63 N). Lalbakeya is merging with Bagmati river at point 2, which is 1.8 km northwest from point 1. The confluence point shifted to point 3 for 2000, situated at 1.4 km northeast from point 2. After the year 2000, it moved 1.5 km south-east of point 3 and repositioned itself to point four by 2010, and this point again shifts to point 5 (1.15 km, north-east of point 4) by 2016. The confluence points for the year 1975,1990,2000,2010, and 2016 are shown in Figure 11-28 to 11-32.

At upstream of confluence, the width of River Bagmati (at 1000 m U/S) reduces from 229 m in 1975 to 168m in 1990. The width of Lalbakeya (at 1000 m U/S) upstream decreases from 171m in 1975 to 65m in 1990, whereas the width of combined flow from Lalbakeya -Bagmati measures 288 m in 1975 and 183 m in 1990 at 1000m downstream. At upstream of confluence, the width of River Bagmati (at 600 m U/S) increases from 168 m in 1990 to 226m in 2000. The width of Lalbakeya (at 600 m U/S) upstream increases from 84m in 1990 to 107m in 2000, whereas the width of combined flow from Lalbakeya -Bagmati measures 183 m in 1990 and 448 m in 2000 at 600m downstream. For the year 2000-2010, At upstream of confluence, the width of River Bagmati reduces from 226 m in 2000 to 82 m in 2010. The width of Lalbakeya upstream reduces from 107m in 2000 to 58m in 2010, whereas the width of combined flow from Lalbakeya -Bagmati measures 448 m in 2000 and 135m in 2010. For the year 2010-2016, At upstream of the confluence, the width of River Bagmati increases from 82 m in 2010 to 132 m in 2016. The width of Lalbakeya upstream reduces from 58m in 2010 to 62 m in 2016, whereas the width of combined flow from Lalbakeya -Bagmati measures 134 m in 2010 and 136m in 2016. The average bed slope of 1 km longitudinal section of Bagmati channel, upstream of confluence is 0.001 (direction is towards the confluence point), the average bed slope of 1 km longitudinal section of Lalbakeya channel upstream of confluence is 0.002 (direction is towards the confluence point). The bed slope at 1 km downstream of the confluence is 0.002 (direction is away from the confluence point).  The area of the confluence zone is approximately 0.016 sq. km. in 2016. The Junction angle in 1975 is 91˚, which reduces to 82˚ in 1990 which further reduces to 36.73˚ by 2000, 138˚ in 2010 and reduces to 22˚ by 2016. Due to mix spectral signature in the aerial images, no specific erosion and deposition patterns have been observed. From the analysis, though there is shift in confluence point, the magnitude of the change ranges from 1.15-1.8 km.

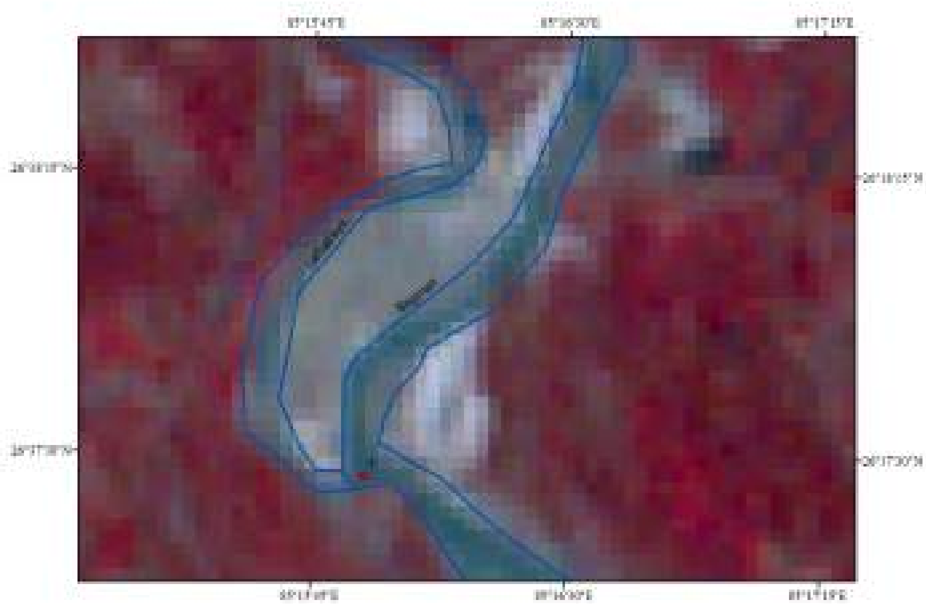


Figure 11-28: Confluence of Lalbakeya-Bagmati in 1975

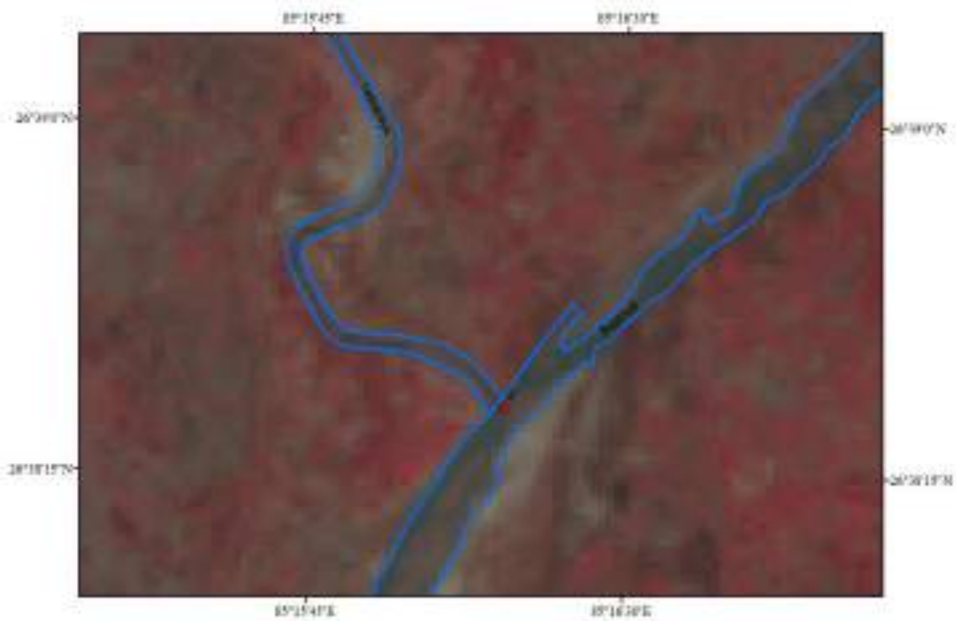


Figure 11-29: Confluence of Lalbakeya-Bagmati in 1990

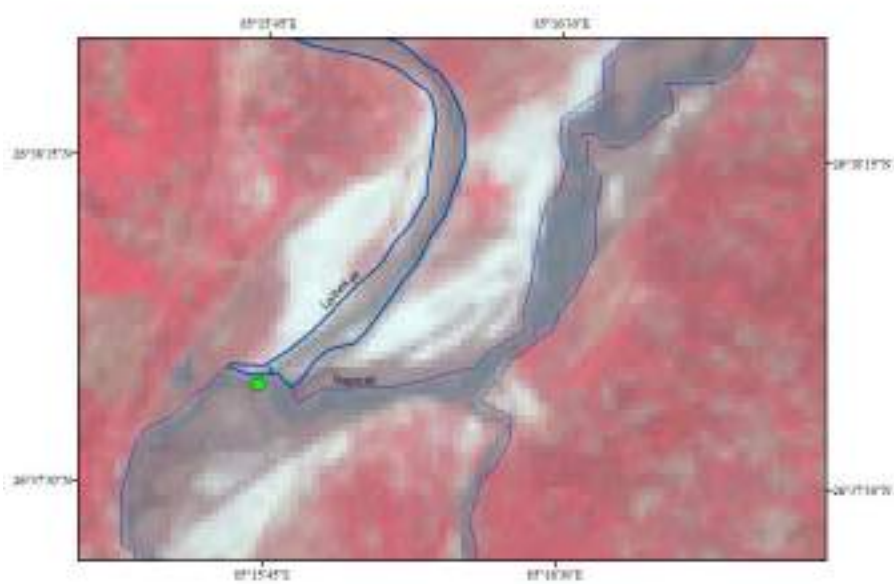


Figure 11-30: Confluence of Lalbakeya-Bagmati in 2000

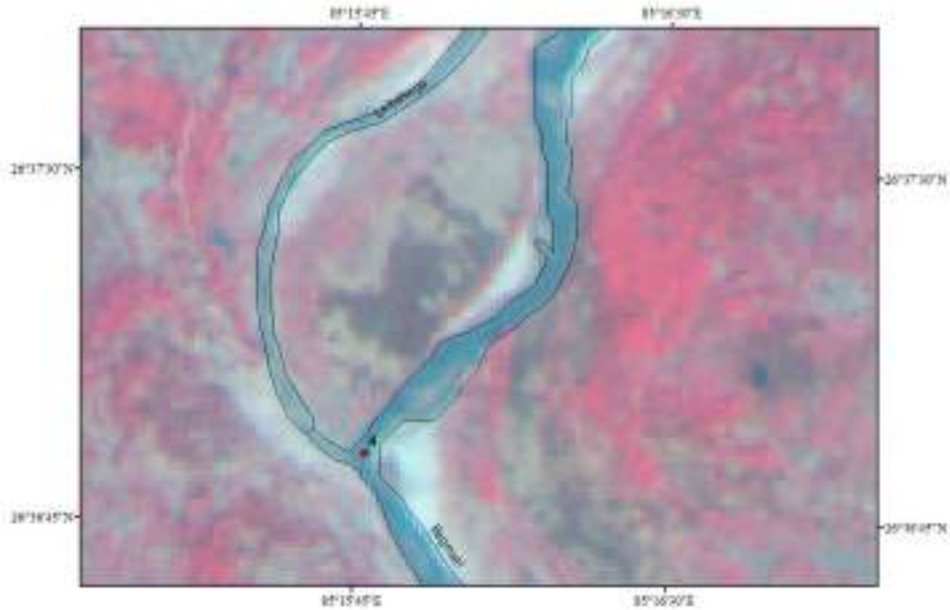


Figure 11-31: Confluence of Lalbakeya-Bagmati in 2010

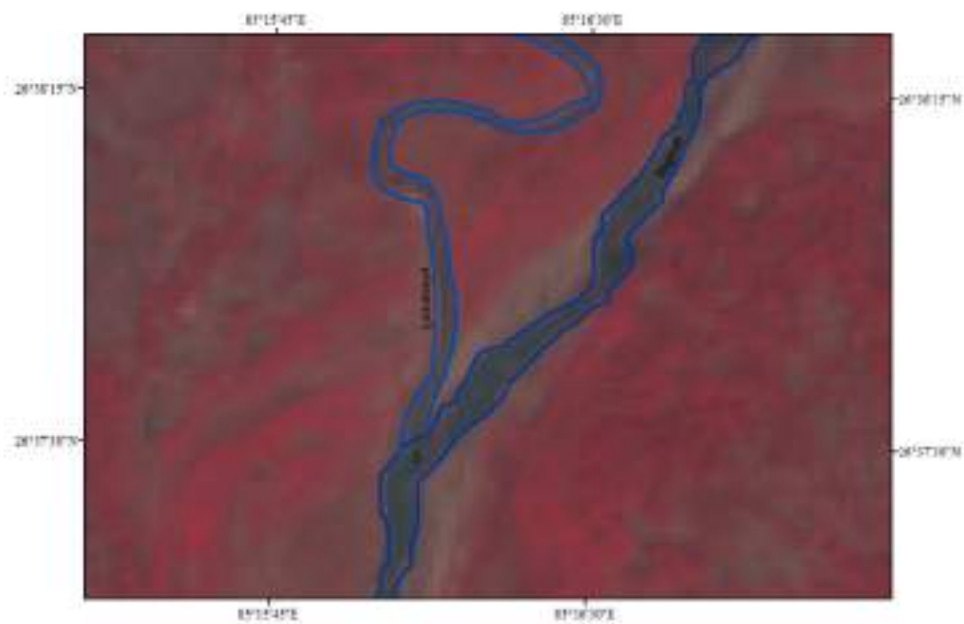


Figure 11-32: Confluence of Lalbakeya-Bagmati in 2016

**2. Kosi-Bagmati**

The confluence points for 1975 and 1990 are labelled as point 1 (86.60 E, 25.57 N) & 2, respectively (86.36 E, 25.73 N). Bagmati is merging with one of the reaches of the Kosi river near

Jagmohra village at Point 2, which is 30.4 km northwest from point 1 (Near Sonbarsha ghat). The confluence point shifted to point 3 for the year 2000, situated at 36 m south-east from point 2. After the year 2000, it moved 57 m south-east of point 3 and repositioned itself to point 4 by 2010, and this point again shifts to point 5 (251 m, south-east of point 4) by 2016. The confluence points for the years 1975,1990,2000,2010, and 2016 are shown in Figures 11-33 to 11-37. The 30.4 km movement of Kosi-Baghmati confluence can be attributed to the anabranching pattern of the Kosi River. Formation of a new branch of Kosi resulted in earlier confluence of Bagmati. Since 1990, the movement of the Kosi-Baghmati confluence is governed by the channel dynamics of Baghmati and Kosi anabranch controlled by the flood embankments.

At upstream of confluence, the width of River Bagmati (at 500 m U/S) increases from 120 m in 1990 to 142m in 2000. The width of Kosi (at 500 m U/S) upstream increases from 45m in 1990 to 65m in 2000, whereas the combined flow from Kosi-Bagmati measures 98 m in 1990 and 130m in 2000 500 m downstream. For the year 2000-2010, At upstream of confluence, the width of River Bagmati reduces from 142 m in 2000 to 130 m in 2010. The width of Kosi upstream reduces from 65m in 2000 to 68m in 2010, whereas the width of combined flow from Kosi-Bagmati measures 130 m in 2000 and 145m in 2010. For the year 2010-2016, At upstream of confluence, the width of River Bagmati increases from 130 m in 2010 to 132 m in 2016. The width of Kosi upstream reduces from 68m in 2010 to 90 m in 2016, whereas the width of combined flow from Kosi-Bagmati measures 145 m in 2010 and 155m in 2016. The average bed slope of the 1 km longitudinal section of the Bagmati channel upstream of confluence is 0.001 (direction is towards the confluence point), the average bed slope of the 1 km longitudinal section of the Kosi channel upstream confluence is 0.002 (direction is towards the confluence point). The bed slope at 1 km downstream of the confluence is 0.002 (direction is away from the confluence point). The area of the confluence zone is approximately 0.009 sq. km. in 2016. The Junction angle in 1990 is 127˚, which becomes 143˚ by 2000, 132˚ in 2010 and reduces to 81˚ by 2016. Due to mix spectral signature in the aerial images, no specific erosion and deposition patterns have been observed. From the analysis, it can be observed that though there is the shift in the confluence point, however, the magnitude of the change is less except in the year 1975-1990.

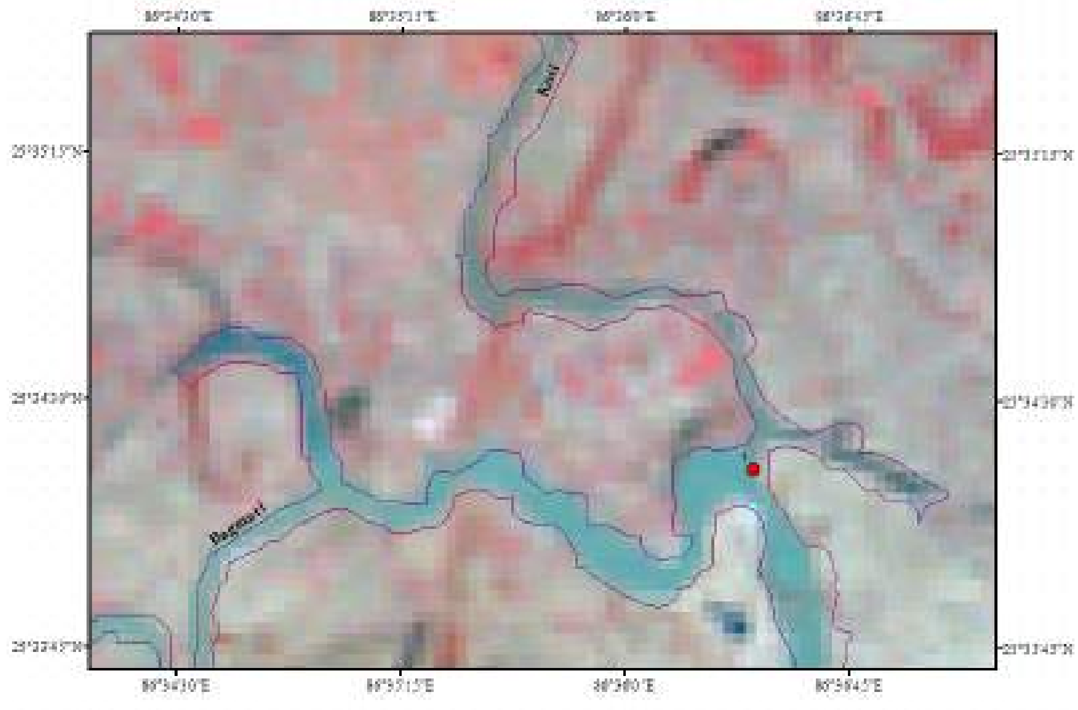


Figure 11-33: Confluence of Kosi-Bagmati in 1975

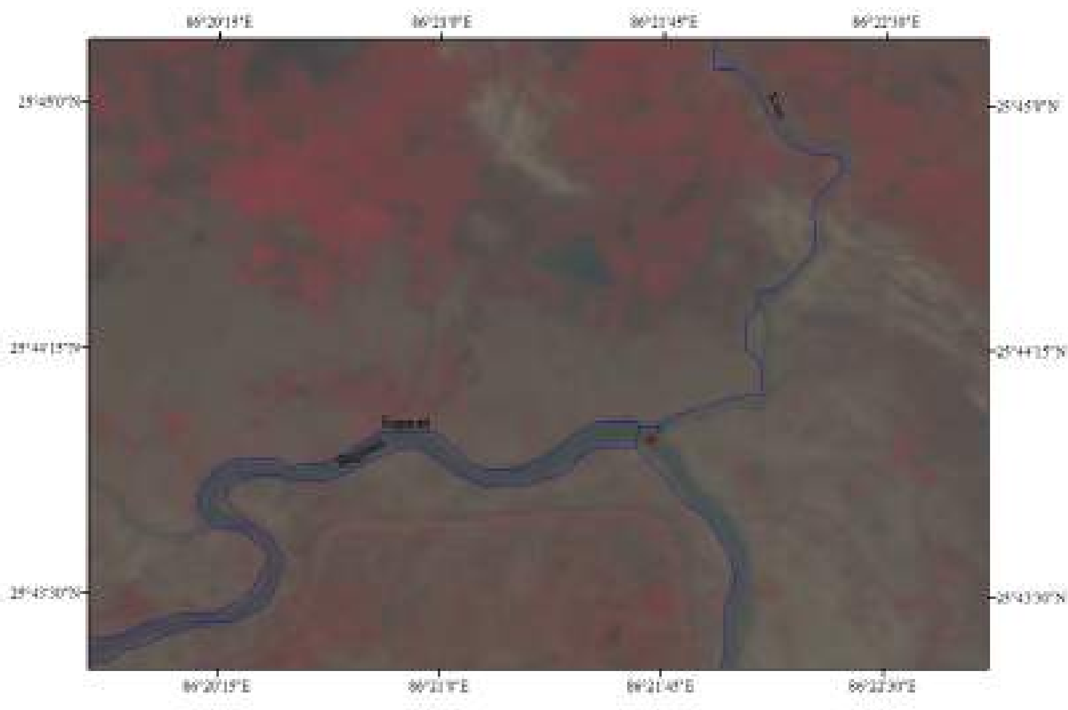


Figure 11-34: Confluence of Kosi-Bagmati in 1990

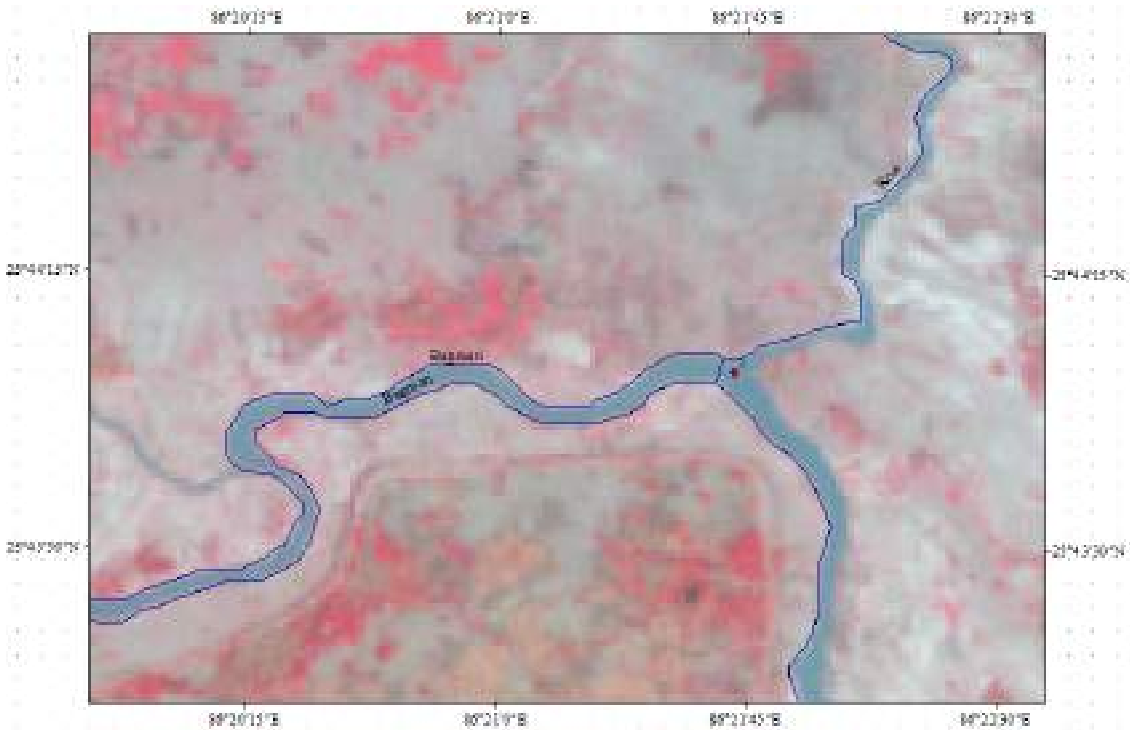


Figure 11-35: Confluence of Kosi-Bagmati in 2000

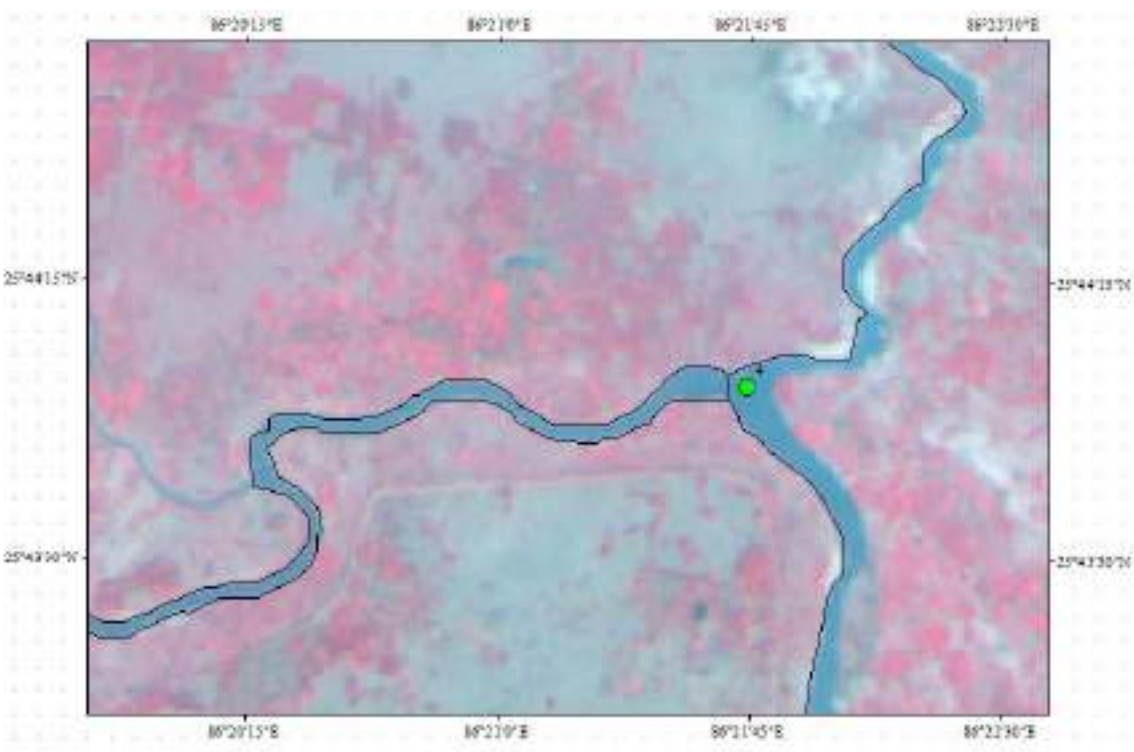


Figure 11-36: Confluence of Kosi-Bagmati in 2010

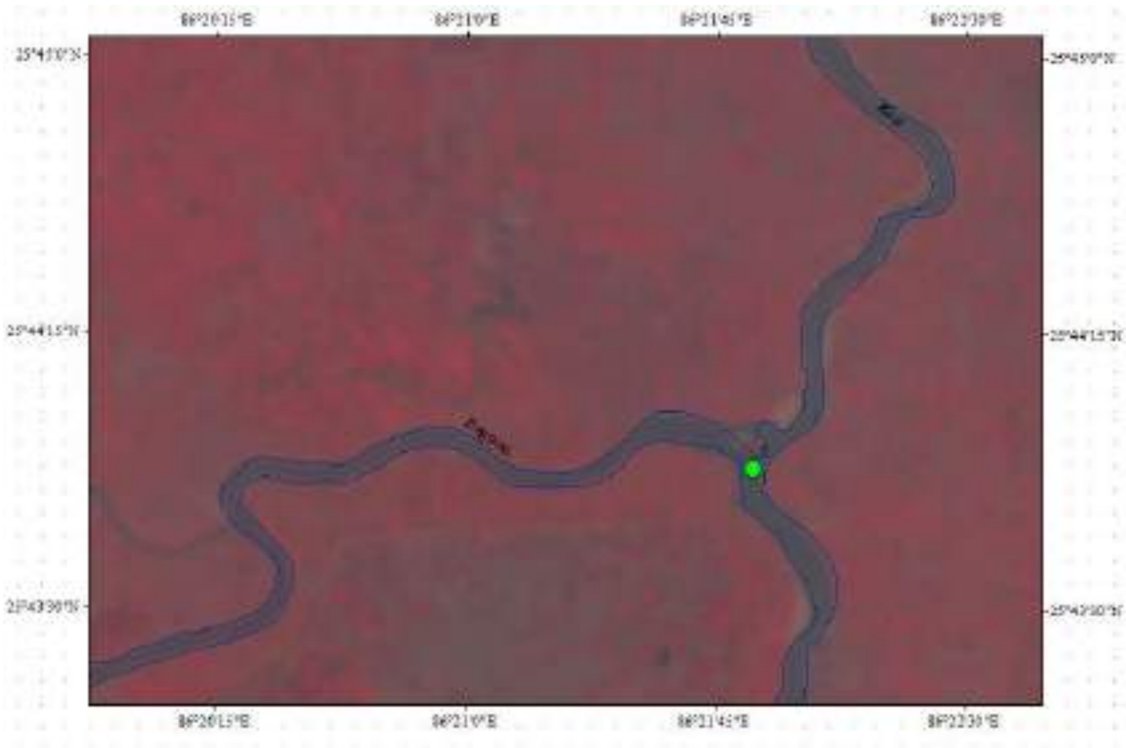


Figure 11-37: Confluence of Kosi-Bagmati in 2016

## 11.8 Abandoned Channels and Oxbow formations

Abandoned channels are geomorphologic evidence of channel movement. They are most likely outcome of channel shifting processes, such as meander cut-off and channel-belt avulsion. Abandoned channels are considered as oxbow lakes when sediment plugs cause the flow to change course. The oxbow lakes are formed from natural and engineered processes. Three stages of abandonment are generally noticed in case of meander cut-off,

(1) Cut-off initiation–the triggering of the cut-off when most of the river discharge becomes diverted from the meander and starts to flow along the newly activated channel (Lewis and Lewin, 1983; Hooke, 1995);

(2) Plug bar formation–an in-channel sedimentary response to reduced discharge that results in blockage of the upper and lower entrances, leading to further diversion and increased trapping of bedload and suspended load in old channel (Fisk, 1947; Constantineet al., 2010);

(3) Disconnected stage–discharge is no longer carried regularly through the old channel. The channel is 'disconnected' from the network of active river channels, and old channel is transformed into a floodplain lake that only receives suspended load during floods.

Based on the satellite image analysis on decadal scale, following observations have been made about abandoned channels and oxbow lake formations.

A former stream channel that was cut off from the rest of the river and characteristically lacks year long standing water, is known as an Abandoned Meander Channel. For Bagmati river system, abandoned channel analysis has been done. The results are shown in Table 11-8. The values obtained for the periods 1979-2000, 1990-2000, 2000-2010 and 2010-2016.

Table 11-8. Abandoned channels and Ox-bow formations

| S. No | Chainage | Nearby Village / town | Position | 1975-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
|---|---|---|---|---|---|---|---|
| 1. | 100-104 | Gaihati | 85.67 E, 26.18 N | Reach has moved to the right side & formation of two small oxbows have been observed across the left side of the river reach. Tonal variations seen in the satellite image of the year 1975 indicate that specified reaches were part of the main channel, and the oxbow lake has formed between 1975-1990 | Reach swung towards its right. The year 2000 image is slightly smaller than the oxbow in the year 1990. | Reach swung towards its right. At chainage 101-102. Both oxbow lakes are visible in the year 2010. | In the year 2016, one of the oxbow lake's footprint is visible while the other one gets eliminated |

| S. No | Chainage | Nearby Village / town | Position | 1975-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
|---|---|---|---|---|---|---|---|
| 2. | 119-123 | Kalyan pur | 85.77 E, 26.03N | One oxbow at the right side of the river can be seen in 1975 imagery at chainage 121. The reach swung towards its left, and the oxbow lake becomes more visible in the 1990 year imagery | The reach swung towards its right, which led to the formation of the oxbow lake at chainage 119. The Chainage at 121 is visible in the 2000-year imagery | The reach has partially gone back to its older course, which led to the size reduction of the oxbow lake at 119 chainage | Formation of two oxbows at 119 chainages, as the meander length reduces from 2010-2016 |
| 3. | 129-136 | Waris-nagar | 85.86 E, 26.03 N | One oxbow lake in the process at the left side of the river can be seen at chainage 133 in 1975, while two oxbow lakes are visible at the right side of the river at 133 and 135. During 1975-1990, the oxbow lake is formed at chainage 133. | No significant change | The river reaches swing towards its right, which caused a new oxbow lake at 129-130 chainage oxbow. Oxbow lakes situated at 133 chainages are still visible in 2010 imagery, while oxbow | No significant change, though oxbow lake at 135 chainages became visible in 2016 imagery. |

| S. N o | Chainage | Nearby Village / town | Position | 1975-1990 | 1990-2000 | 2000-2010 | 2010-2016 |
|---|---|---|---|---|---|---|---|
| | | | | | | lake at chainage 135 fads away. | |
| 4. | 160-161 | Baheri | 86.05E, 25.87 N | In the process at the left side of the river, one oxbow lake can be seen at chainage 161 in the year 1975, during 1975-1990, the oxbow lake is formed at chainage 161. | Oxbow lake became more visible and bigger in the 2000 year imagery. | River reach swings towards its left, which causes the reduction in the size of oxbow lake | River reach swings towards its left, and lake size reduce. |

## 11.9 Improvements over existing Plan Form Index

As defined earlier by Sharma (1995), Plan Form Index has considered a number of braids in its formulation. However, the standalone value of index number is not good enough to capture the attributes of the same. In this regard, Parmar and Khosa, (2017), have discussed in detail some shortcomings in this approach and, further, the authors suggest the following alternatives as improvements to the existing PFI index.

1. T/B
2. (T/B) +N
3. {(T/B)/N} +N

The variables used in the proposed indices are the similar to PFI index defined by Sharma (1995) where T indicates total flow top width and B indicate entire channel width and N represents the number of braids. The first alternative presents the ratio flow top width (sum of top width from all active channels) to total channel width. Though it misses out on number of braids present in that cross section, it carries important information about proportion of channel which is active and carrying flows at that time. This information is useful in relating aquatic habitat preferences with the hydrodynamics and channel morphology, ecologic corridor planning, and environmental flow management.

Regarding the range of values of first index, if the ratio of T/B is equal to 1, it indicates fully wetted river width and braiding phenomenon is absent. If the value of T/B is less than 1 then further assessment is needed and computation of second index is necessary.

The second index (T/B) +N captures important attributes related to braiding. The index will generate the positive real number, integer part will define the number of braids while fractional part will indicate the ratio of flow top width to channel width. This index in much more comprehensive and should be utilised for finding out plan form index in the future.

The third index as proposed by Parmar and Khosa (2017) has the form {(T/B/N)+N} and is seen as an improved version of PFI index (Sharma, 1995) as it is capable of addressing equifinality present in existing version of PFI on account of multiple combinations of T/N for the same value of B. An example of the improved PFI indices is explained here (Table 11-8), reaches from Grid no 1,3 and 4 is selected for the demonstration.

Table 11-9. Improved PFI indices (Parmar and Khosa, 2017, and comparison with PFI defined by Sharma (1995)

| FID | Length | FTW | N | PFI | Grid no | T/B | T/B/N | (T/B) +N | (T/B/N) +N |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.913115 | 0.423905 | 1 | 46 | 1 | 0.46 | 0.46 | 1.46 | 1.46 |
| 2 | 2.66373 | 1.68888 | 2 | 32 | 3 | 0.63 | 0.31 | 2.63 | 2.31 |
| 3 | 2.21764 | 1.97115 | 3 | 30 | 4 | 0.88 | 0.29 | 3.88 | 3.29 |

## 11.10 Alternative forms of Braiding Indices

The study has utilised the braiding index defined by Friend and Sinha (1993) for the present analysis. After a thorough analysis and understanding the significance of such index, Parmar and Khosa, 2017, have suggested the following indices which can be explored and utilised in the future studies as they capture the braiding phenomenon in greater detail and also highlight other aspects such as junctions, nature of braiding etc. The variables used in defining the indices are as below, Length of Reach: $L_R$ (straight length of river along its course)

Number of Junctions over the given reach: $N_J$

Length of the Main (Principal Channel/Braid): $L_{cmax}$

Total length of all channels/braids over the given reach: $L_{ctot}$

Braiding Ratio: $R_B = L_{cmax} / L_{ctot}$ [Reciprocal of existing Braiding Index (Friend and Sinha, 1993)]

$B_{AV}$: Average bank to bank width of the river over the reach length, $L_R$.

The proposed indices have been categorised into four subcategories as tabulated (Table 11-10& Table 11-11) below:

Table 11-10. Modified Braiding Indices by Parmar and Khosa, 2017

| | INDICES | | | | | | |
|---|---|---|---|---|---|---|---|
| **FORMS** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| INVERSE | $R_B / N_J$ | $(L_R/L_{ctot}) / N_J$ | $L_R / N_J$ | $L_{cmax}/N_J$ | | | |
| PROPORTIONATE | $N_J / R_B$ | $N_J /(L_R/L_{ctot})$ | $N_J / L_R$ | $N_J / L_{cmax}$ | $L_{ctot} / L_{cmax}$ **(F-S Index)** | $L_{ctot} / L_R$ **(Variant of F-S Index)** | $N_J / (L_R*B_{AV})$ |
| NEUTRAL | $N_J/ L_{ctot}$ | $L_{ctot} / N_J$ | | | | | |
| OTHERS | $N_J*(L_{ctot}/L_R)$ | $N_J*(L_{ctot}/L_{cmax})$ | | | | | |

For illustration purpose, indices computed for grid no. 14 and 30 based on the satellite imagery of the year 2016 are shown in table below,

Table 11-11. Modified Braiding Indices by Parmar and Khosa, 2017

| **Sr No.** | **Grid Number** | **14** | **30** |
|---|---|---|---|
| 1 | Lctot | 20.07 | 15.87 |
| 2 | Lcmax | 17.25 | 13.23 |
| 3 | LR | 11.11 | 10.80 |
| 4 | Braiding Ratio (RB) | 1.16 | 1.20 |
| 5 | Nj | 17.00 | 5.00 |
| 6 | $R_B / N_J$ | 0.07 | 0.24 |

| Sr No. | Grid Number | 14 | 30 |
|---|---|---|---|
| 7 | (LR / Lctot) / NJ | 0.03 | 0.14 |
| 8 | $L_R$ / $N_J$ | 0.65 | 2.16 |
| 9 | $L_{cmax}$ /$N_J$ | 1.01 | 2.65 |
| 10 | $N_J$ / $R_B$ | 14.61 | 4.17 |
| 11 | $N_J$ /( $L_R$ / $L_{ctot}$) | 30.71 | 7.35 |
| 12 | $N_J$ / $L_R$ | 1.53 | 0.46 |
| 13 | $N_J$ / $L_{cmax}$ | 0.99 | 0.38 |
| 14 | $N_J$ / $L_{ctot}$ | 0.85 | 0.32 |
| 15 | $L_{ctot}$ / $N_J$ | 1.18 | 3.17 |
| 16 | $N_J$ *( $L_{ctot}$ / $L_R$) | 30.71 | 7.35 |
| 17 | $N_J$ *( $L_{ctot}$ / $L_{cmax}$) | 19.78 | 6.00 |

It may be noted that these indices capture the presence of junctions, so innately typical to Braided reaches, which is one of the important attributes of braided river system. In general, high value of the number of junctions indicates a higher level of braiding severity and vice versa. When this information is used with other attributes it provides a significant range which can be used to define the overall braiding phenomenon over a defined reach length. As an illustrative example, values obtained by $N_J$ /($L_R$/$L_{ctot}$) for the grids, 14, and 30 are 30.72 and 7.35 respectively and these indicate the severity of braiding. It is a proportional measure, i.e. higher the value of ratio, high braiding and lower value indicate low braiding in the reach. Reference may be made to Parmar and Khosa, 2017, for more details regarding the analysis procedure to that is recommended to implement and explore the use of the suggested indices.

## 11.11 Conclusion

From the analysis of various attributes of river morphology, the following conclusions have been drawn,

1. The sinuosity index does not show any significant trend. The average Sinuosity for the entire stretch of Bagmati River is 1.59, whereas the radius of curvature varied from 0 to 0.33km. However, the scale of digitisation and number of bends have a significant role in determining the index. Therefore, the Sinuosity and radius of curvature presented in the present chapter indicate average values for the grid it belongs to.
2. Braiding index are computed on a grid scale, while plan form index is computed at 4 km chainage scale. It has been observed that braiding is significant in selected reaches (Grid 14 and 44), majorly situated in the Sitamarhi district, formation and abandonment of oxbow lakes have shown its bearing on braiding pattern (Table 11-7).
3. The braiding index (Friend and Sinha, 1993) and plan form index capture braiding pattern in two different forms. The first one captures it at reach scale, whereas the planform index captures it at cross-section scale. Though both represent braiding phenomenon, cross section-based index highly localised and dependent on top flow width driven by flow depth and overall hydrodynamics of the channel, which cannot be captured properly using remote sensing data. On the other hand, the braiding index suggested by Friend and Sinha is driven by channel length and not directly linked with the parameters related to the depth of flow. Therefore, in estimating the braiding phenomenon using remote sensing data, the braiding index by Friend and Sinha (1993) scores over the PFI index suggested Sharma (1995).
4. Shifting analysis of Bagmati River has been carried out at 1 km interval, and it has been seen that river has experienced changes in river course at few locations (chainages 37-57). The significant shifting is observed near 72-88 km chainage in the year 2010-16. The probable reason behind this shifting is the construction of the railway bridge, which cause the shift in the natural course of the Bagmati River.
5. Further, Improved Planform Indices (IPFI) and Modified Braiding Indices (MBI) as proposed by Parmar and Khosa (2017), are recommended for use in future river morphology studies over those proposed by Friend and Sinha (1993) and Sharma (1995).

It is seen that IPFI and MBI by Parmar and Khosa (2017) better capture the number of braids, the overall braiding phenomenon as well as the ratio of flow top width to fully wetted river width.

6. From the analysis of confluence points, the confluence points over the entire Lalbakeya-Bagmati confluence zone is observed to have shifted by distances ranging from 1.15-1.8 km and therefore show a marginal level of instability which is in sharp contrast with the confluence site of River Kosi with Bagmati which has shifted by 23 km between 1975 to 1990 albeit having recorded a shift of less than 500m over the next timeline between 1990 to 2016.

# Chapter 12 Erosion and Deposition

## 12.1 Channel Evolution analysis

Channel Evolution analysis delineate river channel geometry that includes channel dimensions, pattern, and longitudinal profiles. Other aspects of channel evolution on a macro scale include identifying distinct river segments, i.e. channel in the upper reach, a channel in flood plains, also aggradation and degradation zones, and bank erosion. Such a study is carried out mainly from field survey. Some of the aspects derived from observed cross-sections data have been discussed in chapter 10, i.e., channel form and pattern. In the present chapter areal retreat of erosion and deposition estimated from satellite imageries on the decadal scale is presented.

## 12.2 Erosion and Deposition

Areal Retreat (area in $km^2$) of erosion and deposition is computed from digitised features. The difference in channel area, sandbars and water bodies based on their tonal variations as observed in satellite images are considered for estimation of erosion and deposition. Accordingly, erosion deposition for the whole stretch of Bagmati has been carried out on a grid basis. The following map indicates the grid index. These grids represent the main channel of Bagmati River.

## 12.3 Results and Analysis

Channel bank Retreat due to erosion and deposition for the time frames of 1975-1990, 1990-2000, 2000-2010 and 2010-2016 have been estimated on grid-scale and tabled in Table 12-1. Results represented in the table are displayed in the tabular format. Each map indicates Grid wise channel bank retreat of erosion and deposition computed for the period mentioned on the map. This chapter discusses the results of erosion, and deposition behavior of the Bagmati River.

Table 12-1. Computation of areal retreat of erosion-deposition on grid basis (All units are in km)

| Grid Name | | | 216 | 204 | 187 | 170 | 160 | 144 | 135 | 120 |
|---|---|---|---|---|---|---|---|---|---|---|
| In Decimal Degree | Latitude | | 25.69 | 25.78 | 25.78 | 25.78 | 25.87 | 25.87 | 25.96 | 25.96 |
| | Longitude | | 86.32 | 86.31 | 86.21 | 86.12 | 86.11 | 86.01 | 86.01 | 85.91 |
| River Length (km) | | | 18.78 | 5.49 | 17.84 | 6.76 | 16.17 | 10.66 | 14.99 | 8.63 |
| All units in sq. km | 1975 - 1990 | Erosion(-) | -5.85 | -0.54 | -8.38 | -1.59 | -2.55 | -0.25 | -0.27 | -0.04 |
| | | Deposition(+) | 0.64 | 0.00 | 0.12 | 0.18 | 0.75 | 1.46 | 1.43 | 1.13 |
| | | Change in sandbars | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Net | -5.21 | -0.54 | -8.25 | -1.41 | -1.80 | 1.21 | 1.17 | 1.09 |
| | 1990 - 2000 | Erosion(-) | -1.60 | 0.00 | -0.23 | -0.12 | -1.29 | -5.40 | -4.80 | -1.68 |
| | | Deposition(+) | 0.39 | 0.02 | 0.88 | 0.58 | 0.39 | 0.05 | 0.04 | 0.00 |
| | | Change in sandbars | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Net | -1.21 | 0.02 | 0.65 | 0.46 | -0.90 | -5.35 | -4.77 | -1.68 |
| | 2000 - 2010 | Erosion(-) | 0.00 | 0.00 | -0.08 | -0.07 | -0.05 | -0.07 | -0.14 | -0.08 |
| | | Deposition(+) | 10.36 | 0.43 | 10.12 | 2.46 | 7.18 | 5.84 | 4.78 | 1.52 |
| | | Change in sandbars | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| | | Net | 10.36 | 0.43 | 10.03 | 2.39 | 7.13 | 5.77 | 4.64 | 1.44 |
| | 2010- 2016 | Erosion(-) | -0.35 | -0.01 | -0.23 | -0.08 | -0.20 | -0.19 | -0.25 | -0.18 |
| | | Deposition(+) | 0.26 | 0.02 | 0.43 | 0.19 | 0.82 | 0.43 | 0.57 | 0.20 |
| | | Change in sandbars | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 | 0.00 | 0.00 |
| | | Net | -0.10 | 0.01 | 0.20 | 0.11 | 0.61 | 0.24 | 0.32 | 0.02 |

| Grid Name | | | 112 | 98 | 84 | 78 | 72 | 60 | 55 | 44 |
|---|---|---|---|---|---|---|---|---|---|---|
| In Decimal Degree | Latitude | | 26.05 | 26.05 | 26.05 | 26.14 | 26.23 | 26.23 | 26.32 | 26.32 |
| | Longitude | | 85.91 | 85.81 | 85.91 | 85.71 | 85.71 | 85.61 | 85.61 | 85.51 |
| River Length (km) | | | 15.96 | 14.85 | 18.65 | 19.93 | 5.05 | 15.05 | 2.92 | 17.25 |
| All units in sq. km | 1975 - 1990 | Erosion(-) | -0.21 | -0.19 | -0.33 | -0.78 | -0.11 | -0.39 | -0.02 | -0.25 |
| | | Deposition(+) | 2.72 | 1.55 | 1.82 | 1.75 | 0.35 | 1.73 | 0.52 | 2.66 |
| | | Change in sandbars | -0.15 | -0.03 | 0.00 | -0.17 | 0.00 | -0.01 | 0.00 | -0.01 |
| | | Net | 2.36 | 1.33 | 1.50 | 0.80 | 0.23 | 1.33 | 0.50 | 2.40 |
| | 1990 - 2000 | Erosion(-) | -2.19 | -0.70 | -1.27 | -0.85 | -0.14 | -0.54 | -0.08 | -0.85 |
| | | Deposition(+) | 0.12 | 0.52 | 0.52 | 0.71 | 0.14 | 0.67 | 0.01 | 0.46 |
| | | Change in sandbars | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Net | -1.99 | -0.18 | -0.75 | -0.14 | 0.00 | 0.13 | -0.07 | -0.39 |
| | 2000 - 2010 | Erosion(-) | -0.83 | -0.66 | -0.77 | -0.53 | -0.09 | -0.33 | -0.05 | -0.99 |
| | | Deposition(+) | 1.80 | 0.48 | 0.98 | 0.55 | 0.09 | 0.52 | 0.08 | 0.88 |
| | | Change in sandbars | -0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Net | 0.89 | -0.18 | 0.20 | 0.02 | 0.00 | 0.19 | 0.04 | -0.11 |
| | 2010- 2016 | Erosion(-) | -0.31 | -0.56 | -0.52 | -0.72 | -0.15 | -1.03 | 0.00 | -4.66 |
| | | Deposition(+) | 0.46 | 0.55 | 0.38 | 0.55 | 0.10 | 0.67 | 0.15 | 1.01 |
| | | Change in sandbars | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 3.53 |
| | | Net | 0.16 | -0.01 | -0.15 | -0.17 | -0.05 | -0.33 | 0.15 | -0.12 |

| Grid Name | | | 40 | 30 | 27 | 20 | 18 | 16 | 14 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|
| In Decimal Degree | Latitude | | 26.41 | 26.41 | 26.50 | 26.41 | 26.50 | 26.59 | 26.68 | 26.77 |
| | Longitude | | 85.51 | 85.41 | 85.41 | 85.31 | 85.31 | 85.31 | 85.30 | 85.30 |
| River Length (km) | | | 3.75 | 13.23 | 1.32 | 2.99 | 10.71 | 17.78 | 13.72 | 13.49 |
| All units in sq. km | 1975 - 1990 | Erosion(-) | -0.28 | -0.43 | 0.00 | -0.08 | -0.41 | -2.57 | -2.43 | -0.93 |
| | | Deposition(+) | 0.49 | 2.55 | 0.00 | 0.27 | 1.54 | 3.57 | 1.15 | 0.32 |
| | | Change in sandbars | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.19 | 0.02 |
| | | Net | 0.20 | 2.12 | 0.00 | 0.18 | 1.15 | 1.03 | -1.10 | -0.59 |
| | 1990 - 2000 | Erosion(-) | -0.40 | -4.29 | 0.00 | -0.64 | -2.44 | -10.21 | -3.59 | -5.60 |
| | | Deposition(+) | 0.06 | 1.10 | 0.00 | 0.02 | 0.09 | 0.11 | 1.07 | 2.06 |
| | | Change in sandbars | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 | 4.74 | -0.08 | -0.03 |
| | | Net | -0.35 | -3.19 | 0.00 | -0.62 | -2.14 | -5.35 | -2.60 | -3.56 |
| | 2000 - 2010 | Erosion(-) | -0.24 | -0.74 | -0.10 | -0.25 | -0.55 | -1.95 | -2.19 | -1.71 |
| | | Deposition(+) | 0.28 | 3.52 | 0.00 | 0.50 | 1.16 | 9.96 | 2.80 | 5.19 |
| | | Change in sandbars | 0.01 | 0.01 | 0.00 | 0.02 | 0.11 | -4.55 | 1.53 | 0.11 |
| | | Net | 0.04 | 2.78 | -0.10 | 0.27 | 0.72 | 3.45 | 2.14 | 3.59 |
| | 2010-2016 | Erosion(-) | -5.95 | -1.91 | -0.14 | -0.27 | -0.41 | -1.23 | -0.96 | -1.22 |
| | | Deposition(+) | 0.12 | 0.66 | 0.05 | 0.26 | 0.84 | 2.40 | 2.60 | 1.79 |
| | | Change in sandbars | 5.66 | 1.53 | 0.00 | 0.00 | -0.02 | 0.08 | -1.39 | 0.06 |
| | | Net | -0.18 | 0.28 | -0.09 | -0.01 | 0.41 | 1.26 | 0.25 | 0.63 |

## 12.4 Discussion on the result

Following conclusions have been drawn from erosion and deposition analysis.

1. Grid no: 12, 14, 16, and 18, which cover the chainage (based on reference line: created from 1975 river centreline) between 0 to 44 km, Dheng Bridge Ghorha indicate an erosion in 1990-2000 while for other periods, deposition has been noticed. Erosion of 13.65 sq. km and deposition of 12.94 sq. km have been estimated for 1990-2000 and other periods, respectively.
2. Grid no: 20, 27, 30 and 40, which cover the chainage (based on reference line: created from 1975 river centreline) between 45 to 65 km, Ghorha to Runnisaidpur, indicates an erosion 1990-2000 while for other periods, deposition has been noticed. Erosion of 3.19 sq. km and deposition of 5.19 sq. km have been estimated for 1990-2000 and other periods, respectively.
3. Grid no: 44, 55, 60 and 72, which cover the chainage (based on reference line: created from 1975 river centreline) between 66 to 100 km, Runnisaidpur to Katra indicate an erosion in the 1990-2000 and 2010- 2016 while for other periods, deposition has been noticed. Erosion of 0.70 sq.km and deposition of 4.58 sq.km have been estimated for the periods 1990-2000 & 2010-2016 and 1975-1990 &2000-2010 respectively.
4. Grid no: 78, 84, 98and 112, which cover the chainage (based on reference line: created from 1975 river centreline) between 101 to 140 km, Katra to Warisnagar indicate an erosion in the 1990-2000 & 2010-2016 while for other periods, deposition has been noticed. Erosion of 3.23 sq.km and deposition of 6.92 sq.km have been estimated for the periods 1990-2000 & 2010-2016 and 1975-1990 &2000-2010 respectively.
5. Grid no: 120, 135, 150 and 160, which cover the chainage (based on reference line: created from 1975 river centreline) between 141 to 168 km, Warisnagar to Singla indicate an erosion in 1990-2000 while for other periods, deposition has been noticed. Erosion of 12.69 sq. km and deposition of 21.85 sq. km have been estimated for 1990-2000 and other periods, respectively.
6. Grid no: 170, 187, 204 and 216, which cover the chainage (based on reference line: created from 1975 river centreline) between 169 to 208 km, Singla to Cherakhera indicate an erosion in 1975-2000 while for 2000-2016, deposition has been noticed. Erosion of 15.49 sq. km and deposition of 23.44 sq. km have been estimated for 1975-2000 and 2000-2016, respectively.

# Chapter 13 Major Structures and Their Impact on River Morphology

## 13.1 Identification of Structures

Various Structures built across the mainstream of Bagmati have been identified using satellite imagery and written in subsequent sections. Some of the other pertinent such as length of the bridge and average width of the river, are obtained from secondary data (satellite images, high-resolution dataset on google earth). They have been presented in table form in the following sections.

## 13.2 Road Bridges on Bagmati River

Road crossings, either permanent or temporary, including national and state highways, expressways, district roads, small bridges, have been captured using remote sensing observations such as Google Earth Pro; associated river width and bridge details are mentioned in Table 13-1. The spatial association of bridges and river Bagmati is shown in Figure 13-1.

Table 13-1. Road Bridges across Bagmati River

| S.No. | Bridge/Road Name | Average width of the channel (m) |
|---|---|---|
| 1 | Piprahi Basantpatti Sisaula Road | 41.85 |
| 2 | Dubba Bridge: SH 48 | 47.69 |
| 3 | Marrar Bridge: Belsand Meenapur Road | 124.25 |
| 4 | Unknown (Near Kansar and Mehthi) | 106 |
| 5 | Unknown (Near Kansar and Mehthi) | 92.69 |
| 6 | Unknown (Near Kansar and Mehthi) | 95.46 |
| 7 | Gangeya Bridge | 45.25 |
| 8 | East-West Expy | 37.85 |
| 9 | Unknown (Near Balha) | 50.30 |
| 10 | Unknown (Near Pandaul) | 70.73 |
| 11 | SH-50 | 37.54 |
| 12 | Kareh Bridge | 48 |
| 13 | Hathauri Kothi Singhauti Road | 57.4 |
| 14 | Baheri Hathauri Kothi Road | 60.1 |
| 15 | Bariyahi Ghat Bridge | 81.2 |
| 16 | Kakarghat Bridge | 75.9 |

| S.No. | Bridge/Road Name | Average width of the channel (m) |
|---|---|---|
| 17 | Kelhua Ghat Bridge | 69.17 |

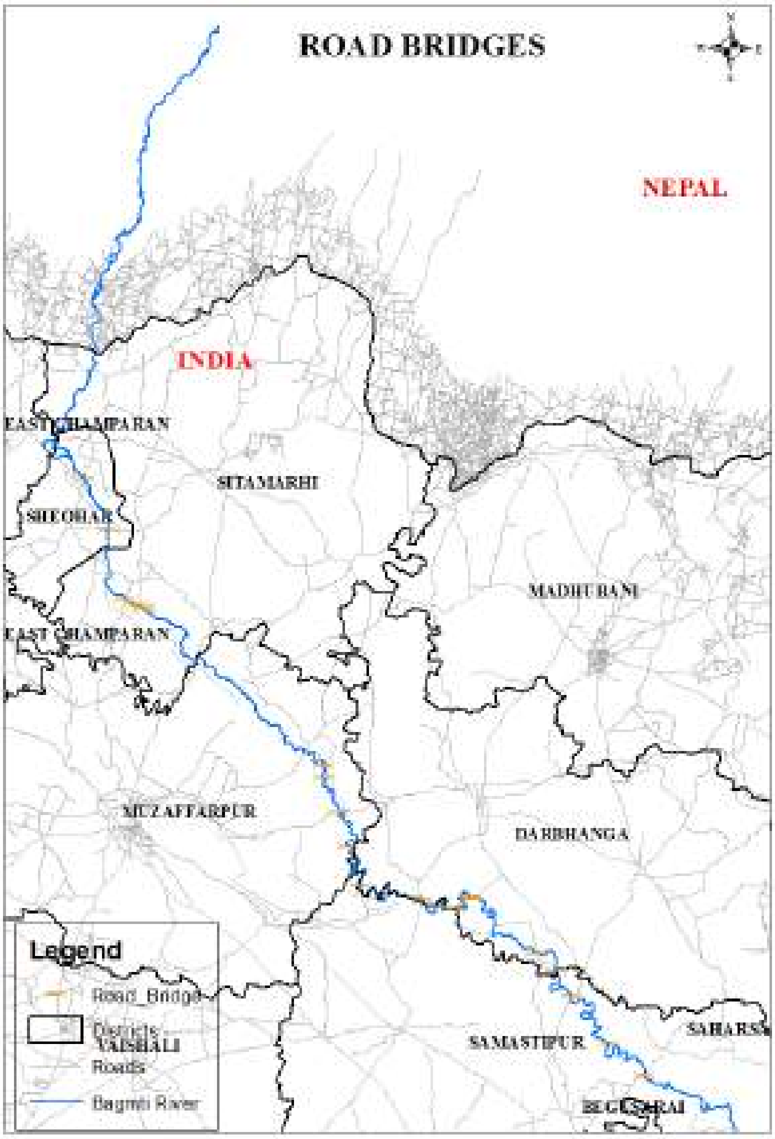



Figure 13-1: Road Bridges and Road Network on Bagmati River

## 13.3 Railway Bridges on Bagmati River

Railway bridges constructed across the Bagmati River are as below, and the location map of the following bridges is shown in Figure 13-2.

Table 13-2. Railway Bridges across Bagmati River

| S.No. | Name of Bridge | Length of Bridge (m) | Average Width of the River (m) |
|---|---|---|---|
| 1 | Dheng Bridge | 600 | 400 |
| 2 | Near Benipurgram Hault Railway Station | 600 | 120 |
| 3 | Kareh Bridge | 197 | 48 |
| 4 | Badlaghat Bridge | 300 | 140 |

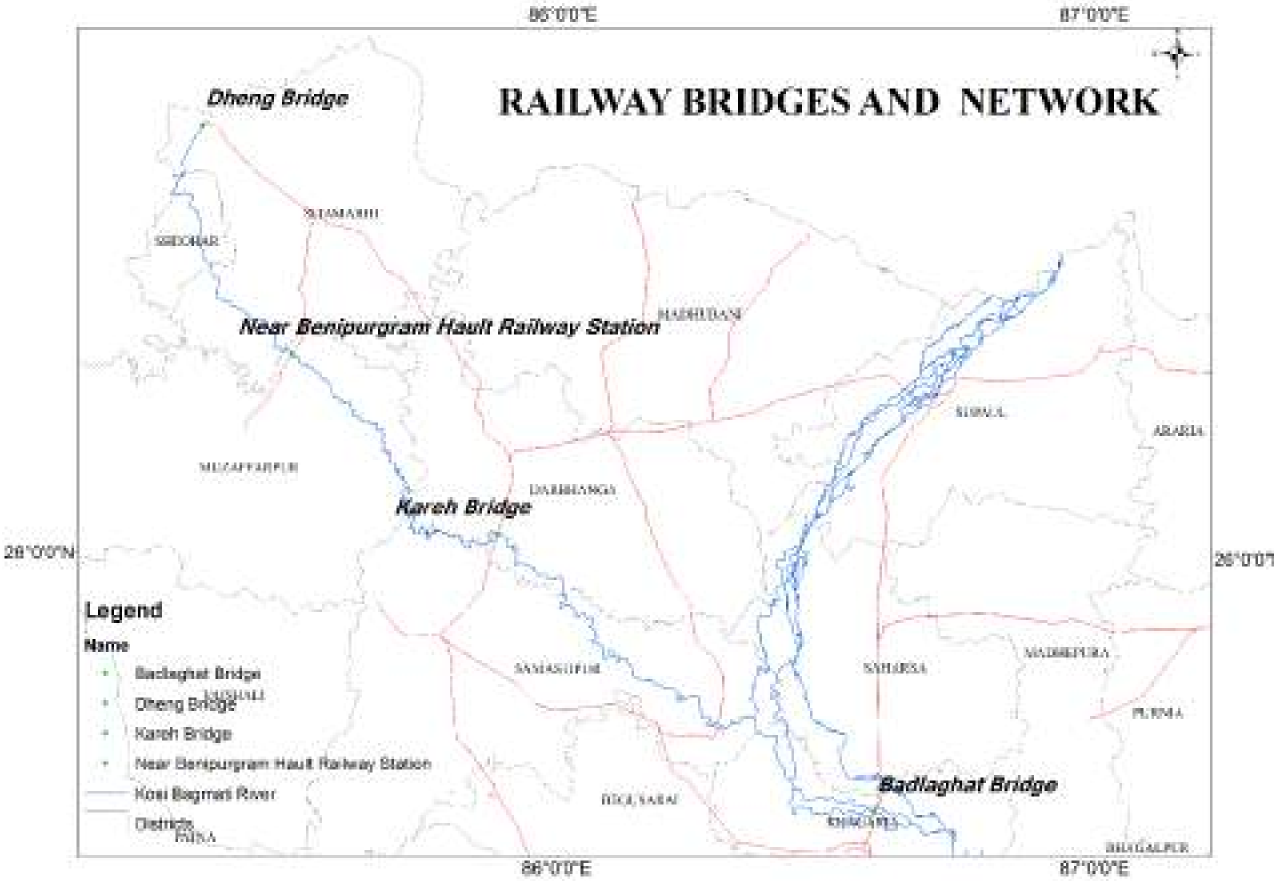



Figure 13-2: Railway Bridges and Network on Bagmati River Course

No such significant changes in the river course have been observed except near Benipurgram Hault Railway Station. Within this chainage (69-70 km), the river behaves astonishingly, there is no substantial change in the course of the river till the year 2000, but in 2010 river started to divide into channels (Figure 13-3), and in 2016 imagery, it can be seen that more water is flowing through the newborn channel. The reason behind this bifurcation situates in the topography of the area and the construction of the railway bridge. It is plausible that the soil is excavated from the nearby region during the Railway Bridge construction, introducing the change in elevation and the energy gradient difference. Due to the developed energy gradient, water started flowing in both channels (existing and excavated). This division's topography is that topography of this region is flat terrain (2 to the 5-meter difference in the whole plain), so a slight change in elevation value can change the water flow direction.

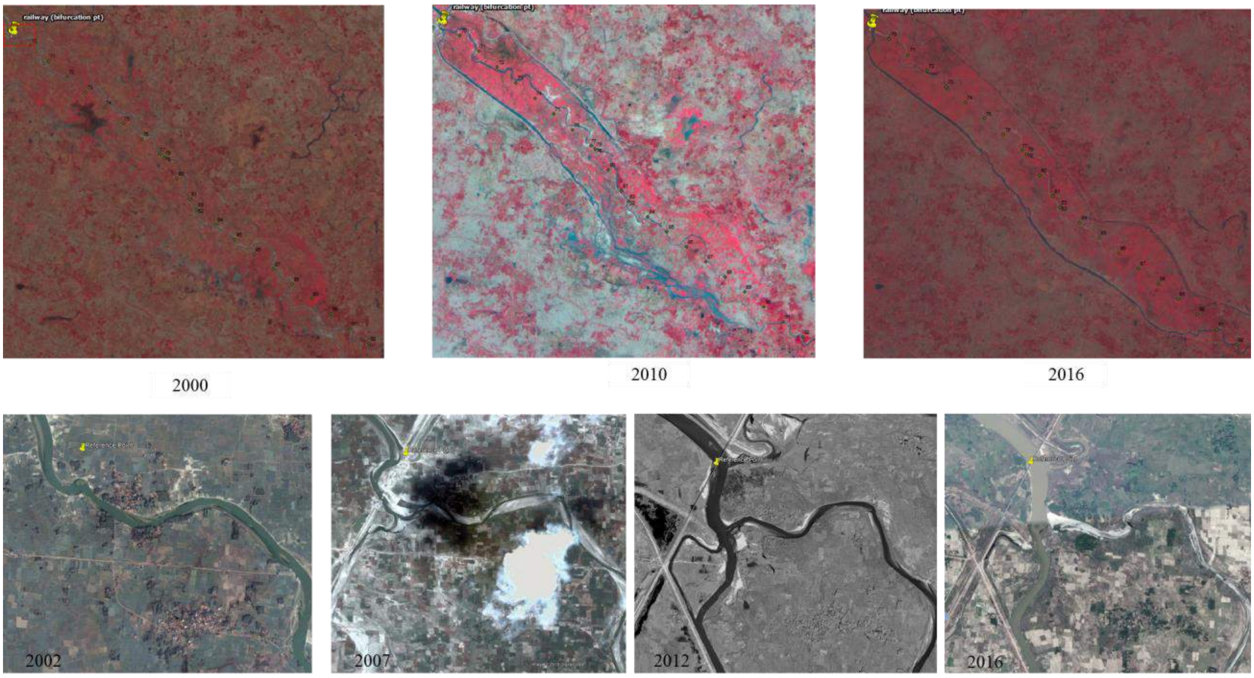



Figure 13-3: Change in river course Near Benipurgram Hault Railway Station

## 13.4 Impact of Embankments

The main tributaries of the Bagmati River are the Lalbhekya, Lakhandei and Adhwara group of rivers. The majority of water supposed to flow through Hayaghat is spread in the surrounding region with a topography like a plate. Unless and until the plate overflows, water cannot move ahead. In this region flood water of Bagmati intrudes in its tributaries and cause flood situation in their catchments. This typical topographic feature put villages located alongside Bagmati between Dheng to Hayaghat into dangerous flood situations. Without flooding the region in between, Bagmati cannot move ahead to Hayaghat. So, this area is prone to flood (Mishra 2010).

To tackle the flood situation, the construction of an embankment along the channel is done. It protects villages by establishing a safe zone. Moreover, that is what is being done for the last 50 years under various irrigation and flood control schemes. Embankments above Sitamarhi – Sheohar road crossing up to Indo-Nepal border were constructed in 1979-80 and are known as

Bagmati afflux bund. The left afflux bund is around 50.5 km, the right afflux bund is approximately 32.8 km, and the Bargania ring bund is 7.2 km. Embankments below Sitamarhi –Sheohar road crossing and just upstream of Muzaffarpur-Sitamarhi road crossing have also been constructed. The length of the left and right embankments is around 24 km. The left embankment from Hayaghat to Phuhia (approximately 73 km) and the right embankment from Surmarhat to Badlaghat (about 145 km) on river Kareh were constructed in 1956 design discharge of 1416 cumec. Later on, these embankments were strengthened in 1981 for a design discharge of 3695 cumecs. The embankments on the Bagmati river are shown in Figure 13-4.

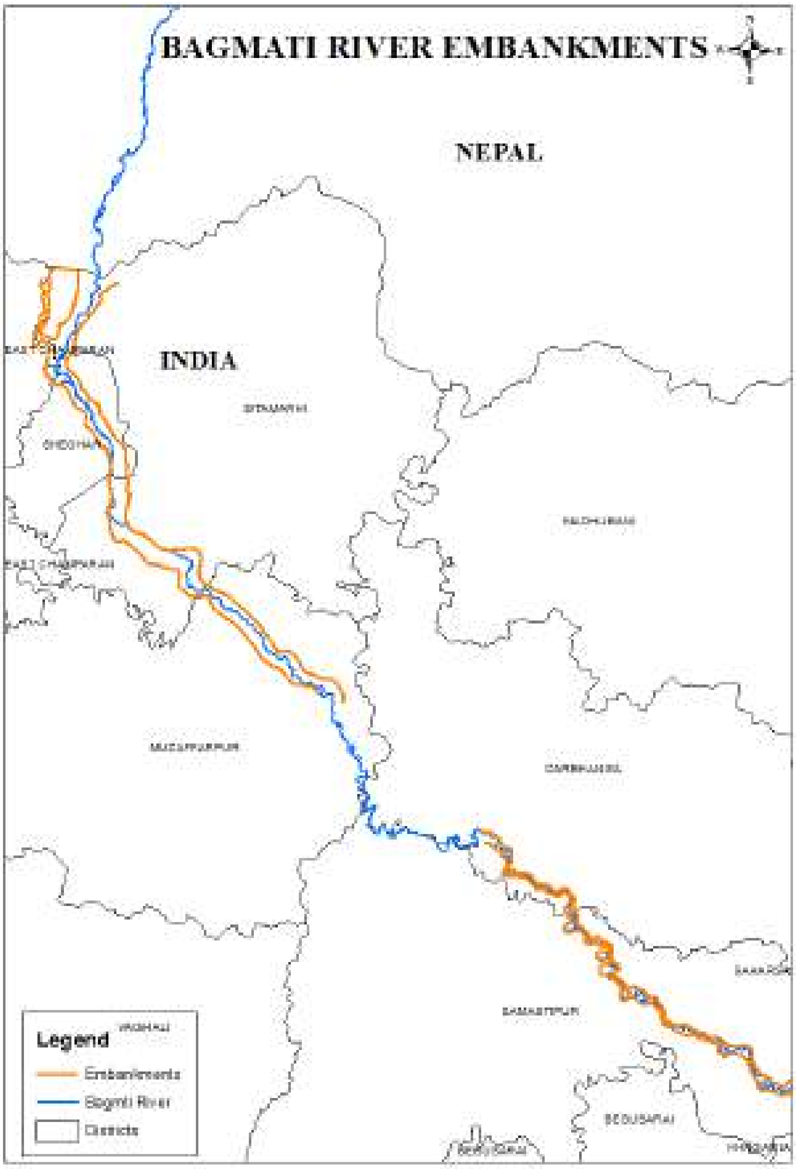



Figure 13-4: Existing Embankments along Bagmati River extracted from Google Earth.

## 13.5 Conclusion

Following are the major conclusions drawn concerning the impacts of the structures on the river from the analyses of the imageries and the visit made to these sites.

1. After constructing the Benipurgram Hault Railway bridge, an abrupt shift in the river, the course is observed within 2000-16.
2. No significant impact has been observed of road bridges on the river course within 1977-2016.
3. Adverse impacts of Embankments as suggested by Mishra (2010):
   3.1 The embankment protects agricultural field from floodwater, and thus, fields do not get fertile silt and consequently loses its fertility.
   3.2 Water from local subsidiary streams cannot enter the mainstream. Then either it flows in a backward direction or moves along to the mainstream but outside the embankment. In both scenarios, it submerges surrounding villages.

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# Chapter 14 Islands and Sandbars

## 14.1 Islands and Sandbars

The land feature which is formed in a water body (lake, river, ocean) & surrounded with water on all its sides is considered as an island. Typically, an island is above the water level at all times. Above argument also suggests that even in high tide, an island will have at least part of its surface visible.

Moreover, islands are more likely to an outcrop with some form of geologic formation underneath. Therefore, island features are permanent and do not change very often. From geologic formation and foundation point of view, the island is significantly different from the bars.

A bar in a river is an elevated section of sediment that has been deposited by the flow. They can be categorised into mid-channel bars, point bars, and mouth bars. The depositional pattern and settings of bars are driven by the geometry of the river and the quantum of flow through it. Presence of bars and their characteristics reflect upon sediment supply conditions and the transport capacity of the river.

A mid-channel bar is also known as a braid bar because they are mostly noticed in braided river channels. These kinds of river systems are characterised by a steep slope, high sediment supply, more stream power, and bedload transport. The unpredictable channel patterns and varying sediment size of the braided system are responsible for the formation of mid-channel bars in the channel. Anastomosing river channels also produce mid-channel bars, but they are more likely to result in barrier island, which supports vegetation growth.

The other category of the sandbar is a point bar, it is formed due to deposition typically observed in meandering rivers at the inside curve of meandering bend. The amount of sediment in excess of transport capacity settle down and forms a point bar over the period. These bars are mostly seen in the slow-moving, and shallow parts of rivers and occupy the area farthest from the channel centerline on the outside curve of the river bend. Over an extended period, the combination of deposition along point bars, and erosion along cut banks results in the formation of an oxbow lake.

A mouth bar is an elevated region of sediment mostly seen at the deltaic region near the mouth of a river into the ocean. This is the most likely result of widening of river width near the mouth, which then translates in low flow velocities and finally results in sediment deposition at the mouth. As the sediment concentration increases across the river's mouth, it builds up to eventually create a sand bar that has the potential to extend the entire length of the river mouth and block the flow.

## 14.2 Remote Sensing observations of Sandbars and Islands

From the satellite image observations, it is challenging to distinguish sandbars from islands. Though the indirect interpretation about sandbars and islands can be made from remote sensing data, confirmation from laboratory tests are essential. An indirect way of interpretation includes changes in shape, size and centroid of the sandbar/ island. The other characteristics include vegetation and land-use patterns.

In general, sandbars are temporary and vanish during flood seasons. However, with changes in flow characteristics (velocity, magnitude) and floods, some sandbars settle at specific locations and remain for several years and start supporting vegetation growth. For example, sandbars seen around the Chilka lake, Orrisa, feature dense vegetation which has a similar spectral signature to the forest. From remote sensing observation, one may interpret it as an island, though, from the ground observation, it is evident that it is a sandbar.

Figure 14-1: Sandbar around the Chilka Lake (google earth image)

## 14.3 The terminology used in the present study

Considering the limitations of remote sensing observations in distinguishing sandbars from islands, the present study attempts to define sandbars/islands based on their geometric characteristics and the period of their existence in the limited context of the scale of the present study. Sandbars and islands in the present study are categorised into two categories, i) permanent sandbars and ii) temporary sandbars.

i) Permanent Sandbars: These are islands or sandbars features observed in satellite imageries of River Bagmati for more than 30 years. Moreover, geometric properties such as shape and centroid are constant. Though changes in the size of these are observed, they are attributed to different flow conditions. Based on these characteristics and extended period of existence, these are termed permanent sandbars.

ii) Temporary Sandbars: These are sandbars or islands that are visible in satellite imagery but are not inconsistent. The geometric properties of these features have changed over a period. Significant changes in centroid, shape and size of these features, shifting of these features over a period indicate the temporary nature. Thus, features are termed temporary sandbars.

There are no permanent sandbars present in the Bagmati system which can be extracted from the satellite imagery. Discussion on some of the Temporary sandbars analysed using remote sensing imageries is presented here. These features are listed here based on their location.

***Temporary sandbars in Bagmati River***

The sandbars of Grid 14 for 1975, 1990, 2000, 2010, and 2016 is shown in Figure 14-2. The total area of sandbars for the years 1990, 2000, 2010 and 2016 are 0.19 sq. km, 0.10 sq. km, 1.70 sq. km, and 0.4 sq. km. The sandbars of Grid 16 for 1975, 1990, 2000, 2010, and 2016 is shown in Figure 14-3. The total area of sandbars for the year 1975, 1990, 2000, 2010 and 2016 are 0.007 sq. km, 0.04 sq. km, 4.81 sq. km, 0.34 sq. km and 0.32 sq. km, respectively. The sandbars of Grid 44 for 1975, 1990, 2000, 2010, and 2016 is shown in Figure 14-4. The total area of sandbars for the year 1975, 2010 and 2016 are 0 0.005 sq. km, 0.02 sq. km and 10.66 sq. km, respectively.

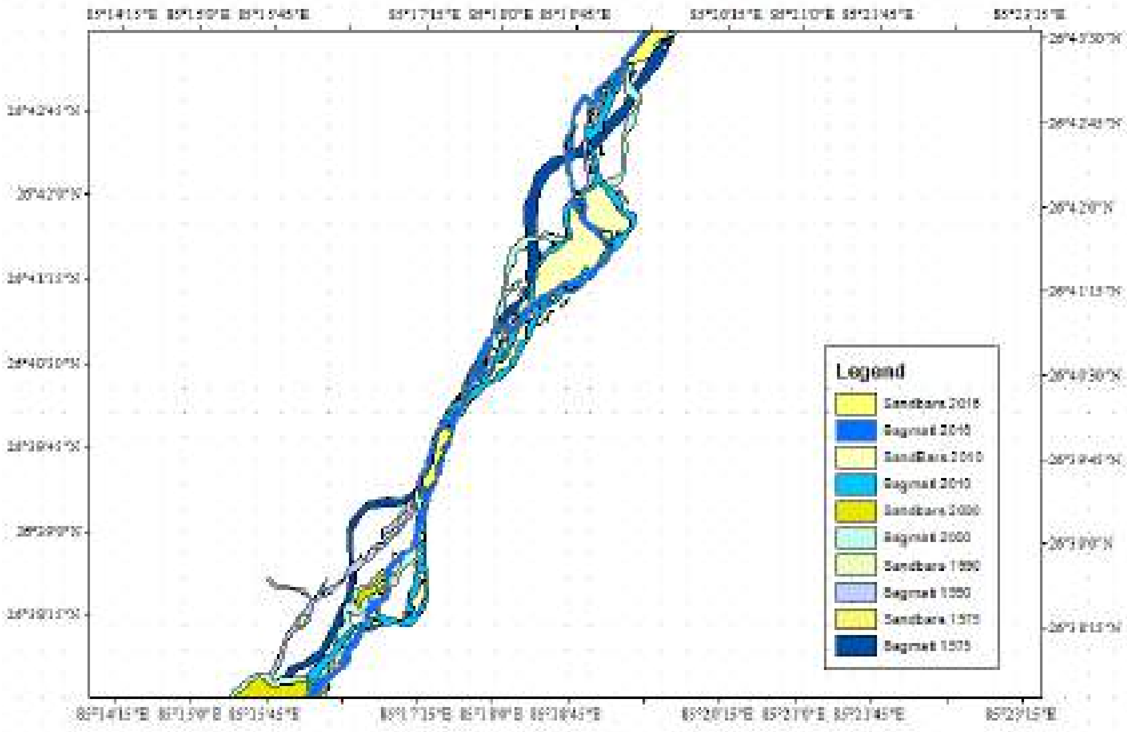



Figure 14-2: Sandbars in Grid 14

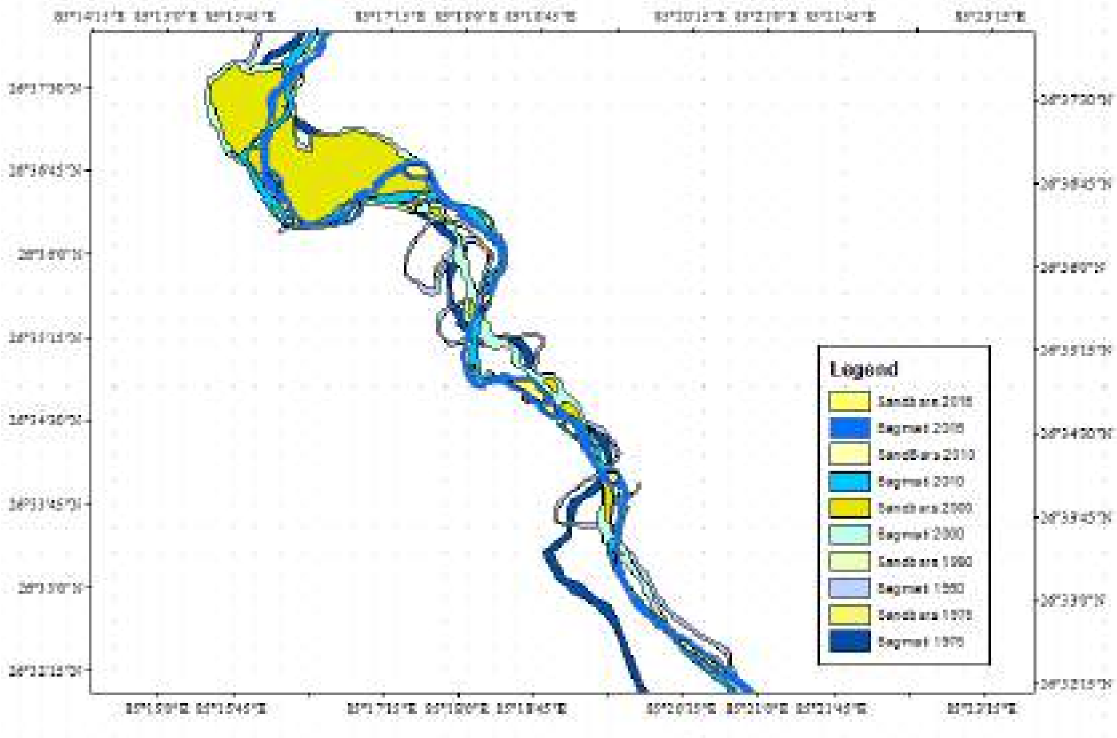



Figure 14-3: Sandbars in Grid 16

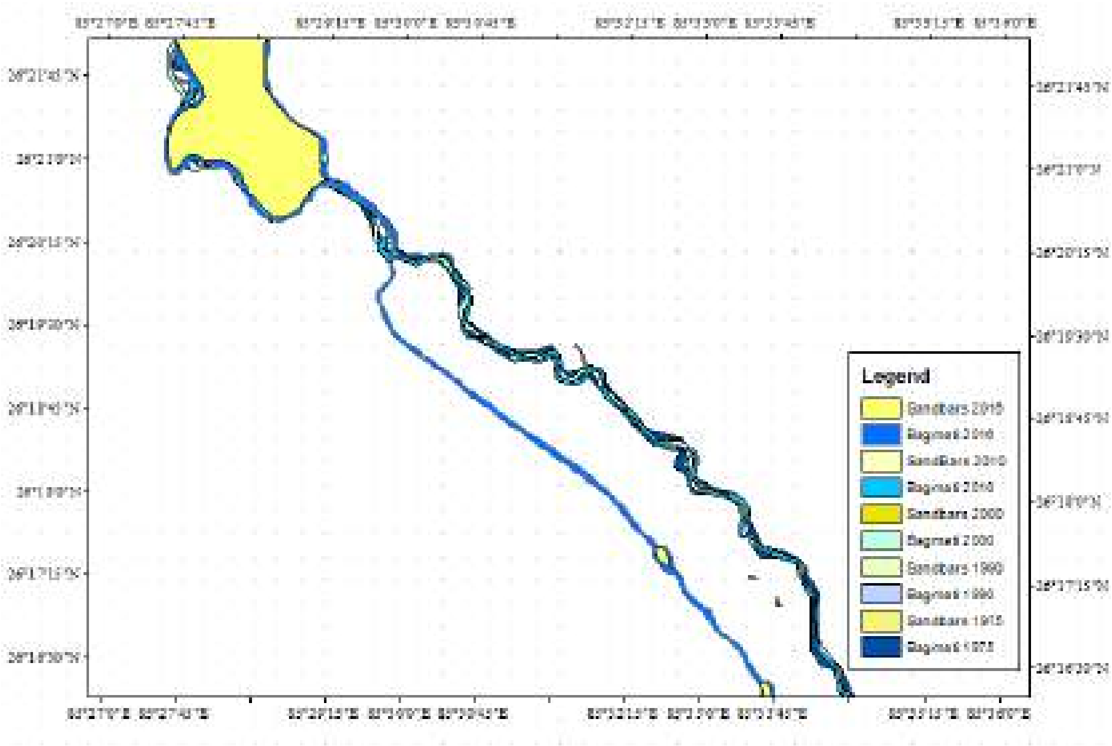



Figure 14-4: Sandbars in Grid 44

## 14.4 Conclusion

From the above analysis of sandbars/ islands, it can be concluded that:

i) Differentiation of sandbars and islands is not possible based on remote sensing observations, and laboratory-based analysis must identify an appropriate geologic foundation to establish conclusive evidence.

ii) In the limited context of morphological study using remote sensing technique, sandbars or islands used for agriculture activity and if farmers lawfully own the land, it may be considered a critical segment for some return period flood events, more specifically higher return period floods.

iii) The geometric properties and changes in the size of the sandbar/ island on a decadal scale have been used while computing the areal retreat of erosion and deposition.

iv) No permanent sandbars or islands are present in the Bagmati system, which can be extracted from the satellite imagery.

# Chapter 15 River Flood Affected Areas

## 15.1 General

Bagmati river has a very typical topographical characteristic which makes this system susceptible to flood. After crossing Himalayas, the slope of the Bagmati reduces significantly, and the river flows through flat topography till it meets Kosi. The main river course's bed slope is almost flat, 0.14m/km between Dheng railway bridge and Hayaghat, 0.4m/km between Hayaghat and Phuhia and 0.11m/km between Phuhia and Badlaghat (Refer chapter, Table 4-2). At such a low slope, water flow is sluggish. Even a tiny obstacle in a flow can push water upstream by a significant length in such circumstances.

Furthermore, it is one reason that the region remains waterlogged for days after the flood (Mishra 2010; Tiwale 2012). Also, the sediments deposited in the channel reduce Bagmati's cross-section and, therefore, water carrying capacity. In this situation, a sudden rise in water flow forces the water to cross its banks and flood the surrounding region.

## 15.2 Historic Flood events

The historical flood events of the Bagmati system are recorded with the help of FMIS and Mishra (2010) and presented here.

In 1975, the embankments' construction was almost completed, but some space was left to install During the flood of 1975, the Bagmati river's water level has risen approximately 1.90 m (above HFL) and 2.30 m (above HFL) at the Dheng and Hayaghat, respectively. This gap between the embankments has increased the intensity of the flow, which has submerged the 'safe zones. The Sitamarhi, Muzaffarpur, and Darbhanga districts were adversely affected by the flood. The combined loss, which includes crop and public property were seven crores 75 lacs were damaged.

In 1993, there were two flood events, the first one occurred on 21$^{st}$ July, and the other one is in the second week of August. During this event, the water level in the river has risen to 10 metres.

In the year 2001, north Bihar was badly affected by flood due to heavy rain in Nepal's rivers. Western Kosi embankment, Bhutahi Balan right embankment, Bagmati left embankment, and Burhi Gandak left embankment were partially damaged. Crop of rupees 26721.79 lacs and public property of rupees 18353.78 lacs were damaged.

The 2004 catchment area of the North Bihar rivers received heavy rainfall in the first week of July. Flood level at Dubbadhar site on river Bagmati surpassed all-time high flood level by about 1.18 m.

In 2007 the flood situation was serious in north Bihar due to heavy rainfall in almost all rivers flood situation in 2007 was very serious in north Bihar. There were 28 breaches at different locations of the embankments during the 2007 flood season. A heavy spell of rainfall (average 82.70mm) was observed at the beginning of the flood season. There has been regular rainfall in Burhi Gandak and Bagmati river basins in July and August, keeping the river water level rising. Almost north Bihar was badly affected, and heavy losses of crops and public property occurred.

In the year 2009, The first appreciable rainfall was recorded in late June-09 and early July-09. There were few isolated storms at few stations of some basin in September and October. Flood situation remained normal this year except few breaches such as Tilak Tajpur on the right embankment of river Bagmati under Runnisaidpur block of Sitamarhi district, Gobindpur site Labha Choukia Paharpur embankment of Mahananda river and Sallehpur Tandespur site of Gandak river. The loss to life and property brought to a minimum by undertaking rescue and relief measures.

## 15.3 Flood Maps

Bagmati river path across the districts is shown in Figure 15-1.

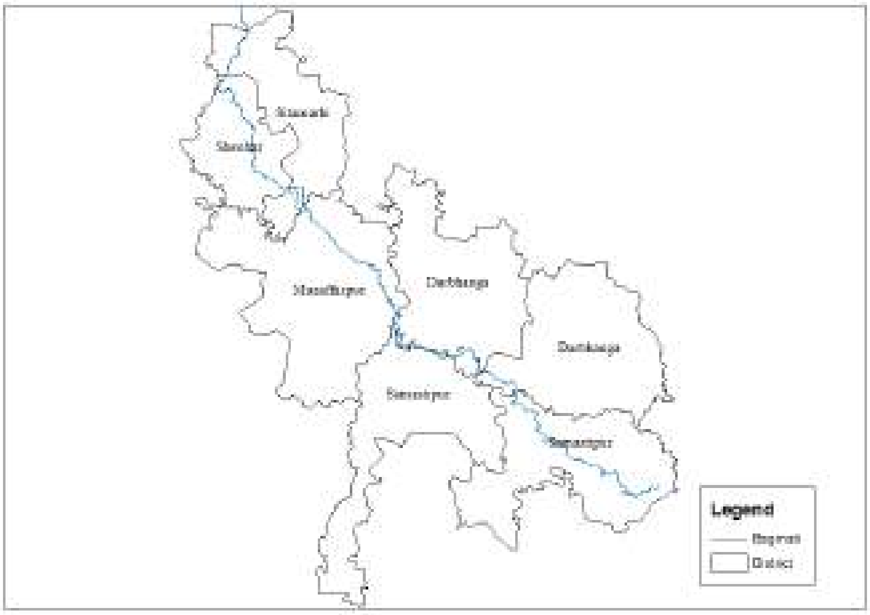



Figure 15-1: Bagmati river path across the districts

The district-wise flood inundation map and flood hazard map are shown below in Figures 15-2 & 15-6. The map is collected from the Bihar State Disaster Management Authority's online portal (http://bsdma.org/Atlas.aspx).

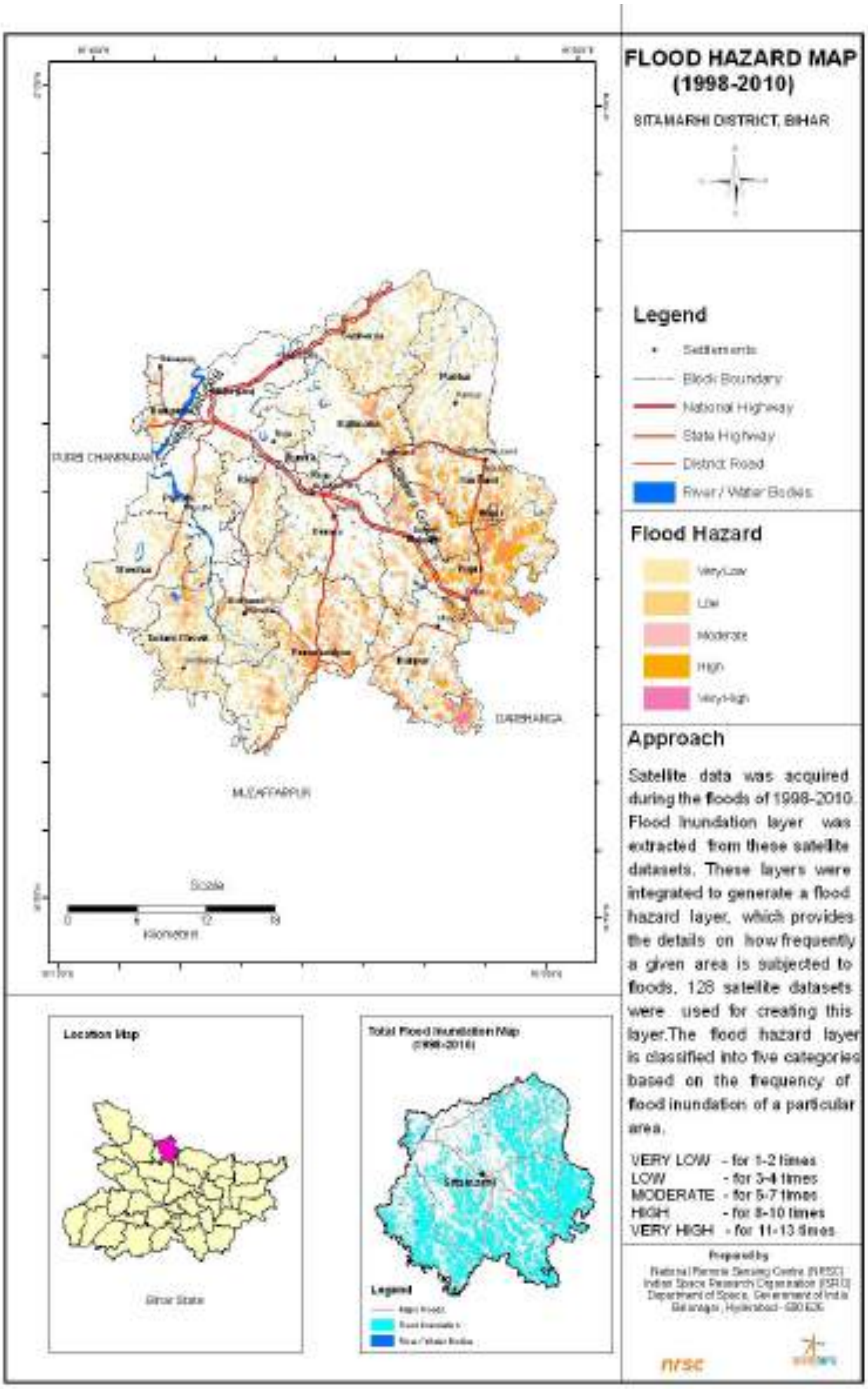



Figure 15-2: Bagmati river path across the Sitamarhi district

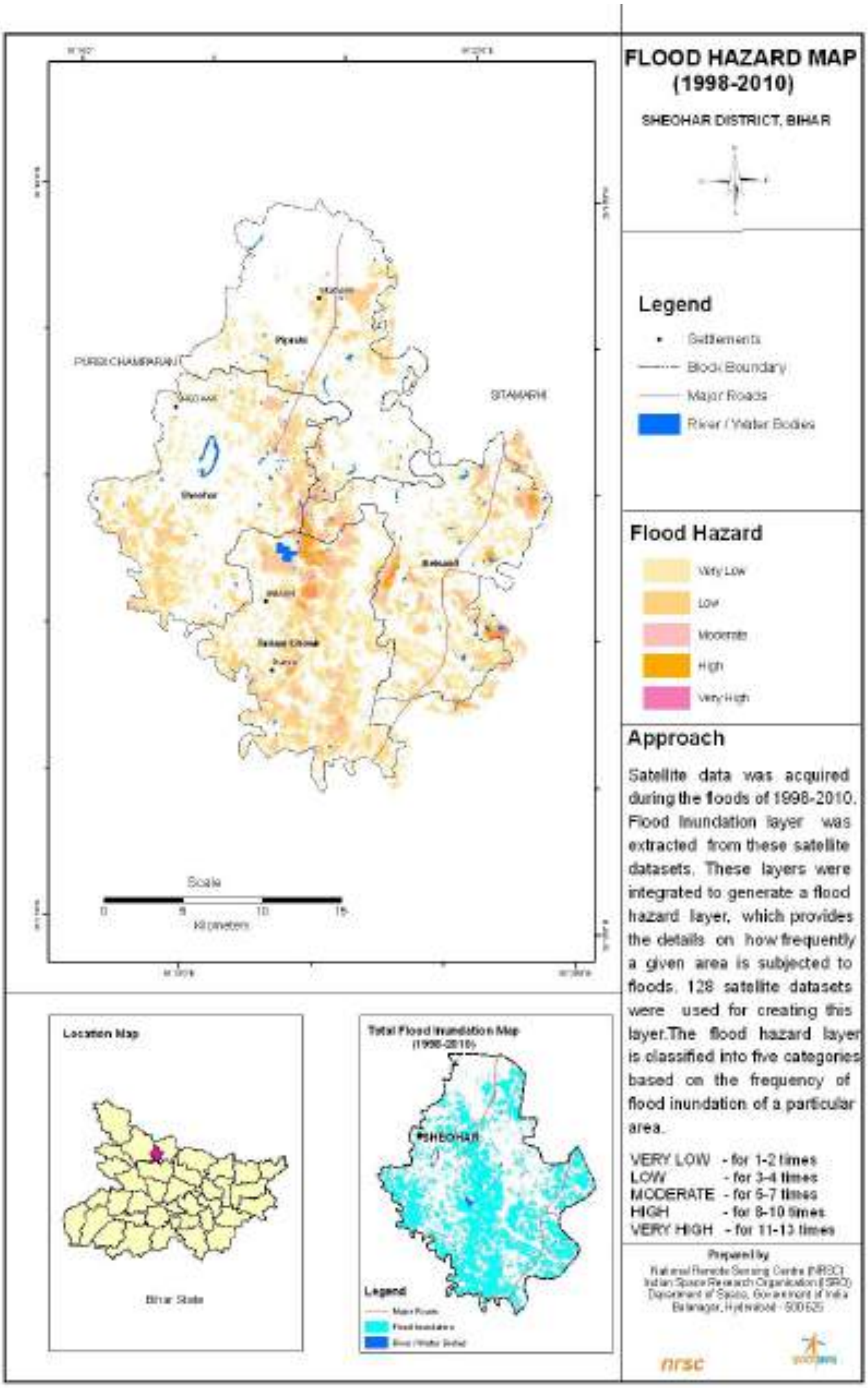



Figure 15-3: Bagmati river path across the Sheohar district

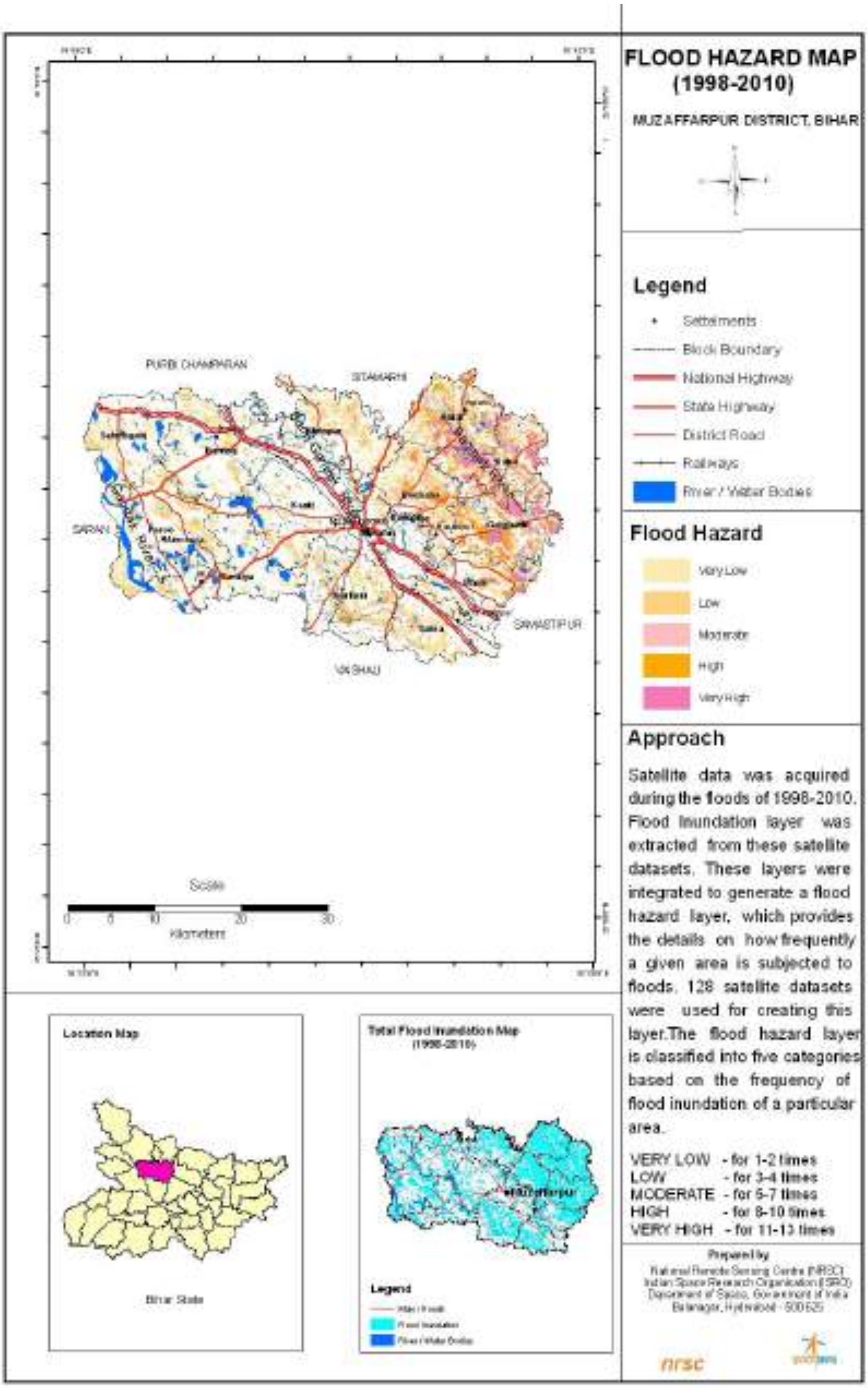



Figure 15-4: Bagmati river path across the Muzaffarpur district

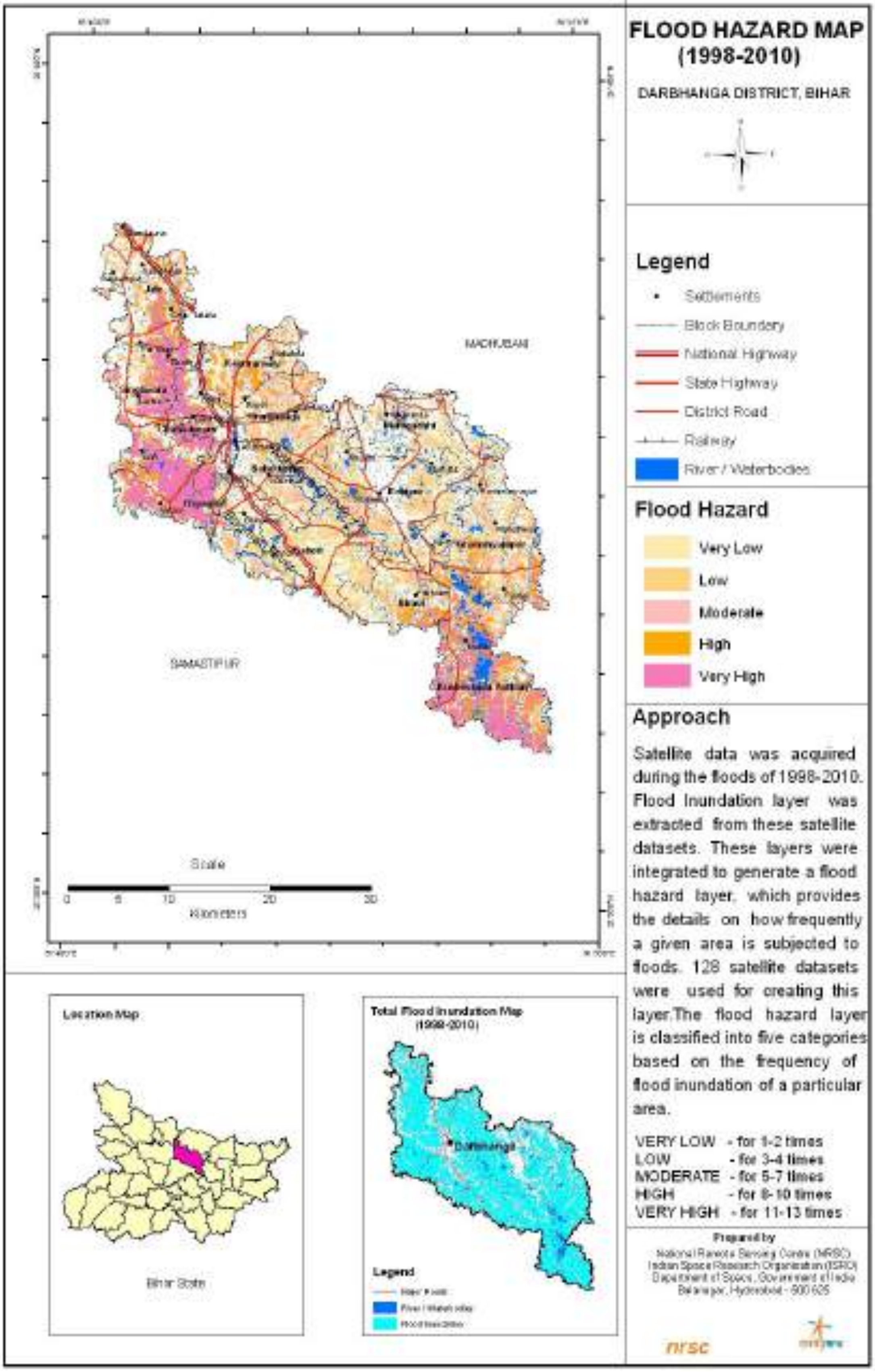



Figure 15-5: Bagmati river path across the Darbhanga district

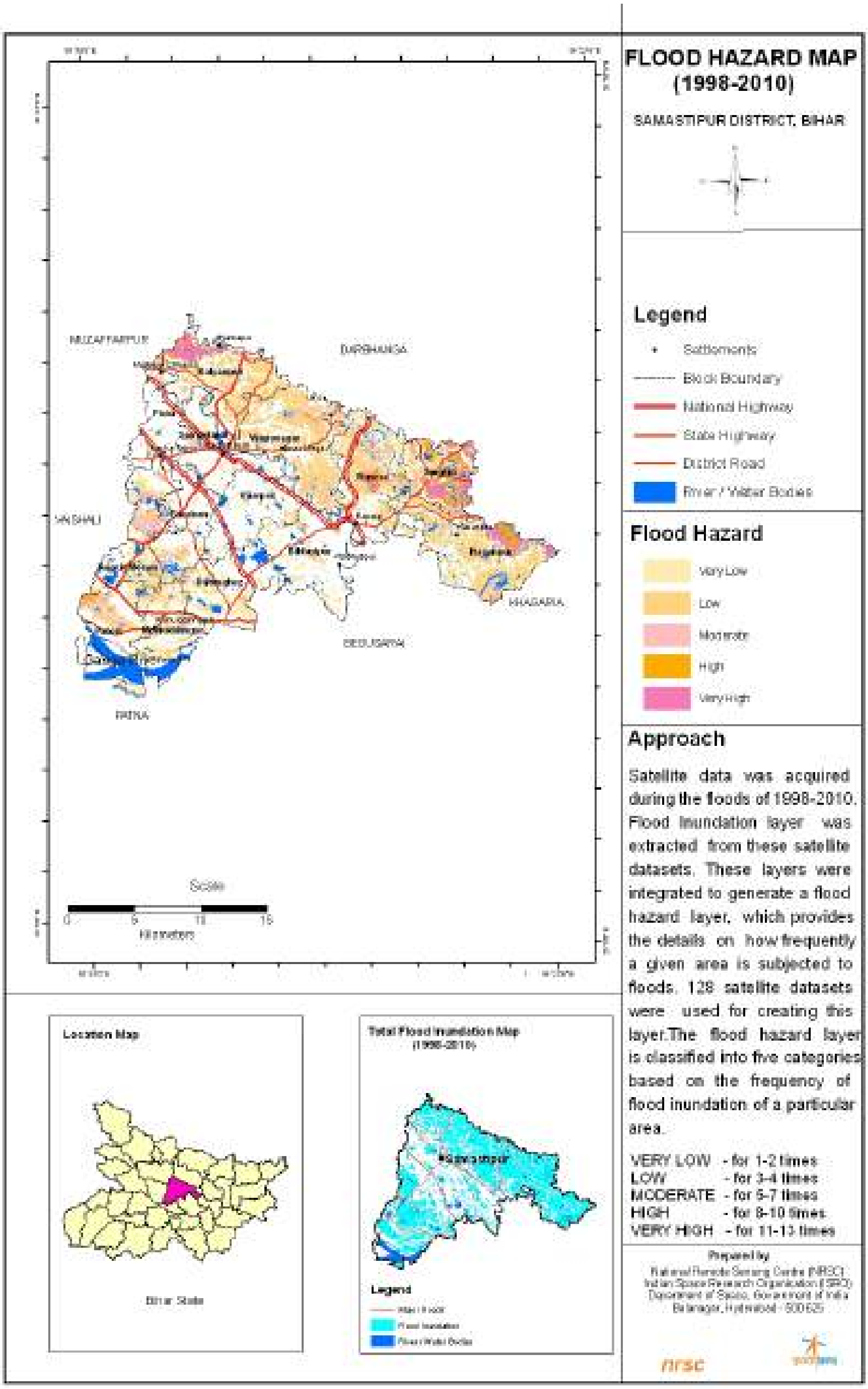



Figure 15-6: Bagmati river path across the Samastipur district

## 15.4 Morphological Changes

Bagmati flows through typical topography during its course between Dheng to Hayaghat. Its flow should increase because of additional water drained by its tributaries and increased catchment area. Nevertheless, Bagmati shows a reverse trend during the flood period. Flood events usually result in alternation between the two processes of erosion and deposition, and deposition in the channel reduces the cross-section depth. In the 1975 flood, river flow was less in Hayaghat than in Dheng, when Hayaghat is 196 km downstream to Dheng (Mishra 2010). The plausible reason to describe such reduction is that the majority of water that was supposed to flow through Hayaghat was spread in the surrounding region, which has topography like a plate. Unless and until the plate overflows, water cannot move ahead. In this region flood water of Bagmati intrudes in its tributaries and cause flood situation in their catchments.

Flood events also trigger the morphological evolution of cross-sections. Because of this, cross-sections at selected locations are analyzed to understand aggregation and degradation patterns. Detailed analysis of such sections and linking those results with satellite image observations is presented in Chapter 12. Therefore, in the present study, the information obtained from secondary sources about inundated areas in the past is used while discussing stable/ critical reaches in Chapter 16.

# Chapter 16 Identification of Critical Reaches

## 16.1 General

Erosion and deposition often occur and result in the changes in channel morphology. This change in channel morphology then leads to change in inundation patterns in adjacent floodplains. Flood occurrence also modifies the landforms each year, and this leads to instability at the riverbank. The cyclic process ultimately results in the collapse of riverbank along with the river network and loss of the land in the vicinity. However, the movement of the river in its corridor is a natural process and an essential aspect of river landscape evolution. Therefore, to term or to define a river reach as stable/ unstable/ critical/ evolving is the topic for discussion and needs detailed discussion on various aspects which have a significant bearing on such identification/labelling. These aspects may broadly range from scale issues, modelling exercises, understanding and recreating historical events, perspective to priorities of the individuals and the organizations. Following on the above discussion, the approach adopted in the present study to define stable/critical reaches is presented as follows.

## 16.2 Scale Issues

Morphological processes occur at wide range of scales. For example, channel geometry and fluvial dynamics are not just determined by local geomorphological settings rather they are the results of influxes from the upstream watershed. Over a period, (different temporal scales ranging from seconds to million years: geologic time scales), combined effects of discharge and sediment transport within the local environment (e.g., geology, topography, microclimatic conditions) results in the formation of certain channel patterns. However, the typical sequence of morphological settings along a river's course from constrained upstream gorges to braided and meandering rivers to, finally, anastomosing lowland rivers is not observed in most of the river systems. Tectonic activities may foster channel patterns that would normally not be expected at a respective site in a given period of time. Changes in upstream sediment carrying capacities and altered hydrological regimes due to anthropogenic activities also trigger local channel alterations. Even downstream hydro-morphological changes may result in upstream channel geometry fluctuations due to retrograde soil erosion. Therefore, morphological behavioural characteristics observed at selected river reach do not only affect the physical configuration and dynamic fluvial processes at the respective river reach but rather influence much longer river sections or even the whole river system, including the tributaries. Lane and

Richards, (1997) discussed that the traditional view regarding interlinking of scales (that different scales of form and process are causally independent of each other) cannot be sustained, as short timescale and small space-scale processes influence processes over longer timescales and larger space-scales. Considering the importance of scale issue, the terms associated with scale issues, i.e. process scale, observation scale and modelling scales, scaling and linkages across scales in modelling framework are defined below. More details about these terms are available in Bloschl and Sivapalan (1995).

1. Process Scale:

   The process scale is the scale that natural phenomena exhibit and is beyond our control. They are further classified into 'characteristic time scales' and 'characteristic space scales'. As the morphological changes in the river are highly driven/influenced by hydrologic changes, characteristics time and space scales of hydrological processes also affect channel morphology. Characteristic time scales of a hydrological process can be defined as (a) duration of the event (for intermittent processes such as a flood, drought, rainfall event); (b) the cycle: recurrent phenomenon (for a periodic process such as snowmelt, monsoon rainfall); and (c) the correlation length (for a stochastic process exhibiting some sort of correlation). Similarly, characteristic space scales can be defined either as spatial extent, period or integral scale, depending on the nature of the process.

2. Observation Scale:

   The definition of the observation scale is related to the necessity of a finite number of samples. Consequently, observation scale in space and time can be defined as: (a) the spatial/ temporal extent; (b) resolution; or (c) the integration volume/ time of a sample. Ideally, processes should be observed at the scale they occur. However, this is not always feasible. Often the interest lies in large-scale processes while only (small-scale) point samples are available. Also, hydrological and morphological processes are often simultaneously operative at a range of scales.

3. Modelling Scale:

   In space, typical modelling scales (Dooge, 1982; 1986) are: the local scale (1 m); the hillslope (reach) scale (100 m); the catchment scale (10 km); and the regional scale (1000 km). In time, typical modelling scales are the event scale (1 day); the seasonal scale (1 yr); and the long-term scale (100yrs). Unfortunately, often, the modelling scale is much larger or much smaller than the observation scale. To bridge that gap, 'scaling' is needed.

4. Scaling and linkages across scales in modelling:

   Upscaling refers to transferring information from a given scale to a smaller scale, whereas downscaling refers to transferring information to a larger scale (Gupta et al., 1986a). For example, measuring evapotranspiration in a Lysimeter and assuming it applies to the surrounding area involves upscaling. Also, flood frequency analysis for higher return period based on limited data involves upscaling. Conversely, using runoff coefficients derived from a large catchment for culvert design on a small catchment involves downscaling (Mein, 1993). Regionalization, on the other hand, involves the transfer of information from one catchment (location) to another (Kleeberg, 1992).

To bring in the component of scale is essential in the context of morphology study as the autocyclic and allocyclic processes which are core to channel evolution occur at different scales. The terms autocyclic and allocyclic processes are discussed below.

1. Autocyclic Processes

   According to Beerbower (1964), autocycles are produced by processes within sedimentary systems. Autocyclic processes tend to be instantaneous geologic events that are random in both time and space, and they contain few interregional feedback mechanisms. As a result, autocyclic processes are aperiodic. Autocyclic processes include phenomena such as stream avulsion and meandering, and fluvial point-bar migration or lateral migration of beach-barrier bars. Responses to autocyclic processes tend to be local and may range from millimetre-scale ripple migration to regional-scale events such as delta switching.

2. Allocyclic Processes

   Allocycles result from processes external to sedimentary systems and include tectonic activity, climatic change, and eustasy. Importantly, allocyclic changes commonly induce changes in autocyclic processes. For example, an allocyclic rise or fall in sea level may cause changes in the nature and degree of delta switching. Sedimentary responses to allocyclic processes may occur on geographic scales that range from basin to global. For example, tectonic subsidence or uplift may affect only a single basin, but plate collision and/or rates of sea-floor spreading may have global implications.

Both autocyclic and allocyclic processes are responsible for changes in channel morphology, and they occur at different spatial and temporal scales. Moreover, one process also influences the characteristics of other processes. So, there is a significant overlapping of scales. For example, changes in channel morphology can be driven by changes in land use whereas evolution in channel morphology may lead to a change in land use type. Example of two systems, River Yamuna and River Kosi may be considered to elaborate little further. In case of River Yamuna, catchment land-use change might have triggered changes in channel morphology whereas, in case of Kosi, changes in channel morphology, the evolution of river system might have caused the change in land use type. In view of the above, to define a river reach either stable or critical without giving due attention to autocyclic and allocyclic processes may not be appropriate. In the case of River Yamuna, considering the geologic stability of the system, one may tend to consider the sole effect of autocyclic processes in defining the stability of the reach.

## 16.3 Scale effects on the drainage pattern of the Bagmati River

Scale effects usually refer to the changes in the result of a study due to a change in the study's scale. Figure 16-1 explains the effect of spatial resolution in the extraction of drainage patterns. The drainage pattern extracted from both DEMs does not share the same geometric properties. For example, few places (Figure 16-1), drainage bifurcates in 12.5 m DEM while in 30 m DEM, it shows single drainage. Hence, working on a different scale can lead to an entirely different conclusion. However, at broader scales, physical processes may dominate or dissipate these effects. For example, the relationship between climate and vegetation evident at broad scales (Time and Space) may disappear at finer scales, overridden by the effects of competition and other natural processes (Turner et al. 1989).

Characteristic scales and scale effects are inherently related to the issue of scaling. While characteristic scales provide a conceptual basis and practical guidelines for scaling, quantitative descriptions of scale effects can directly lead to scaling relations (Wu 1999). As one changes scale, systems may change between "closed" and "open". Natural processes do not exist in isolation; they are typically "open" concerning the movement of energy, materials, and organisms into and out of the system. However, systems can become "closed" when transfer rates among adjacent systems approach zero or when the differences in process rates between adjacent elements are so significant that the dynamics of the elements are effectively decoupled from one another. In closed systems, context does not matter as much. Importantly, as one changes the scale, the system may switch between "closed" and "open". For example, change detection within a specific class is an open system at a cartographic scale as land use land cover is a dynamic process. However, the LULC may be relatively closed to change, wherein the class can be treated as an autonomous (closed) unit. Different patterns emerge at different scales of investigation of virtually any aspect of any morphological system (Blöschl & Sivapalan 1995).

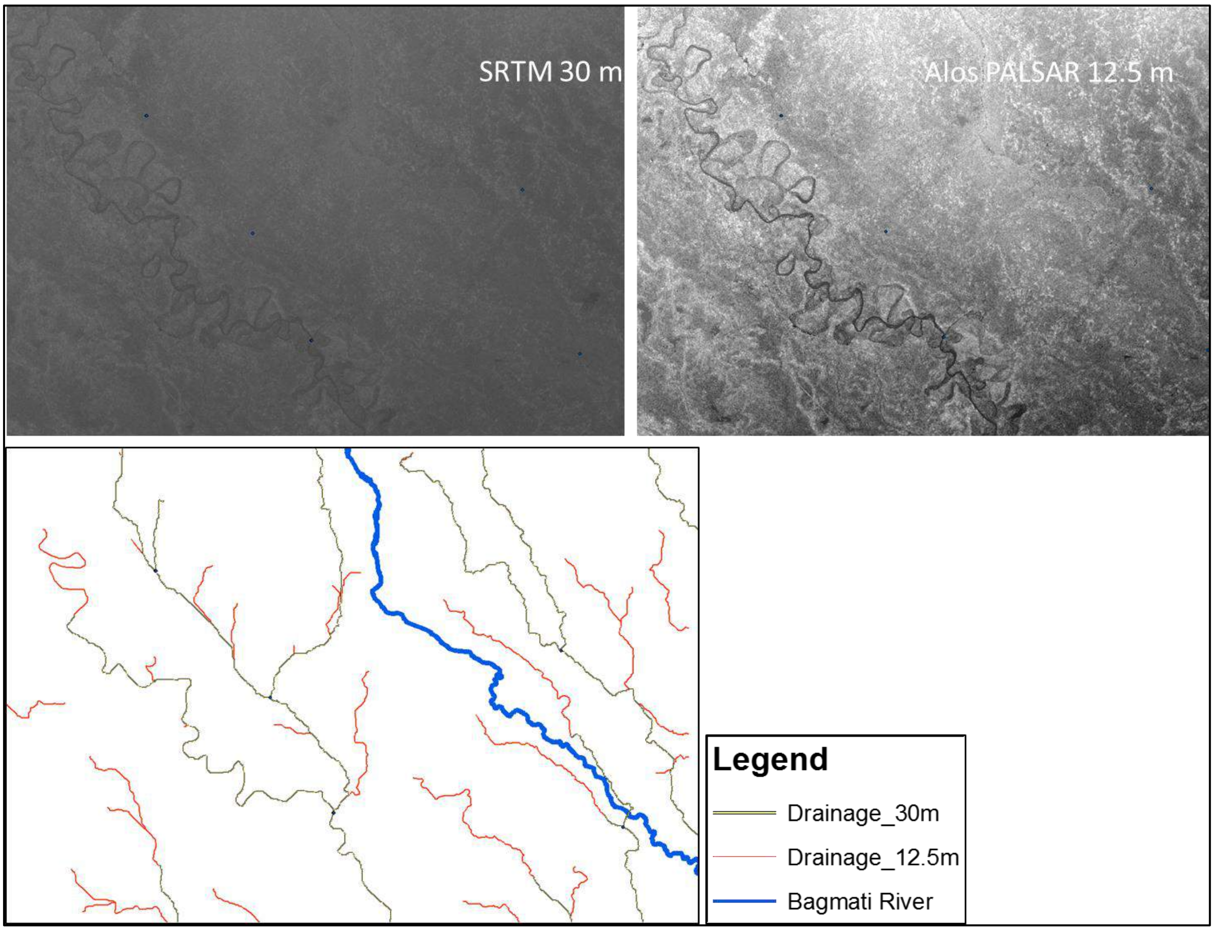



Figure 16-1: Effect of grain size on drainage pattern of Bagmati River Stretch

### 16.3.1 Fractal Dimension of Bagmati Drainage Pattern

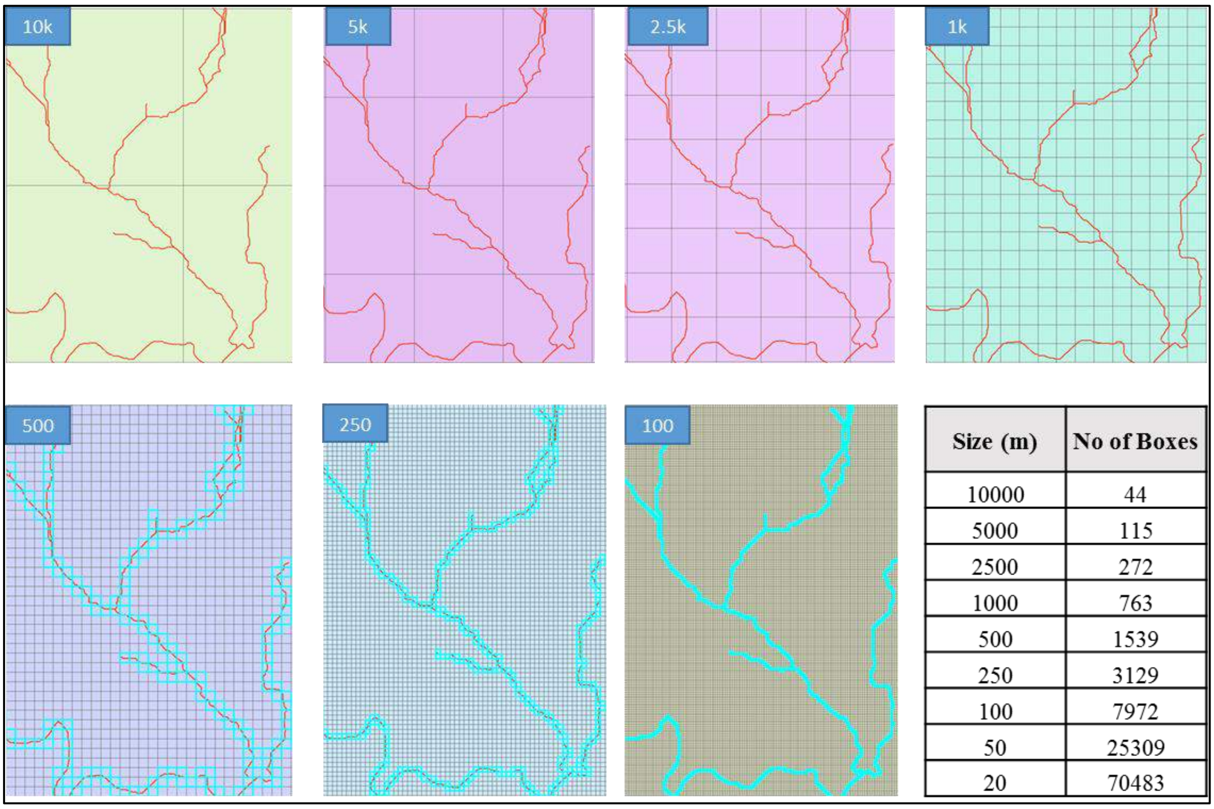
Mandelbrot coins the term "Fractal" in 1967. It can be defined as:

1. A geometric object or shape which exhibits self-similarity across the scales.
2. Dimension of an object is not necessarily an integer value.

Self-similarity is a phenomenon that occurs when the structure of a sub-system resembles the structure of the system as a whole, and then the structure of a sub-system within that sub-system resembles the structure of the larger sub-system. Without an object with a characteristic dimension, such as a tree or house, the event's size cannot be determined. Self-similarity is the defining property of fractals.

*Box Counting Method*

A fractal dimension measures complexity expressed as a scaling rule comparing the number of new parts and scale. The box-counting dimension is a type of fractal dimension. The box-counting fractal dimension is measured from the ratio of increasing detail with increasing scale (ε). The ratio quantifies the increase in detail with increasing magnification or resolution seen in fractals but also microscopy. In essence, several grids of decreasing calibre (box size) are placed over an image, and the number of boxes that contain pixels is counted for each grid (boxes containing pixels correspond to the number of parts or detail), shown in Figure 16-2. Data are gathered for each grid box (grid size is specified by the user or calculated automatically). The DB is based on the calculation of a scaling rule or fractal dimension using. DB= -lim[logNε/logε] This is read as "the negative limit of the ratio of the log of the number of boxes at a certain scale over the log of that scale". The DB is the slope of the regression line for the log-log plot of box size (or scale) and count, which is 1.16 (Figure 16-3).




| Size (m) | No of Boxes |
|---|---|
| 10000 | 44 |
| 5000 | 115 |
| 2500 | 272 |
| 1000 | 763 |
| 500 | 1539 |
| 250 | 3129 |
| 100 | 7972 |
| 50 | 25309 |
| 20 | 70483 |

Figure 16-2: Box Counting method (Bagmati River Stretch)

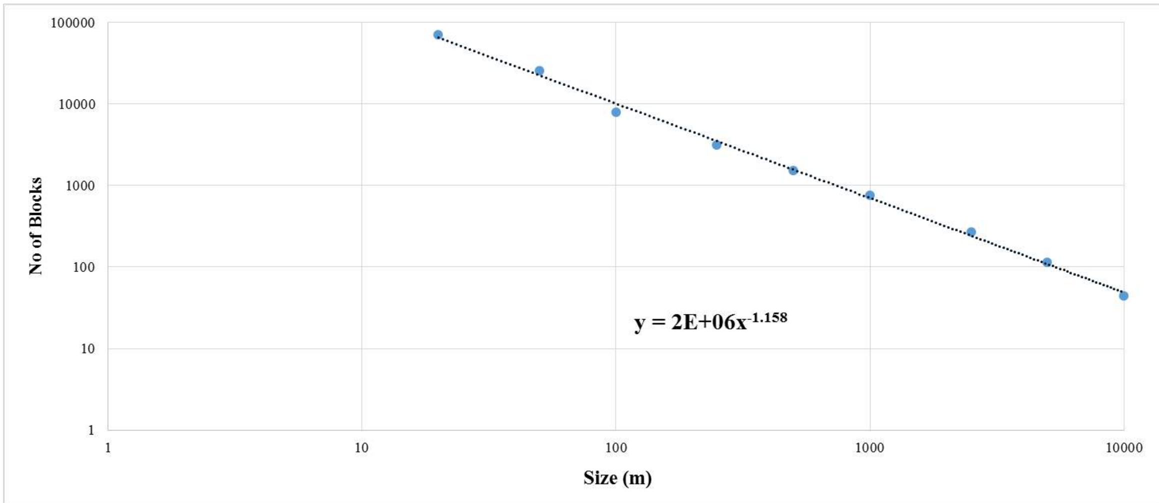



Figure 16-3: Fractal Dimension calculation (Bagmati River Stretch)

The following conclusion can be drawn from the analysis: 1. The estimated properties of any feature are scale specific. Hence if the scale of the analysis changes, the outcome will also change 2. The drainage pattern of the basin is fractal with 1.15 dimensions. Fractal dimension is a measure of how "complicated" a self-similar figure is.

## 16.4 Perspective

To identify or to define a stretch either critical or stable has a lot to do with the perspective. Role of observer and object at multiple scales is important. Consider an example of an ant on a paper. For an ant if her position on the paper remains constant and if outside environment is not significantly different, there will not be an issue regarding criticality or stability even if the paper has moved from one place to another with above conditions. However, if an ant moves from one location to another on the given paper by a narrow distance which is beyond the observation scale of the observer, for him there may not be any change but for an ant, it may result in an unpleasant situation. So, the perspective, in this case, matters a lot as both ant and observer see the same things differently. For one it is stable whereas for the other it is critical. There are different viewpoints about defining the river reach as either stable or critical. Some of these are presented below.

### 16.4.1 Hydrologist

For a hydrologist, various aspects such as water audit, basin planning, design value for different hydraulic structures and other allied studies, require a thorough understanding of flow regime. Pattern, changes and variations in flow regimes often result in modification of overall basin hydrology. Hydrologist may find a river reach critical if there is a significant change in flow regime or the pattern of changes, within or across defined time periods.

### 16.3.2 Ecologist

Ecological, hydrological and biogeochemical functions of river ecosystems provide a set of well-known ecosystem services. When ecosystems are maintained in a healthy state, their ability to provide these services is more significant, whereas deterioration of ecosystems may reduce the viability of the provided services. Intact river ecosystems are more effective at processing nutrients, breaking down waste, filtering water and providing habitat, food and shelter for the biota. The concept of environmental flow is based on this phenomenon. It has been discussed/ defined in several ways by outlining the required characteristics of flows regime by hydrological, hydraulic, eco-hydraulic and holistic means either alone or in combination. For an ecologist, a stretch of a river may be critical if water quantity and/ or quality is not up to the desired level for the species that are indigenous to that system. The other way of saying it is, if the environmental flow is not fulfilled the reach may be called critical.

### 16.3.3 Water User

For different water users like farmers, industries of different scales, hydropower generators and fishing community etc., definition of stability/criticality of a river reach may vary from that of above.

- For farmers cultivating in and around the floodplain- the quantity of water (water levels in a river during various seasons) and the quality of water is important. While sometimes lack of surface water from the river may be a manageable issue (groundwater resources may be used in such case), increase in water levels leading to inundation of crops is a difficult situation for them. Poor water quality may harm the quality of farm produce. River streams leading to such risks may be described as critical for farmers.
- For industries and hydropower generators, non-availability of standard water quality and quantity may lead to critical situations resulting in operational losses.
- For a fishing community which directly depends on certain river reaches, water quantity and quality are both important. For them river reaches prone to incidences/impacts such as extreme events, manmade changes (dried river reach on account of diversion/ abstraction), etc., can be critical. For them, the river reaches that

have minimal effects due to anthropogenic activities etc., will be most stable - if they depend on indigenous aquatic species which thrive under such conditions.

### 16.3.4 Administrator/ Decision maker

Administrators and decision-makers ranging from the local body (panchayat) to district, state and federal government authorities are responsible for managing the water resources at the respective levels. Several issues such as management in case of extreme events, demand and supply analysis, prioritization of demands, trade-off among the different users and interstate dispute issues may trigger in demarcating river reach accordingly. For example, based on flood plain zoning, some of the areas are considered as prohibitive and restrictive zones. Existing settlements in such zones based on their vulnerability to flood events make that river reach critical.

## 16.5 Present study and approach

As discussed above, defining a reach as either critical or stable is an open-ended question. Based on the scale, perspective and interaction of variables driving the overall system one may choose one stretch as critical while others may term the same as stable. In the limited context of the morphological study of Bagmati River system, the results from remote sensing image analysis can be used in combination to term the reach as either stable or critical. So, changes occurred over a period (between the years 1975 and 2016) have been used to understand the dynamics of the river course, the channel bank retreat on account of erosion and deposition and rate of meander migration. Our understanding of natural systems suggests that the river system in the unregulated flow scenario should be considered as a reference to discover changes occurred in the system over a temporal domain. In the present study, the system observed in the year 1975 is considered as a reference condition. Various features as explained in Chapter 6 (Section 6.1) are marked on 1975 image and used as a reference. Distance between bank lines (endpoints of channel area as observed in non-monsoon season) is used to obtain the location of centerline and channel width. From the remote sensing analysis rate of channel bank retreat and river course dynamics in the form of movement of channel centreline have been determined. The proposed basis for identification of the critical reaches are as follows,

### 16.5.1 Pendulum analogy and the grid template

In the case of a simple pendulum, three types of states are possible, i) at rest ii) undamped oscillations and iii) damped oscillations (Figure 16-4). A similar analogy can be drawn to a river system. Let us consider the river centerlines for different years obtained from remote sensing images. The movement of centrelines for different years also reflect the similar pattern of swing and shown in Figure 16-5 and the extent of swing can be considered swing zone of the river channel which is bound by river corridor. The annexed memorandum (Parmar and Khosa, 2017) may be referred to for a comprehensive discussion on the concept.

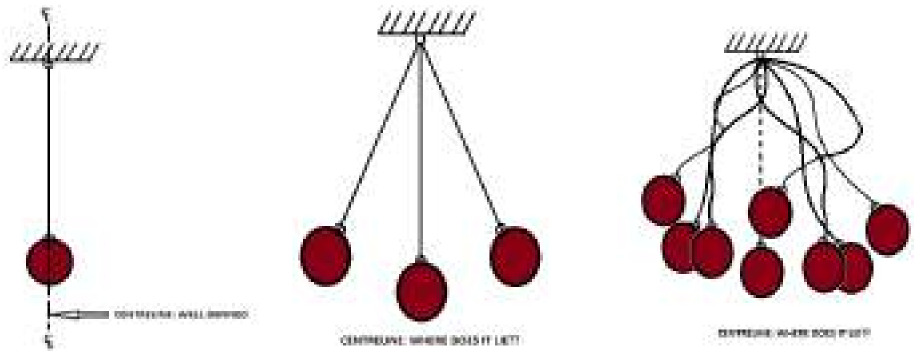


Figure 16-4: Movement of Simple Pendulum

*River Corridor*

In general, for majority of major river systems across the globe, geological foundations such as fault lines provide a dedicated corridor for drainage paths to develop and which over time, acquire the configuration of river channels and the processes such as erosion and deposition occurring over a range of spatiotemporal scales results in evolution of channel geometry. Significantly, the aforementioned dedicated river corridor demarcates the swing width within which the riverflow can rightfully assume any pathway depending upon the topology of the available potential energy field and its lateral connectivity and exchange with subsurface flow pathways – a reality that has hitherto been disregarded or, at best, given a casual treatment in theoretical abstraction. The annexed memorandum (Parmar and Khosa, 2017) may be referred to for a comprehensive discussion on the concept.

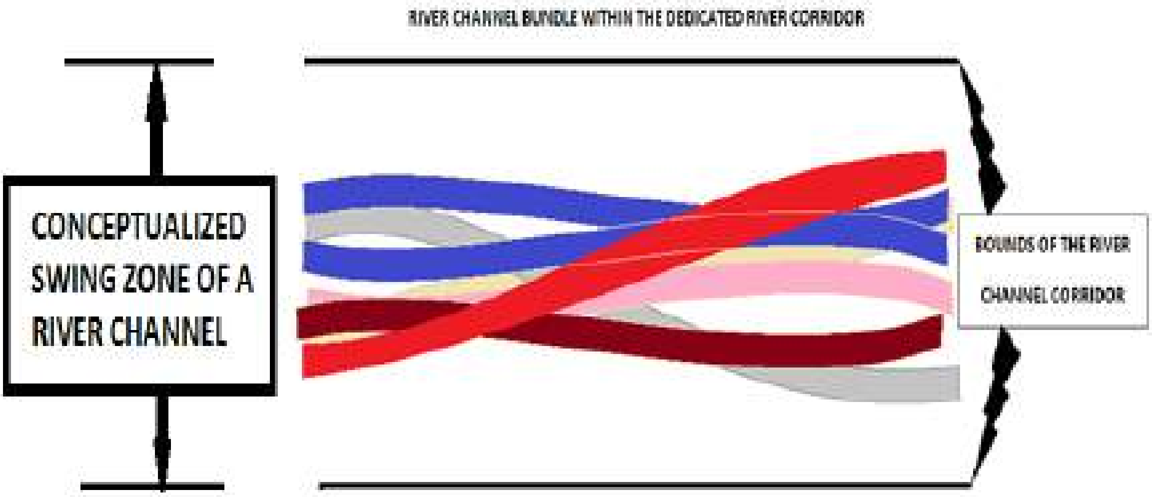



Figure 16-5: Swing Zone of River Channel and River Corridor

However, to demarcate the boundaries of the river corridor may not be unidirectional. In case of upstream reaches of river which are generally bound by mountains, the river is restricted by adjacent valley and thus have well-defined swing zone for mean flow passing through that channel but when the river enters the plains, river moves to adjacent floodplain quite often and thus defining the corridor boundaries in such case becomes difficult. Though some attempts to define the river corridor in the form of meander belt and floodplain zones are made in the past it remains an open question. Several issues such as selection of return period for defining floodplain, spatial and temporal scale of study to define meander belt, nature of change (systematic or random and reversible or irreversible), unique characteristics of each river systems, both allocyclic and autocyclic drivers and most importantly interlinking and overlapping of scales in parameters which drives channel morphology influence the criteria of selection process and often ends with expert or administrative judgement which may lack scientific credence.

For example, river system such as Kosi which shifted its course for more than 133 km from east to west during the last 200 years, it is impossible to define the boundaries of the river corridor. These are most likely influenced by change/ pattern in the geologic foundation, movement of tectonic plates, the overall change in physiography or combination of these factors. Though attempts to construct embankments and river training works are made in the past to restrict river course and reduce the impact of flooding, these attempts could not solve the issue at large. Therefore, understanding of the system behaviour becomes critically important prior to decision making.

In comparison with Kosi, River Bagmati has not changed much in the last century even though changes of smaller magnitude have occurred in a few stretches of River Bagmati. From a broad perspective, it can be said that River Bagmati has maintained its course from 1975 to 2015 (scale of this study) and swing is limited to its swing zone. For detailed analysis, grid template as shown in Figure 17-6 is used.

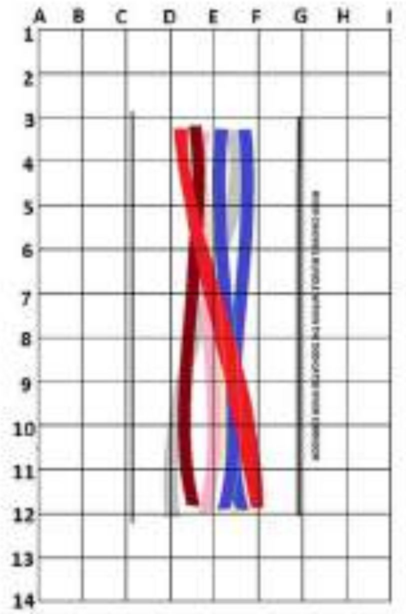



Figure 16-6: Grid Template for Swing analysis

A grid size of 25 km is chosen, and channel centerlines are captured on a decadal scale. Based on the analysis, if channel centerline has moved from one grid to another grid and/ or if angle θ between centerlines of two different time periods is more than 180º which represents unstable/equilibrium stage of a pendulum, these are analyzed further. Such river reaches can be considered as unstable/ critical.

The outcome from this analysis indicate that none of the rivers reaches has moved from one grid to another grid and angle between centrelines is well within the equilibrium limits. Therefore, none of the reaches is considered as unstable/ critical based on the above criteria.

However, it is difficult to isolate the reason for the same. Though the physiography of basin seems to be the fundamental reason, the role of altered flow regime should not be neglected. Both natural and anthropogenic activities have a significant bearing on channel morphology. Topography, well-defined valley, the geology of the basin did not change much and thus helped in maintaining the channel morphology. On the other side, anthropogenic activities such as encroachment, channelization of river courses, river training works and altered flow regime (reduction in flood events, and low flows on account of diversion) mostly result in stabilization of river courses. In the view of the above discussion, the entire course of River Bagmati can be considered as stable.

### 16.5.2 Swing of channel centerline from the reference and its comparison with the channel width

If the swing of the channel centerline between various years is more than the width of the channel in that stretch, it is analyzed further to understand the dynamics of river functioning. If the swing is limited to channel width, it is considered as natural phenomena of river hydraulics and it may not be attributed as a critical reach.

This concept is also analogous to pendulum analogy with the swing zone limited to twice of the channel width. If the centerline fluctuation between two years is less than the width equivalent to twice of channel width, then section can be considered as stable. However, the inverse of the above may not be always true. For example, section with centerline movement of 2km and channel width of 600m may be considered as unstable based on above criteria, however, if section is meandering and oxbow formation, neck cutoff in the section may be the primary cause for centreline fluctuation and thus reflect the characteristic behaviour of particular river reach and may be considered as stable. Also, the scale at which these analyses are performed plays important role in defining a reach as either stable or unstable. If reach is studied at 1 km interval, there might be several stretches which will come under unstable criteria but if the same reach is studied at 10 km interval, it may fall under the category of stable reach.

### 16.5.3. Rate of channel bank retreat and changes in channel width

In case rate of channel bank retreat is high without any significant swing of channel centerline, it indicates uniform expansion/ contraction of the channel area. This might be on account of encroachment, building of flood control walls, spurs etc. This type of reaches may become critical as reach with loss of channel capacity results in restricted channel pathway which might be insufficient to dissipate the energy associated with flood event.

Unstable/critical reaches based on the above approach are discussed below.

### 16.5.4 Unstable and stable reaches

Based on the above approach following reaches have been identified as unstable. However, to call them as critical or not is something related to perspective as mentioned earlier.

1. Chainage 20-24 (Near station Barahi)

   From the remote sensing observations, variations in channel geometry are observed from the year 1975 to 2016. Though channel variations have reduced in the year 2010-16, the overall width of the river in which channel and active water areas are fluctuating is close to 1.8 km. It is significantly more than its observed width in any of the years. The plausible reason behind the shifting can be the confluence between the Lalbekya river and the Bagmati river. The Lalbekya river increased the sediment load, which led to the formation of temporary sandbars. The same can be confirmed from the braiding index analysis (Table 11-4). Figures 16-7 indicate channel area as seen in the year 1975 and the year 2016. From the overall analysis, it can be said that this reach is morphologically active and can be termed as critical as the movement of a river course over 40 years is around 1.8 km.

2. Chainage 101- 106 (Near Benibad Station)

   Tonal variations seen in the satellite image of 1975 indicate that specified reaches were part of the main channel, and the oxbow lake formed between 1975-1990. The river's meandering is quite significant in this segment, and braiding is also observed in all the years, which matches the historical oxbow location (Table 11-2). In 2000-2010, the reach swung towards its right, which caused two more oxbow lakes. Figures 16-8 indicate channel area as seen in the year 1975 and the year 2016.

3. Chainage 129-134 (Near station Hayaghat)

   The satellite image of the year 1975 shows some traces of oxbow lake. Between 1975-1990, one new oxbow lake has formed. The river's meandering is quite significant in this segment, and braiding is also observed in all the years, which matches the historical oxbow location (Table 11-2). In 2000-2010, the reach swung towards its right, which caused one new oxbow lake. Figures 16-9 indicate channel area as seen in the year 1975 and the year 2016.

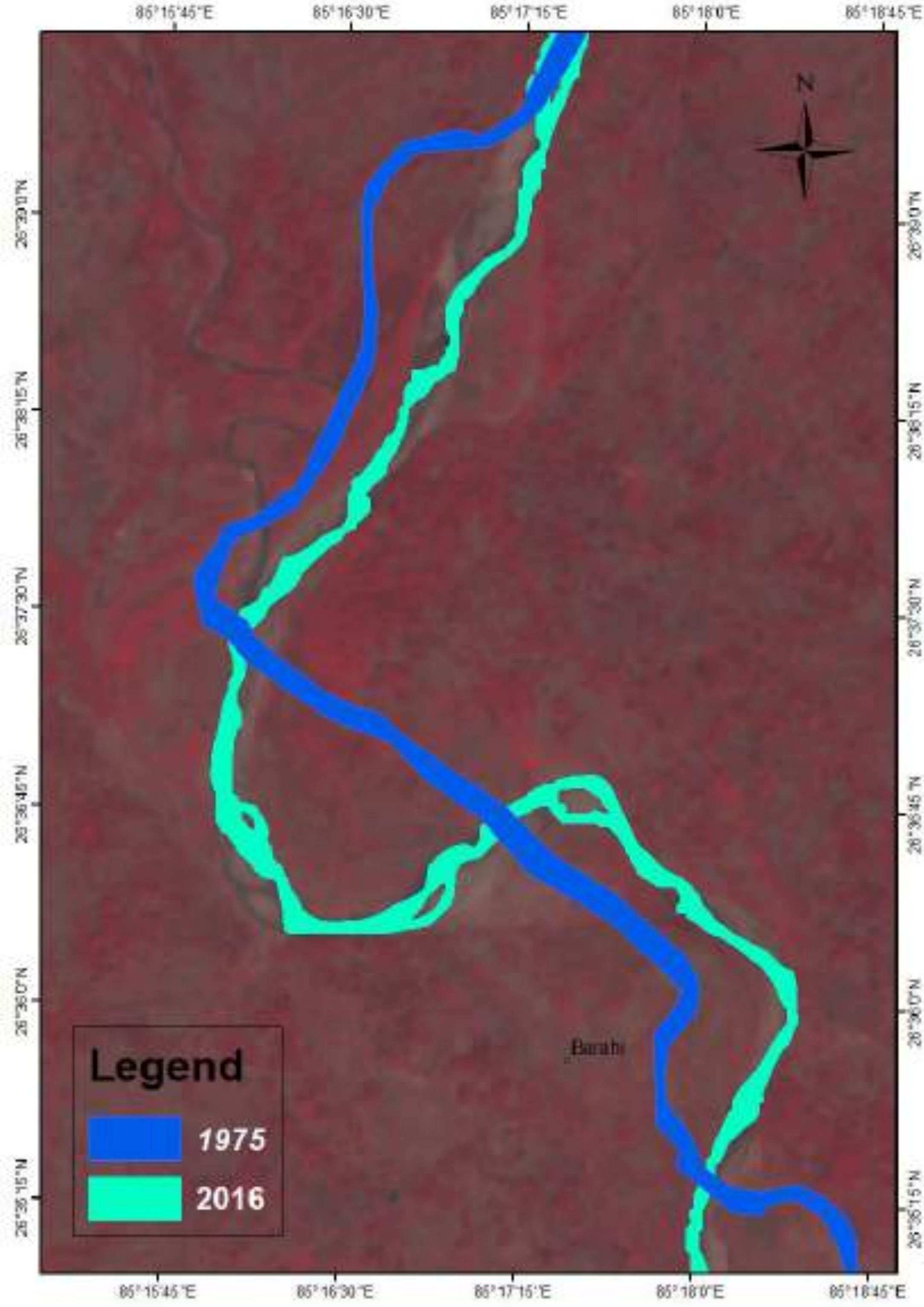



Figure 16-7: Bagmati River for the year 1975 and 2016 around station Barahi

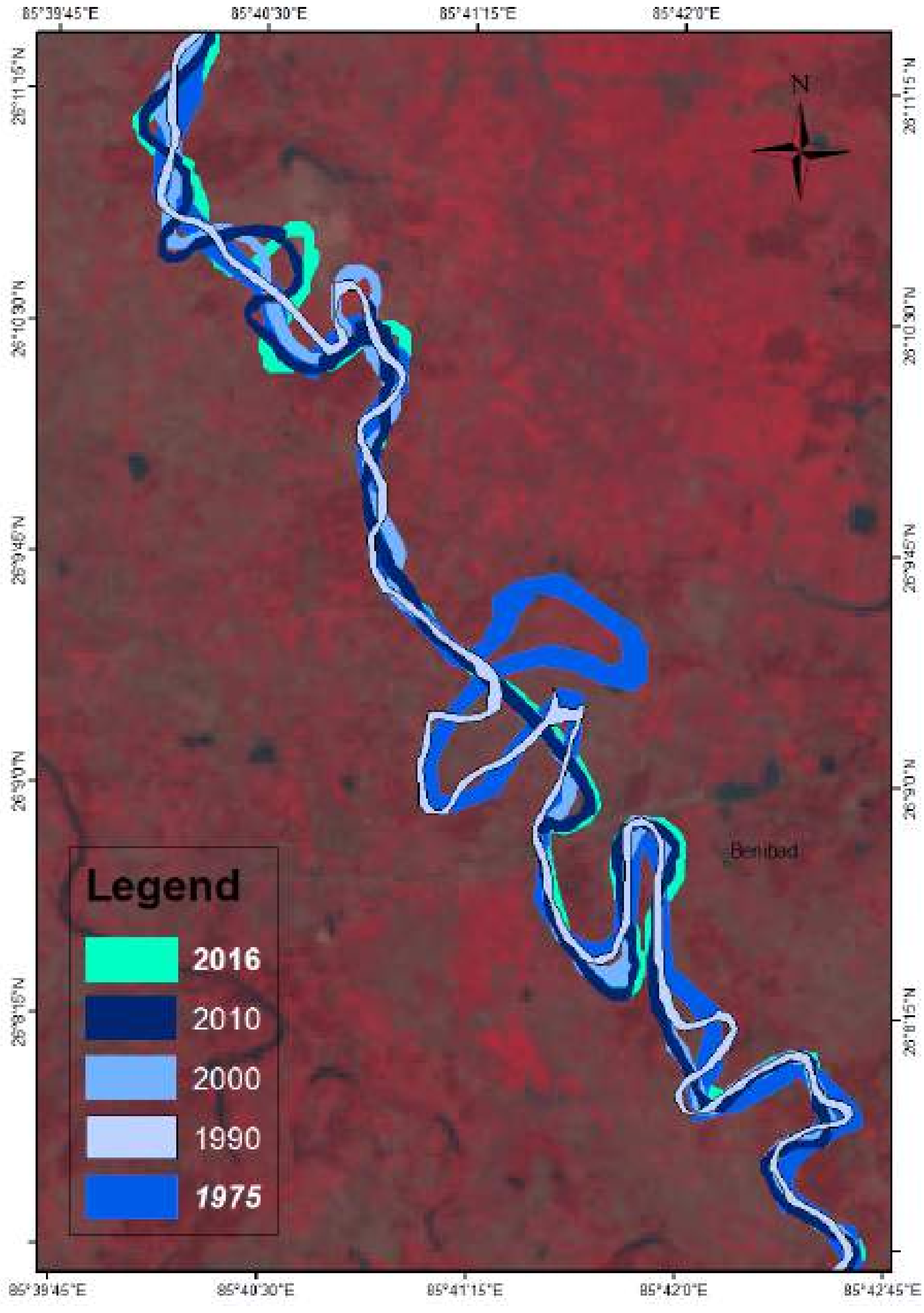



Figure 16-8: Bagmati River for the year 1975, 1990, 2000, 2010 and 2016 around Benibad station

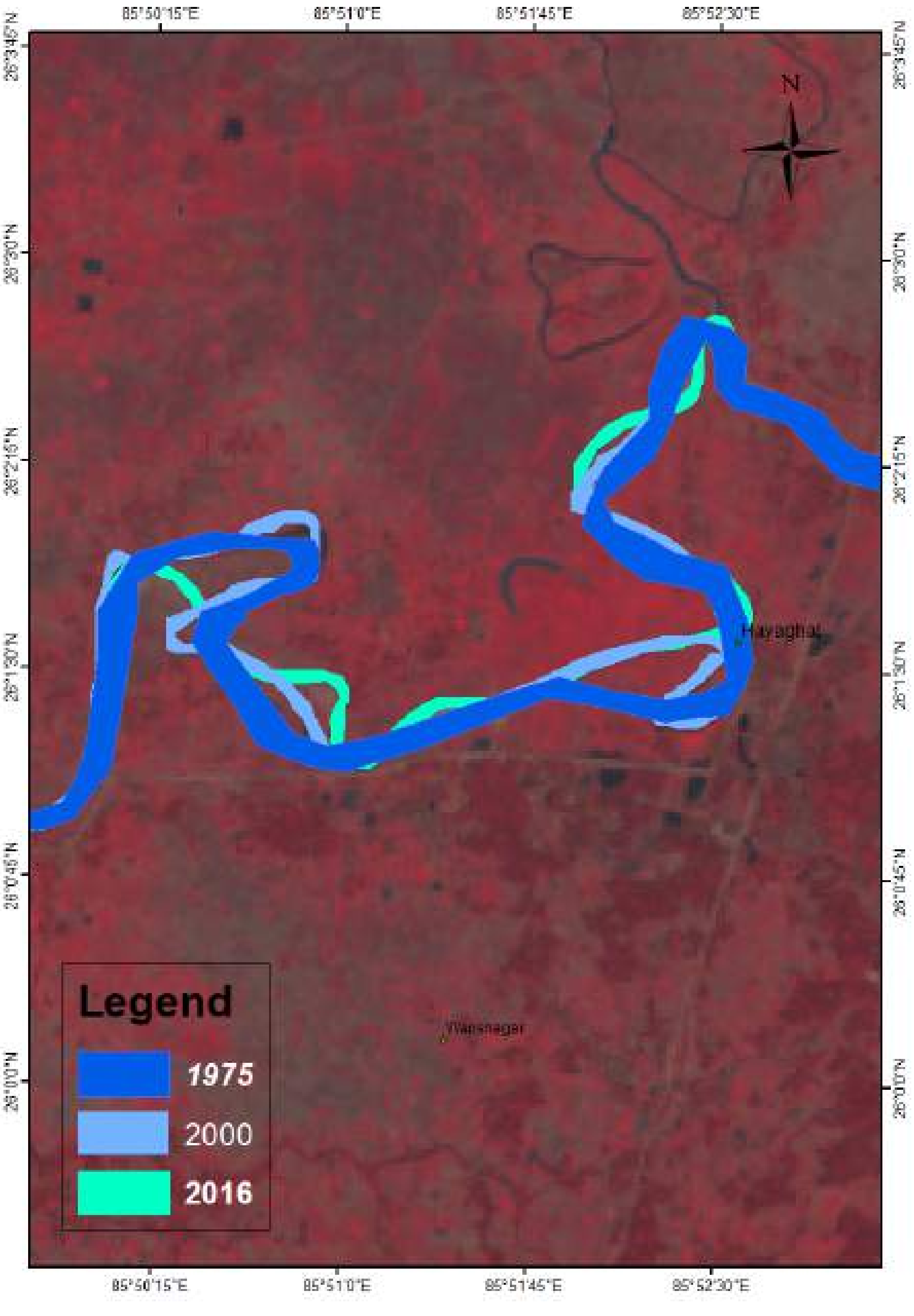



Figure 16-9: Bagmati River for the year 1975, 2000 and 2016 around station Hayaghat

## 16.5 Discussion

The river Bagmati, one of the perennial rivers of North Bihar, originates in the Shivpuri range of hills in Nepal. The Bagmati drainage basin receives nearly 85 per cent of the annual rainfall in the monsoon period between June to October. There is a thick alluvial deposit, part of the Gangetic alluvial plain, in the lower down in the Bagmati flood plain. The alluvial deposition is seen to be progressively finer-textured as one traverse from north to south. The Bagmati-Kosi basin's topography varies between the steep Himalayas to near flat in the middle and lower segments. In contrast with the basin's upper reaches, where the river drops 10 meters in a 1-kilometre stretch, the lower basin's flatter gradients give the Bagmati a highly dynamic character. These typical characteristics of the basin impacted the few reaches of the basin:

1. No such significant changes in river course have been observed within 1975-2010 at few locations. For example, near Benipurgram Hault Railway Station. There was no substantial change in the course of the river till the year 2000, but in 2010 river channel started to bifurcate (Reference: Figure 13-3). It can be seen that more water is flowing through the newly formed channel from 2010 to 2016. The reason behind this bifurcation situates in the topography of the area and the construction of the railway bridge. It is plausible that the soil is excavated from the nearby region during the Railway Bridge construction, introducing the change in elevation and the energy gradient difference. Due to the developed energy gradient, water started flowing in both channels (existing and excavated). This division's topography is that topography of this region is flat terrain (slope variation in the basin is 0.11 to 0.4 m/km), so a slight change in elevation value can change in the water flow direction.
2. The majority of water supposed to flow through Hayaghat is spread in the surrounding region with a topography like a plate (Mishra 2010). Unless and until the plate overflows, water cannot move ahead. In this region flood water of Bagmati intrudes in its tributaries and cause flood situation in their catchments. This typical topographic (Section 4.2) feature put villages alongside Bagmati between Dheng to Hayaghat into flooded situations. Without flooding the region in between, Bagmati cannot move ahead to Hayaghat. Another reason behind the flooding is observed through the field visit was the shallow water table. It also explains why the region between the Dheng bridge to Hayaghat is more active (morphologically) than the other reaches of the river.

## 16.6 Conclusion

A grid-wise analysis is carried out to understand channel bank retreat based on erosion and deposition and dynamics of river course on a decadal scale. The River Bagmati shows distinct patterns of channel bank retreat and river course dynamics. According to these distinct patterns, River Bagmati has been divided into different zones as below:

i. Zone A: Dheng Bridge to Katra (Grid 12 to 60)
ii. Zone B: Katra to Hayaghat (Grid 78 to 98)
iii. Zone C: Hayaghat to Jagmohra (Grid 112 to 216)

These zones are discussed for the results of analyses, along with differences in their morphic characteristics.

**Zone A:**

This zone mainly covers the reach of Bagmati from Dheng bridge to Katra. The first 90 km of the reach of this zone represents a river flowing through a shallow and braided channel. The braiding index is relatively high in the grids from 12 to 60. River Lalbekya confluence with Bagmati in Grid 16 and their confluence can be considered stable, as the shift in confluence point ranges from 1.15-1.8 km. The channel pattern is mostly sinuous.

**Zone B:**

This zone mainly covers the reach of Bagmati from downstream of Katra to the Hayaghat. The 95-140 km of the reach of this zone represents a river flowing through a meandering channel. The meandering behaviour has significantly increased, and the swing in the centerline caused the formation of the several oxbows lake along the river channel.

**Zone C:**

This zone mainly covers the reach of Bagmati from downstream of Hayaghat to the confluence with Kosi. The 140-208 km of the reach of this zone represents a river flowing through a meandering channel. Significantly higher erosion and deposition are observed in the grid 144,187 and 216. From the analysis, it can be observed that though there is a shift in the confluence point of the Kosi and Bagmati, as Bagmati is merging with one of the reaches of the Kosi river near Jagmohra village instead of Sonbarsha ghat, which is approximately 30 km apart. However, the magnitude of the change has reduced for the rest of the years.

# Chapter 17 Conclusion

The conclusions drawn from the present study are discussed in this chapter.

1. Land-use changes in Bagmati River Basin have been estimated using remote sensing imageries of different years. The major part of the basin is covered with agriculture (based on land use of the year 2010), accounting for 36.19%, followed by Barren/Fellow land (31.5%), forest (24.376%), Snow/Glaciers (3.68%). Water bodies (2.6%), and Built-Up Land (0.341%). However, land-use changes reported in this study indicate that the built-up area has increased by 62.8%, whereas forest has shown a reduction of 1.12%.
2. Considering the overlapping of scales, as discussed in Section 16.2 in Chapter 16, assessing the impact of land-use change on morphology cannot be achieved. However, based on changes in land use type, one may indirectly predict the pattern of erosion and deposition. Accordingly, it can be said that over the years, a decrease in forest and increase in the urban area has been observed, which might have resulted in increased erosion in the basin.
3. Hydrologic analysis of the observed streamflow data has been carried out and presented in detail in Chapter 9. From the analysis of 1.5 and 2-year return period flood events, sudden rise or fall in streamflow values have been observed at few locations. This can be attributed to the joining of tributaries.
4. Though the frequency analysis based on observed streamflow has been attempted, it may not represent the actual reality of the system as a regulated flow regime in the present condition has been used to perform the frequency analysis. Therefore, the results of this frequency analysis may be used in the limited context of the morphological study and might not be suitable for other applications such as design flood estimation.
5. Indices to understand sinuosity, the radius of curvature, braiding, planform of the river have been estimated. The average sinuosity for the entire stretch of Bagmati River is 1.5, whereas the radius of curvature varied between 0 to 0.33 km. Based on Braiding Index, it can be said that braiding is higher in selected reaches, mainly from the grid 12 to 44.
6. River course dynamics has been analysed in the form of movement of channel centreline at 1 km interval, and it has been seen that river has experienced changes in

its course at a few locations. Those locations are concentrated in the middle stretch of the river (Near chainage 37-57).

7. From the analysis of confluence points, except Kosi-Bagmati confluence between 1975-1990, confluence zones are stable and have not gone through significant change in the last 40 years.
8. During the period 1975-1990, an areal retreat of erosion and deposition is equally significant. While significant variation is noticed as the areal extent of erosion is 33.97 sq. km higher than deposition, while in the period 2000-2010, the deposition is quite higher than the erosion. The value of deposition in the 2000–2010-year span is 56.16 sq. km, and during the 2010-2016 time periods, not substantial variations are observed in erosion and deposition. The difference between erosion and deposition is 3.43 sq. km.
9. Aggradation and degradation patterns analysed from observed cross-sections are in line with satellite-based erosion deposition maps.
10. A few locations have been identified in the stretch of Gaihati to Baheri (100-161 km) that may experience neck cut off/ ox-bow formation/ abandonment of reach.
11. From the combined approach of remote sensing image analysis and simulation studies, chainages are identified as morphologically active/ critical for stretches Chainage 20-24 (Near station Barahi), Chainage 101- 106 (Near Benibad Station) and Chainage 129-134 (Near station Hayaghat).
12. Based on the physiography of River Bagmati, the entire stretch is divided into three zones and results from the morphological study are juxtaposed to define the zones, either stable or active.

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**Proceedings of Dissemination Workshop of Morphology Study of Kosi, Bagmati, Yamuna Project held on 15th Jan 2024 at New Delhi**

The Civil Engineering Department, IIT Delhi, organized final workshop for the project: "Morphological Studies of Kosi, Bagmati, and Yamuna Rivers using Remote Sensing Techniques", at the Auditorium, Research & Innovation Park, IIT Delhi, on 15th January, 2024. The project outcomes were presented to the participants of the workshop who were from a range of concerned organizations. Invitation to participate was sent to the State Govt of Bihar, UP, Haryana and their research institutes like IRI, WALMI. Central agencies and academic institutes such as Central Water Commission (CWC), Ganga Flood Control Commission (GFCC), National Institute of Hydrology (NIH), National Remote Sensing Centre (NRSC), Ministry of Jal Shakti (MoJS), IIT Roorkee, IIT Guwahati, IIT Mumbai, IIT Chennai, IIT Kharagpur, IIT Hyderabad, SVNIT Surat, WWF India, etc were also invited to attend the workshop. List of Participants: Annexure I

Prof A.K. Nema, Head of Civil Engineering Department, IIT Delhi, and Mr. D.P. Mathuria, Chief Engineer, CWC, welcomed the participants. It was followed by a short briefing about the project by Prof. A. K. Gosain.

Prof Rakesh Khosa gave an overview of the project and also presented genesis, morphological signatures, quasi-statism of a river course, the concept of the ergodynamics and the river corridor, shifting in a real sense, asymmetry in river drainage network, and various nuances of Kosi's morphological behavior. It was followed by a presentation by Mr. Gaurav Pakhale on methodology and system-specific outcomes of morphological study using remote sensing techniques in Yamuna, Baghmati, and Kosi Basin.

After the presentations, the floor was opened for discussion and comments and questions were invited from the participants. A very intense discussion pursued wherein most of the participants engaged in conversations, shared their views and experiences, and also provided feedback on the study done by IIT Delhi. A few observations were made on the final reports such as providing further clarity on the areal retreat of erosion deposition and to provide additional information, such as the location of nearby villages and the geographical context while discussing various indices and stable or unstable reaches.

**Dissemination Workshop of Morphological Studies of Kosi, Bagmati & Yamuna Rivers Using Remote Sensing Techniques**

**Research & Innovation Park, IIT Delhi**
**15th January, 2024**

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# Annexure I

# MEMORANDUM – I

# MORPHOLOGICAL STUDY OF RIVERS KOSI, BAGMATI AND YAMUNA USING REMOTE SENSING TECHNIQUE

***For:***
Morphology Group
Water Resources Section

By:
Ms. Vilakshna Parmar
Prof. Rakesh Khosa

**DEPARTMENT OF CIVIL ENGINEERING**
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**HAUZ KHAS, NEW DELHI 110016, INDIA**

**October, 2017**

## MEMORANDUM – I

To: Morphology Group, Water Resources Section

From: Vilakshna Parmar and Rakesh Khosa

Topic: Centerline

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### CONCEPT OF RIVER CENTRELINE

A related, and no less profound, missing link in its understanding has made it imperative for morphologists to ponder over whether it is at all possible to develop a consistent association between the concept of 'centreline' and a specific set of hydrological and morphological attributes of the river. In other words, the question that arises is whether the notion of a river's imaginary centreline is and should be just a representation of the current position of the river's wet channel stream or does it indeed hold a deeper philosophical and hydro-morphological relevance.

### Introduction: Genesis of a river course and its innate dynamism

No river in the world exhibits a consistent morphological behaviour across all spatial and temporal scales. Typically, any given reach of a particular river represents a complex mix of various geomorphological patterns and, importantly, may lend themselves to distinct descriptive characterization that depends squarely on the scale over which the reach is abstracted. In the present discussion an effort has been made to present a more rational perspective on the widely used, albeit imaginary, concept of a river '**centreline**'. The memo will also seek to explain its physical significance which is routinely estimated from satellite imageries.

It merits mention to note that an important but often missed morphological reality of a river course is that, by and large, development/evolution of river courses is essentially **intertwined with the occurrence and alignment of local/regional geological fault lineament**. Of course, there are exceptions to this rule such as when an avulsion results in a river changing its course, temporarily or permanently, or indeed when surface incision occurs as illustrated in Figures 1 and 2 (Ref: web resources):

Figure 1: Channel formation by incision

Figure 2: Channel formation by incision

It therefore becomes imperative to acknowledge that in general for a vast majority of major river systems across the globe, these geological fault lines act as delicately balanced cradles that provide a **dedicated corridor** for drainage paths to develop and which over time, acquire the configuration of river channels. Understandably, concomitant erosional and depositional processes, amongst others, would be expected to have shaped changes in the latter channels. The reality of these autocyclic as well as other allocyclic processes has indeed been recorded to be incessant and observed to occur over time scales ranging from geological to relatively more rapid. Further, it must be understood that these river channels do respond to various natural triggers of a diverse nature in an autonomous and spontaneous manner.

Importantly, the aforementioned dedicated river corridor demarcates the **swingwidth** within which the riverflow can rightfully assume any pathway depending upon the **topology of the available potential energy field and its lateral connectivity and exchange with subsurface flow pathways – a reality that has hitherto been disregarded or, at best, given a casual treatment in theoretical abstraction**.

It is reasonable to hypothesize that these aforementioned responses would manifest in various ways and manners including the river channels swinging courses between alternate flow paths, albeit restricted to within the overall corridor of the aforementioned dedicated passage ways as dictated by its underlying tectonic reality. The aforementioned concept of channel course swings as experienced by the channel flow paths is illustrated in the following Figure 3.

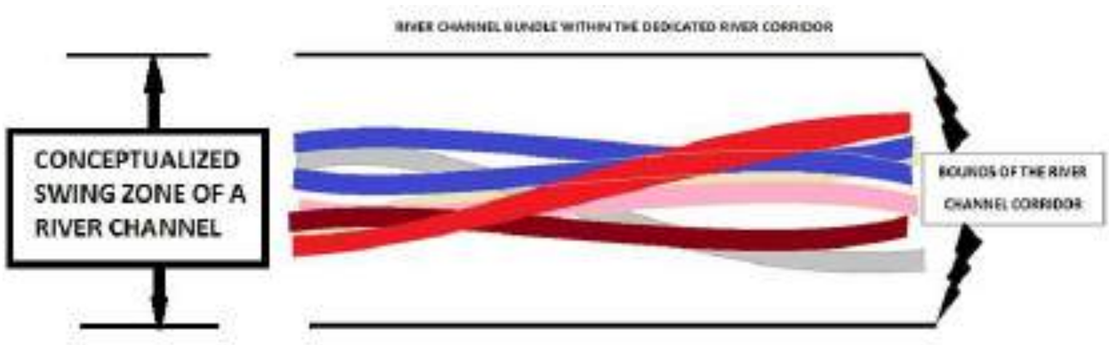
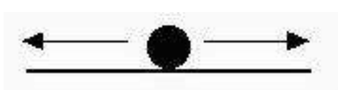



Figure 3: Schematic explaining the concept of alternate flow paths within the dedicated river corridor

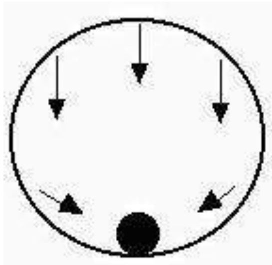
Looking at it from a different perspective, it is now possible to theorize that for a river channel course, in the absence of allocyclic and other avulsive triggers, three broad categories of states, all stable within their respectively restricted context, may be defined. These may be depicted as shown below as Figure 4a, 4b, 4c, 4d and 4e:

(i) Neutrally stable state (Figure 4a):



(ii) Locally stable state (Figure 4b):

(iii) Globally stable state (Figure 4c):



And, of course in the context of the hypothesized dedicated river corridor, globally stable state may be depicted as Figure 4d:

Figure 4d: Globally stable state for a river corridor

Alternatively and more realistically, a globally stable state for a river course may be depicted shown in Figure 4e although, within the overall available swing zone within its dedicated corridor, alternative channel courses are not just possible but indeed is natural:

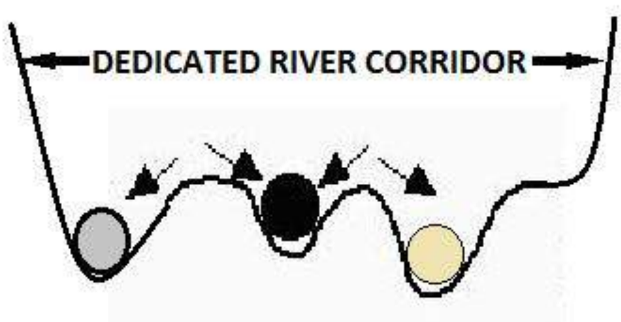



Figure 4e: Alternative representation of globally stable state for a river corridor

Figures 4 (a, b, c, d, e): Contexts of stability of river channel courses

Acknowledging the realism captured in the aforementioned depiction is indeed essential in order to develop an objective capacity to capture the underlying significance of otherwise esoteric concepts related to '**river centreline**', '**river course shifting**', and '**critical river reach**'.

**Centreline: Does it have any one or more definable and distinctive aspects that could lead to its consistent and objective identification?**

Consider the following contending considerations that may provide clues as well as the bases for the enigmatic and obdurate concept of 'centreline':

(i) Does the centerline coincide with the thalweg line?
(ii) Or does the centerline bifurcate the volumetric flow rate into two equal halves?
(iii) Or does it suffice to mark the river 'centerline' from the ad interim widest water bearing channel within the overall swingway of the dedicated river corridor?
(iv) Or does the centerline divide the bankfull width of the river into two equal halves between the connected bank lines?
(v) Or does the centerline bisect the wetted top width between the two water lines along the river banks?

A difficulty presented by the above mentioned posers is that river cross sections are rarely, if ever, symmetric between banks as illustrated in Figure 5.


Figure 5: Asymmetry in river cross section profiles

Also, the waterline is not a static attribute but may show a wide range of variation in the water level between the wet and lean season flows and, as a result, the wet channel may lie quite skewed and off to one side of the river reach as is depicted for clarity in Figures 6 and 7, with the latter showing a reach of river Yamuna upstream of Hathnikund barrage.


Figure 6: Skewed wet channel of a river during season of low flows


Figure 7: Skewed wet channel of Yamuna upstream of Hathnikund barrage

Further, and to complicate the issues further, water may occupy different channels within the overall **<u>dedicated river corridor</u>**, essentially prescribed by the underlying geological fault lineament, in different years and as illustrated above in Figure 3.

Realistically, it merits further mention that a river may have multiple wet channels or in extreme situations, none at all. In some cases the channels may even be disconnected as the river intercepts subsurface seepage. The three cases highlighted above are also captured for clarity in Figures 8, 9 and 10 respectively for river Yamuna.


Figure 8: Multiple wet channels of river Yamuna

Figure 9: No wet channel seen in river Yamuna downstream of Tajewala

Figure 10: Disjointed network resulting perhaps from disjointed interception

and contribution by subsurface flows

## River centreline

For the purpose of illustration, let us examine a parallel analogy with reference to a simple pendulum having stated attributes and placed in the following circumstances:

**Attributes:**

(i) The pendulum string is flexible.

(ii) The inertia of the two components is negligibly small and uniformly distributed over the bob and the string to which it is tethered. (iii) The anchor of the pendulum is fixed.

**Circumstances:**

(i) Pendulum is at rest and in a tranquil/quiescent environment

(ii) Pendulum is swinging in a frictionless and tranquil/quiescent environment (undamped oscillations)

(iii) Pendulum is placed in a zone with strong and randomly turbulent air movements

It is indeed instructive to examine the concept of 'centreline' of the pendulum system corresponding to each of the aforementioned situations. These are shown below as Figures 11, 12 and 13 and with each depiction is an accompanying poser about the concept of the 'centreline' without any further attempts to elaborate and explain these posers.

**Circumstance (i):**

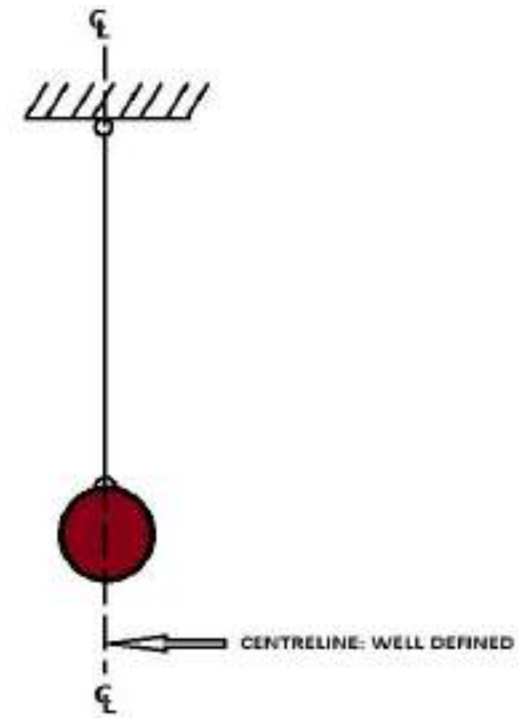



Figure 11: Centreline when Pendulum is at rest and in a tranquil/quiescent environment

**Circmstance (ii)**

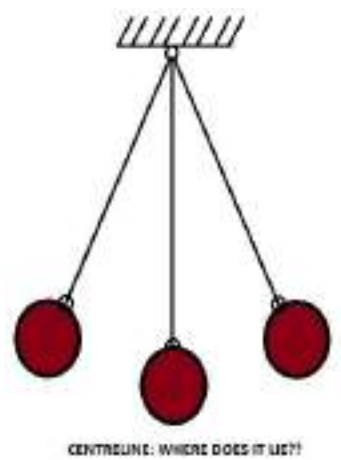



Figure 12: Pendulum is swinging in a frictionless and tranquil/quiescent environment (undamped oscillations)

**Circumstance (iii):**

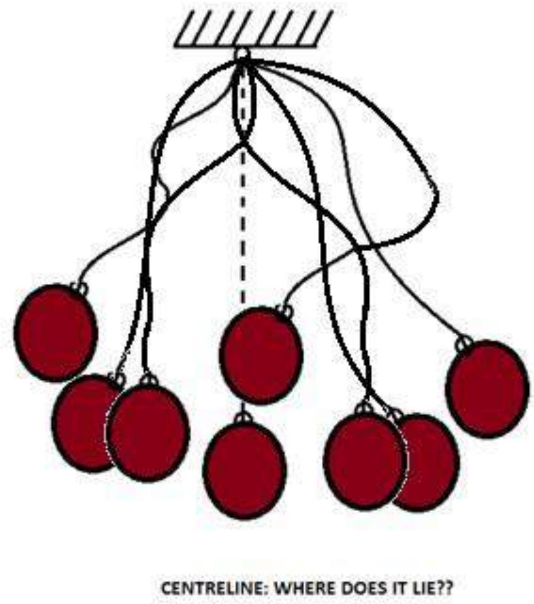



Figure 13: Pendulum is placed in a zone with strong and randomly turbulent air movements

Closely linked with the above illustration is the immutable and undisputed reality that the concept of 'centreline' is deeply rooted in the multi-scale dynamics that underscores the integrated domain of hydro-morphology of rivers together with the issues pertaining to **temporal and spatial scales** at which the natural system is observed and described. The same is illustrated in Figure 3 wherein the essence of the innately transitory nature of the river channel is captured and demonstrated. Accordingly, an attempt to demarcate the centreline of such hydro-morphological entities will not be anything but perilous – an attempt that cannot stand scrutiny of the entire spectrum of plausible contexts.

Figure 14 below shows a schematic of an observable river reach, marked in blue, together with its associated floodplain valley that extends beyond to the watershed divide. Clearly, the centreline will be dictated by the course of the river reach and will match its serpentine planform. Interestingly, it is possible to imagine scales of interest where finer detail features become relatively opaque to observation and, with reference to the following Figure 15, where the river details have been masked for effect, and the planform of the centreline is dictated essentially by the orientation of the floodplain valley.

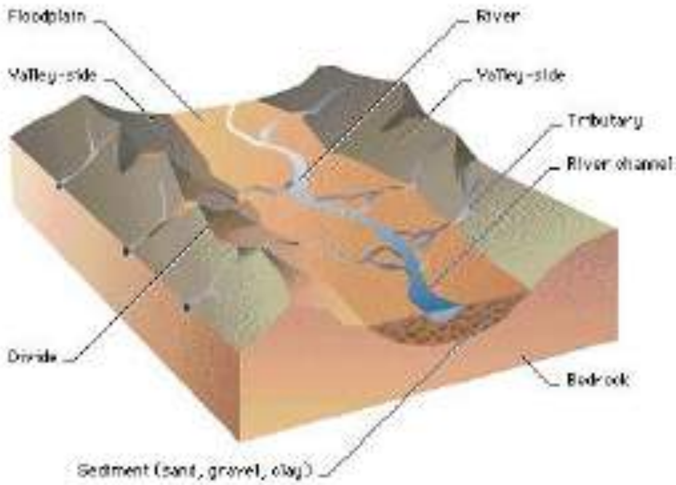



Figure 14: Schematic of a long & narrow floodplain valley along with its principal drainage feature (in blue)

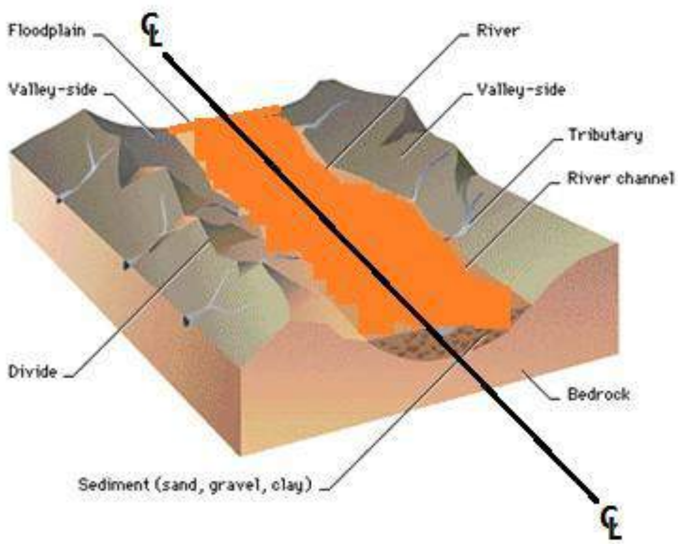



Figure 15: Schematic of a long & narrow floodplain valley with its principal drainage feature masked

Such a scenario is indeed not unrealistic and the underlying lack of integrity in the way centrelines may routinely be marked becomes evident when different perspectives emerge as river valleys are observed during seasons of lean flows and then compared with inferences based on observations recorded during the wet flood seasons.

As a further attempt to explain the proposed hypothesis, consider, for example the schematics shown in Figures 16 that depicts a hypothetical river reach along with some accompanying illustrative details. Figure 17 also depicts the same hypothetical river but in its natural setting complete with its associated floodplain valley and whose given lateral extent on either side stretches to the very edge of its water divide, thus capturing entirely its narrow and elongated floodplain.

During seasons when the flow rate is less than the bankfull rate as in Figure 16, the river channel is clearly visible and its centreline accordingly will follow the river's serpentine course. However, as shown in the accompanying sketch of Figure 17, the flood flows may occupy the entire floodplain valley as well during the ensuing wet season and the dominant flow paths are seen to be oriented along a direction that is essentially parallel to its flood plain valley.

In addition to the energy gradient along the shorter flood plain flow paths, the prevailing flood plain flow velocities also are sharper as compared to the corresponding hydraulic attributes of the segment of the total flood flows, albeit relatively minor, that is confined to the relatively limited waterway of the river channel. Further, the schematic sketch of Figure 17 also suggests the plausible and realistic scenario that the higher wet season flood flows may completely mask the latter river channel from view. Understandably, the centreline, if captured based solely on the wet season flood flow condition, will now be straighter and along the general orientation of the encompassing flood plain valley. Clearly, the sensitivity of the centreline configuration in plan to currently prevailing flood conditions is indeed indicated and, therefore, its suggested underlying hydro-morphological dynamics renders the judgement leading to the latter feature's delineation as inconsistent, subjective and without shelf life!!

**FLOW DIRECTION UNDER NORMAL AND DRY WEATHER CONDITIONS**

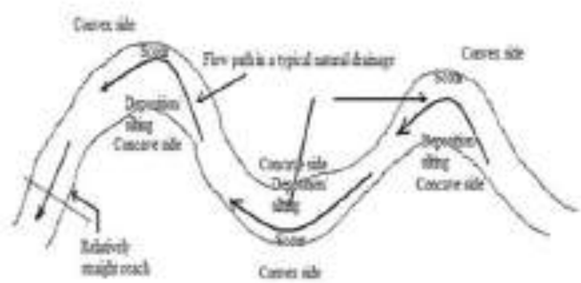


Figure 16

**FLOOD FLOW PROPAGATION UNDER MODERATE TO EXTREME CONDITIONS**

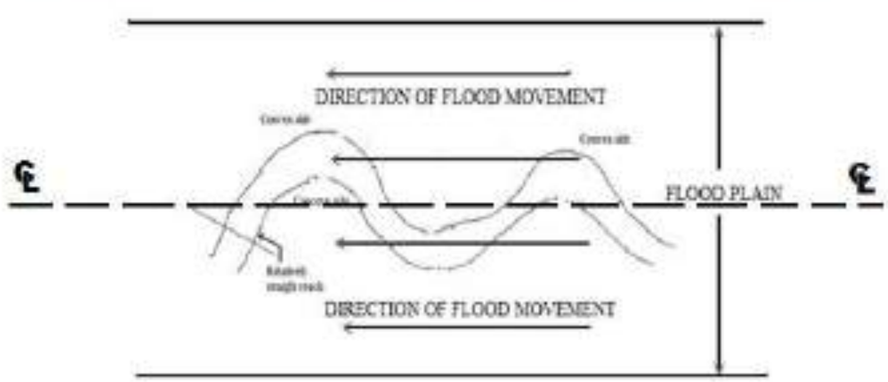



Figure 17

Figures 18 and 19 show a reach of river Gangless in Leh highlighting the constraining influence of the surrounding valley within which the river swings to adopt a transitory course as dictated by ensuing auto-cyclic and hydro-morphological reality.

Figure 18: Dedicated river corridor for Gangless river in Leh Valley (oriented upstream)

Figure 19: Dedicated river corridor for Gangless river in Leh (oriented downstream)

As an illustration of the aforementioned conjecture (ref: Figure 16 and 17), Figures 20 and 21 below show snapshot images of river Jhelum for a comparison between the post September, 2014 flood event wetted area and the wetted area when the flow is within banks.


Figure 20:Wetted area of Jhelum near Srinagar (September 10, 2014 Flood Event)


Figure 21: River course of Jhelum near Srinagar under less than bankfull conditions

While it has been reported in informal studies that the September, 2014 floods was a once in 50 year event, it is indeed understood that nature provides for flow possibilities that could span the entire range in magnitude from the bankfull discharge to the high value magnitude of flow rates observed during the aforementioned 50 year event and indeed beyond on either side of this spectrum. Attempts, therefore, to identify the river centreline from the wetted area would obviously have a severely restricted appeal, constrained as it would be by the specificity of the event captured by the available image which would come tagged by temporal attributes of day,

month, season and year of capture. To further illustrate this point, consider Figure 22 which depicts river Jhelum during the Sptember, 2014 event. (*A satellite based rapid assessment on floods in Jammu & Kashmir-September 2014. Collaboration between NRSC Hyderabad and Deptt. Of Ecology, Environment and Remote Sensing, Govt. of J&K*)

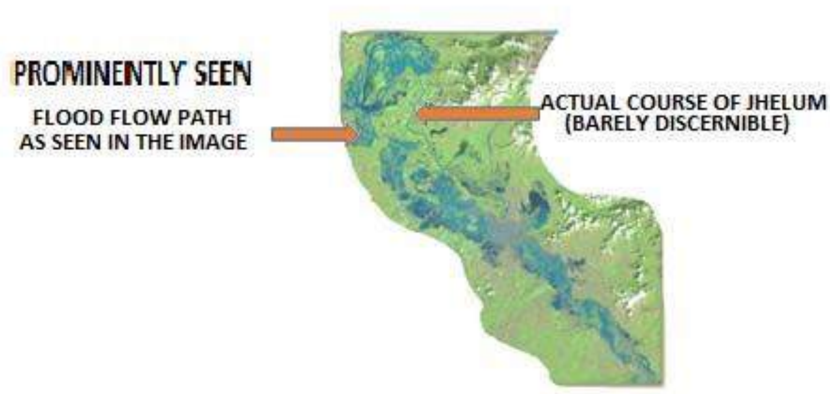



Figure 22: Flood mapping of September, 2014 event

The perils of centreline delineation based on the concept of wet channel, as has been captured by the satellite is clearly evident as the course of the river is likely to be misjudged to be following the wide expanse of water in the NW part of Figure 22 and ostensibly joining with lake Wular further North in the figure. It is indeed noteworthy to mention that this location is actually the site of River Jhelum's exit out of the lake whereas the rightfully designated course of Jhelum is as indicated by the orange arrow in the latter figure. Figure 23 depicts capture of similar details and the course of Jhelum is clearly discernible but has only a scattering of connected flooding pockets along it. To the contrary, the adjoining Flood Channel is seen to indicate extensive flooding along its course but it is noteworthy to recall that the Flood Channel has no formal outfall into any receiving water body, be it a lake or any other river. Clearly, in the task of centreline delineation based on the wetted area concept would result in an absurdity!!!

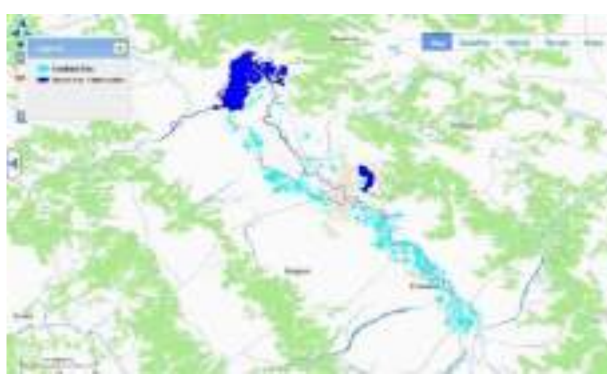


Figure 23: Flood mapping of September, 2014 event

Similar discordance between wet channel and course of Jhelum on its approach to Wular lake can be seen in Figure 24.

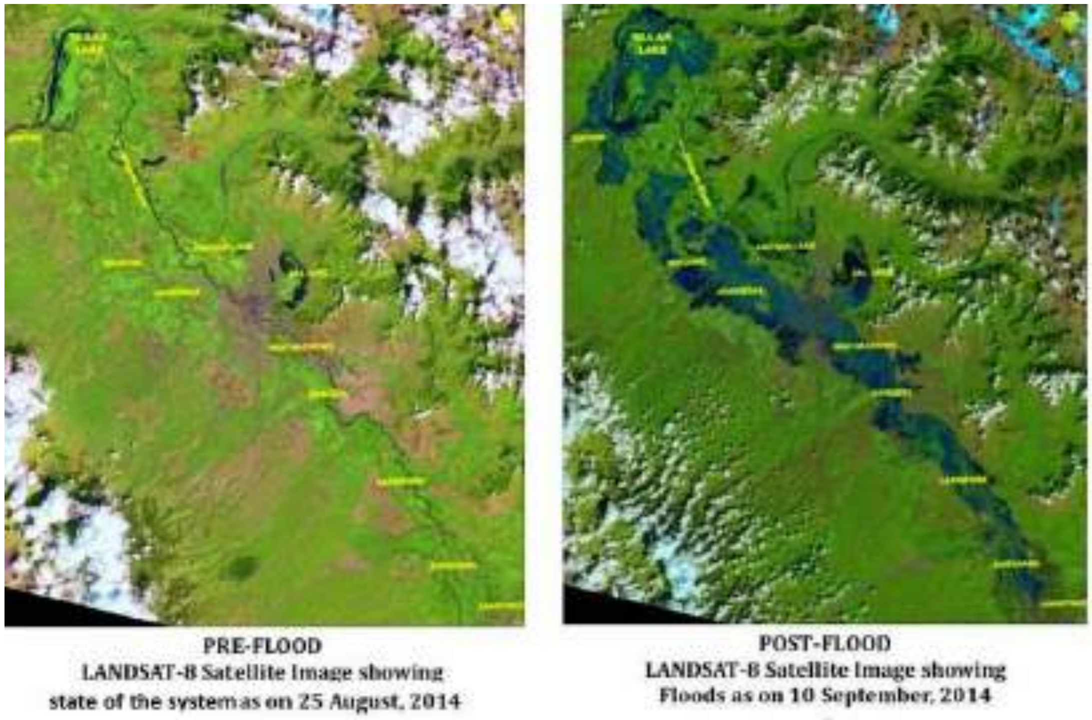



Figure 24: Comparison of river corridor between pre and post September floods

Obduracy innate to the concept of the river centreline is further evident from an examination of river Jhelum as it approaches its intermediate outfall into Wular lake (Figure 25) where the obscurity of a discernible and dominant channel feature is as conspicuous as it is anomalous.


Figure 25: River course of Jhelum as it approaches its intermediate outfall into Wular Lake

From the above discussion, it is evident that there is a need to be able to delineate river channel limits in a manner that is not only consistent but is also amenable to comparison between sites and over time as the river flow levels are indeed expected to be highly dynamic in nature.

Clearly, the river cannot be defined as the wetted area at the time of assessment and understandably, therefore, the results yielded by any specific channel delineation method must not ideally be constrained by the time and day for which the channel image is available.

**Concept of wetted area under 'Bankfull' conditions: A hydrodynamic attribute**

The question of delineation based on the concept of wetted area has also been discussed in various studies (see, for example, Vermont Report) and it has been argued that instead of using wetted area at a given time **to define the river**, it may be more appropriate to define the size of the river based **upon the channel** as defined by the bankfull stage or the point at which the flow just begins to enter the active floodplain (Leopold, 1994). It has been averred in literature that hydro-morphologic significance of the bankfull width/bankfull stage with an average recurrence interval ranging from 1.5 years to 2.2 years, renders the latter concept to be a consistent and identifiable benchmark for spatial and temporal comparison. Remarkably, the latter index does indeed offer the potential to be a benchmark index from which to measure channel sizes for a consistent comparison between sites

The concept of 'bankfull' also has a morphological significance as studies have shown that it is the bankfull flow that transports the greatest amount of material over time (Leopold, 1994). While larger flow events transport greater quantities per event and smaller flow events occur more frequently, it is the bankfull flow that is the most effective determinant of a river's channel morphology and, appropriately, is also referred to as the "effective channel forming flow." An interesting but related concept alludes to a channel being defined as the waterway at bankfull stage beyond which flooding of the active floodplain is an inevitability implying, therefore, that the active floodplain defines the limits of the bankfull channel and may, appropriately, be defined as the flat portion of the valley adjacent to the channel that is constructed by the present river in the present climate (Leopold, 1994).

As has also been illustrated above (see Figure 3), the phrase "by the present river in the present climate" is especially important because as and when the river degrades or incises, a former floodplain may become a terrace or an abandoned floodplain but within the overall confine of the dedicated corridor. An interesting and equally profound emerging corollary of the aforementioned discussion is that in addition to the attribute of an average recurrence interval, bankfull channel/bankfull wetted width also has a **hydrodynamic attribute** which merits much attention in channel delineation exercises.

Difficulty that arises, however, with the hydrodynamic approach relates to the question whether the bank full discharge occupies the entire channel corridor of an otherwise wide and highly braided river reach. For these circumstances, understandably, it is necessary to capture the role of evolving river bed morphology effectively as the latter feature is indeed a significant determinant of hydrodynamic attributes of flood flow propagation down the reach.

This is obviously an important consideration when remote sensing products are the only source of information and river channel is identified on the basis of reflectance characteristics that are typical of sand deposits. Clearly, old sand deposits of currently abandoned river beds are liable to be misconstrued as being part of current river course. Obviously, in case where high resolution bed morphometric details are not available, delineation of the ‘bankfull’ condition for rivers with these complex features is something of an impossibility.

Regardless of these imponderables and in furtherance to the above discussion, it is in order to identify various important suggested indicators of the ‘bankfull’ condition as gleaned from available literature.

**Indicators of ‘Bankfull’**

In addition to the hydrodynamic basis to simulate wetted stage corresponding to flood events corresponding to average recurrence intervals ranging from 1.5 to 2.2 years, the following autocyclic manifestations and bank vegetation characteristics have been suggested as possible indicators of the bankfull stage (Vermont Agency of Natural Resources Report, May 2009).

(i) Nearly flat top of developing point bars as an evidence of developing active floodplain left in the wake of migrating channels.

(ii) Location of break in bank slope from steep to a relatively gentle slope and is seen on reaches of river that are not prone to active floodplain building.

(iii) Lower extent of persistent woody vegetation because only the most water tolerant species of vegetation will typically grow within the bankfull channel.

(iv) Erosion or scour features offer a satisfactory basis for defining bankfull condition on naturally entrenched rivers over steeper gradients wherein the active floodplain is either intermittent or may be absent altogether. It therefore becomes necessary to rely on erosional features along the banks as indicators of the flow stage that performs the most work. It must, however, be understood that erosion can be caused by many diverse nature of processes and may not be related at all to the stage of the bankfull flow. Accordingly, therefore, these features should be relied upon only when absolutely necessary. Two cases are presented as Figures 26 and 27 which respectively show the region around the confluence point of river Zanskar with Indus and a reach along Indus just upstream of this confluence point in Leh. The erosional features on the left and right banks of river Zanskar are indeed clearly evident.

(v) Flat depositional benches or lateral bars are often seen along relatively straighter sections of river and may also represent the active floodplain with its edges corresponding to the bankfull condition.

Figure 26: Erosional features on river Zanskar

Figure 27: Erosional features on Indus upstream of its confluence with Zanskar

## IMPORTANT CONSIDERATIONS FOR RIVER CENTRELINE

### Centreline for dry beds

As an opening remark, the discussion may best be initiated with a question: What constitutes a consistent centreline, arguably an imaginary concept, for a river reach having a dry bed at the time its image was captured by a satellite? Figures 9 and 10, together with Figure 28 represent a generic set of interesting but challenging case studies for centreline demarcation.

Figure 28: A dry and braided river bed and sensed on the basis of reflectance as deposits of white sand

Whether the river reach runs dry for reasons of upstream abstraction or the river is rainfed, ephemeral (non-perennial) and periodically does not receive enough contributions from its headwater reaches, these rivers do face many challenges that directly affect its morphometric prognosis. **Unauthorized sand mining and unregulated, also unauthorized, dumping of municipal and construction related solid wastes** have emerged as a bane for these rivers. A direct consequence of these two but competing practices is seen in the distinctively unnatural morphometric responses of the affected river's bed and banks, which translates into altered fluvial responses as is seen in terms of altered hydrodynamic and sediment transport characteristics. For example, newer braids may be carved and some old ones may experience their abandonment.

**Centrelines with Hydrological Basis:**

The water will occupy the steepest potential gradient and tracing this can give us the probable flow direction and, accordingly, the centerline may be represented by the **Thalweg, wherever it is possible to identify these and in some cases, indeed at multiple locations across a cross section**. The possibility of obtaining multiple 'deepest channel' points are in recognition of (i) limited precision in data as captured by remote sensing equipment, (ii) ability of the sensing equipment to penetrate water in order to capture bed details with precision that is required, (iii) homogeneity of bed deposits, in terms of their reflectance, across the cross section, and (iv) just an 'Act of God' occurrence!

Thalweg also constitutes the basis for delineation of river networks on Digital Elevation Models in hydrological studies but, as is evident, this network is scale/resolution specific (Fractal structure of the river network) and, in relatively plain surface topography, may be influenced by floodplain ponding when the system is imaged during flood season. This definition of centerline may indeed be valid for a river in its upstream headwater reaches where the river is constrained by well defined, and often deep, valleys. It is understood that these river channels in rolling and highly undulating terrain, are generally expected to be rather well defined and the channel floodplain valley and dominant stream flow directions are oriented in a mutually congruous manner. Therefore, thalweg is likely to be a consistent approach as an aid to mark centerline of rivers/streams in the headwater valley reaches.

**Centrelines with Hydrodynamical Basis:**

The centerline may also possibly be defined on the basis of hydrodynamic modelling of flood flows leading also to simulated wetted width. Often, application is restricted to simulation of 1-D, vertically averaged flow velocities and flow depths but, as may be inferred from the schematics of Figures 14, 15, 16 and 17, the flow directions are sensitive to the severity of prevailing flood condition. Clearly, at different flood levels, orientation of flow paths are expected to be different and, as a result, also lending an aspect of dynamism to the orientation of the desired centerline and, as a further consequence, divesting the feature of its integrity as well. This phenomenon is commonly observed in river reaches that are in relatively mildly sloping flood plains and also in distributary systems.

Appropriately, therefore, simulated wetted area corresponding to bankfull discharge may also present itself as the elusive 'consistent' basis for the centerline delineation. Indeed, in fluvial morphology, bankfull discharge together with its connected attribute of bankfull width are important hydro-morpho-dynamic features of river systems as it has been theorized that river channel (cross-section) morphology evolves under the persistent action of this latter flow condition. It is understood, therefore, that centerlines that are mapped based on the simulated 'bankfull' is a valid and consistent approach that can be used for a river along its entire course while, at the same time also presenting important insights about its hydro-geo-morphogenesis.

**Centrelines with Remote Sensing Basis:**

Remotely sensed images of terrestrial features come with the specificity of time and date of image capture. With regards to the task of centreline demarcation, the current practice is to digitize the centreline based on the stream (observed water area) as captured by the satellite and obviously is just a snapshot of an otherwise dynamic wetted stream channel. Since these images are acquired at different times of the year, the centreline can be assumed to be representation of the flow direction in the river at flows as on the date of image capture. Consistency in inferences is clearly compromised as the wet channel may correspond to a specific flow event that was captured in the image and could reflect a hydrological reality across a very broad spectrum of plausible flow conditions.

As an example, an image acquired during the monsoon season may be a precise capture of bankfull conditions or alternatively, may correspond to a relatively more extreme flood event with its water spread extending across a wider expanse. As highlighted in the aforementioned discussion, **bankfull conditions** are indeed of particular interest and, within a very restricted context, may also give a sense of general flow direction in the river during this near median event and may provide a **contextually relevant as well as a consistent** basis for centreline demarcation. However, demarcation of centreline based on the 'bankfull' concept does present issues that may bedevil river morphologists. The challenges that are likely to be encountered with this approach arise as a consequence of the following factors:

(i) Bankfull condition alludes to an integrated outcome of interplay between hydrologic exceedance, hydrodynamic transport attributes of flow and eroded material, contrasts between bank and floodplain vegetation morphology, morphometric attributes of river channel cross section etc.

(ii) Inferences based on examination of remotely sensed images remain conjectural in the absence of a comprehensive field campaign dedicated to site visits and supported by a detailed evaluation of the aforementioned attributes. In most cases capture of ground truths is not possible without a dedicated and patient field based observation study.

(iii) Non-availability of hydro-meteorological data has often been a bane of studies of this nature. These data are required to establish occurrence of bankfull discharge in terms of the average event recurrence interval as well as the specific dates of occurrence, if possible, from the available record.

(iv) Corroboration of these results with corresponding ground features captured in actual images for that day, month and year is often difficult as occurrence of such events is understandably restricted to the monsoon period. Presence of cloud cover, that masks the ground features of interest, is indeed a normal occurrence for this period of the year and this reality poses a challenge when attempting to extract morphometric features from these images.

(v) River cross section details and changes in them over time are either not available or, at best, scarce. Often, river cross section surveys are carried out without due diligence and, as a result, these important river morphometric details are rendered largely unusable.

(vi) The alternative presented by images captured in non-monsoon periods when the sky is expected to be essentially cloud free, presents different kinds of challenges. An important feature often seen in these images in the case of many rivers is the presumed channel area as sensed in the form of extensive sand beds that are characterized by relatively high reflectance. In hope that the region of visible sand area and inferred as the designated stream channel under bankfull conditions presents a convenient paradigm for centreline delineation. However, it is indeed open to debate whether the entire extent of these sand deposits also matches precisely with the water channel that will develop in response to the near median flow event!! In this regard, it is indeed possible, especially under various conditions of channel course stability as have been discussed in the aforementioned sections, the actual stream channel may indeed occupy only a part of the identified field of sand deposits under bankfull conditions. Alternatively, it is also possible that part of the sand field, as captured by the available images may indeed include **abandoned** or **recently vacated, but often temporarily**, channel course.

(vii) Often it has been known in India that migrating populations, in the absence of a formally designated resettlement zones, begin to occupy easily available channel areas. Interestingly, the observed pattern of these settlements see and the occupation is not just limited to occupation of vast tracks of river flood plains but also the ephemeral sand

bars that are commonly found within river corridors. Understandably, with expanding habitation clusters, Agriculture often becomes the principal occupation of the migrant settlers. With time, the occupied channel areas acquire a distinct vegetative cover which alters the reflectance characteristics of the tracts from the previously high values that are normally associated with a bare sand cover. As a result, the (mis)inferred course of the river channel shows a divergence, and may often be large, from the actual channel which in turn leads to an orientation of the centreline feature that is likely to be gross and unrepresentative.

(viii) It is acknowledged that remote sensing products are a source of abundant geophysical data of pertaining to various surface and near-surface aspects of hydrogeomorphological features of the imaged region. However, it is also important to understand that satellites capture just the static snapshot of the otherwise dynamic geomorphic system. Expectedly, therefore, these remotely sensed images cannot explain the dynamics of the system. Accordingly, researchers and other interested investigators need to use patience, cautious judgement and prudence when seeking to attribute any physical meaning to the features extracted from these imageries.

**Multiple Thread (stream) Systems:**

The following discussion features aspects pertaining to two special configurations namely:

a. Braided rivers

b. Anastomosing (anabranching) rivers

Braided rivers are highly dynamic and during a given length of duration, the streams may alternately occupy, abandon and reoccupy different single or multiple segments of the available channel corridor. While the commonly followed practice for centreline delineation is to select only the widest stream (water area), there is however a need for sufficient caution. Centreline delineation based on the widest stream (stream 1 in Figure 29) might lead to a later misjudgement that on the date the image was captured, flow was taking place only in that (single) thread and, in the foreseeable future, if the other stream (stream 2 in Figure 17) gets wider, this could lead to a potentially damaging inference that the river has shifted course and comes with potentially grave ramifications with regards to any future water management proposal for this system.

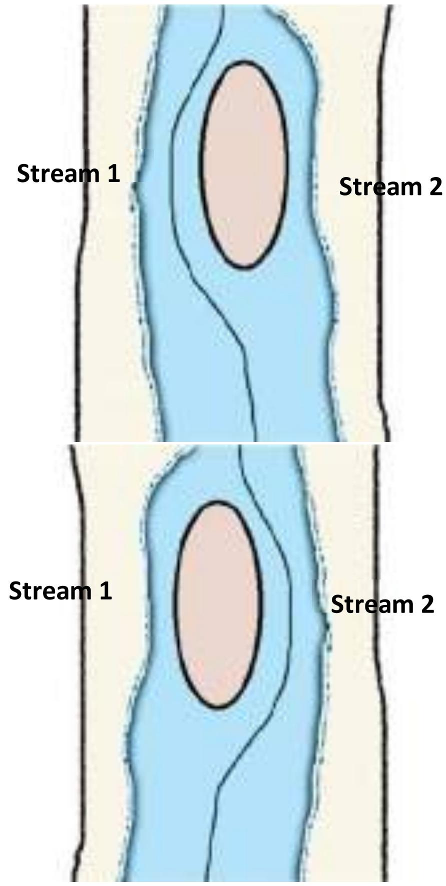



Figure 29: Braided rivers

In braided rivers, the position of the river system, defined in terms of its multiple active as well as currently unoccupied, streams must therefore be identified by marking out, at the very least, **all the occupied threads with corresponding multiple centerlines that pass through each occupied thread**. This obviously will also capture the hydrodynamic reality of flood flow movement in this river system. With regards to images available for the dry (low flow seasons), it therefore is logical to mark all the evident channel threads, including the unoccupied, dry sandy threads. Multiple channels can indeed be marked in a low flow image based on the presence of old sandbars, showing up with their characteristic vegetated or low reflectance signature, and/or river islands, if any. In the absence of these features, the river must be treated as a single stream system which, importantly, is also in accordance with the definition of braided rivers. Similar concept is also expected to work for **anastomosing or anabranching** systems.

## CASE STUDIES:

### CASE 1: Yamuna River

Yamuna is amongst the larger river systems in India and is under current scrutiny on account of the scale of abstraction of its waters for off-stream use and also its impaired water quality. It is observed that downstream of the now defunct Tajewala diversion facility, Yamuna remains dry or is in a near dry state (Figure 9) for some distance before getting replenished by seasonal tributary streams as well as on account of groundwater accruals (Figure 10).

Generally, the river rarely carries very little of its bankfull discharge and the braid like features that are observable (see also Figure 30) might be due to channel occupation by the river with that little flow (Figure 30). In the latter figure 30, the channel area occupation for agricultural landholdings is also clearly visible. The approximate channel and river centerline.


Figure 30: Yamuna River d/s of Hathinikund barrage.

Obviously, with changes in flows, as is inevitable, corresponding changes in the wet channel area are indeed natural. For example, increase in the water area is clearly evident from a comparison between Figures 31 (segment shown as reach 1 is also shown in Figure 7) and 32. Clearly, it follows, that if it is required to use the delineated centerline feature as a basis to calculate the shift in the course of the river channel, use of its wet stream channel is likely to lead to inconsistent and misleading inferences.


Figure 31: Yamuna River u/s of Paonta Sahib.


Figure 32: Yamuna u/s of Paonta Sahib (Imagery of different date).

## IS THERE A WAY FORWARD?

In view of the aforementioned discussion, it is clear that in deference to the underlying hydromorphological multi-scale non-stationarity that is abundantly evident in typical river systems, specification of the **river centreline must only be contextual** and whatever methodology is adopted and whichever context is specified, the same procedure must find a consistent application in order to avoid confusing and possibly conflicting inferences. In order to further illustrate the issues discussed, and as a possible way forward, the centreline may be estimated (or marked) on the basis of any one or more of the various, but context specific, considerations.

### REFERENCE TEMPLATE

From the foregoing discussion, the spatio-temporal non-stationarity of any given river system is an immutable reality and for ease of capture as well as an unambiguous and consistent numerical comparison of the state of its various dynamic attributes is indeed important. For this purpose, a reference frame comprising of a system of meridional and latitudinal lines that enclose a square grid of pre-specified scale and relationship with the geographical coordinate system is proposed to be used as shown below in alternate forms as Figures 33 and 34. The addition of the river channel along with accompanying details are shown for illustration purposes in Figures 35 and 36. It is expected that this grid based reference template will be better able to capture river plan forms and changes in these forms as observed from one timeline to the next available capture. The use of this grid based system will be separately prescribed and communicated.

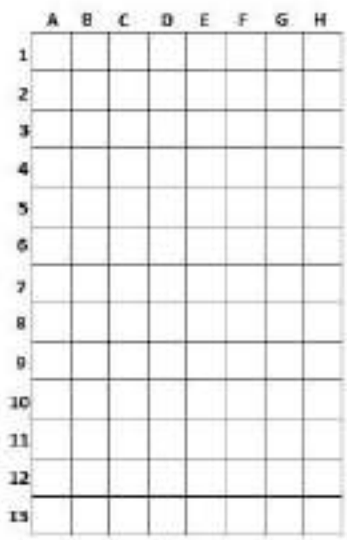



Figure 33: Reference Template (1)

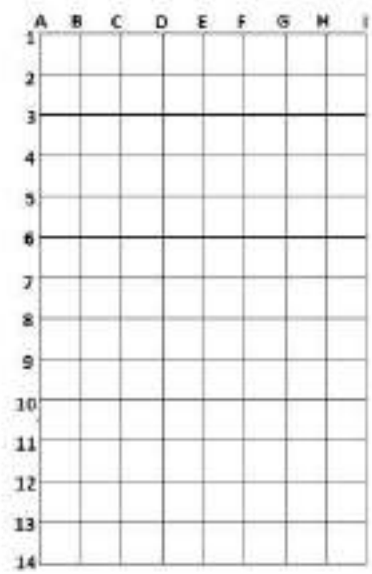



Figure 34: Reference Template (2)

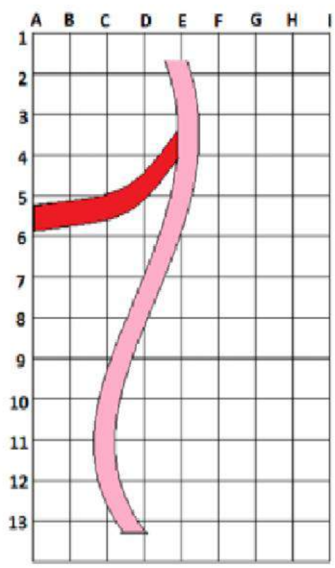



Figure 35: Reference Template

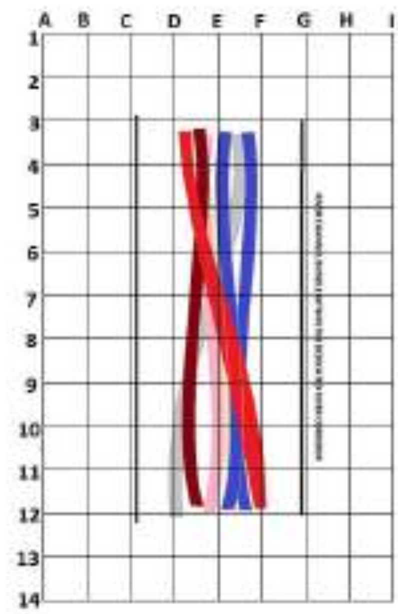



Figure 36: Reference Template

**THE BIG QUESTION: HOW CAN A CENTRELINE BE DEMARCATED FOR AN ESSENTIALLY MULTIPLEX MORPHOLOGICAL ENTITY?**

The discussion so far seems to lend weight to the hypothesis that, in general, any given river system is anything but intransigent and the position of its observed course over a given, but within a limited span, observational window is just a fleeting reality.

The relentlessness of underlying autocyclic as well as, to some extent allocyclic, triggers is a common and acknowledged reality facing all river systems. However, there indeed are differences in the scale of time, or morphometric epochs, over which these individual systems are observed to occupy a given state (for example, a river channel's course) between successive concomitant paired events of channel abandonment and a spontaneous and perhaps a simultaneous occupation of a newer one. Thus, rivers may differ in terms of (i) scale of changes that are observed, (ii) pace at which such transitions are seen to occur in them, (iii) length of the reach seen to be most vulnerable, and also (iv) time span over which transit in (or over) a given state is observed prior to its abandonment. It therefore merits mention that in addition to the strength of the underlying allocyclic and autocyclic, the duration of these latter transits are also controlled by the scale of morphological restraints and, importantly, by anthropogenic considerations.

**The way forward**

**A.** A consistent and appropriately calibrated reference system shown as Figure 33 or 34 should serve as the basic template on which geo-referenced morphological entities can be mapped to scale together with a priori specified important attributes and corresponding chronology.

**B.** With regards to the task of delineation of the specific attribute of the river centreline, the latter feature should be captured in terms of its **<u>entire range</u>** of possible morphological facets. For example:

- **(i)** Centreline corresponding to bankfull width.
- **(ii)** Centreline of all continuous (uninterrupted) wet channels in the case of braided and ephemeral reaches.
- **(iii)** In the case of dry reaches, centerline should be obtained for all discernible but 'plausible' channel trails as captured in terms of a sharp contrast in observed reflectance values between sand deposits, as an evidence of possibly consistent but intermittent stream pathways, and off piste regions beyond.
- **(iv)** Centreline between the edges of active floodplain on either side of the observed river course regardless of the extent of the observed wetted channel width.

**C.** Features captured on the reference template should also include numbered address (preferably a numerical bearing) of crossings of the mapped morphological entities with grid lines corresponding to each snap shot in time.

**D.** This will facilitate:

- **(i)** Easy referencing
- **(ii)** Mapping of timeline of changes from one image to the next in chronology
- **(iii)** Some basic operations on the reference templates to model the captured transient nature of the underlying physical system and their rates along the entire timeline of interest.

# ANNEXURE II:

# Erosion/ Deposition Maps

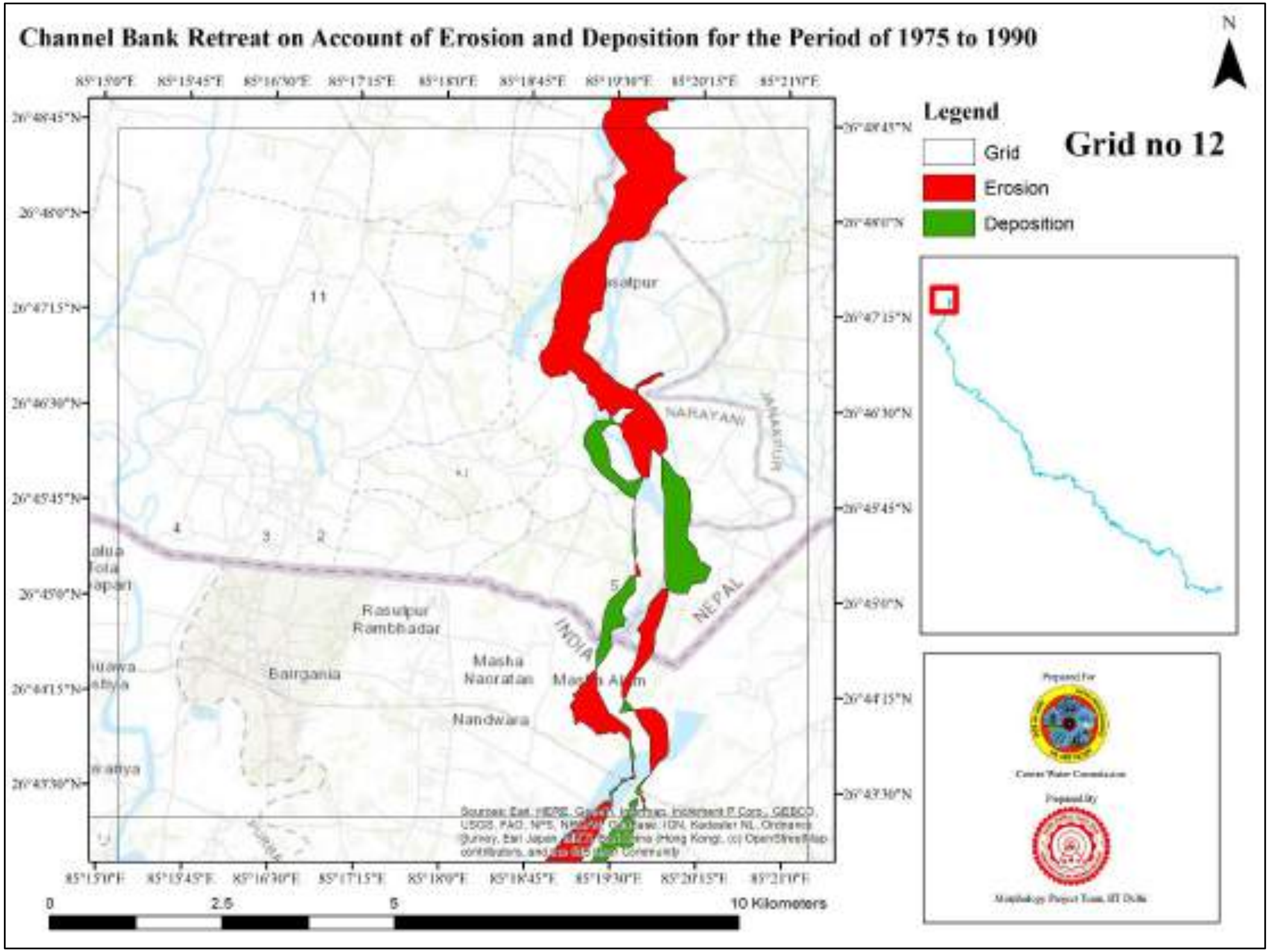



Figure **Error! No text of specified style in document.**-1: Erosion/Deposition Map of Bagmati River for Grid 12 for year (1975-1990)

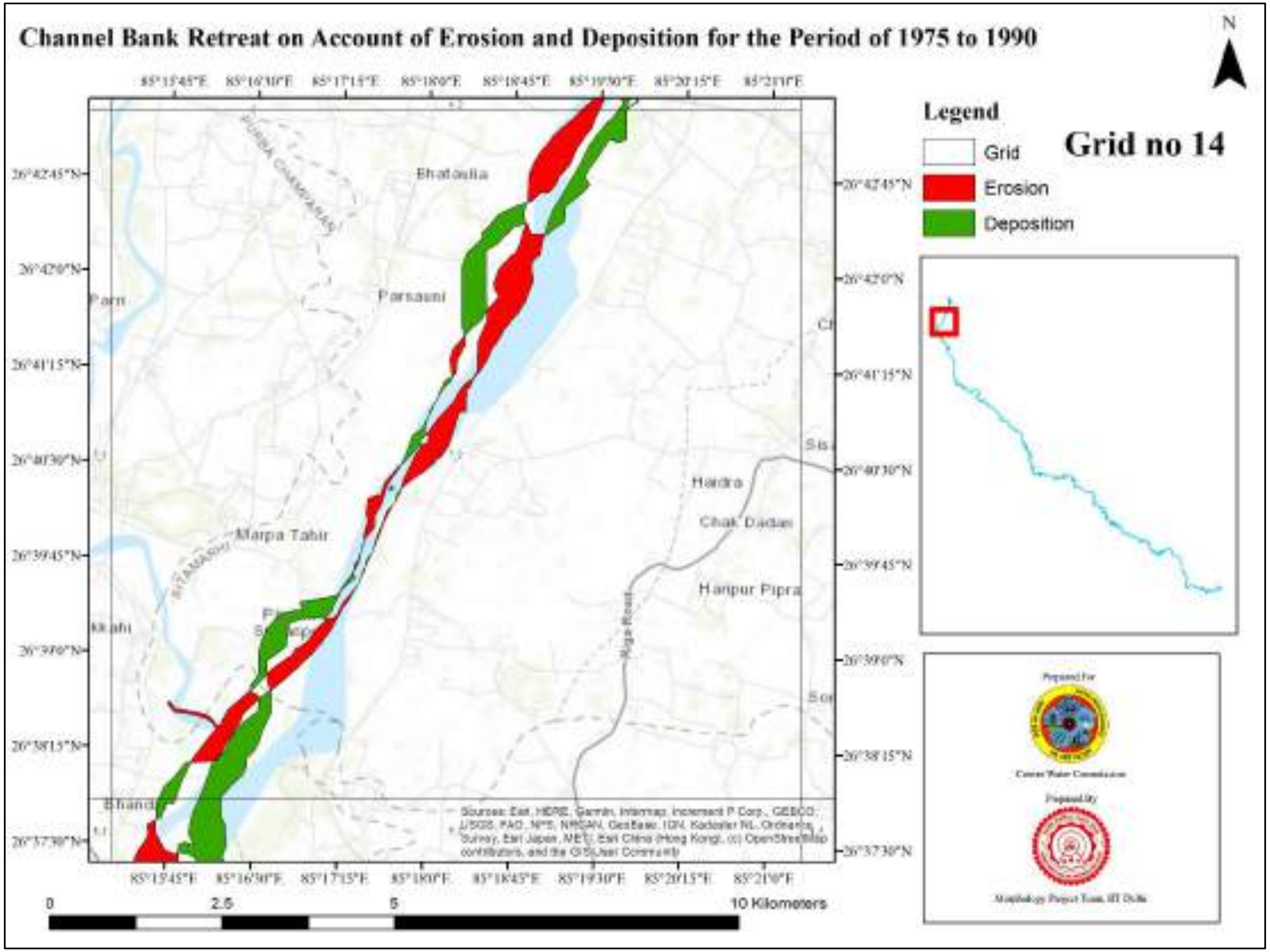



Figure **Error! No text of specified style in document.**-2: Erosion/Deposition Map of Bagmati River for Grid 14 for year (1975-1990)

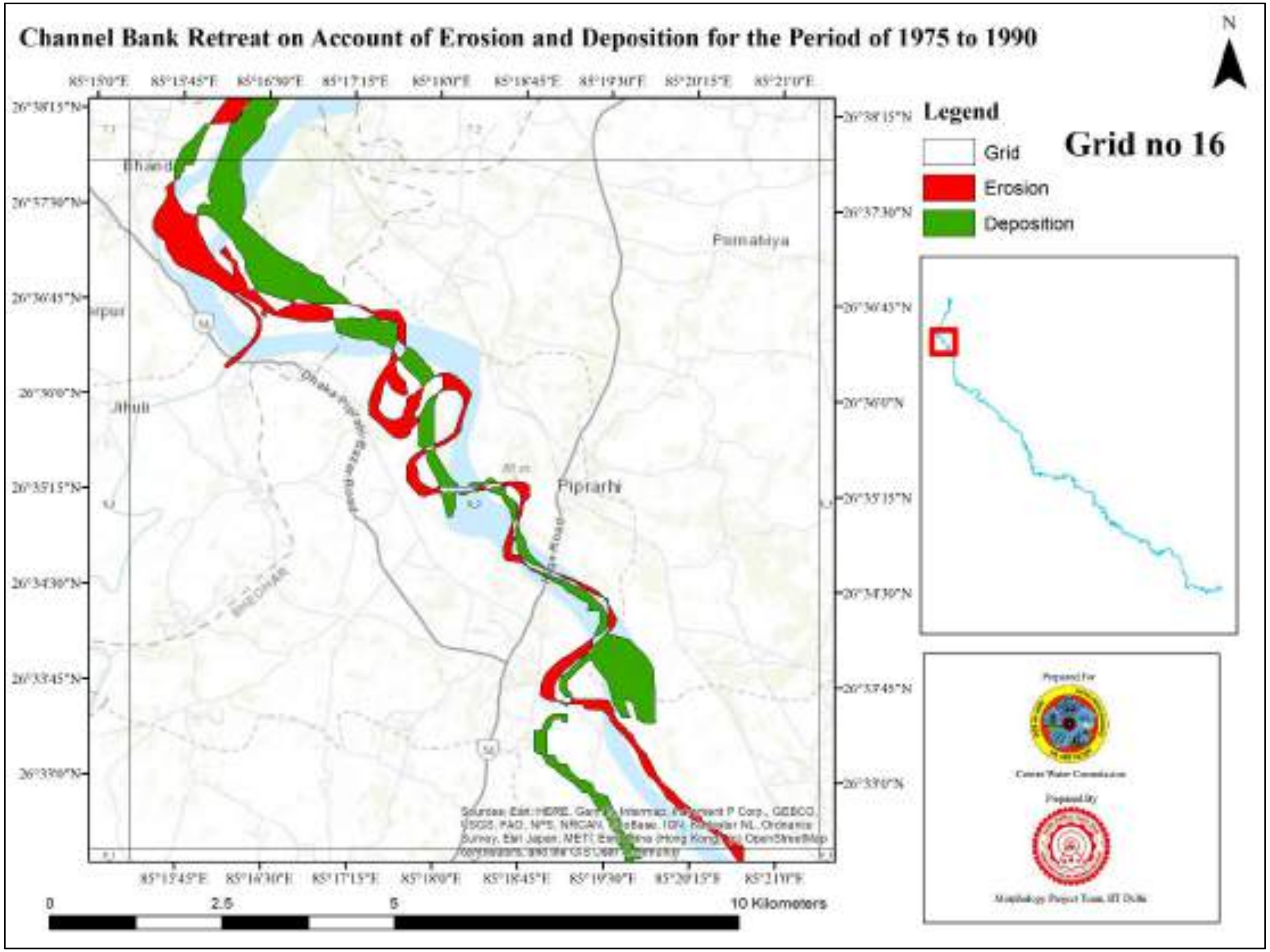



Figure **Error! No text of specified style in document.**-3: Erosion/Deposition Map of Bagmati River for Grid 16 for year (1975-1990)

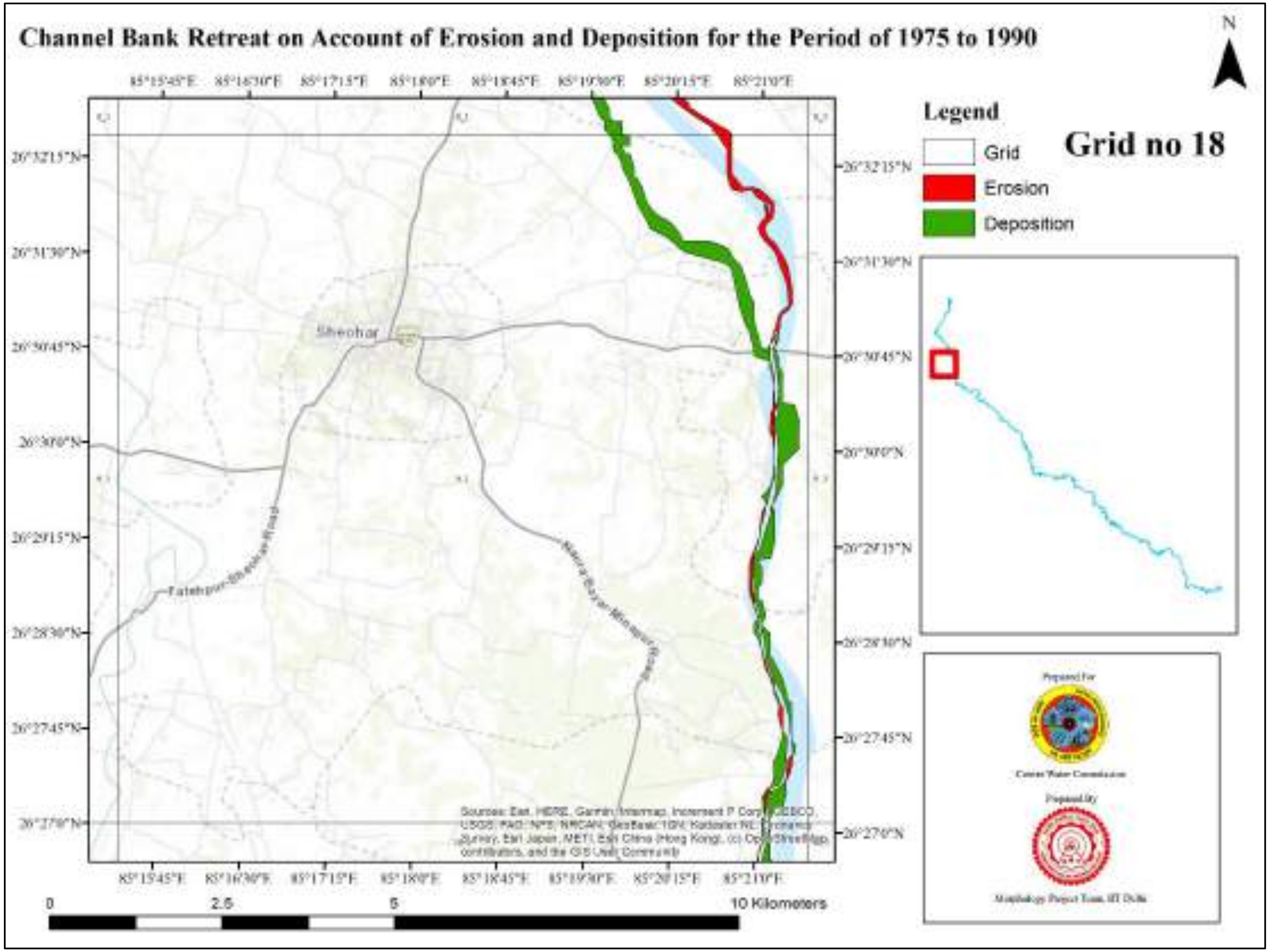



Figure **Error! No text of specified style in document.**-4: Erosion/Deposition Map of Bagmati River for Grid 18 for year (1975-1990)

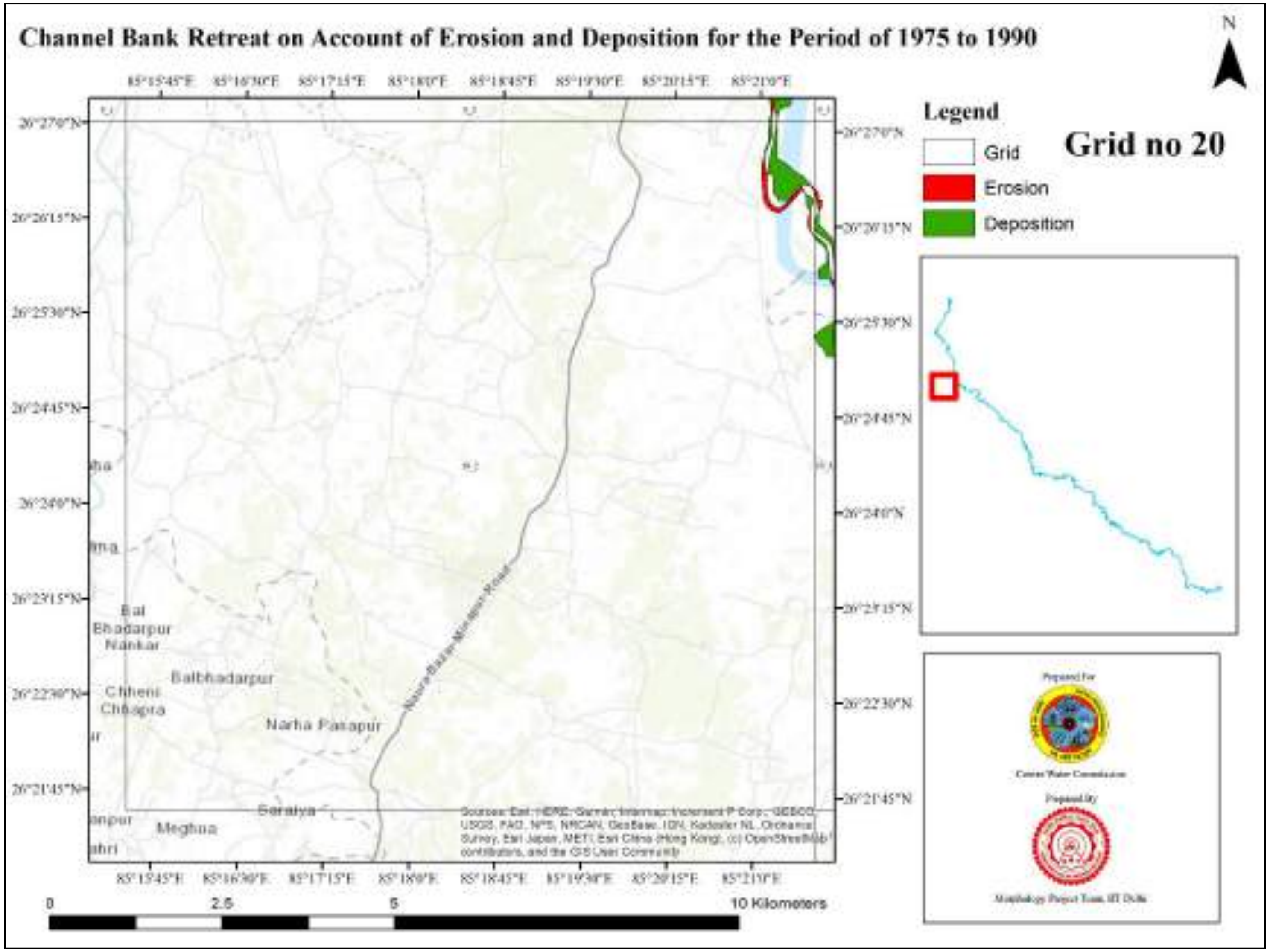



Figure **Error! No text of specified style in document.**-5: Erosion/Deposition Map of Bagmati River for Grid 20 for year (1975-1990)

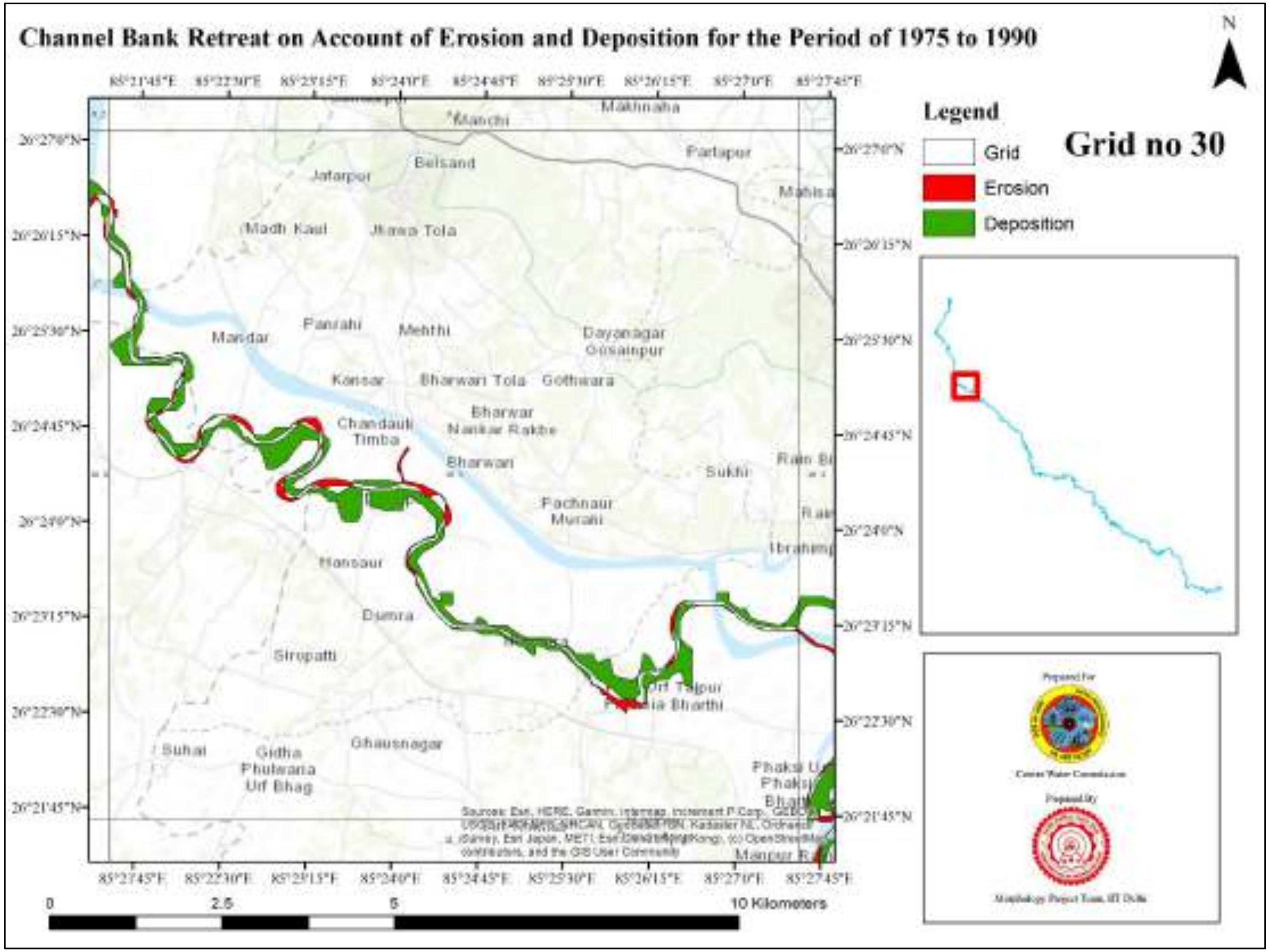



Figure **Error! No text of specified style in document.**-6: Erosion/Deposition Map of Bagmati River for Grid 30 for year (1975-1990)

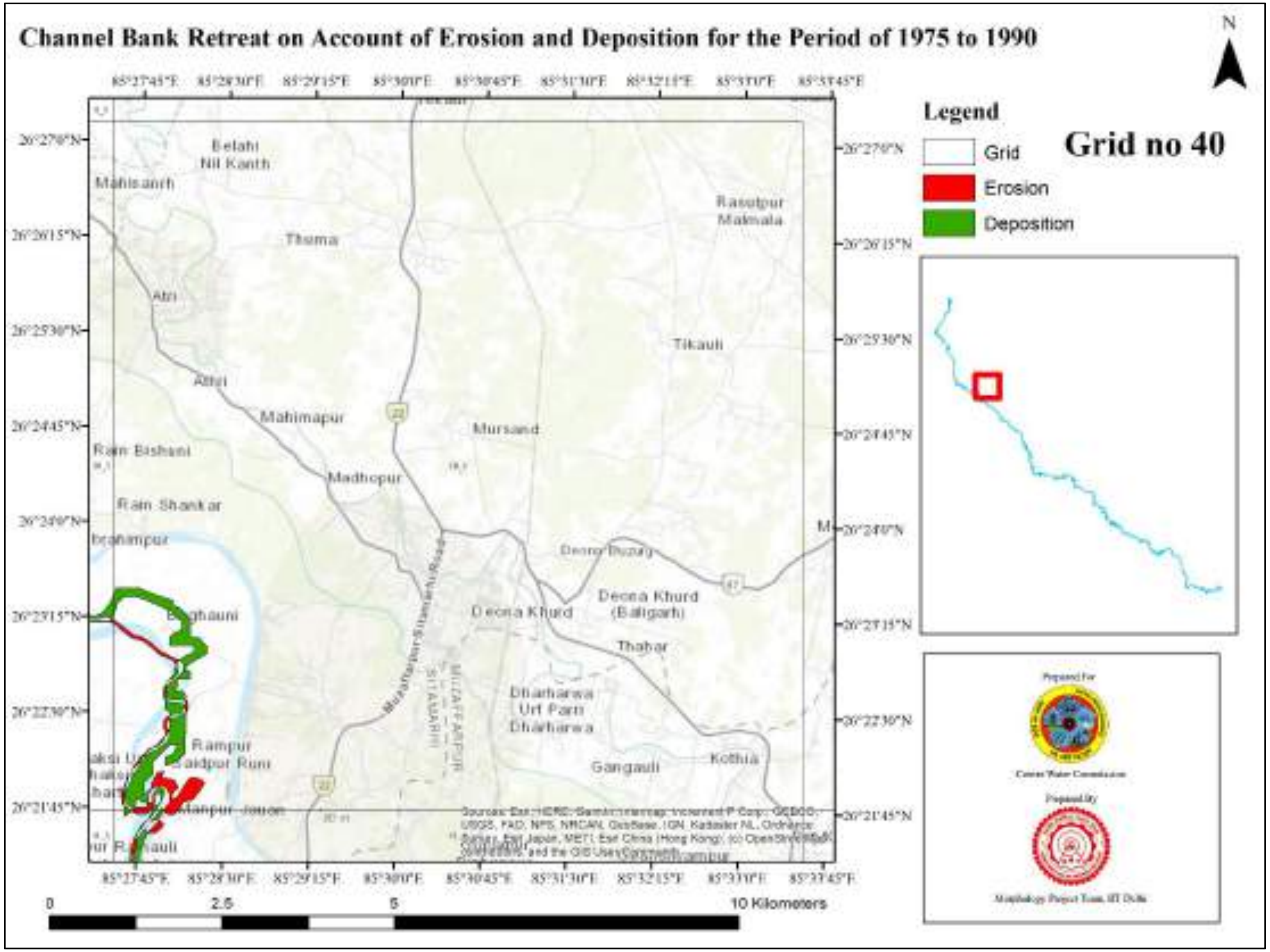



Figure **Error! No text of specified style in document.**-7: Erosion/Deposition Map of Bagmati River for Grid 40 for year (1975-1990)

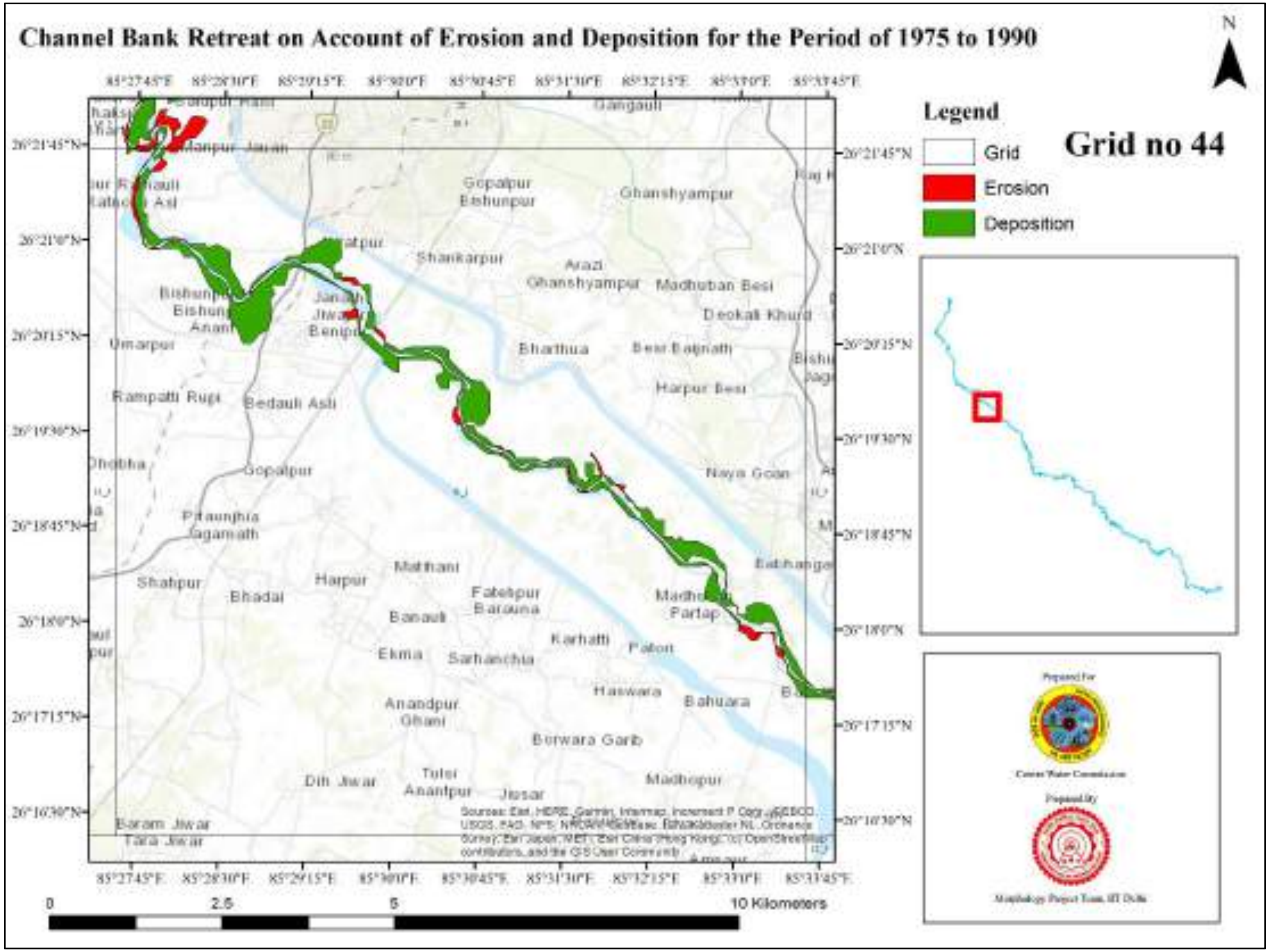



Figure **Error! No text of specified style in document.**-8: Erosion/Deposition Map of Bagmati River for Grid 44 for year (1975-1990)

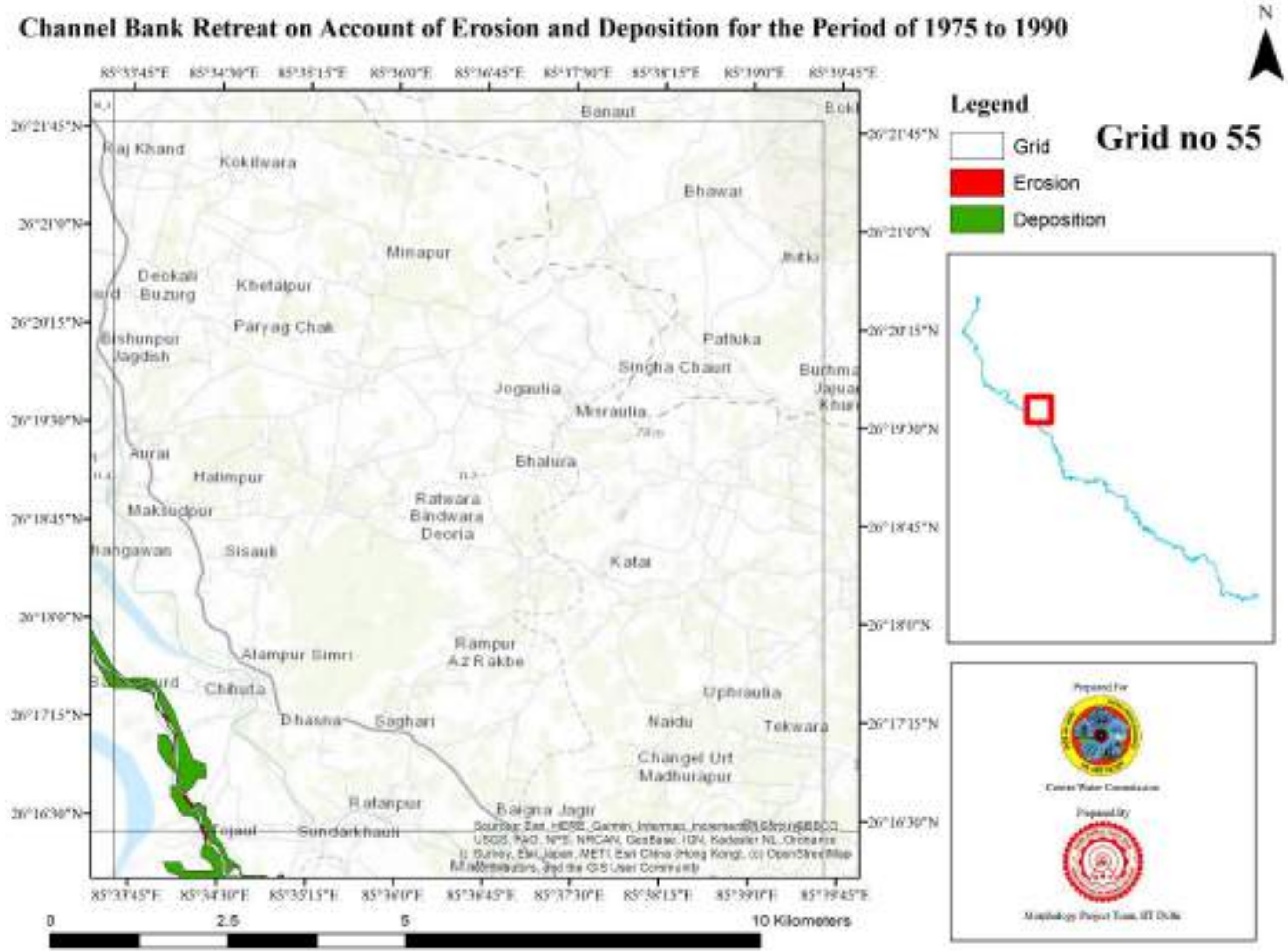



Figure **Error! No text of specified style in document.**-9: Erosion/Deposition Map of Bagmati River for Grid 55 for year (1975-1990)

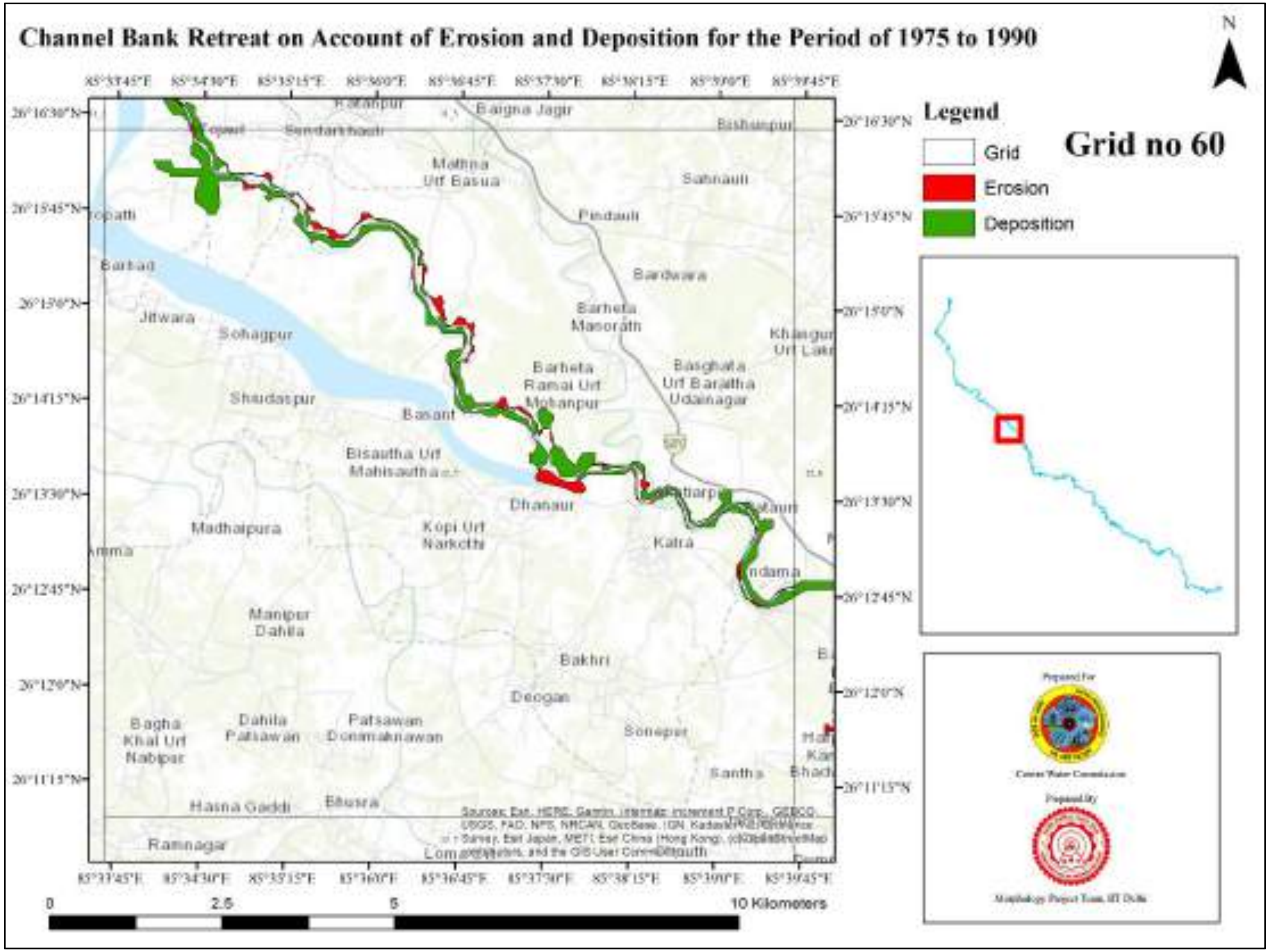



Figure **Error! No text of specified style in document.**-20: Erosion/Deposition Map of Bagmati River for Grid 60 for year (1975-1990)

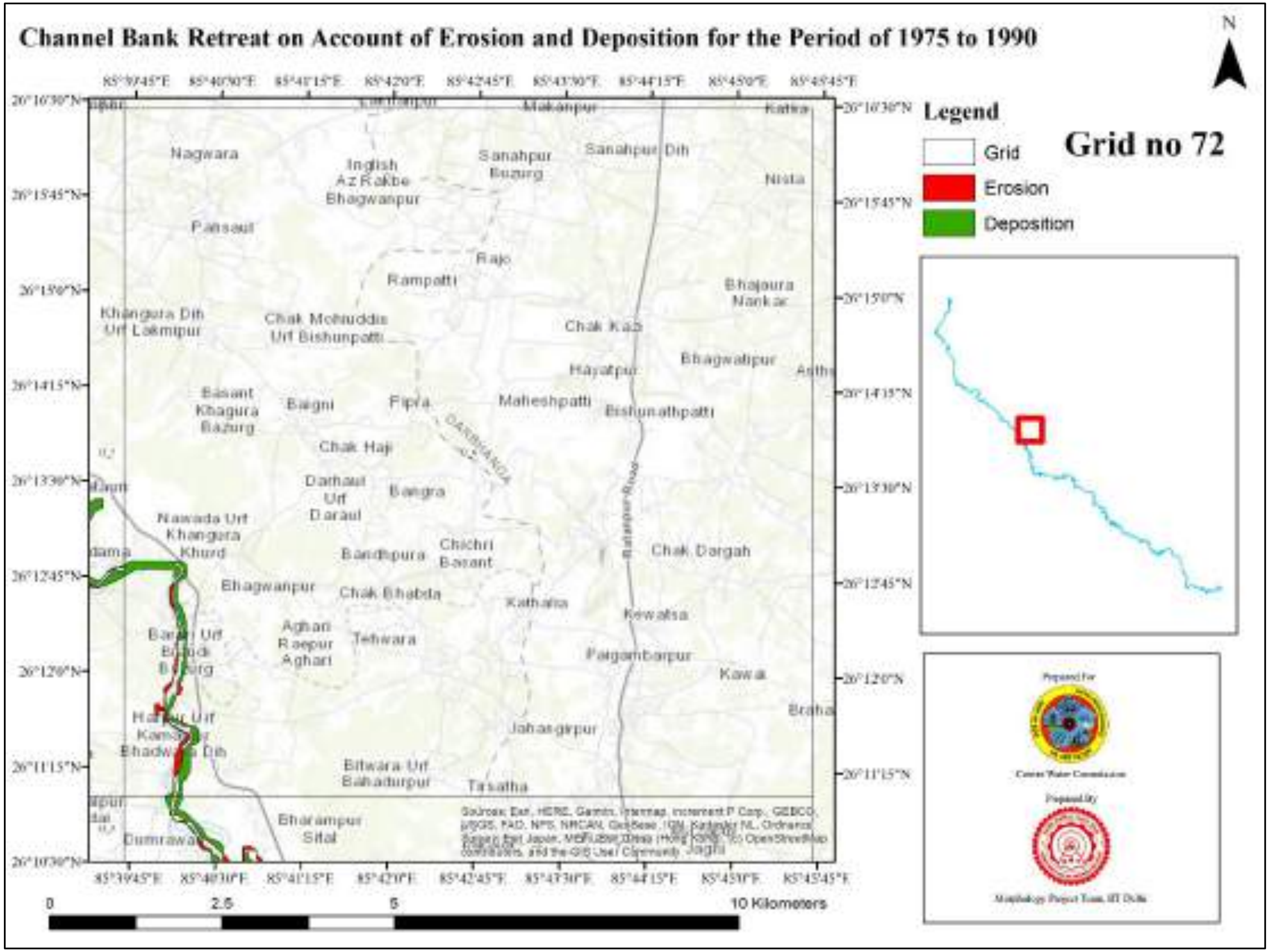



Figure **Error! No text of specified style in document.**-31: Erosion/Deposition Map of Bagmati River for Grid 72 for year (1975-1990)

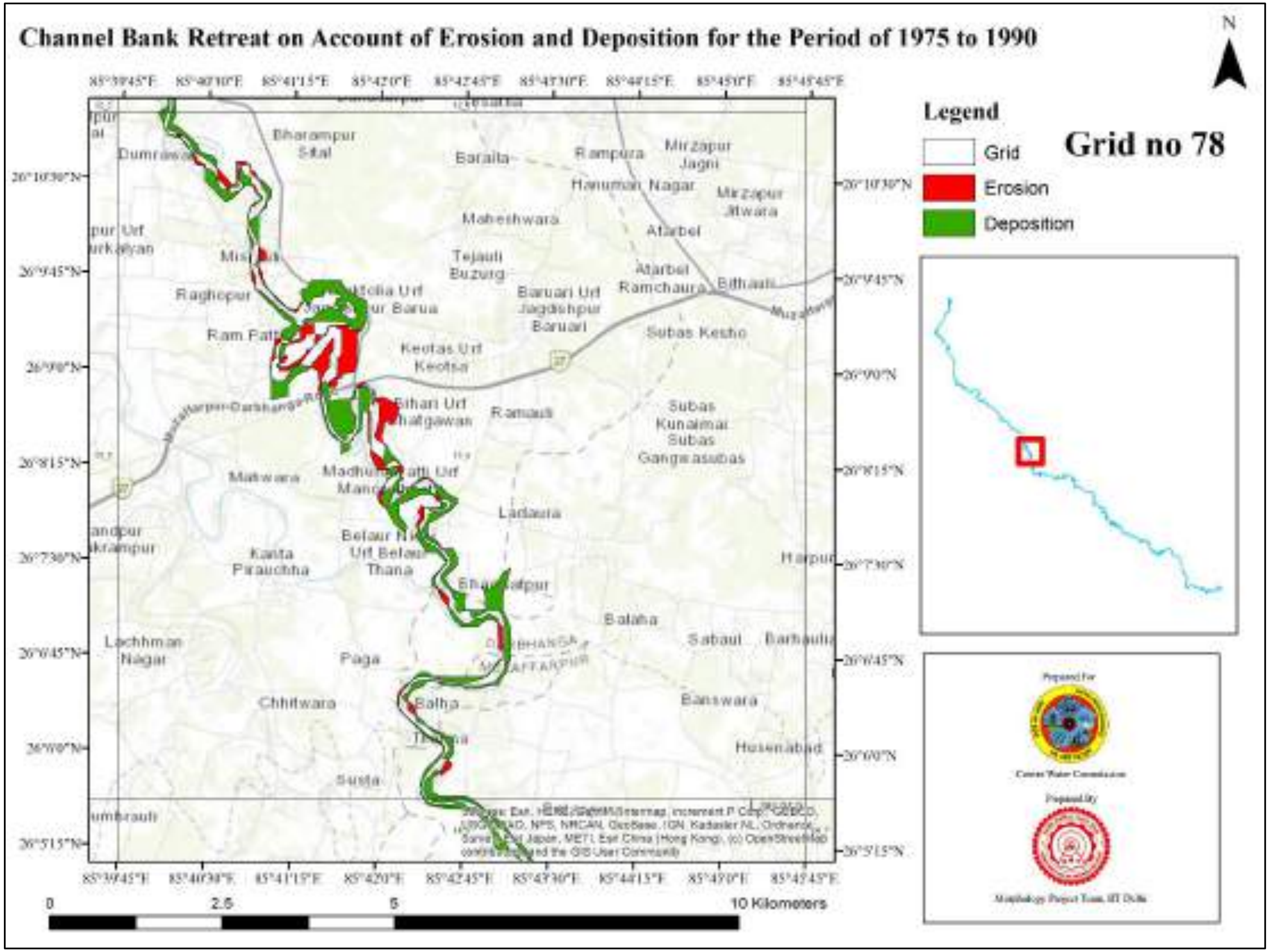



Figure **Error! No text of specified style in document.**-42: Erosion/Deposition Map of Bagmati River for Grid 78 for year (1975-1990)

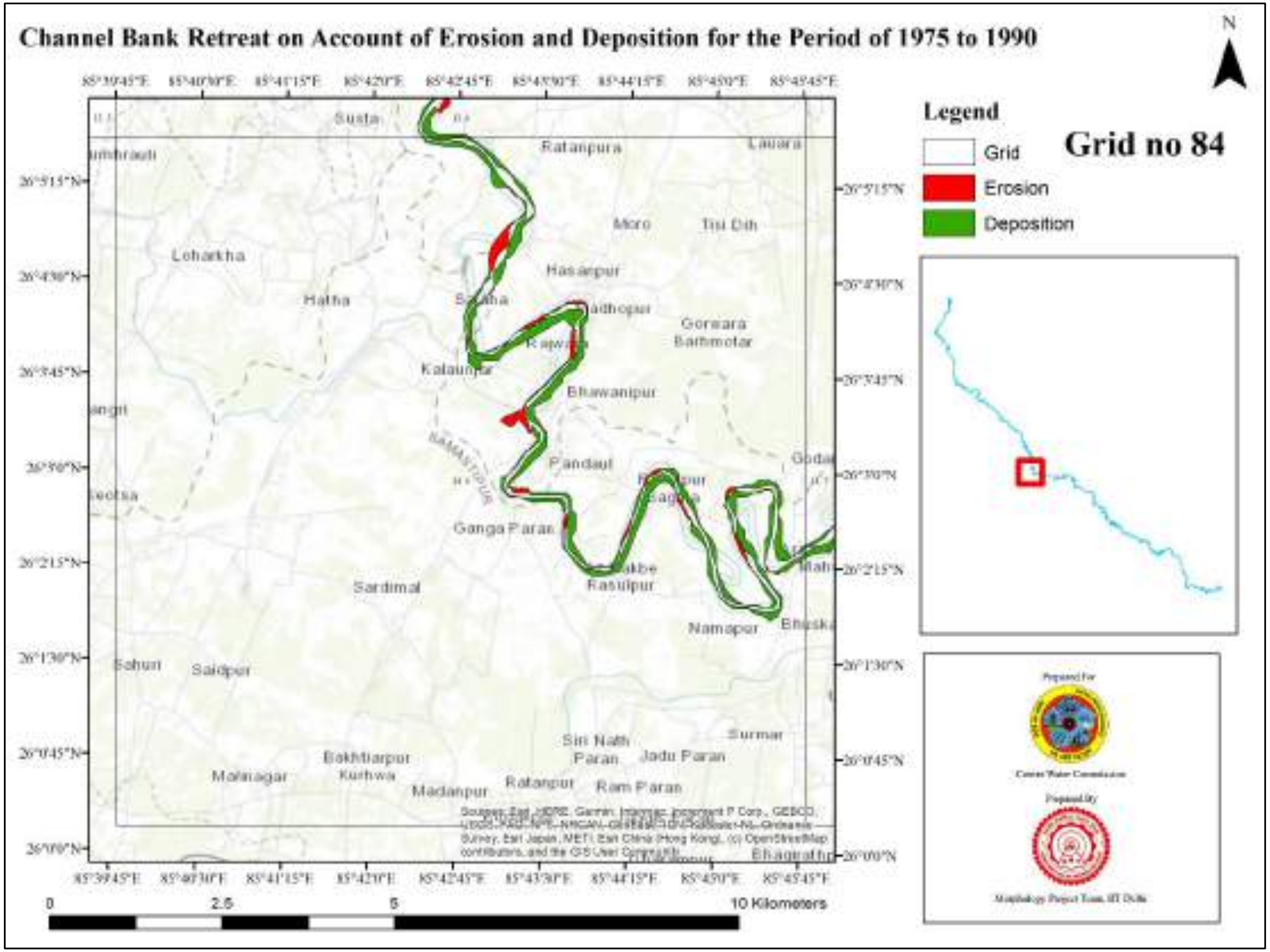



Figure **Error! No text of specified style in document.**-55: Erosion/Deposition Map of Bagmati River for Grid 84 for year (1975-1990)

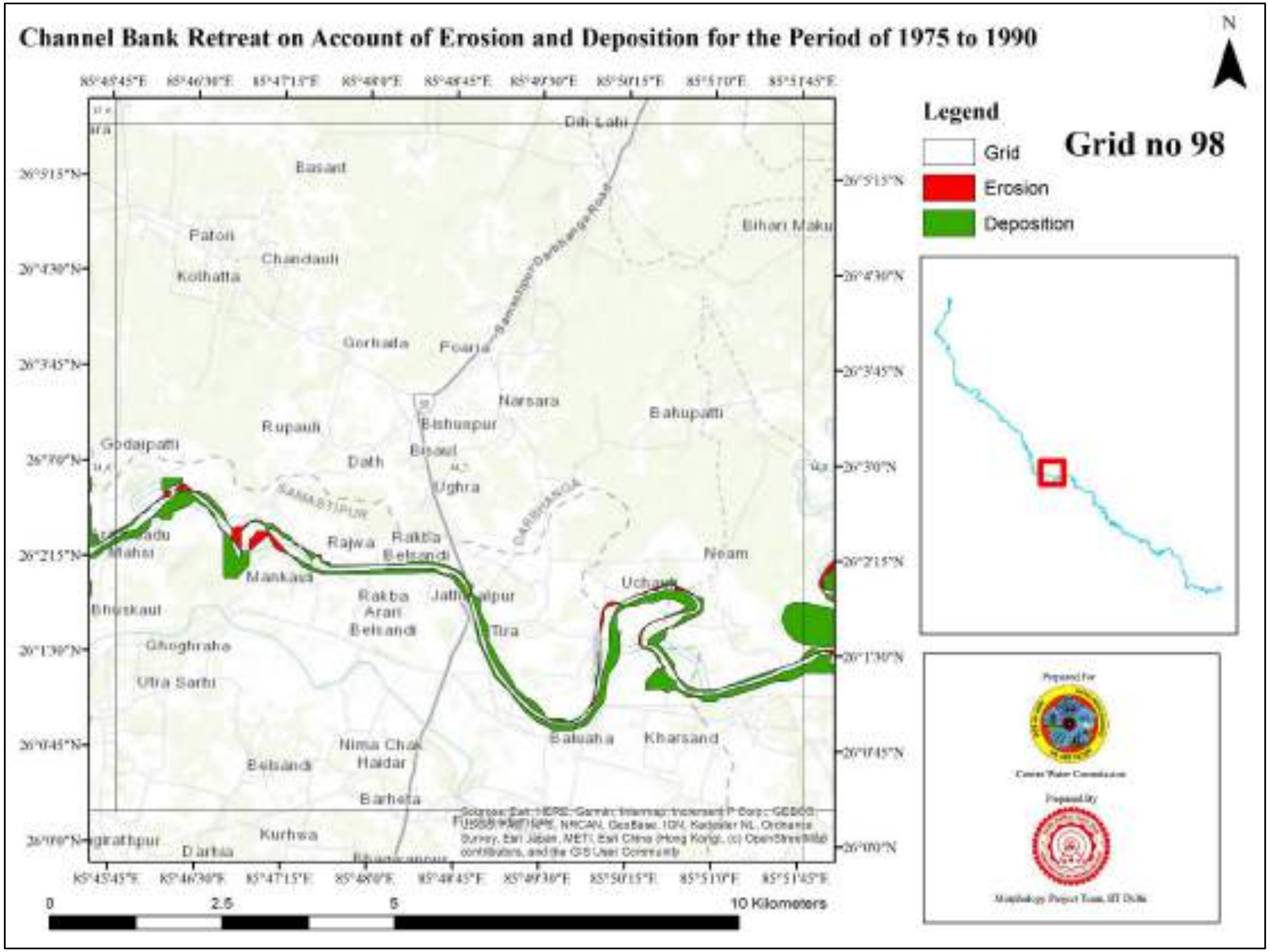



Figure **Error! No text of specified style in document.**-66: Erosion/Deposition Map of Bagmati River for Grid 98 for year (1975-1990)

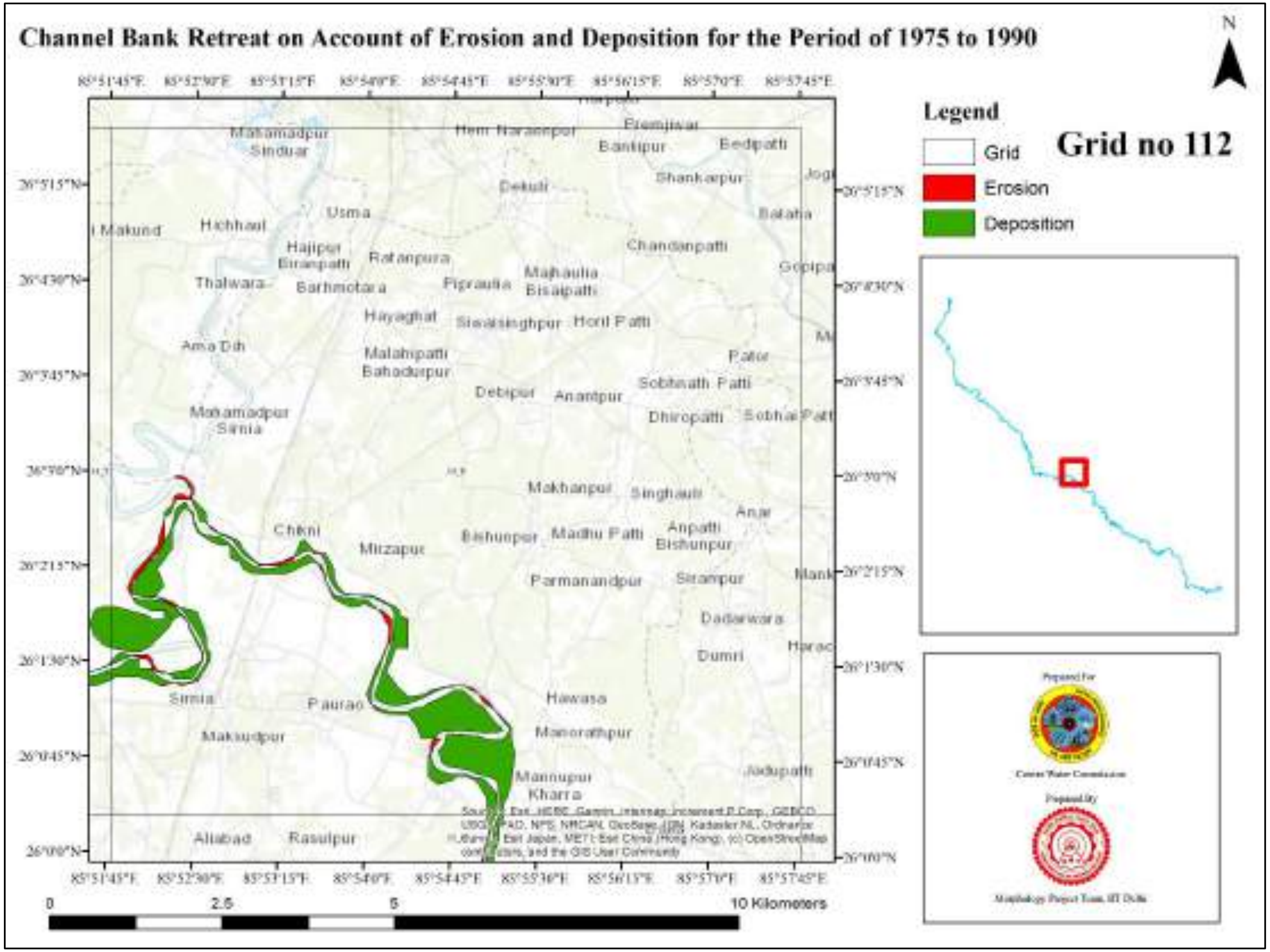



Figure **Error! No text of specified style in document.**-77: Erosion/Deposition Map of Bagmati River for Grid 112 for year (1975-1990)

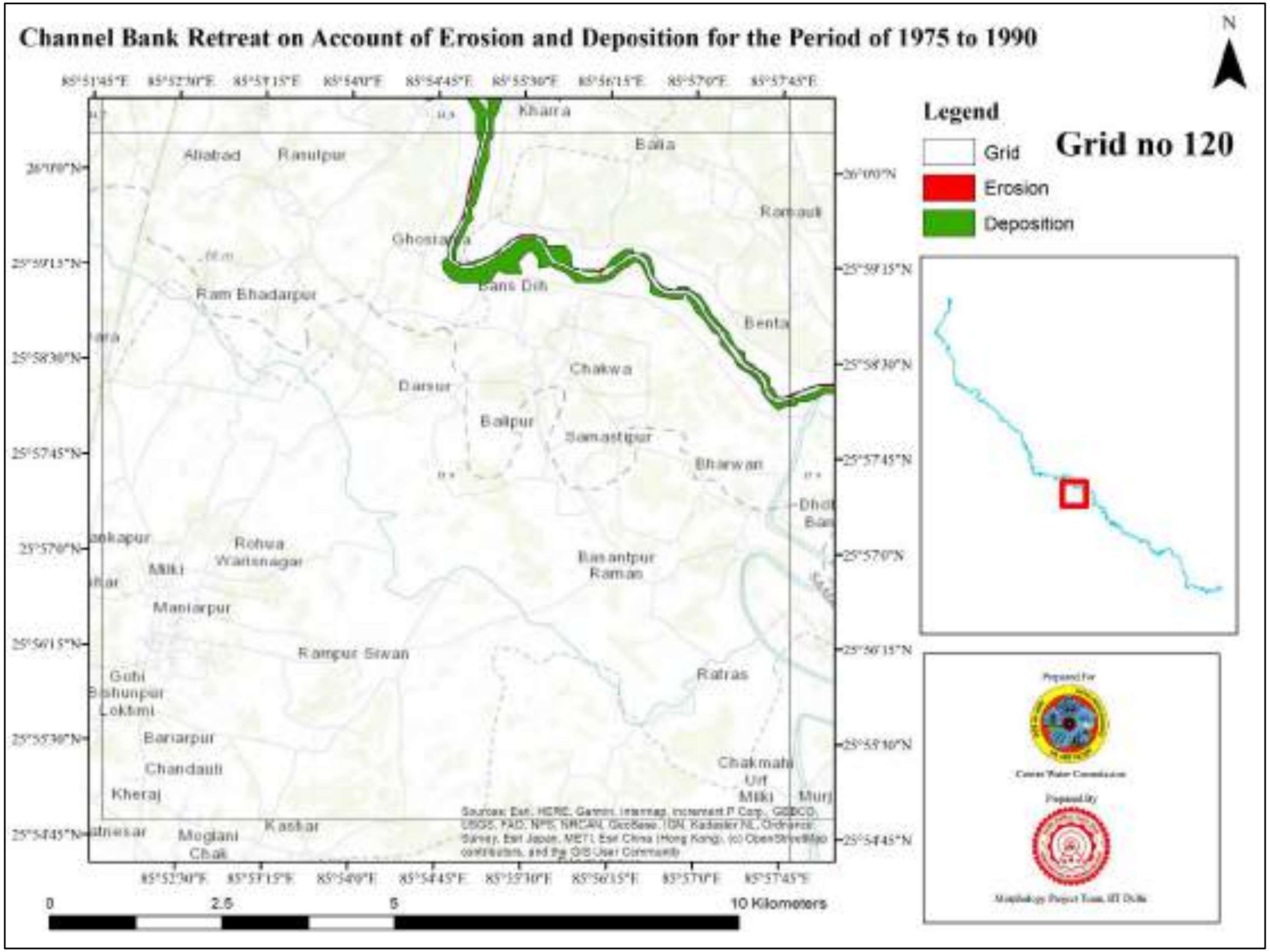



Figure **Error! No text of specified style in document.**-88: Erosion/Deposition Map of Bagmati River for Grid 120 for year (1975-1990)

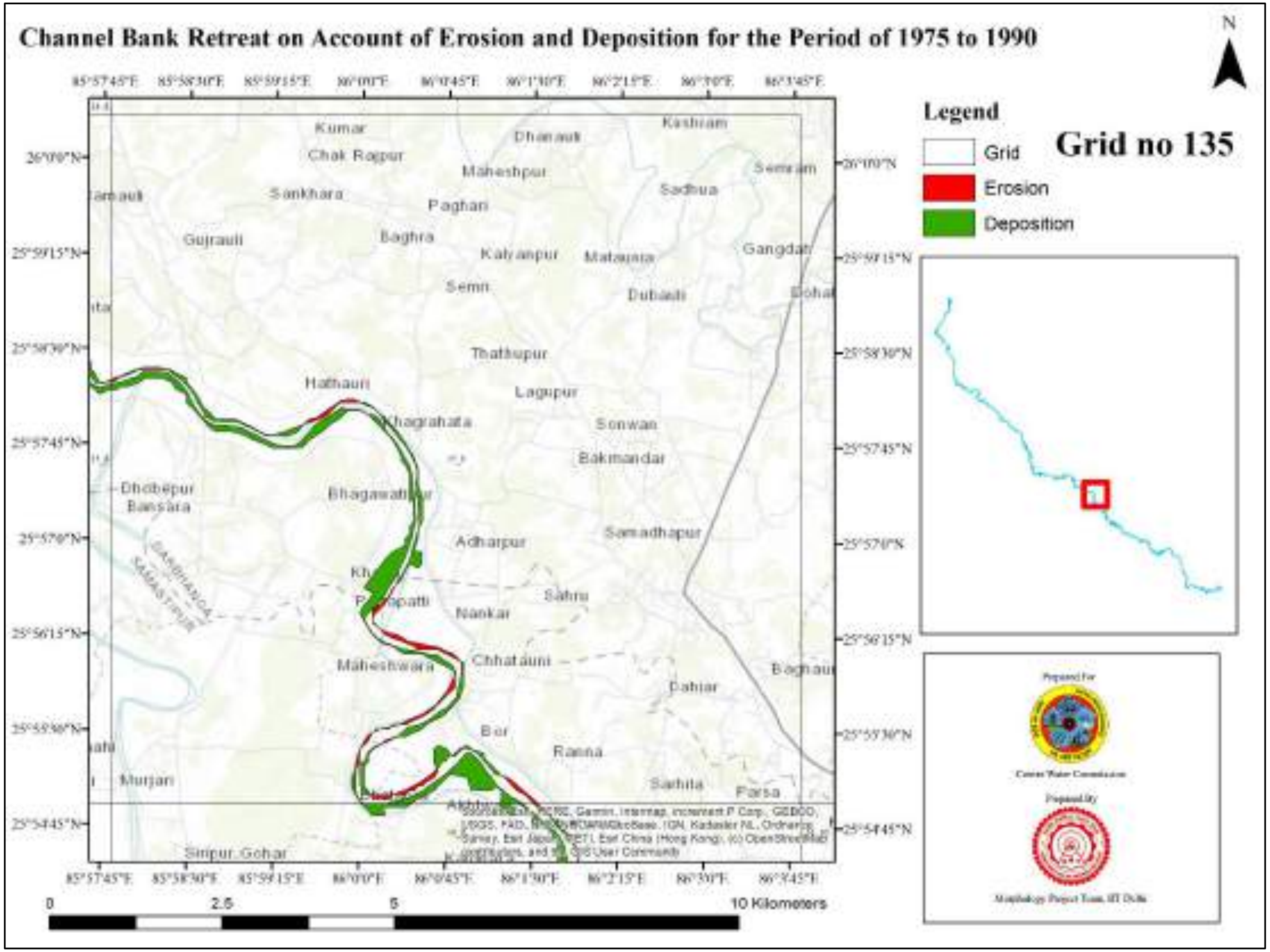



Figure **Error! No text of specified style in document.**-99: Erosion/Deposition Map of Bagmati River for Grid 135 for year (1975-1990)

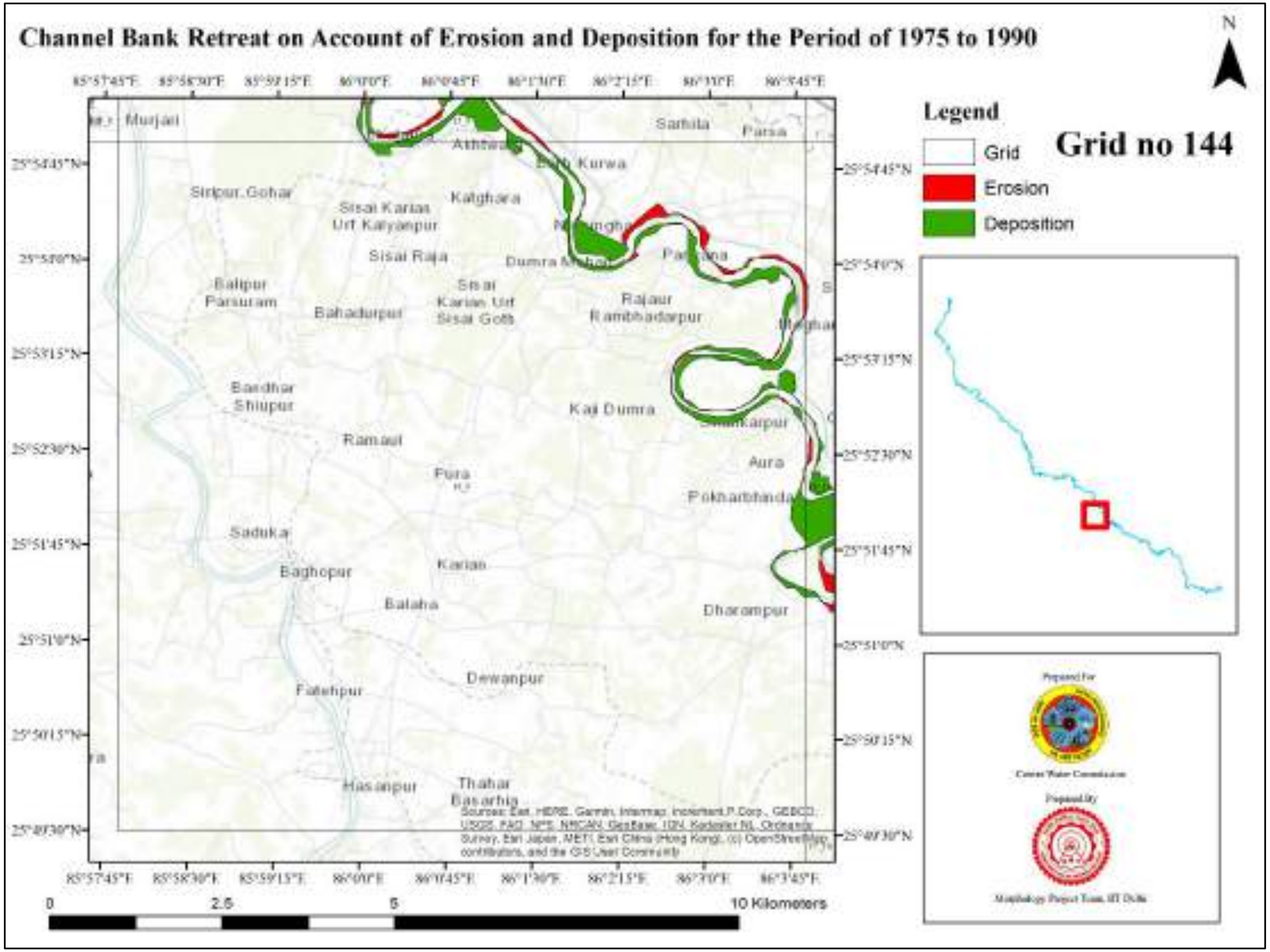



Figure **Error! No text of specified style in document.**-20: Erosion/Deposition Map of Bagmati River for Grid 144 for year (1975-1990)

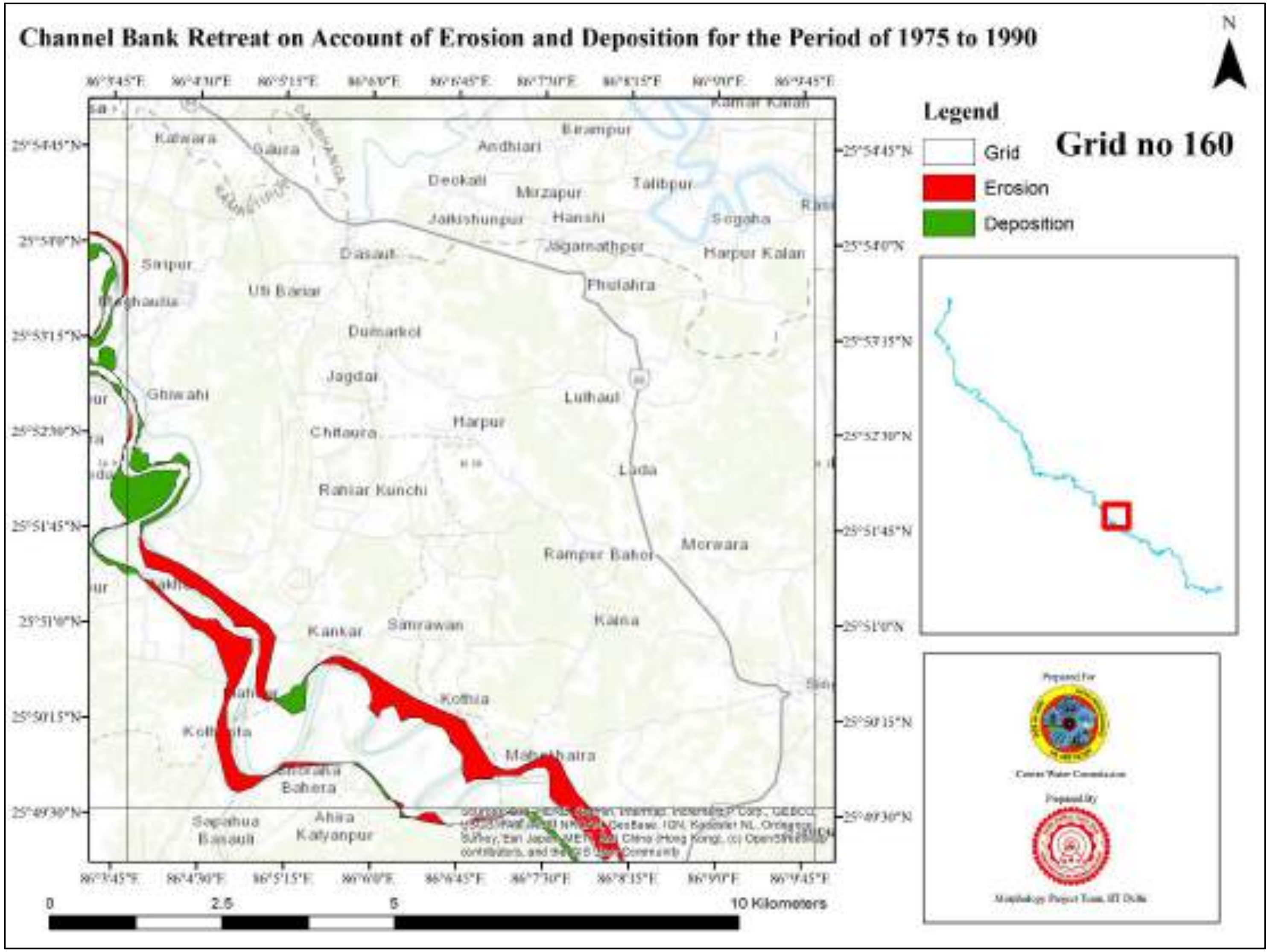



Figure **Error! No text of specified style in document.**-210: Erosion/Deposition Map of Bagmati River for Grid 160 for year (1975-1990)

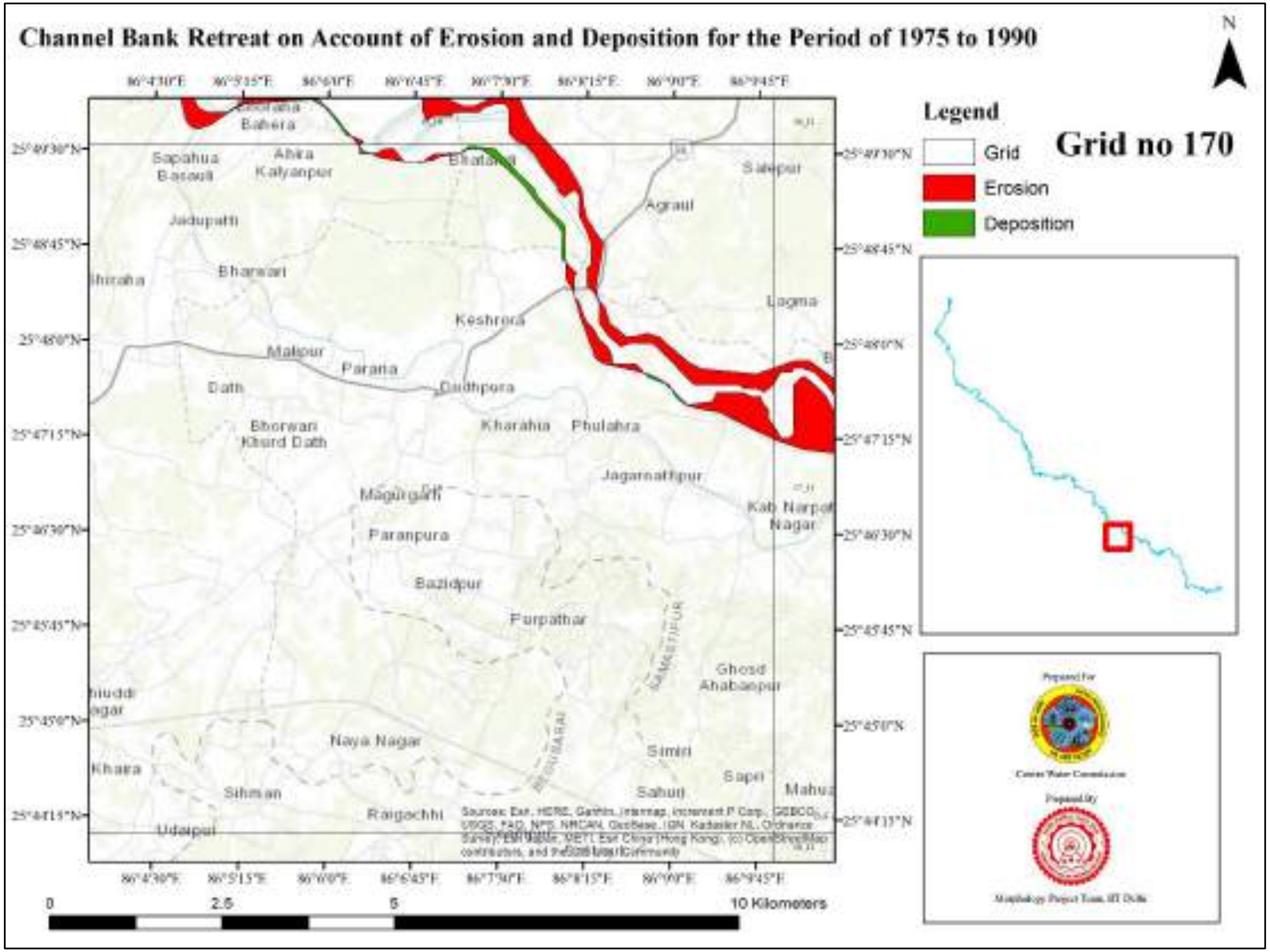



Figure **Error! No text of specified style in document.**-22: Erosion/Deposition Map of Bagmati River for Grid 170 for year (1975-1990)

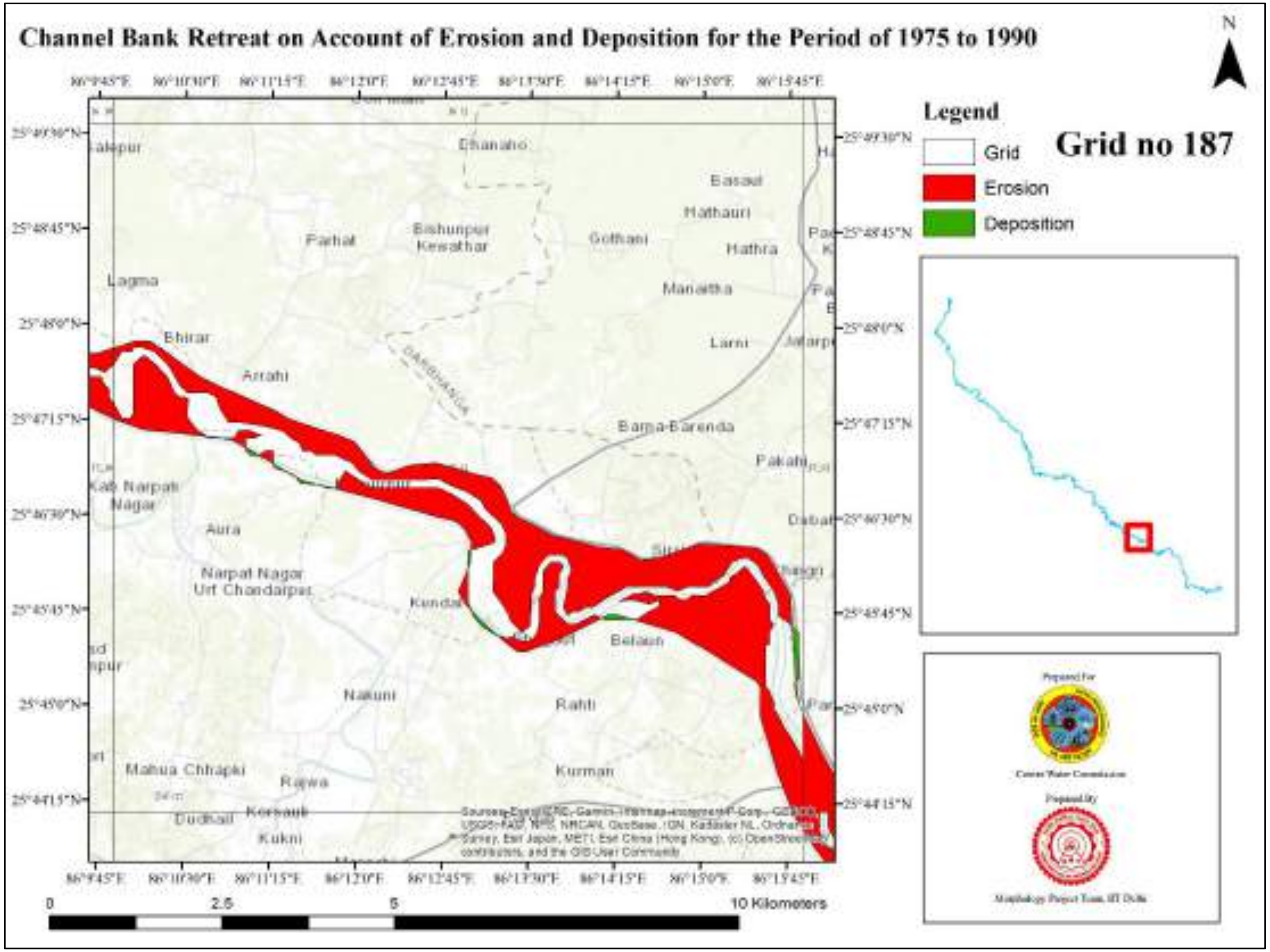



Figure **Error! No text of specified style in document.**-23: Erosion/Deposition Map of Bagmati River for Grid 187 for year (1975-1990)

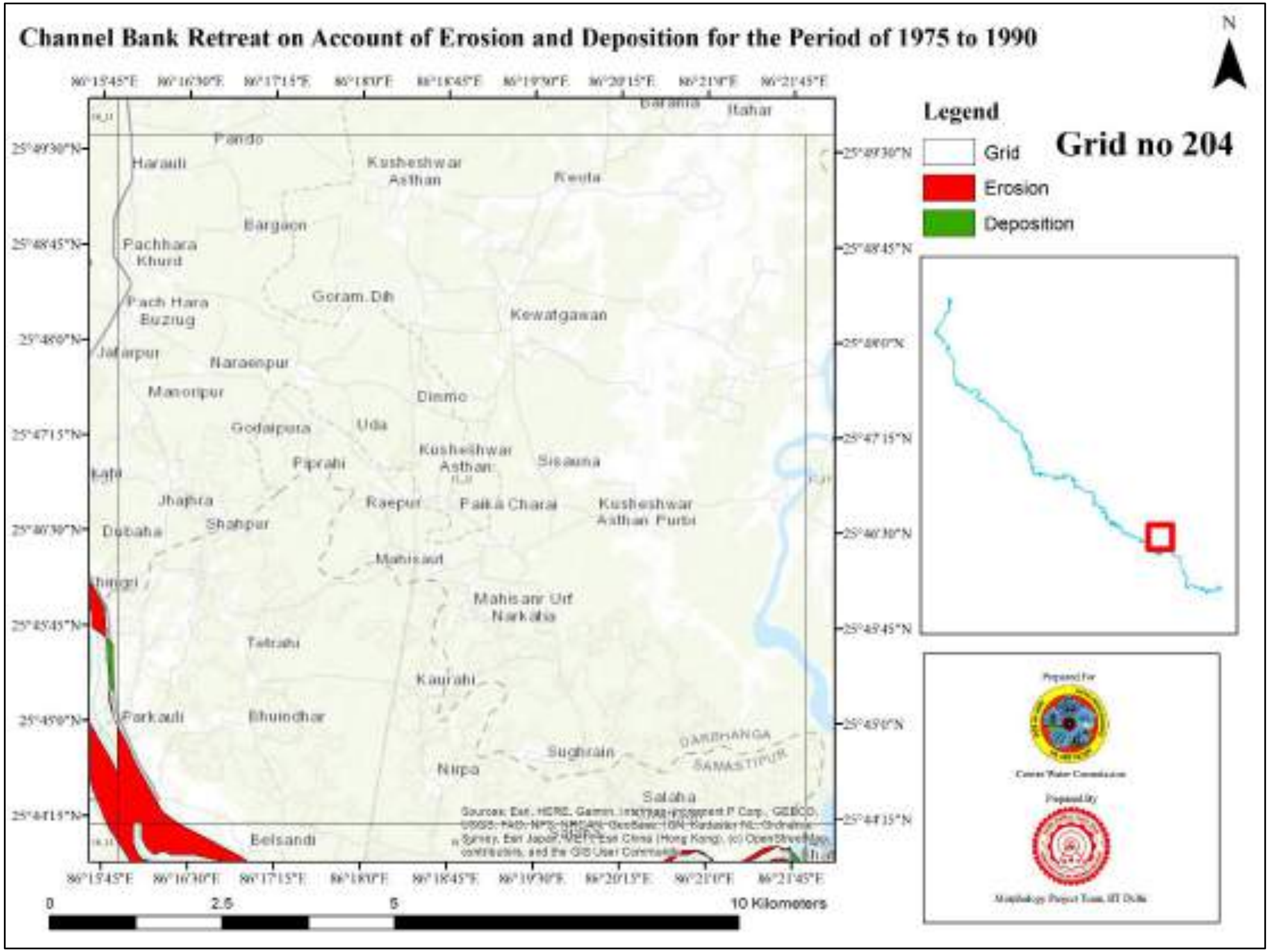



Figure **Error! No text of specified style in document.**-24: Erosion/Deposition Map of Bagmati River for Grid 204 for year (1975-1990)

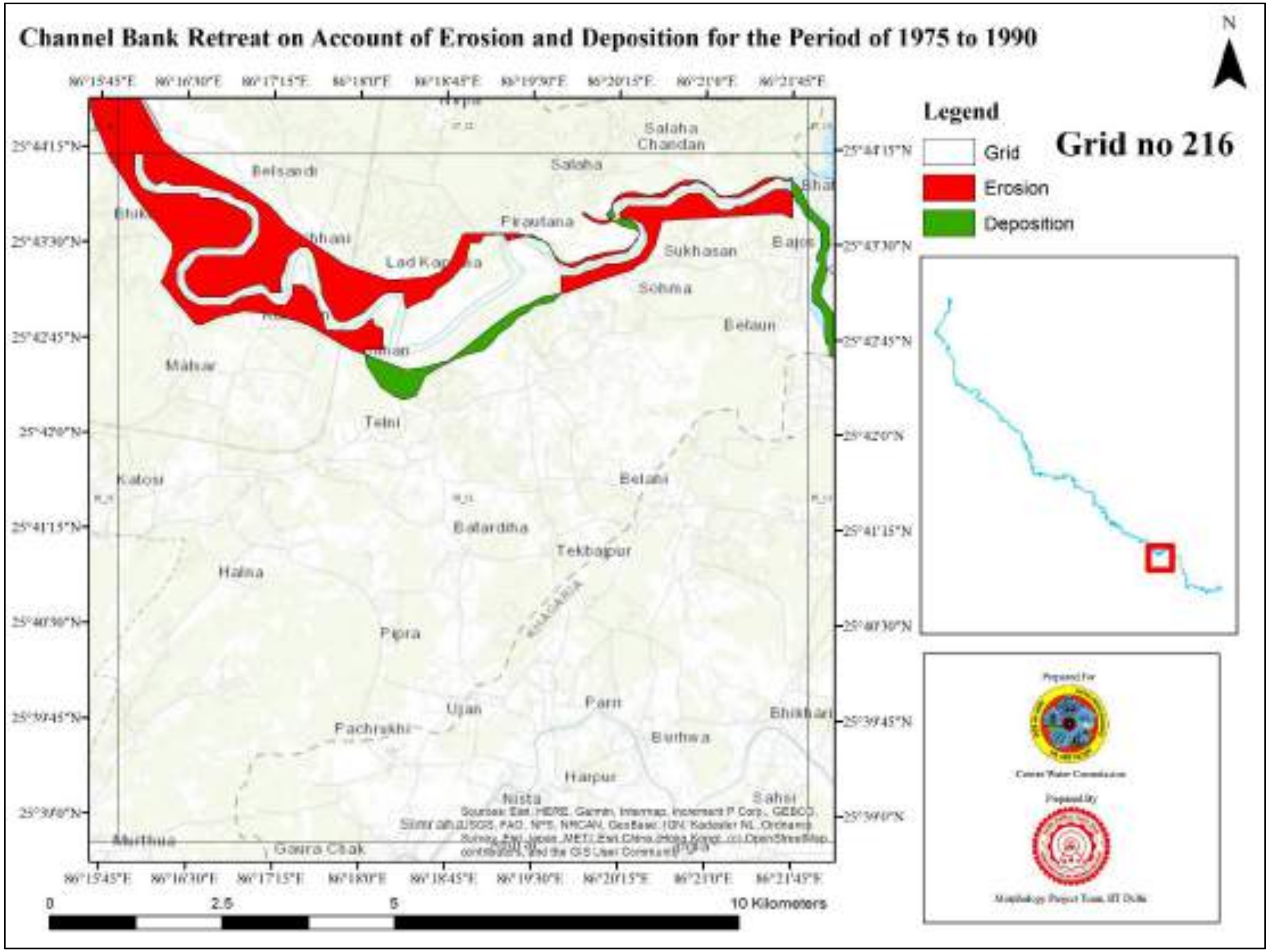



Figure **Error! No text of specified style in document.**-25: Erosion/Deposition Map of Bagmati River for Grid 216 for year (1975-1990)

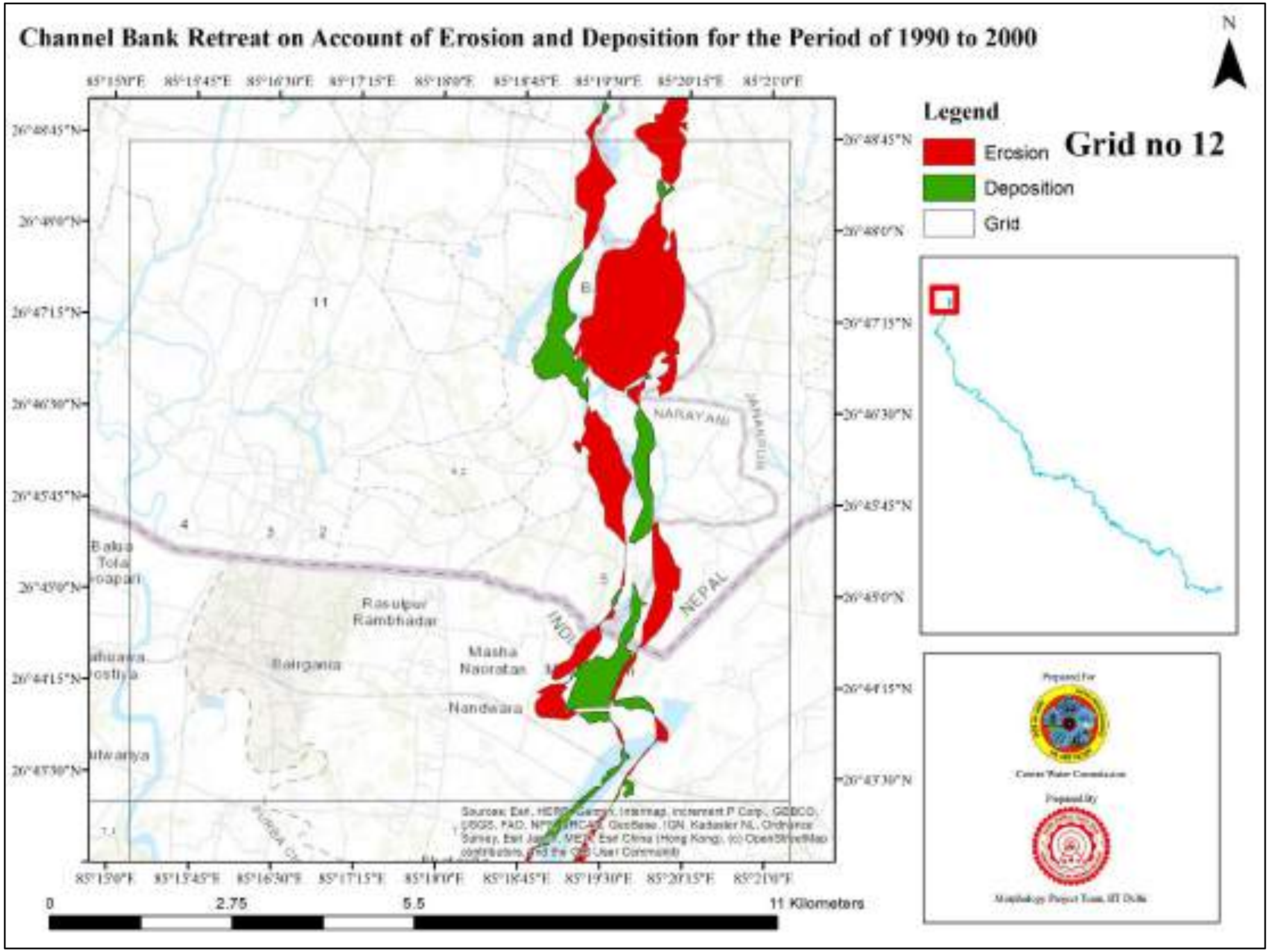



Figure **Error! No text of specified style in document.**-26: Erosion/Deposition Map of Bagmati River for Grid 12 for year (1990-2000)

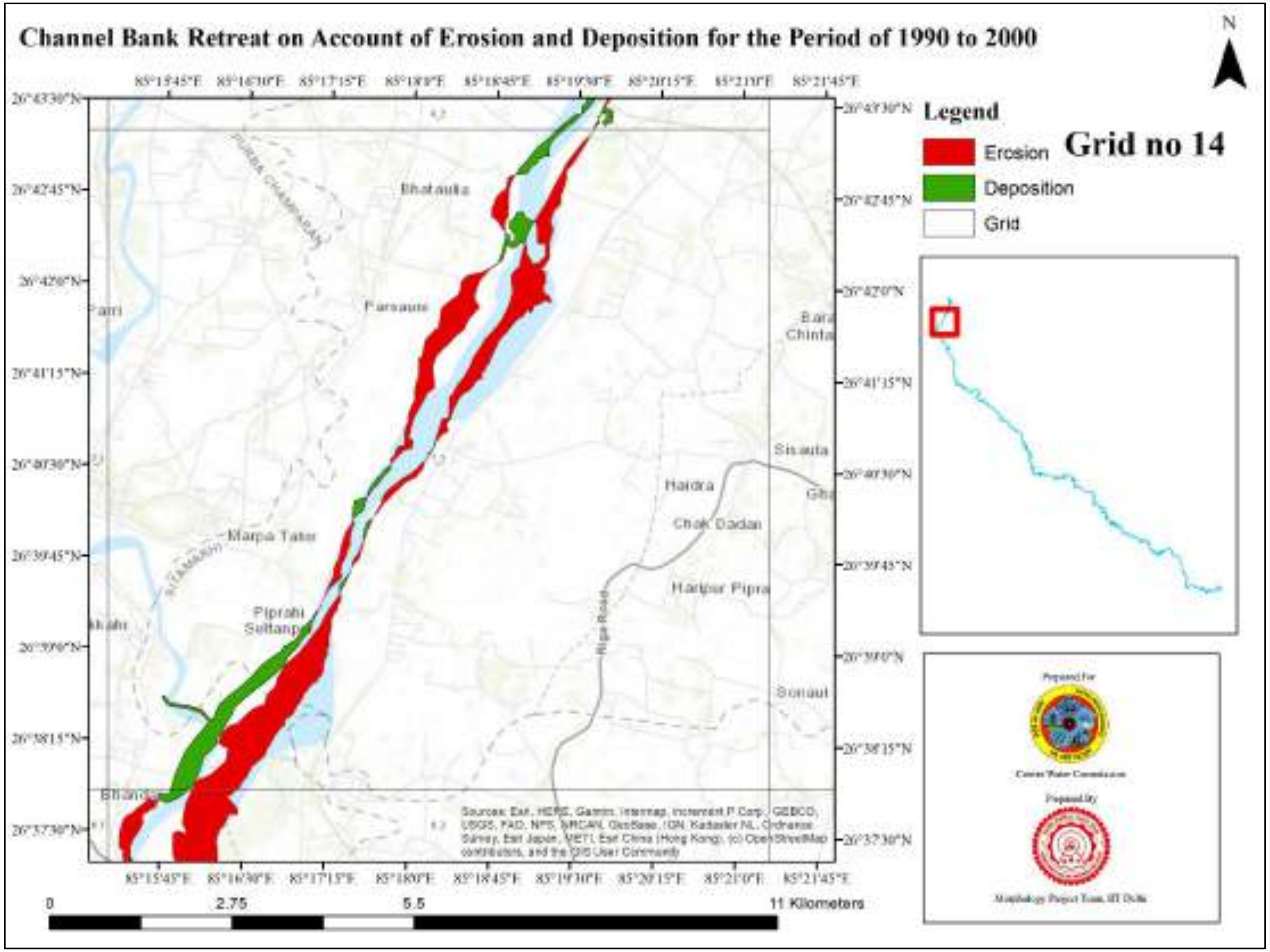



Figure **Error! No text of specified style in document.**-27: Erosion/Deposition Map of Bagmati River for Grid 14 for year (1990-2000)

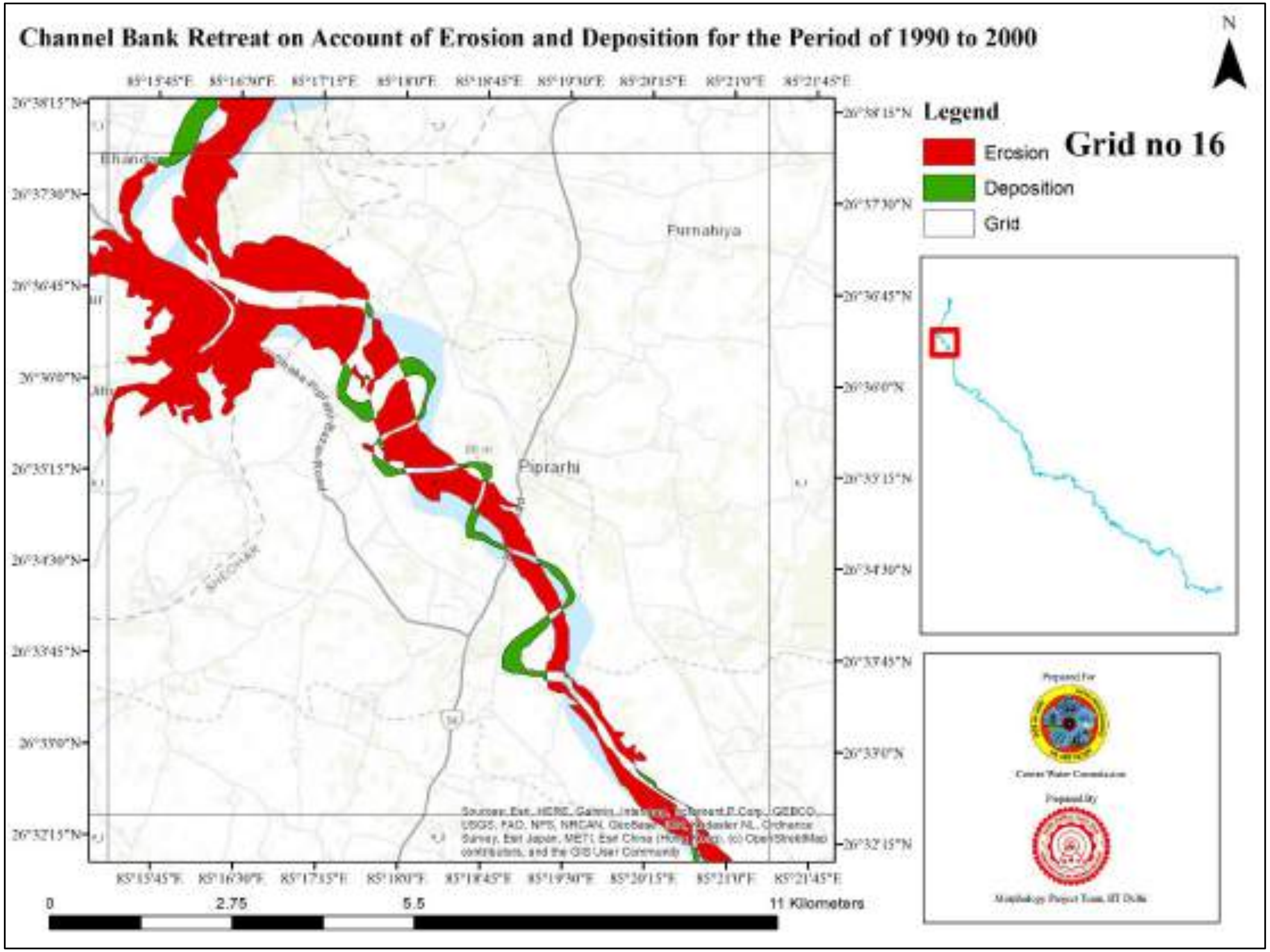



Figure **Error! No text of specified style in document.**-28: Erosion/Deposition Map of Bagmati River for Grid 16 for year (1990-2000)

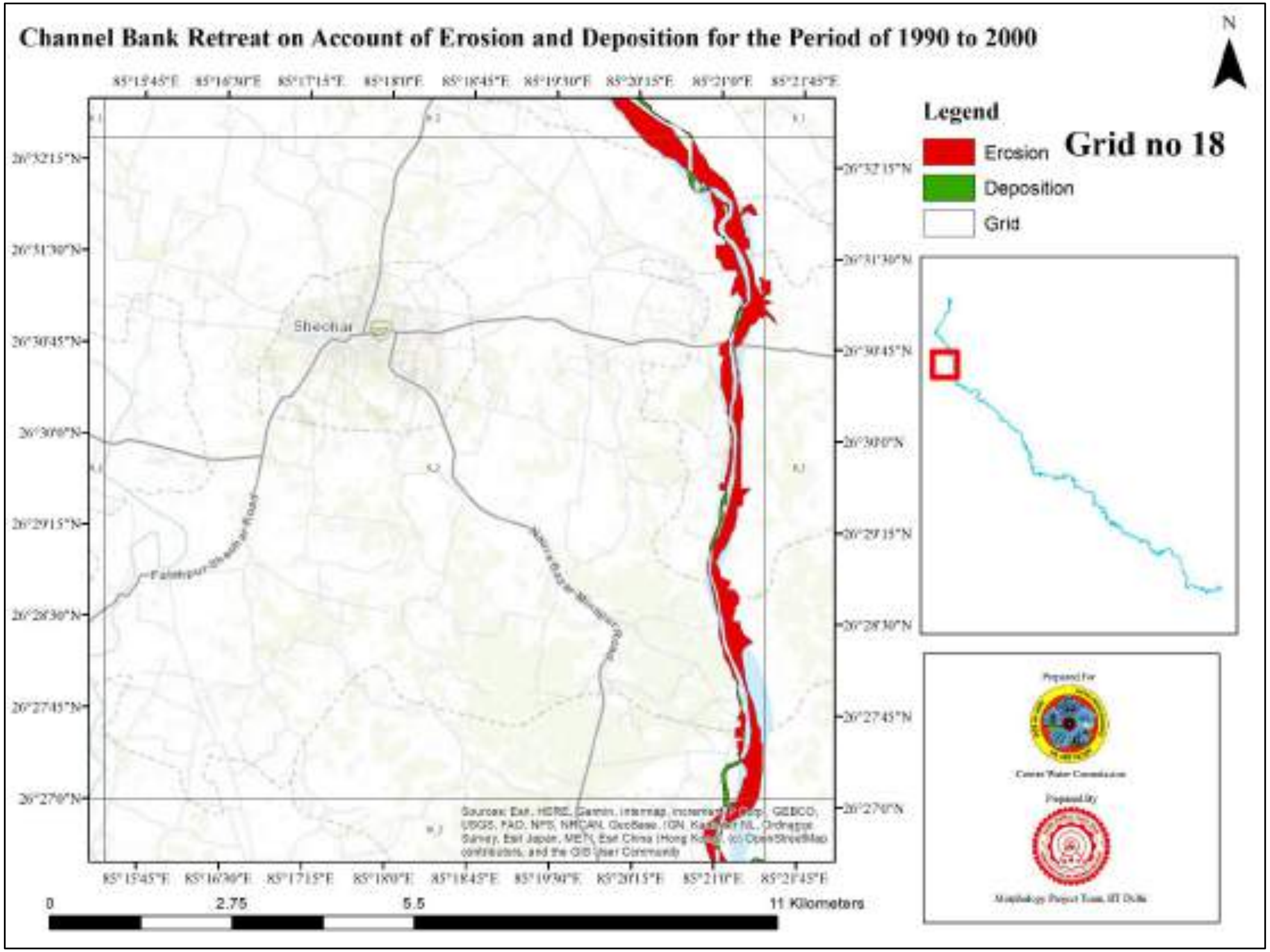



Figure **Error! No text of specified style in document.**-29: Erosion/Deposition Map of Bagmati River for Grid 18 for year (1990-2000)

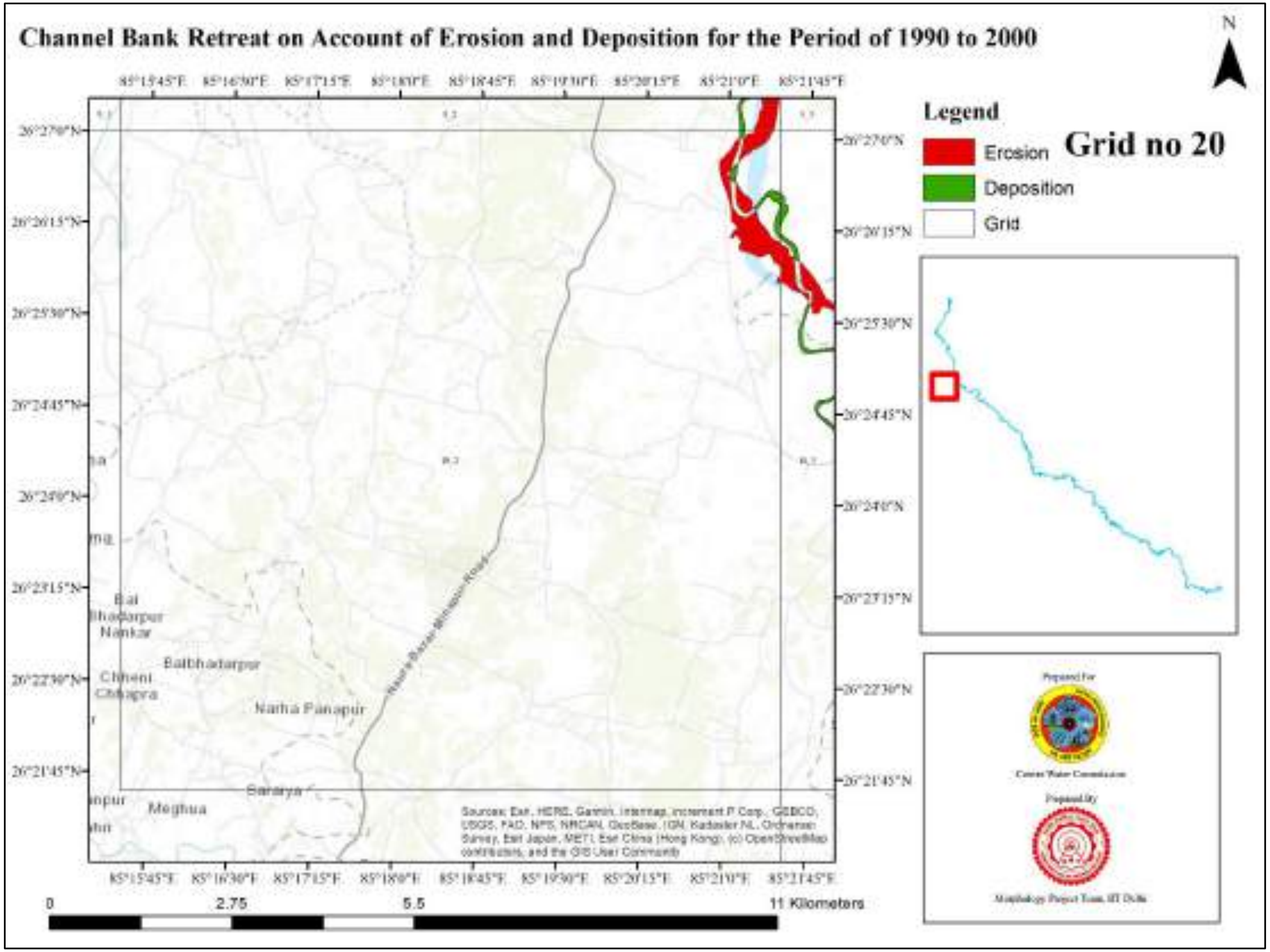



Figure **Error! No text of specified style in document.**-30: Erosion/Deposition Map of Bagmati River for Grid 20 for year (1990-2000)

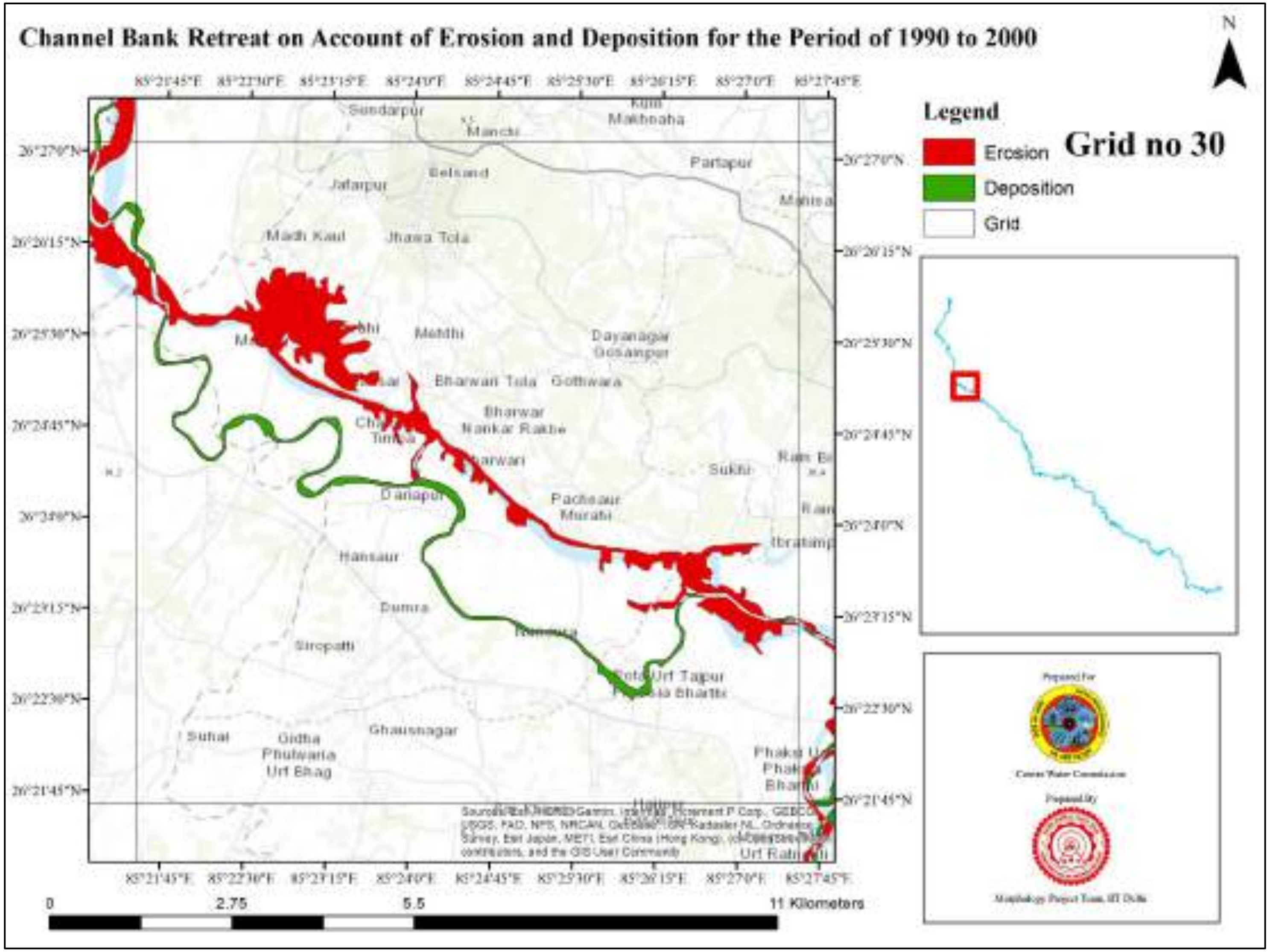



Figure **Error! No text of specified style in document.**-31: Erosion/Deposition Map of Bagmati River for Grid 30 for year (1990-2000)

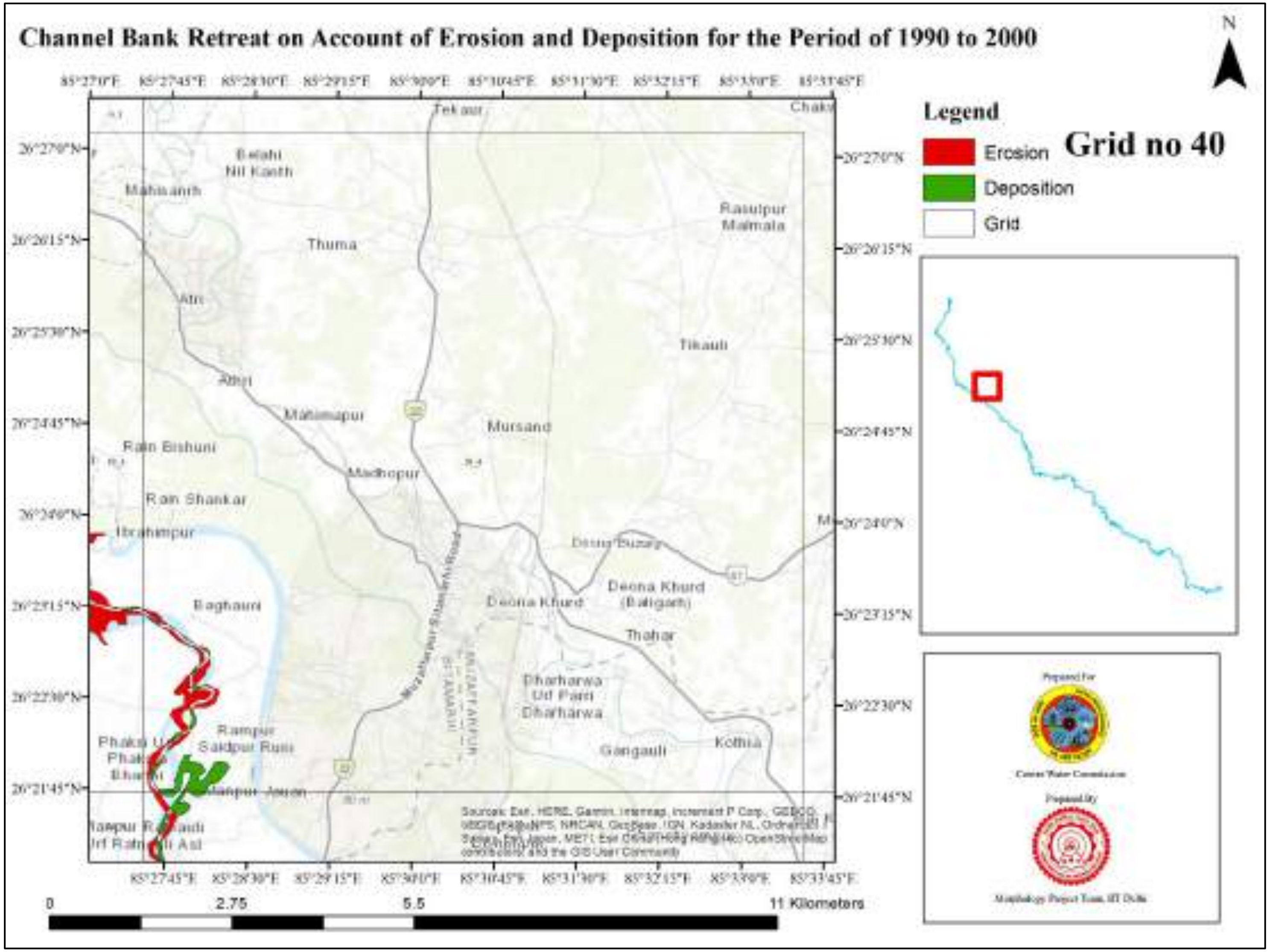



Figure **Error! No text of specified style in document.**-32: Erosion/Deposition Map of Bagmati River for Grid 40 for year (1990-2000)

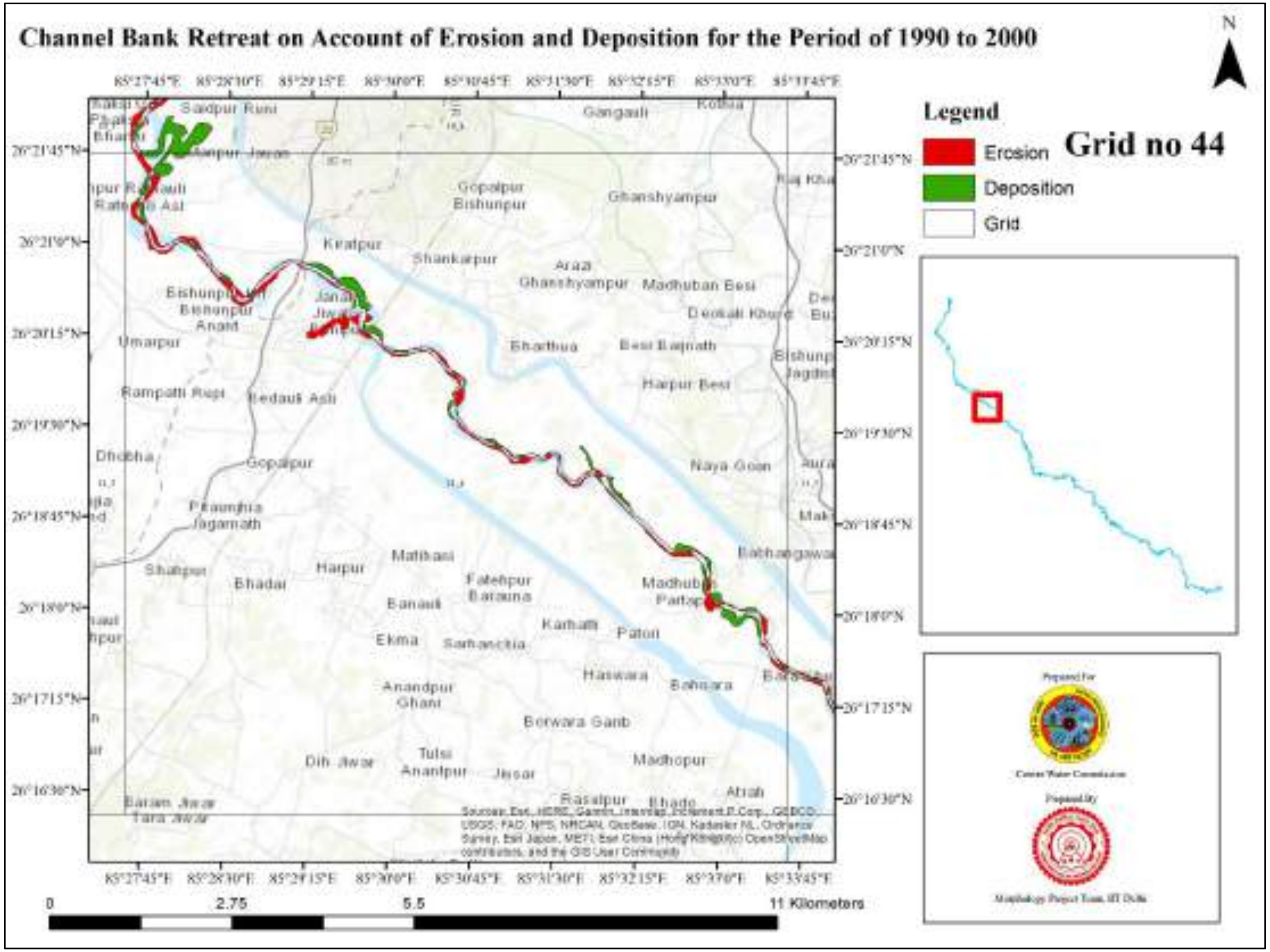



Figure **Error! No text of specified style in document.**-33: Erosion/Deposition Map of Bagmati River for Grid 44 for year (1990-2000)

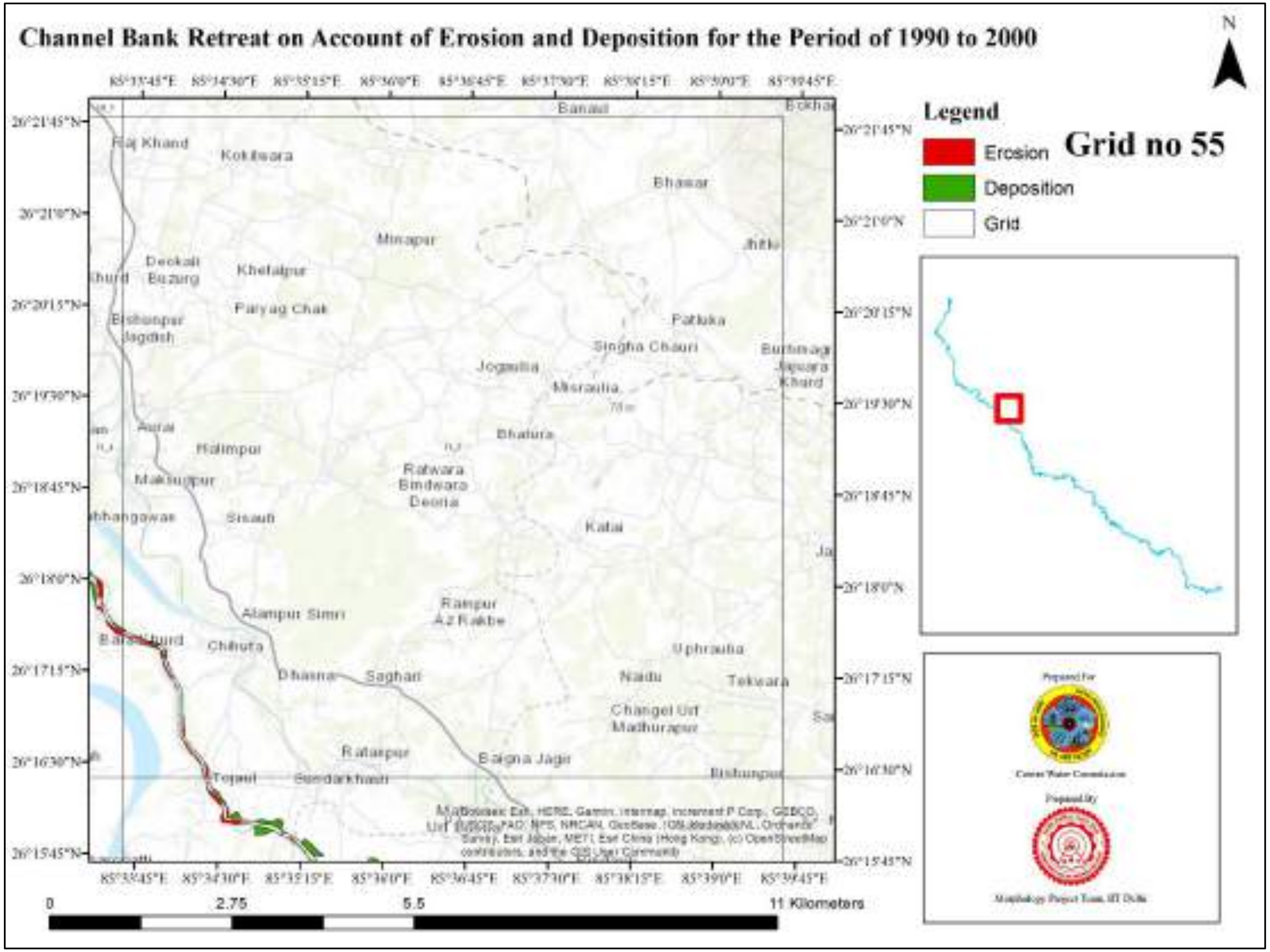



Figure **Error! No text of specified style in document.**-34: Erosion/Deposition Map of Bagmati River for Grid 55 for year (1990-2000)

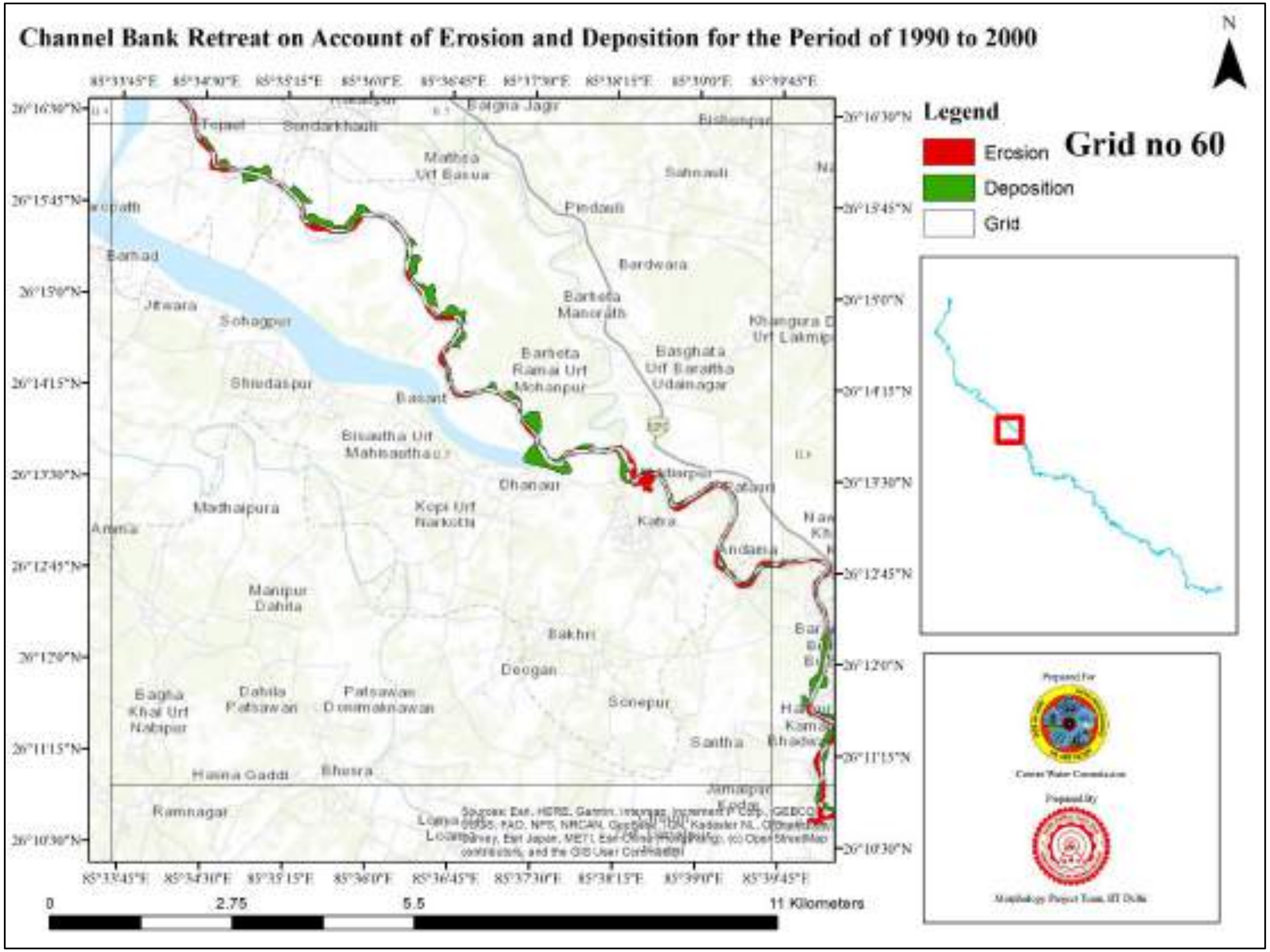



Figure **Error! No text of specified style in document.**-35: Erosion/Deposition Map of Bagmati River for Grid 60 for year (1990-2000)

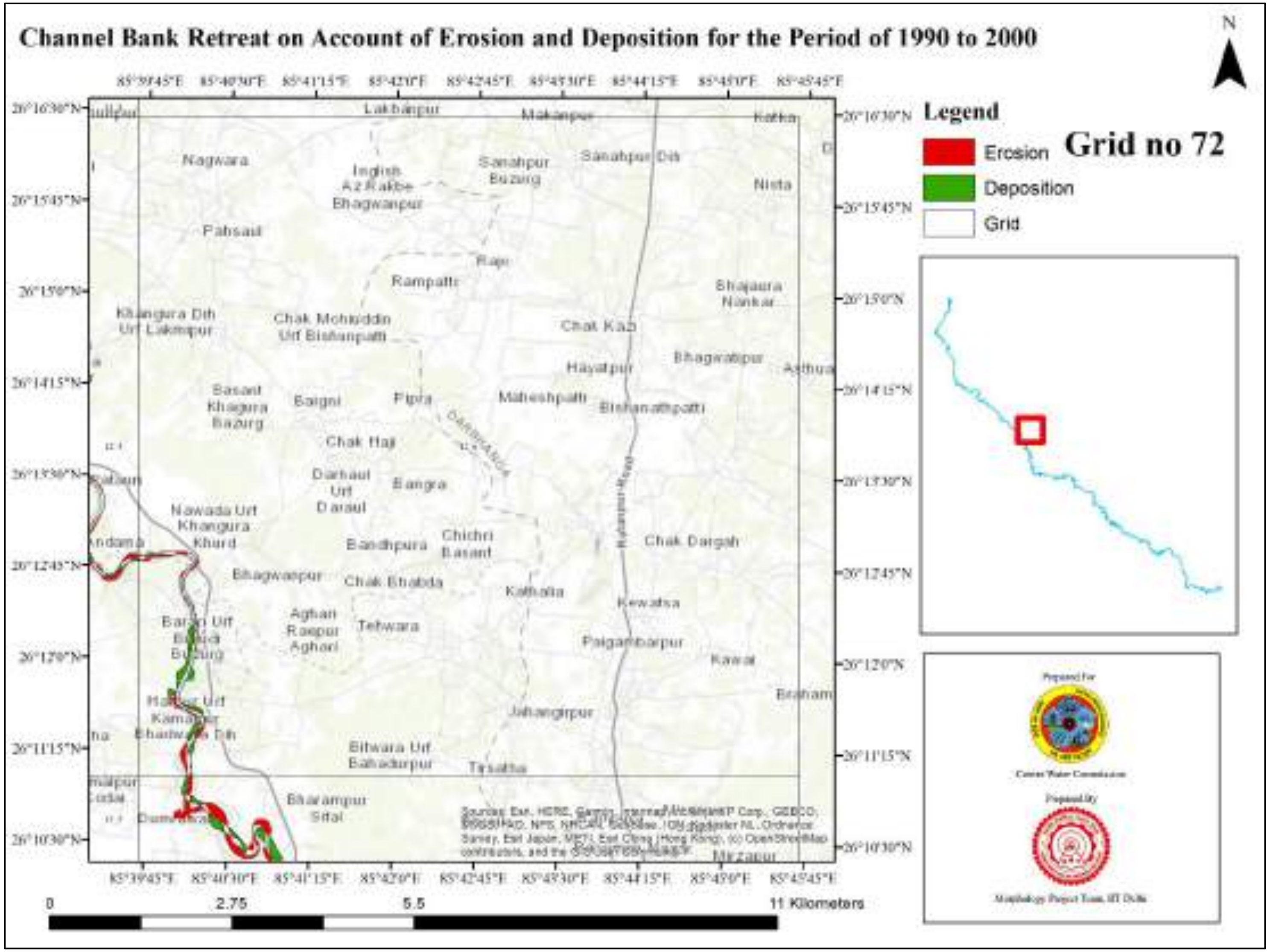



Figure **Error! No text of specified style in document.**-36: Erosion/Deposition Map of Bagmati River for Grid 72 for year (1990-2000)

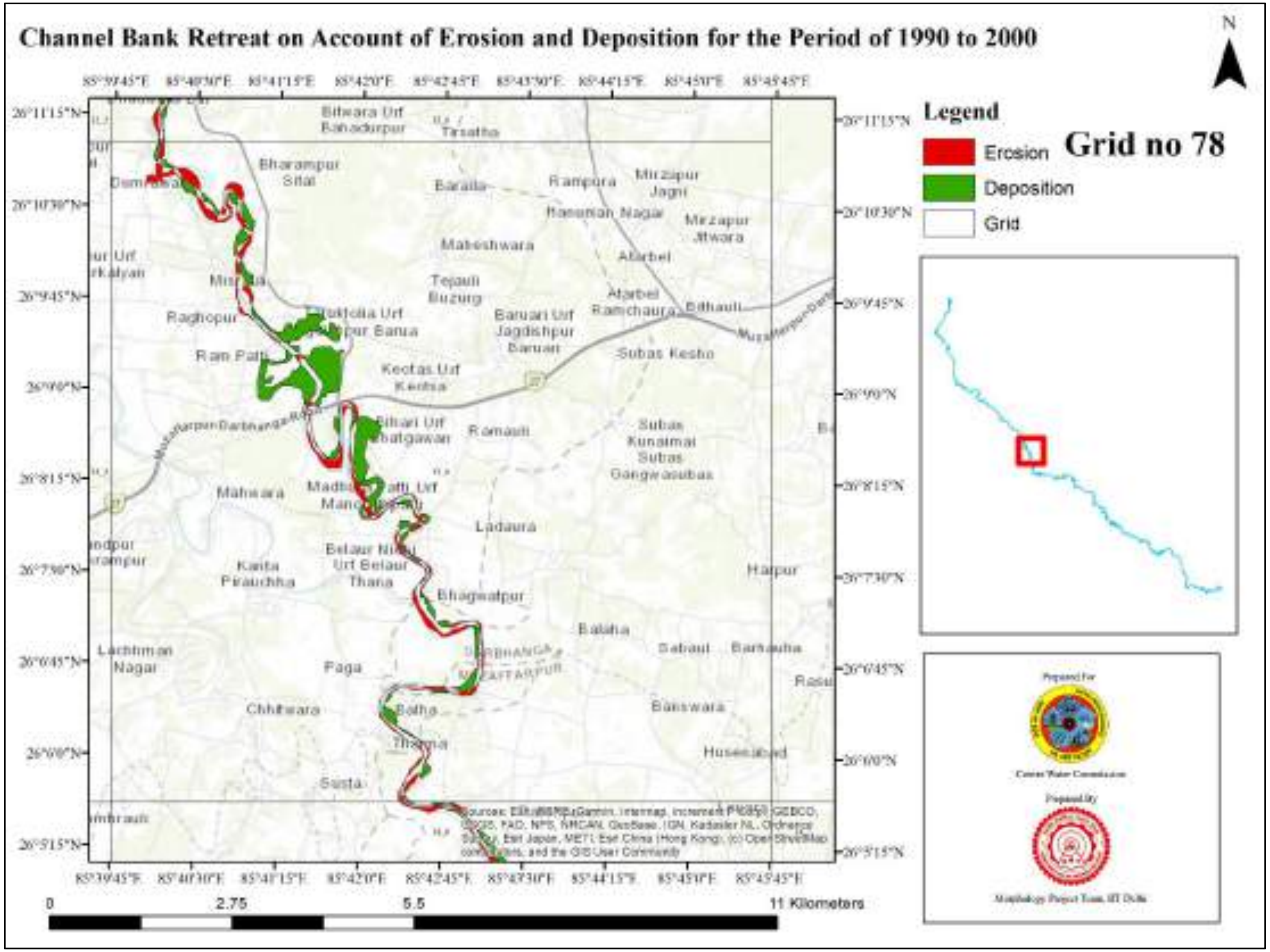



Figure **Error! No text of specified style in document.**-37: Erosion/Deposition Map of Bagmati River for Grid 78 for year (1990-2000)

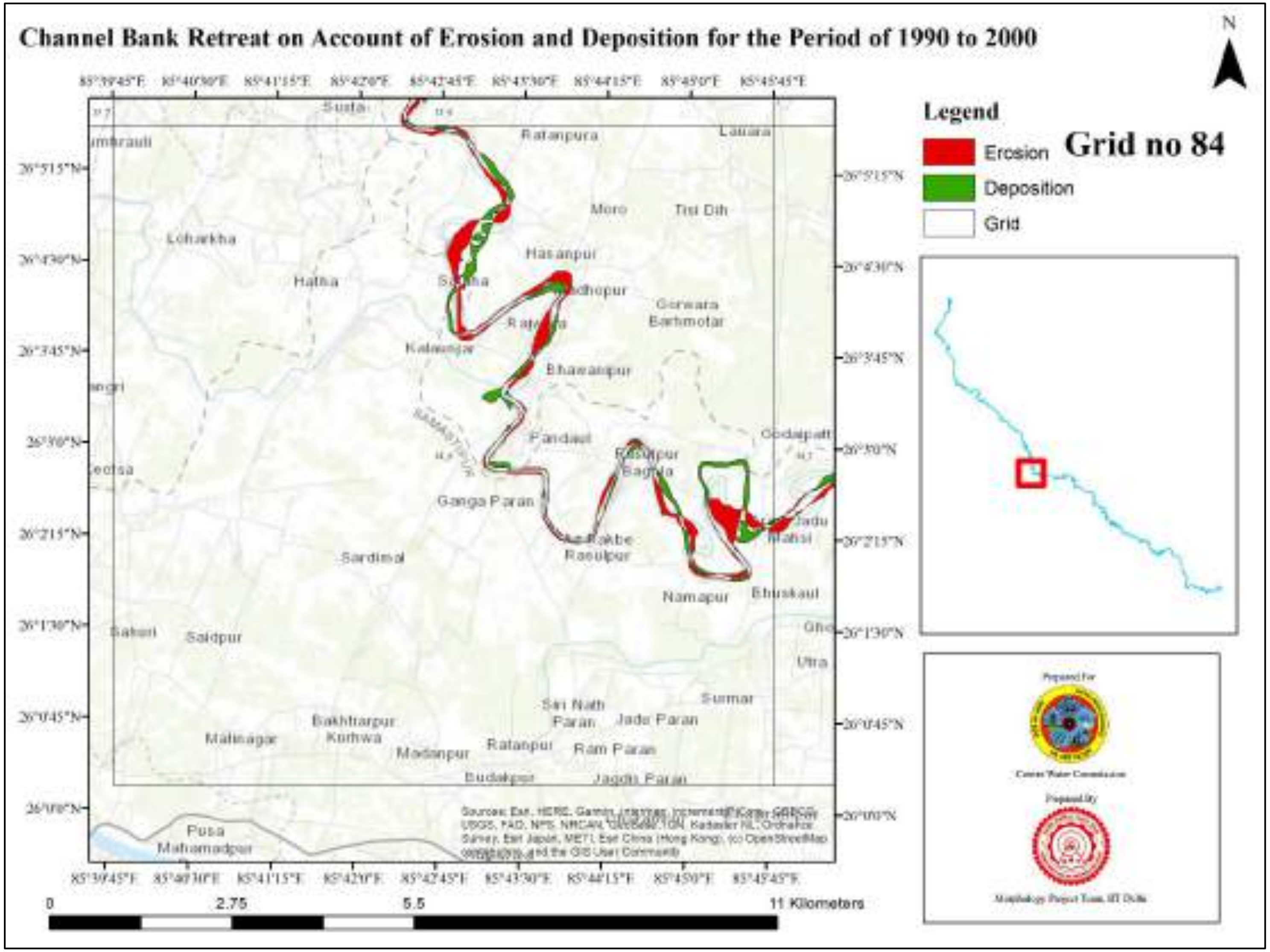



Figure **Error! No text of specified style in document.**-38: Erosion/Deposition Map of Bagmati River for Grid 84 for year (1990-2000)

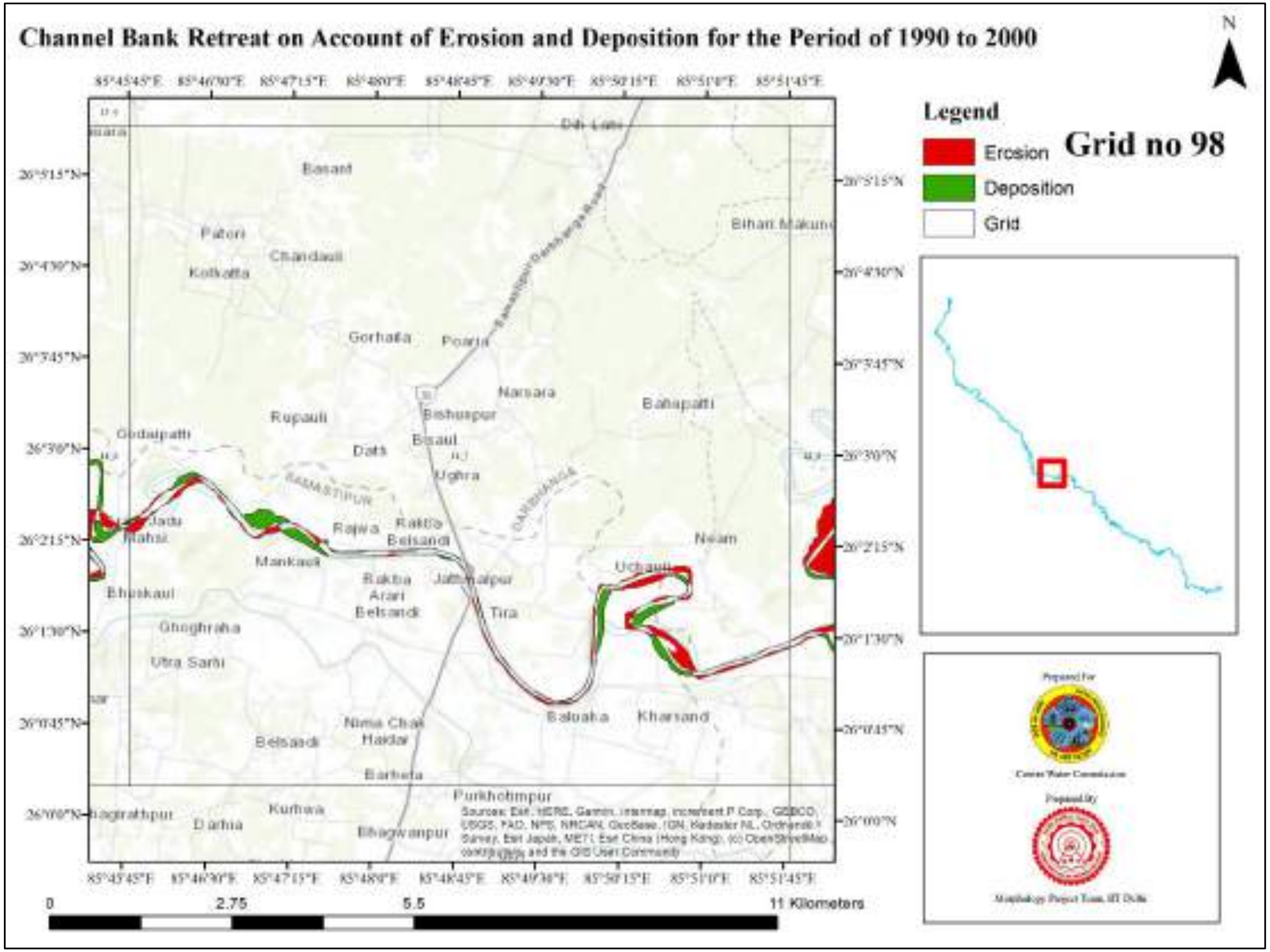



Figure **Error! No text of specified style in document.**-39: Erosion/Deposition Map of Bagmati River for Grid 98 for year (1990-2000)

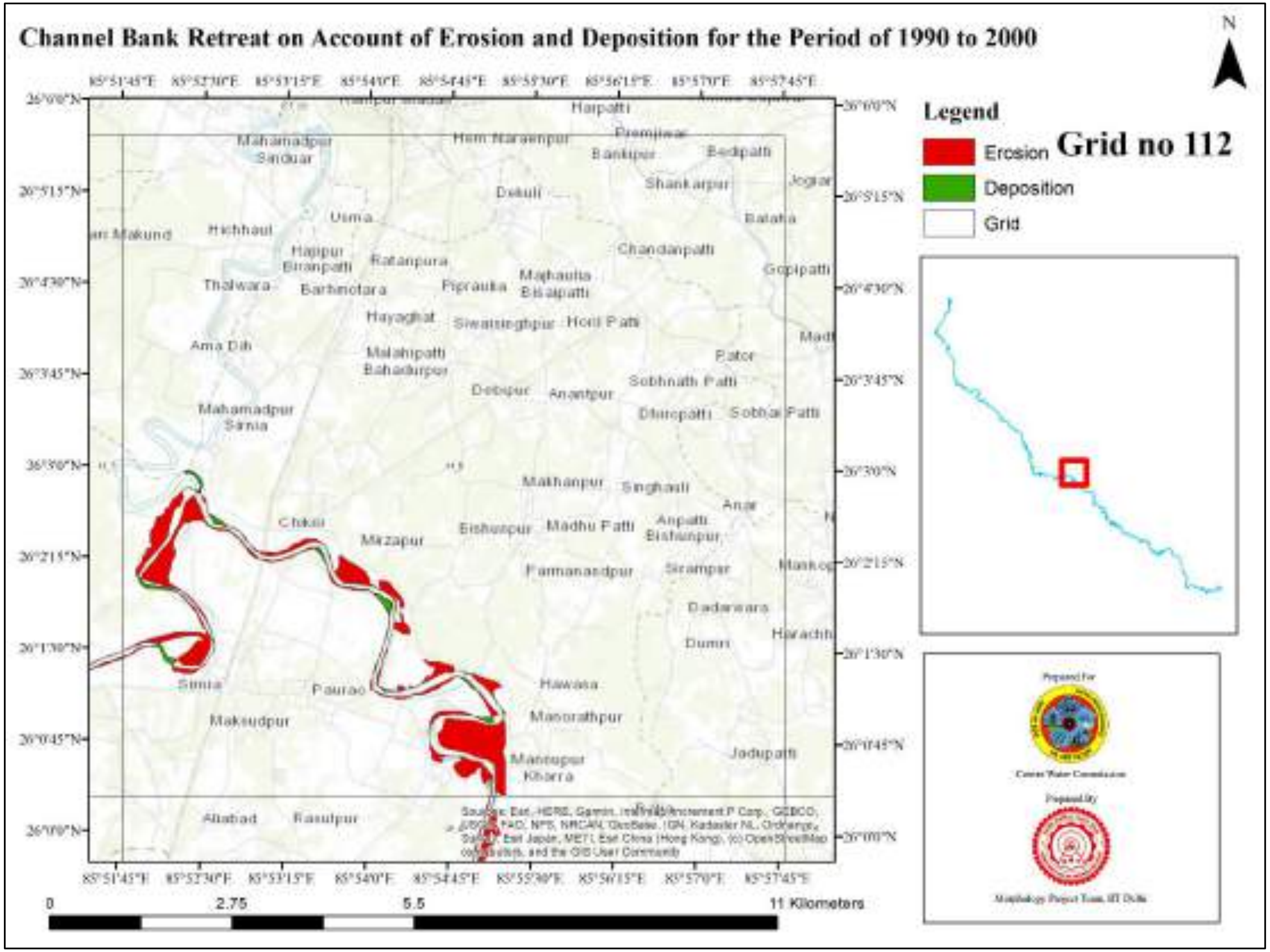



Figure **Error! No text of specified style in document.**-40: Erosion/Deposition Map of Bagmati River for Grid 112 for year (1990-2000)

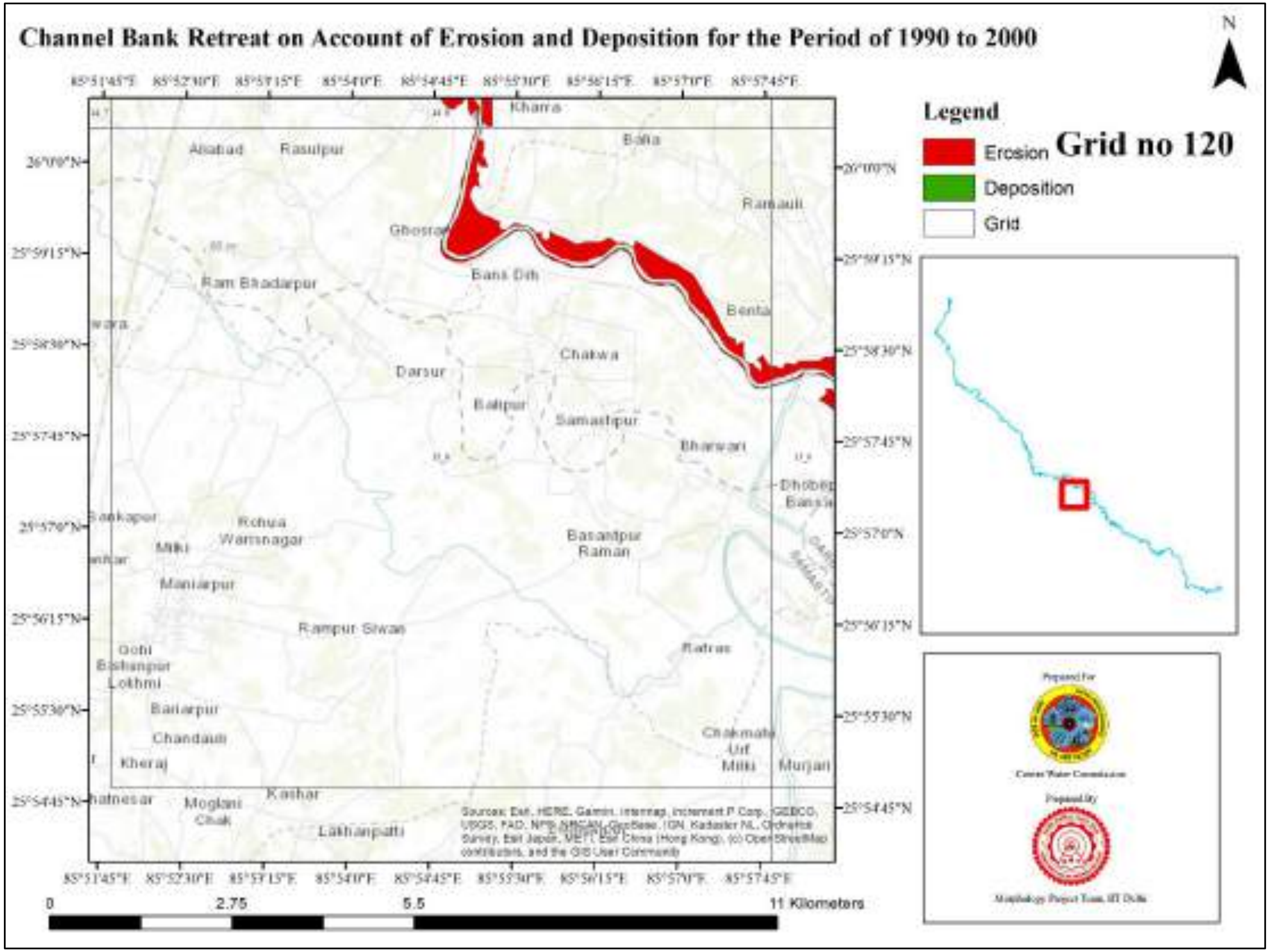



Figure **Error! No text of specified style in document.**-41: Erosion/Deposition Map of Bagmati River for Grid 120 for year (1990-2000)

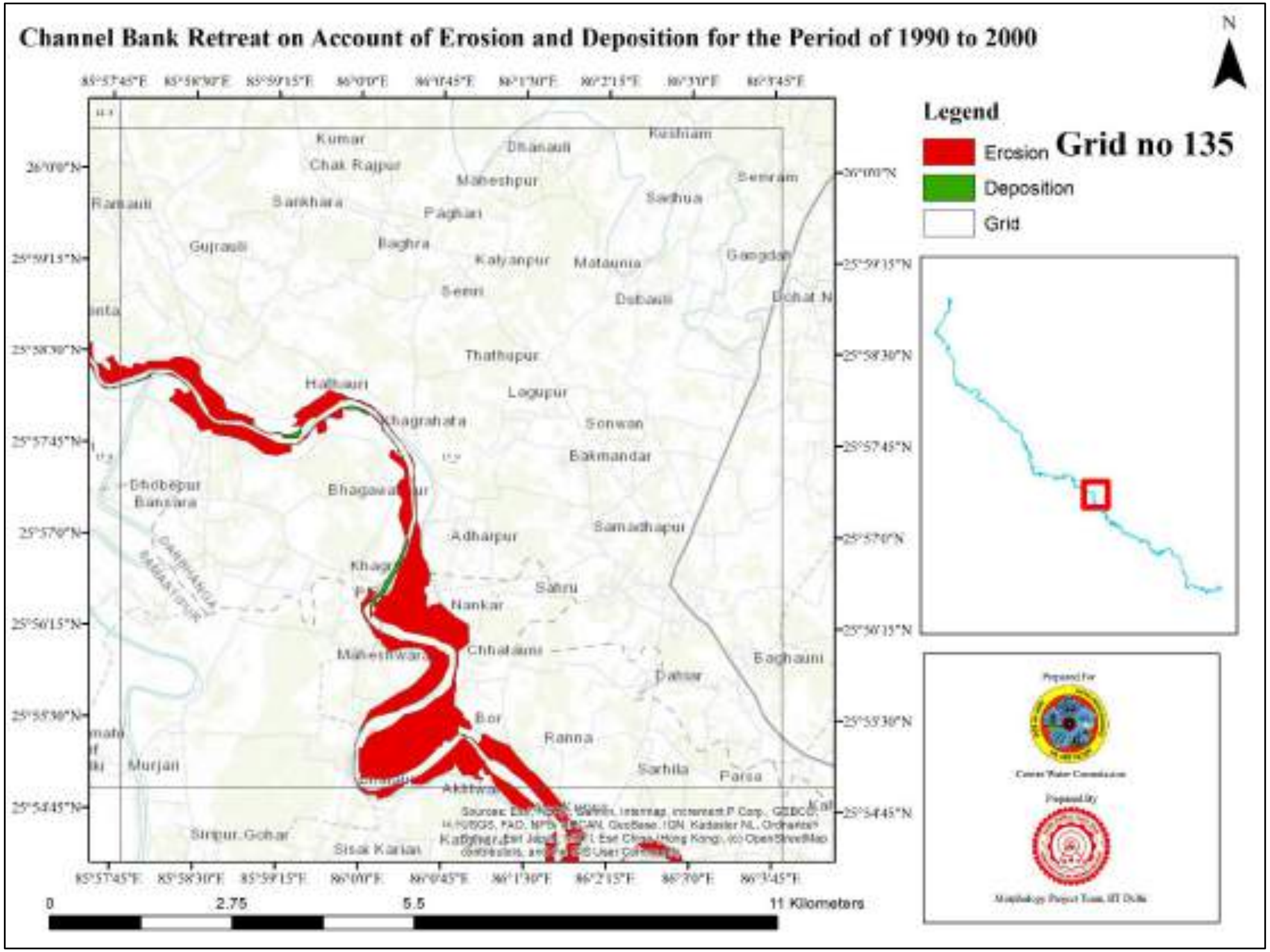



Figure **Error! No text of specified style in document.**-42: Erosion/Deposition Map of Bagmati River for Grid 135 for year (1990-2000)

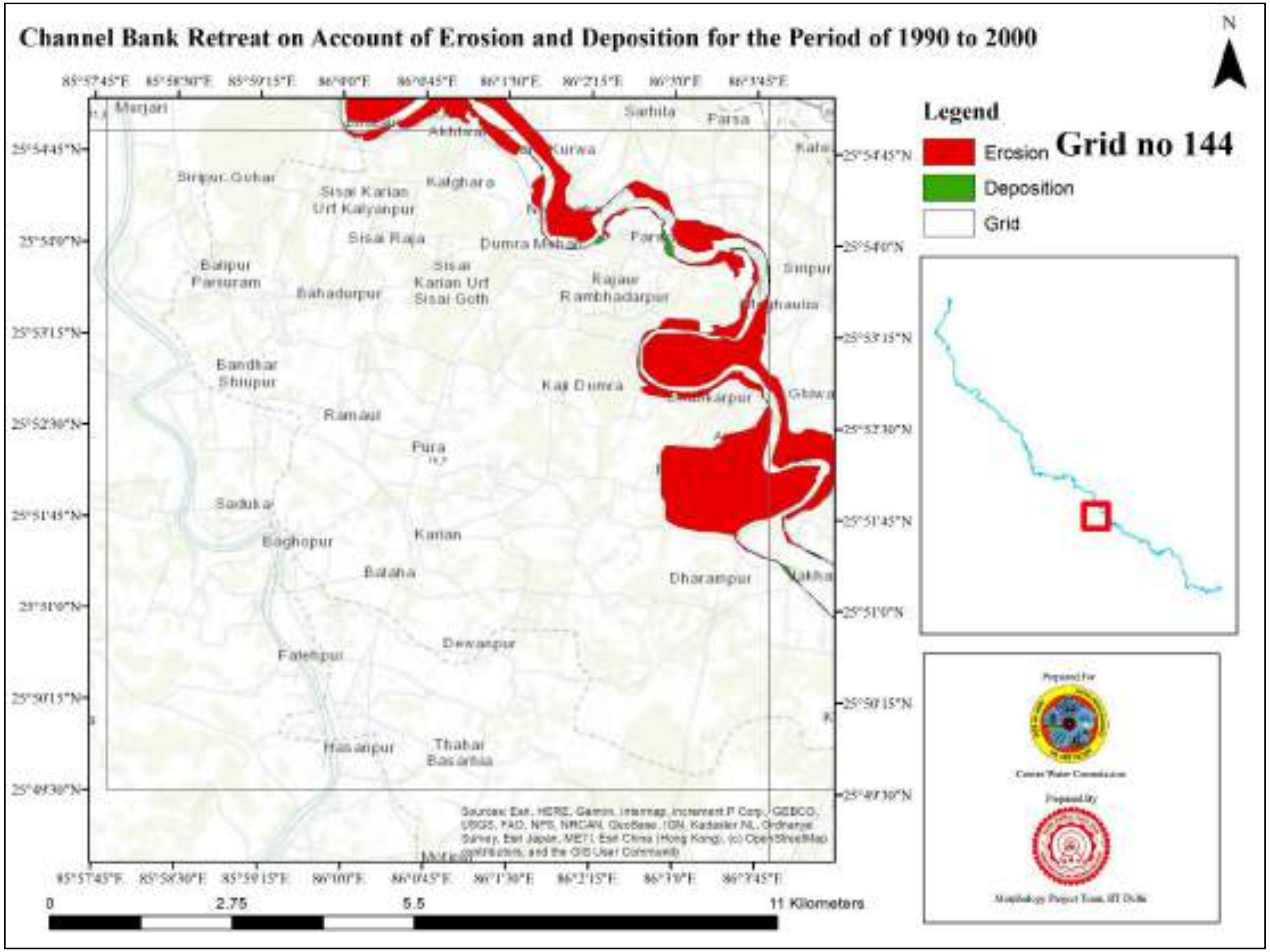



Figure **Error! No text of specified style in document.**-43: Erosion/Deposition Map of Bagmati River for Grid 144 for year (1990-2000)

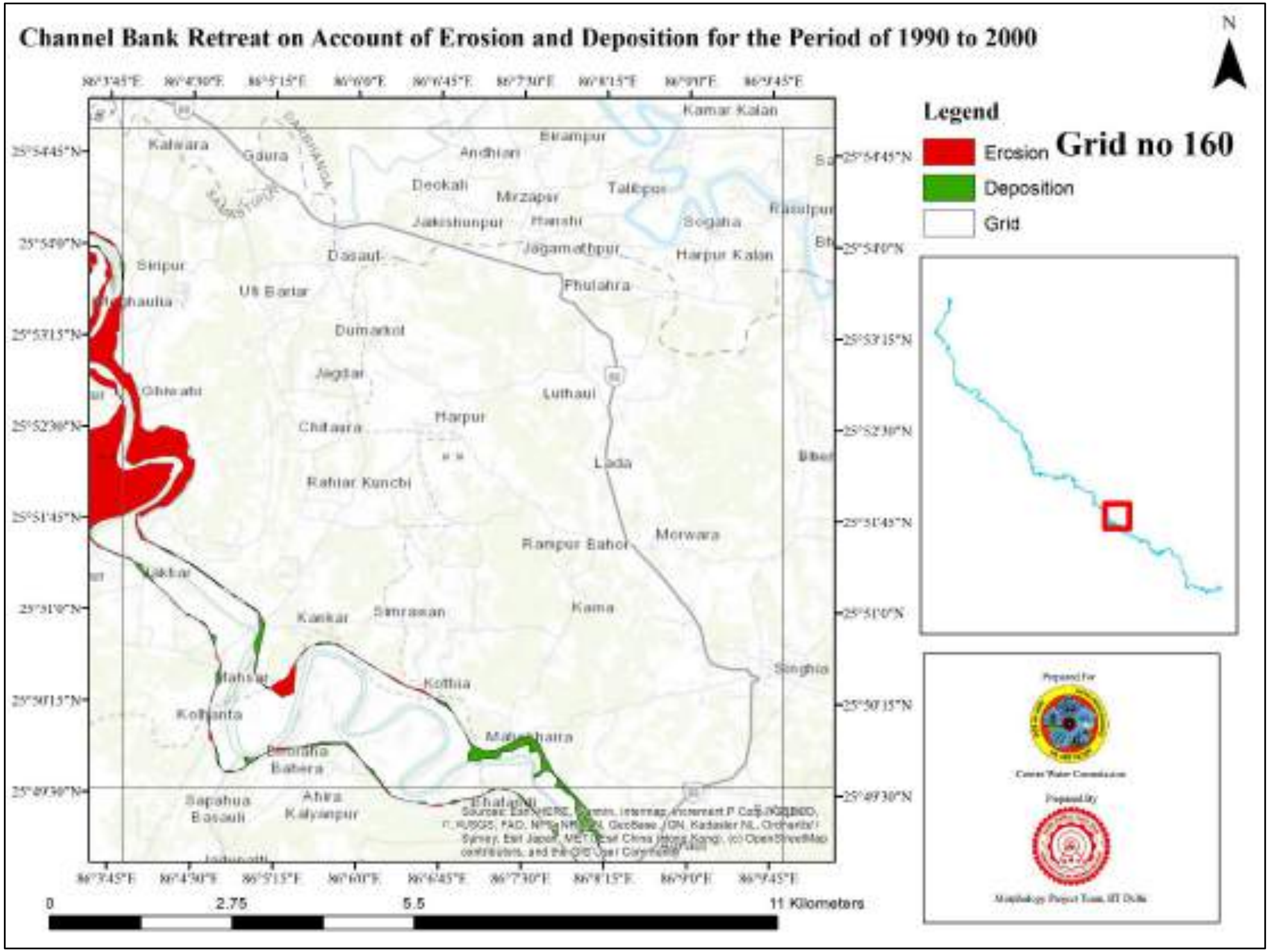



Figure **Error! No text of specified style in document.**-44: Erosion/Deposition Map of Bagmati River for Grid 160 for year (1990-2000)

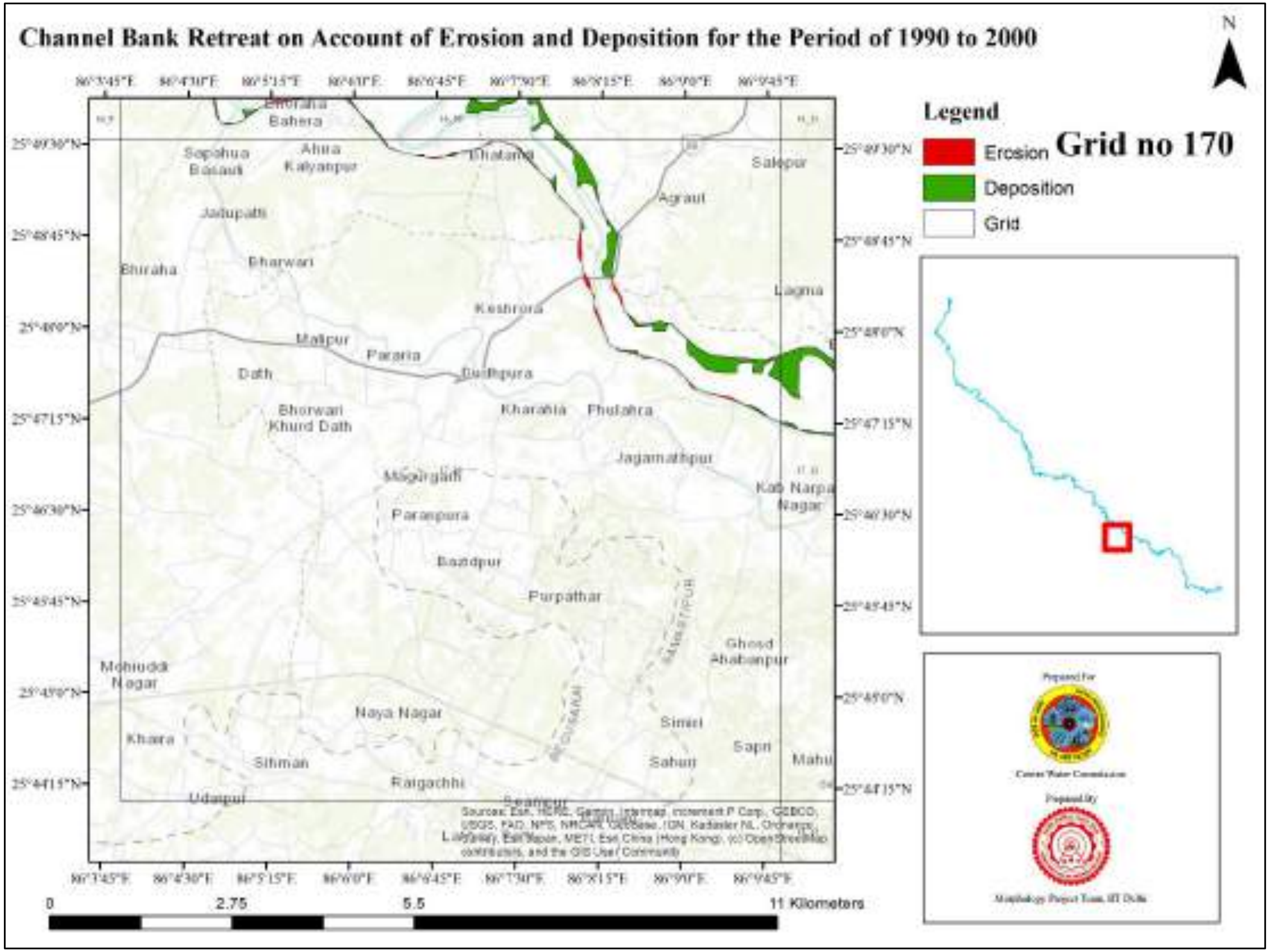



Figure **Error! No text of specified style in document.**-45: Erosion/Deposition Map of Bagmati River for Grid 170 for year (1990-2000)

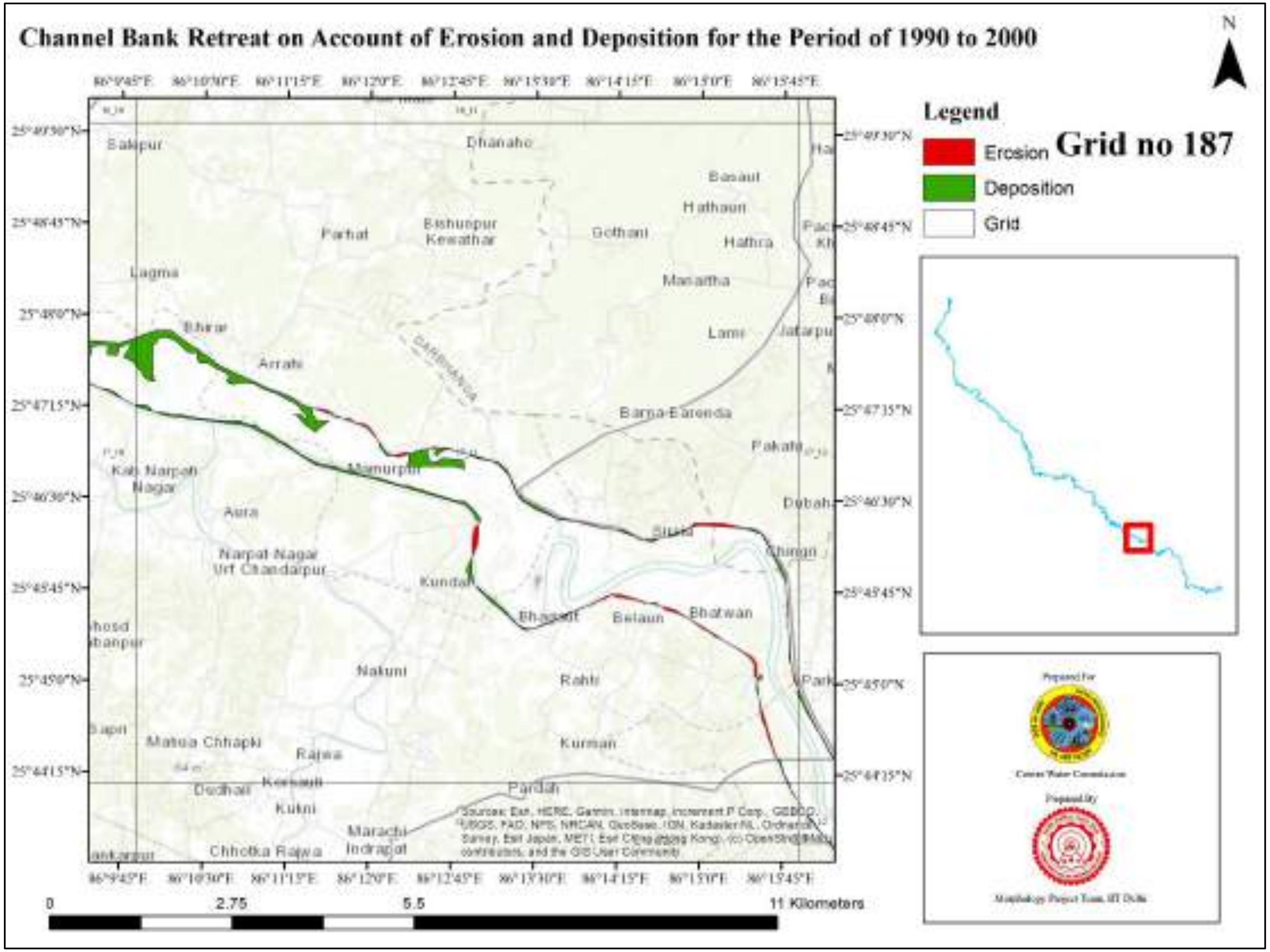



Figure **Error! No text of specified style in document.**-46: Erosion/Deposition Map of Bagmati River for Grid 187 for year (1990-2000)

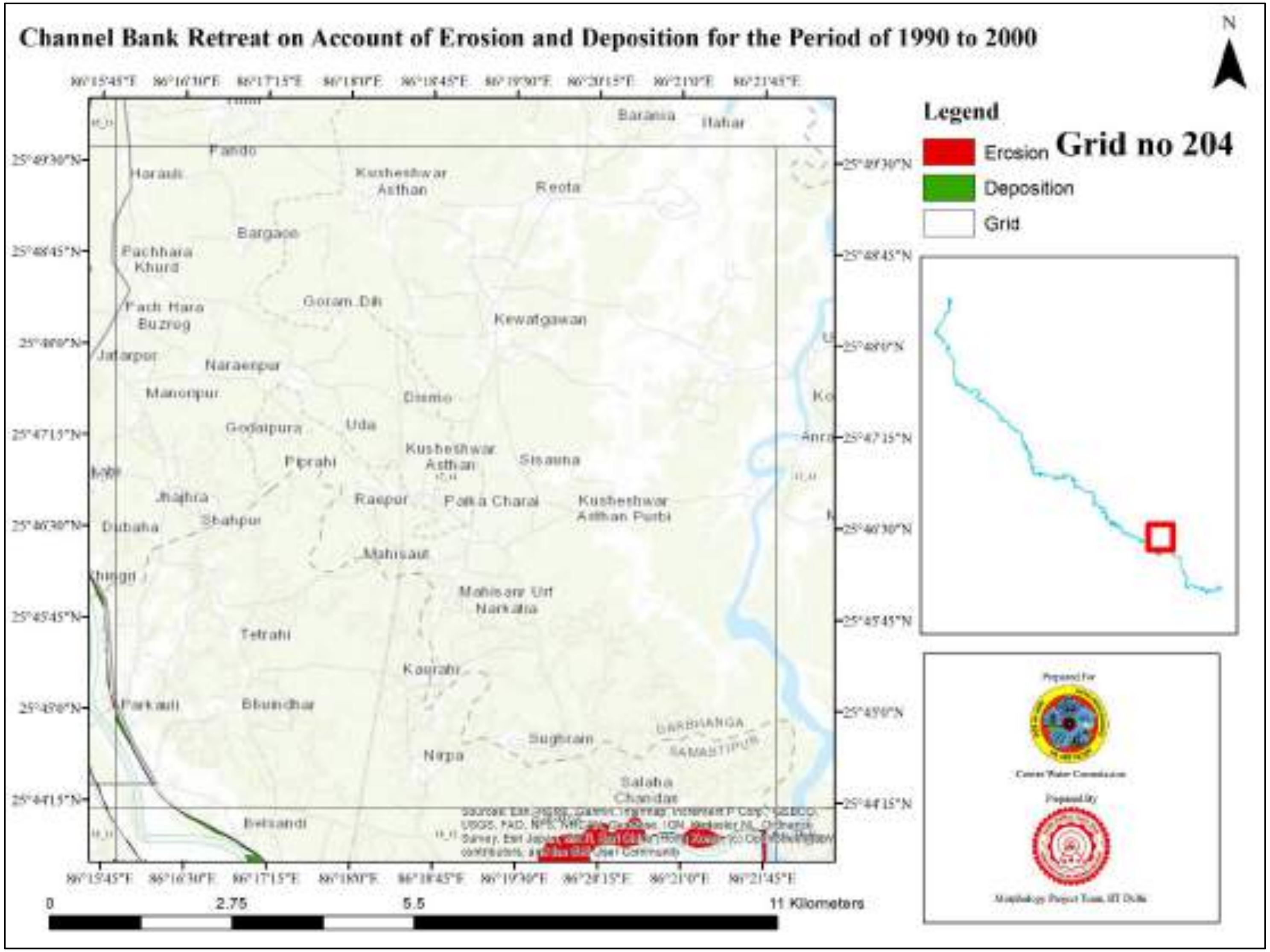



Figure **Error! No text of specified style in document.**-47: Erosion/Deposition Map of Bagmati River for Grid 204 for year (1990-2000)

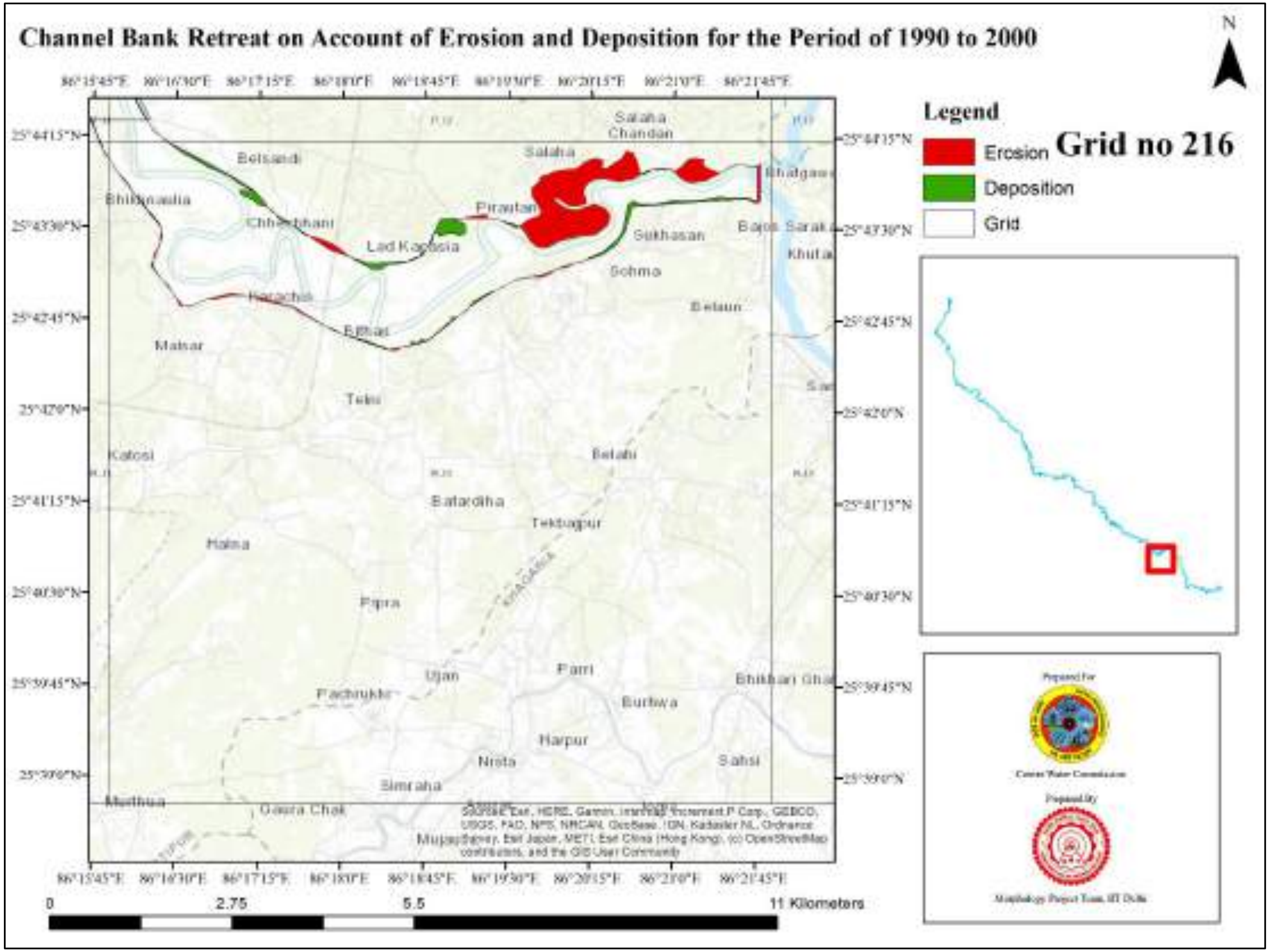



Figure **Error! No text of specified style in document.**-48: Erosion/Deposition Map of Bagmati River for Grid 216 for year (1990-2000)

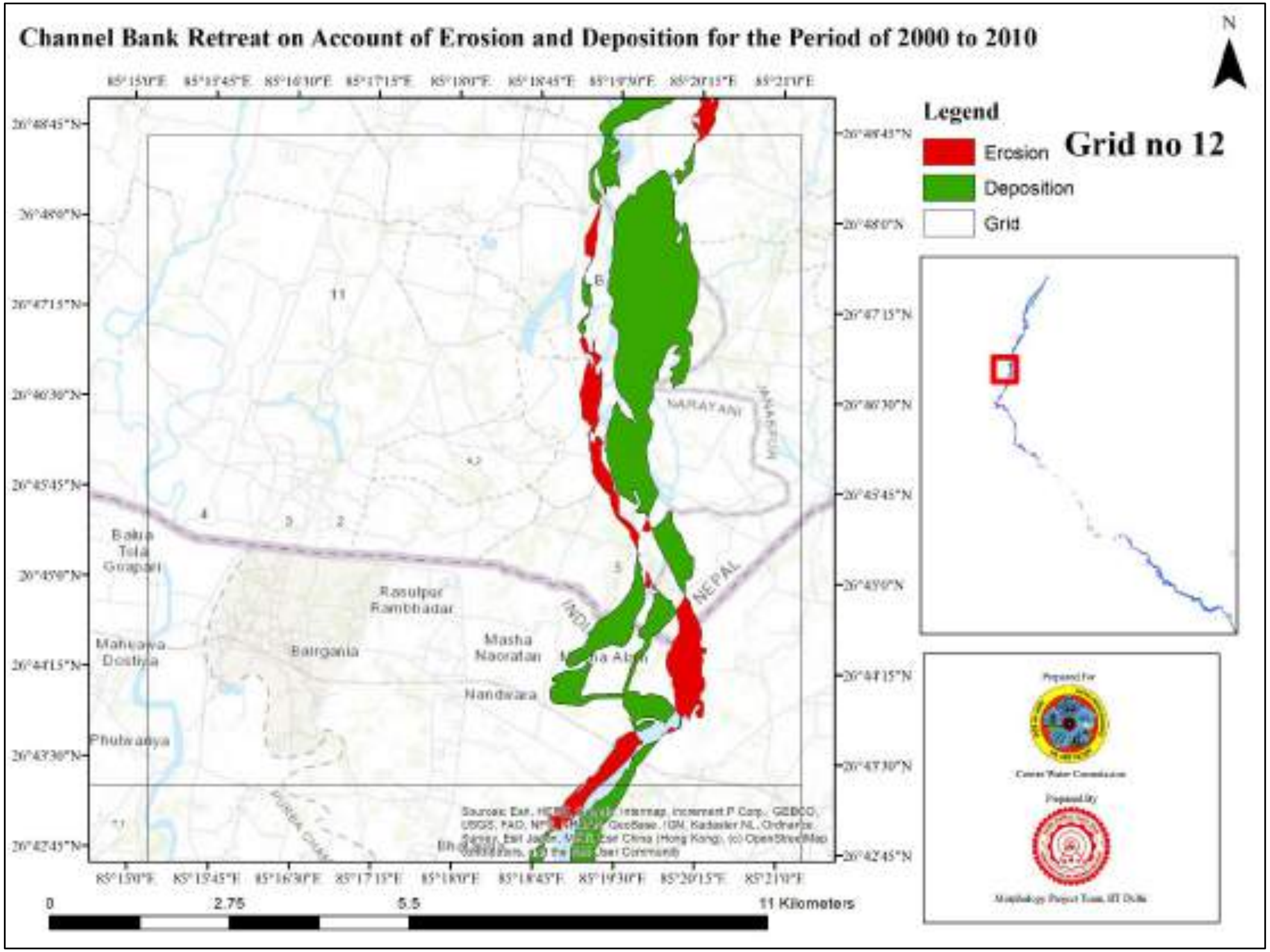



Figure **Error! No text of specified style in document.**-49: Erosion/Deposition Map of Bagmati River for Grid 12 for year (2000-2010)

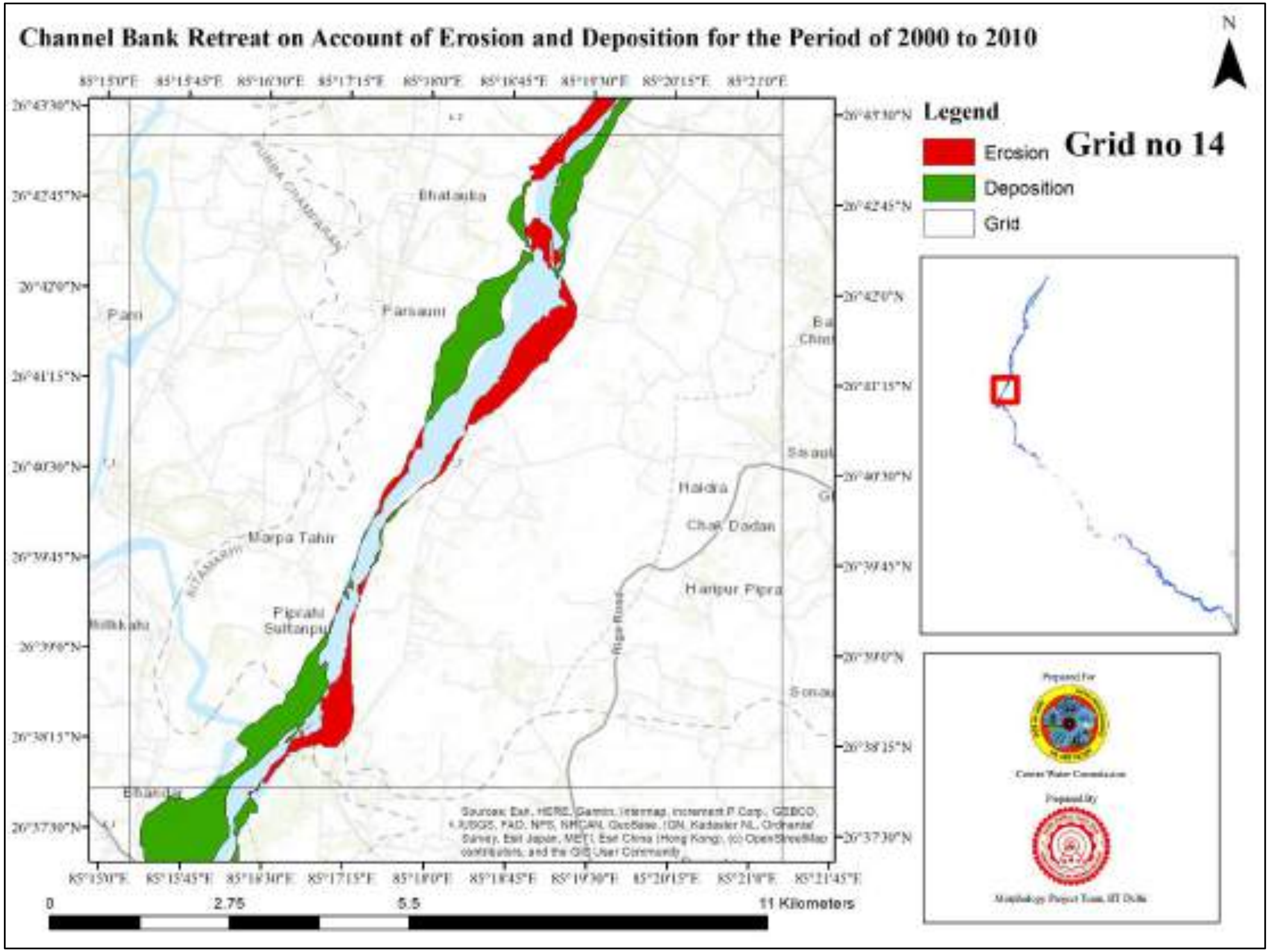



Figure **Error! No text of specified style in document.**-50: Erosion/Deposition Map of Bagmati River for Grid 14 for year (2000-2010)

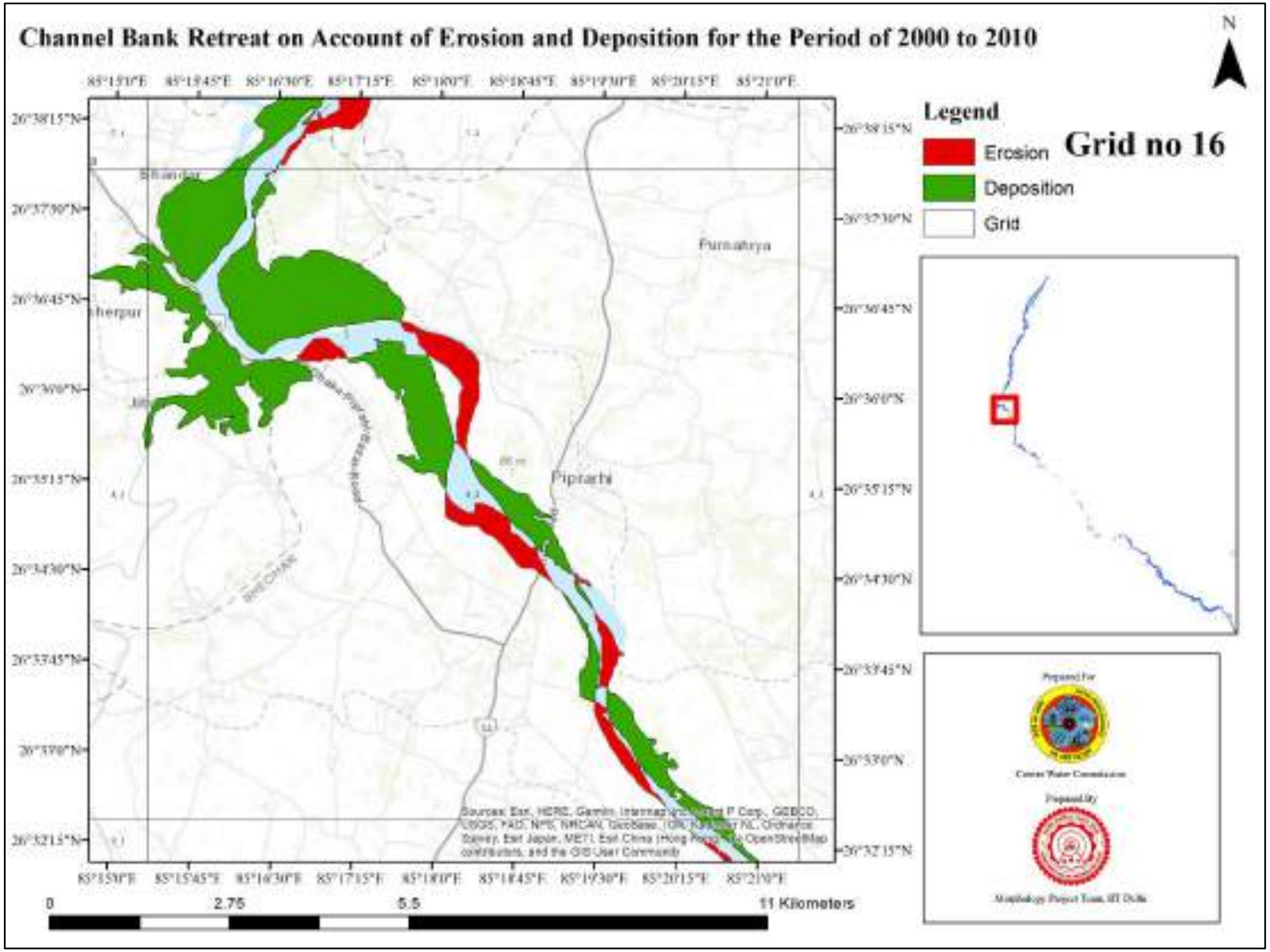



Figure **Error! No text of specified style in document.**-51: Erosion/Deposition Map of Bagmati River for Grid 16 for year (2000-2010)

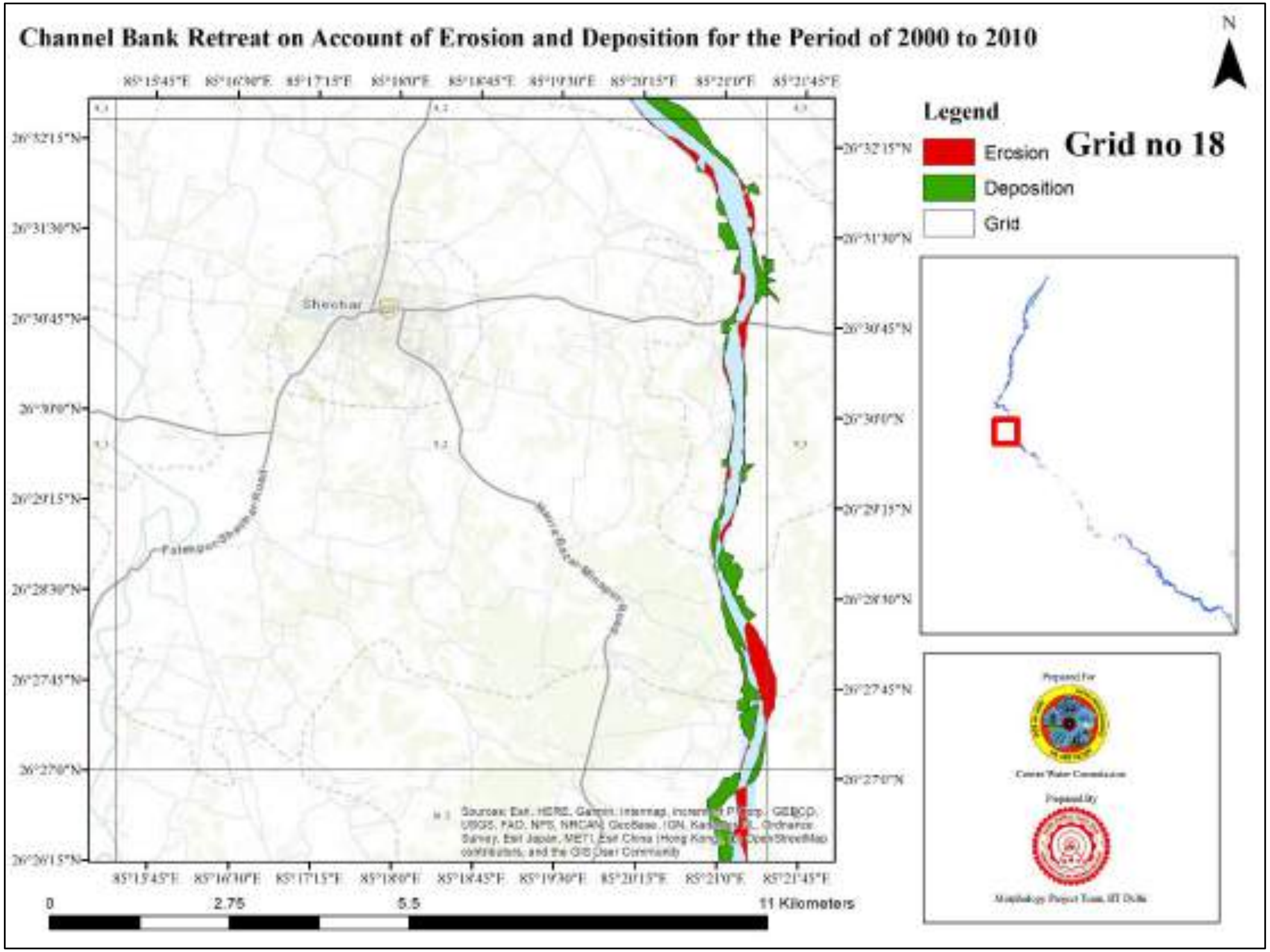



Figure **Error! No text of specified style in document.**-52: Erosion/Deposition Map of Bagmati River for Grid 18 for year (2000-2010)

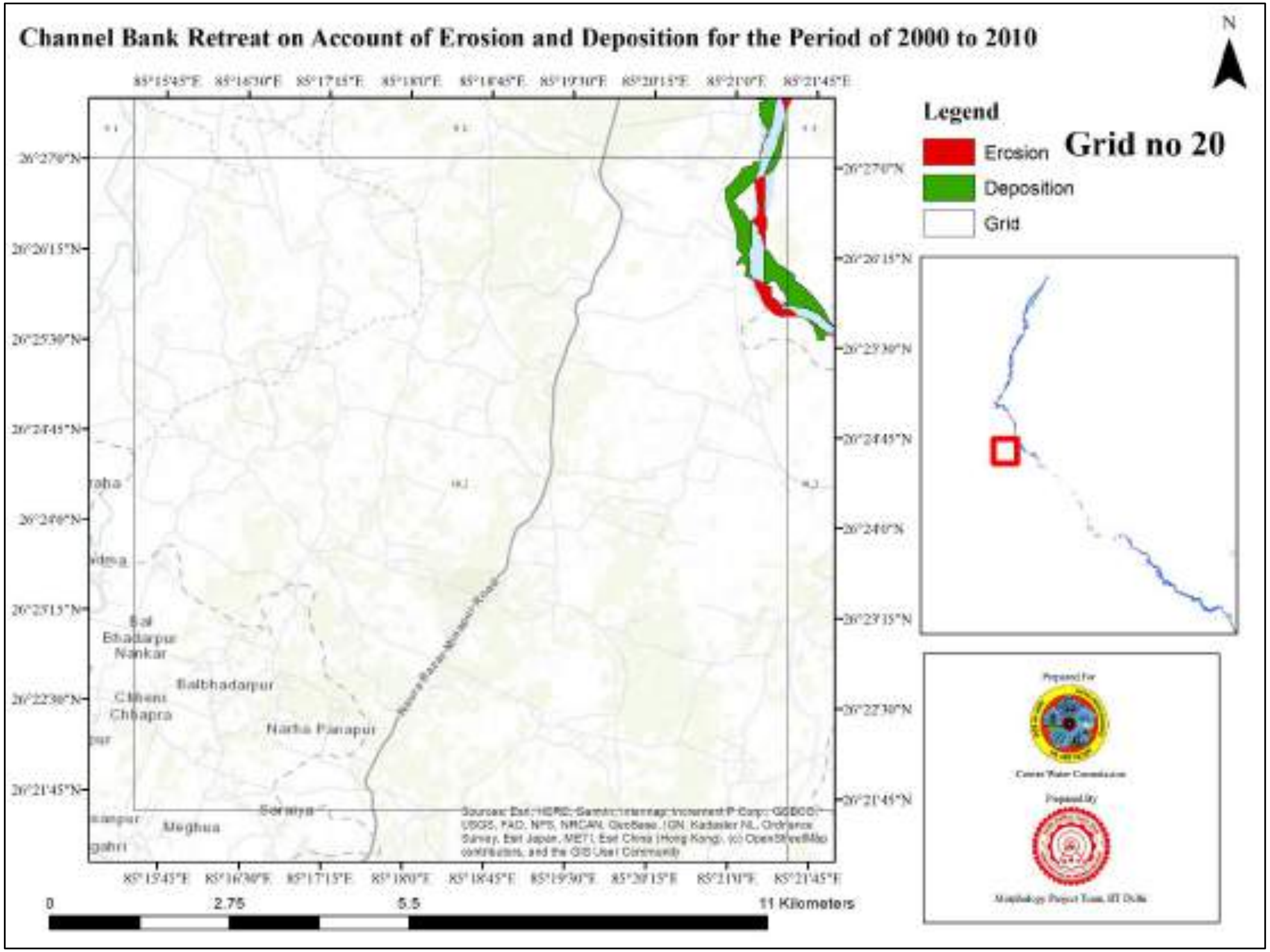



Figure **Error! No text of specified style in document.**-53: Erosion/Deposition Map of Bagmati River for Grid 20 for year (2000-2010)

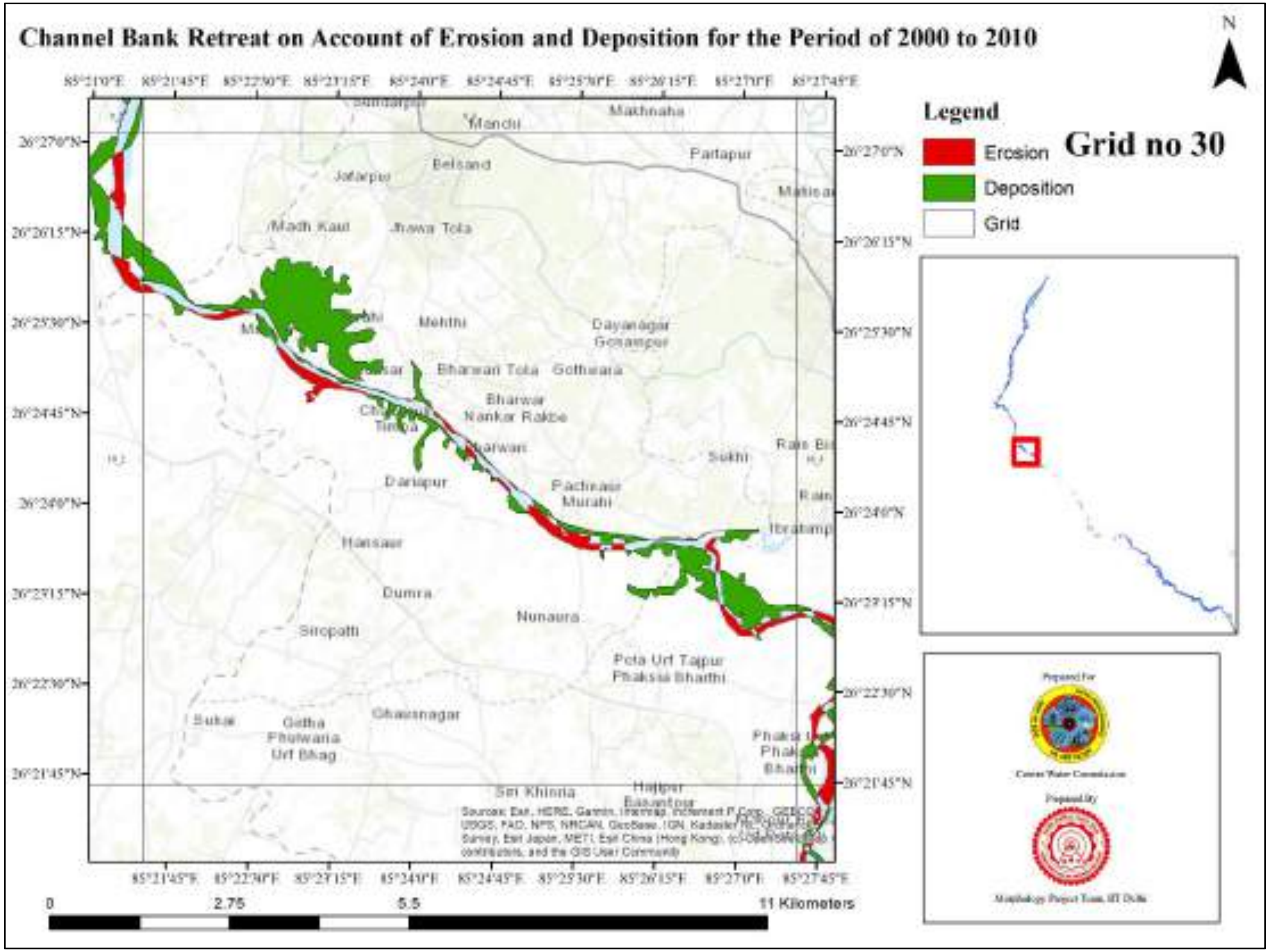



Figure **Error! No text of specified style in document.**-54: Erosion/Deposition Map of Bagmati River for Grid 30 for year (2000-2010)

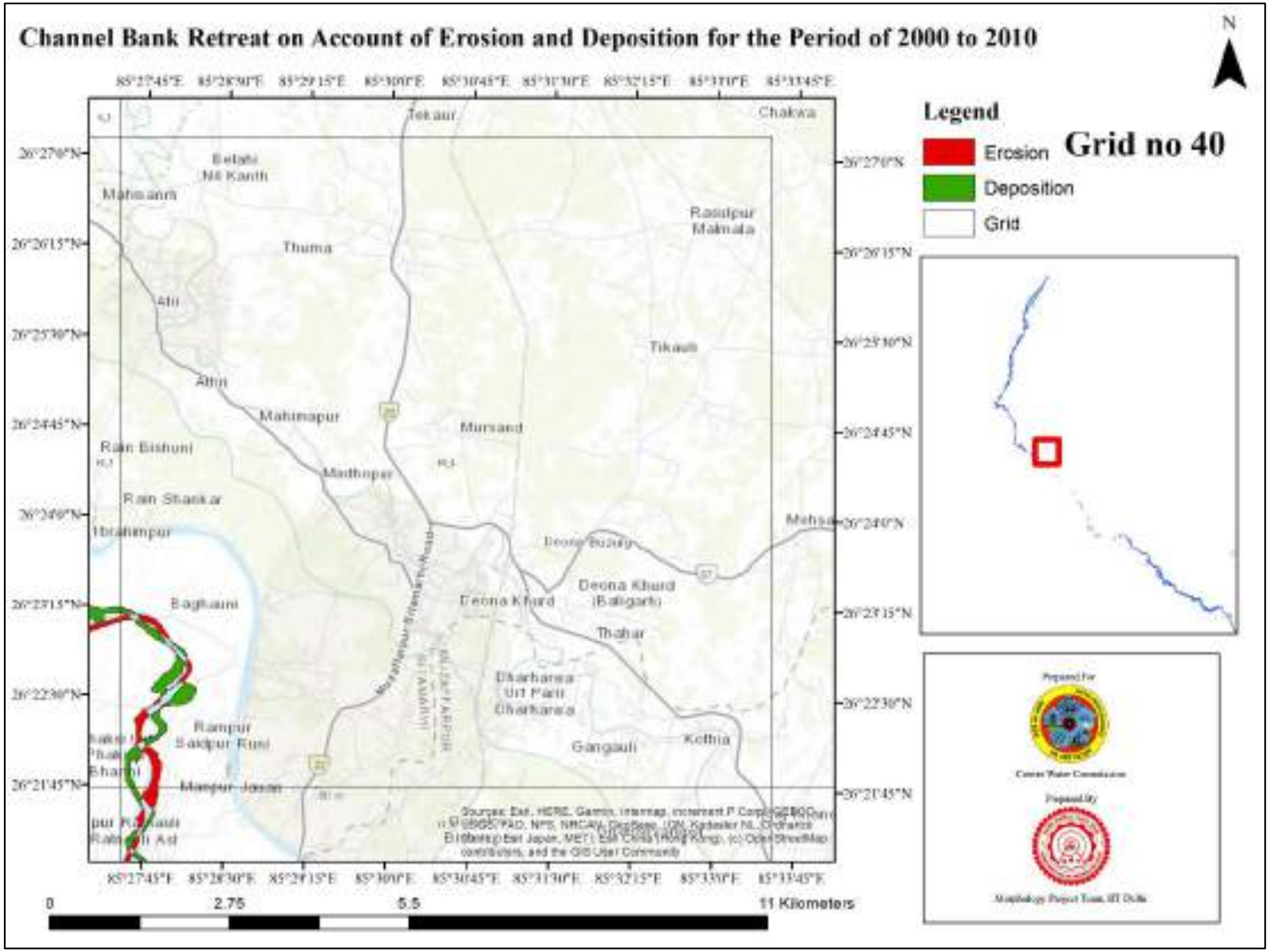



Figure **Error! No text of specified style in document.**-55: Erosion/Deposition Map of Bagmati River for Grid 40 for year (2000-2010)

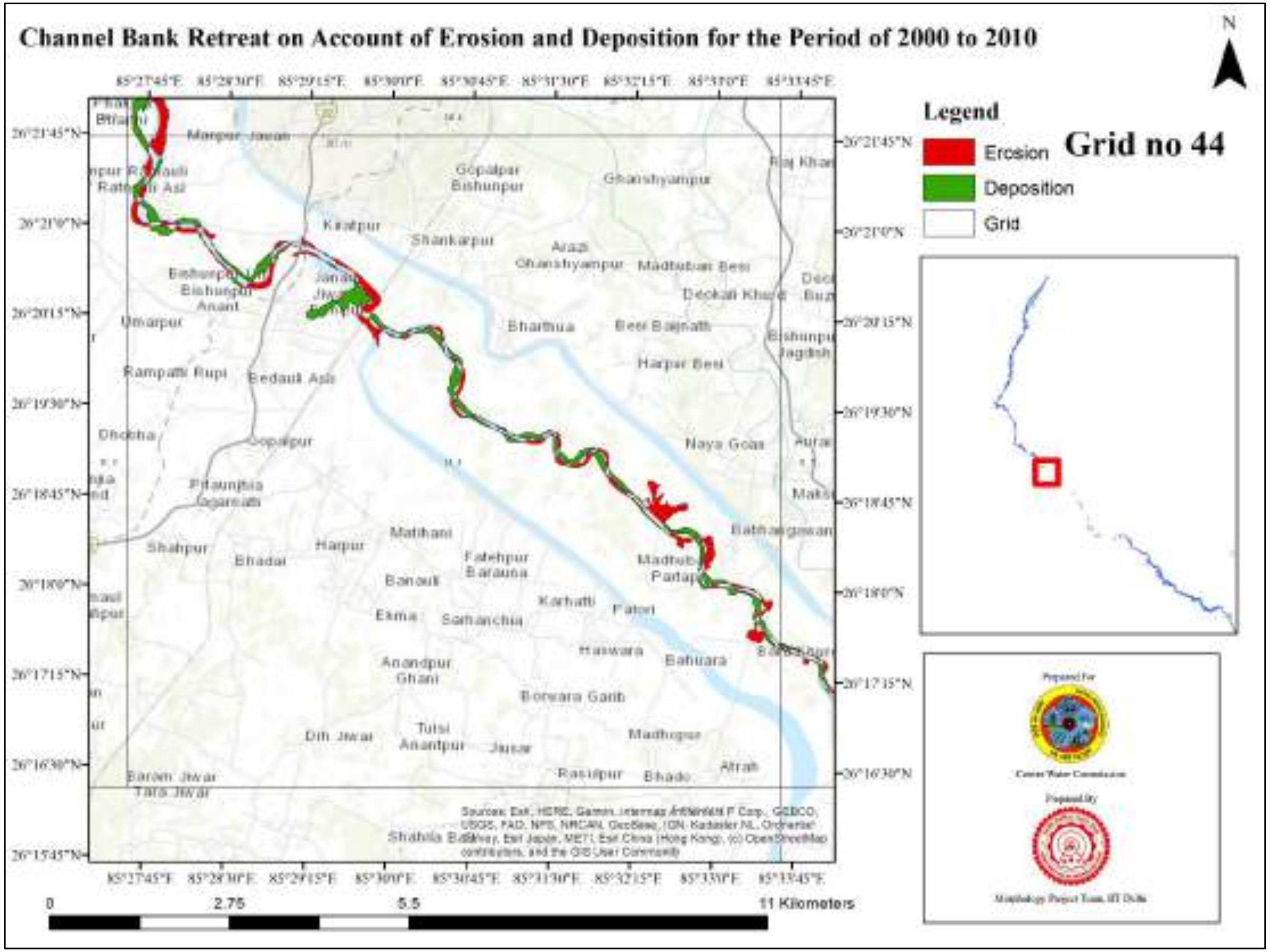



Figure **Error! No text of specified style in document.**-56: Erosion/Deposition Map of Bagmati River for Grid 44 for year (2000-2010)

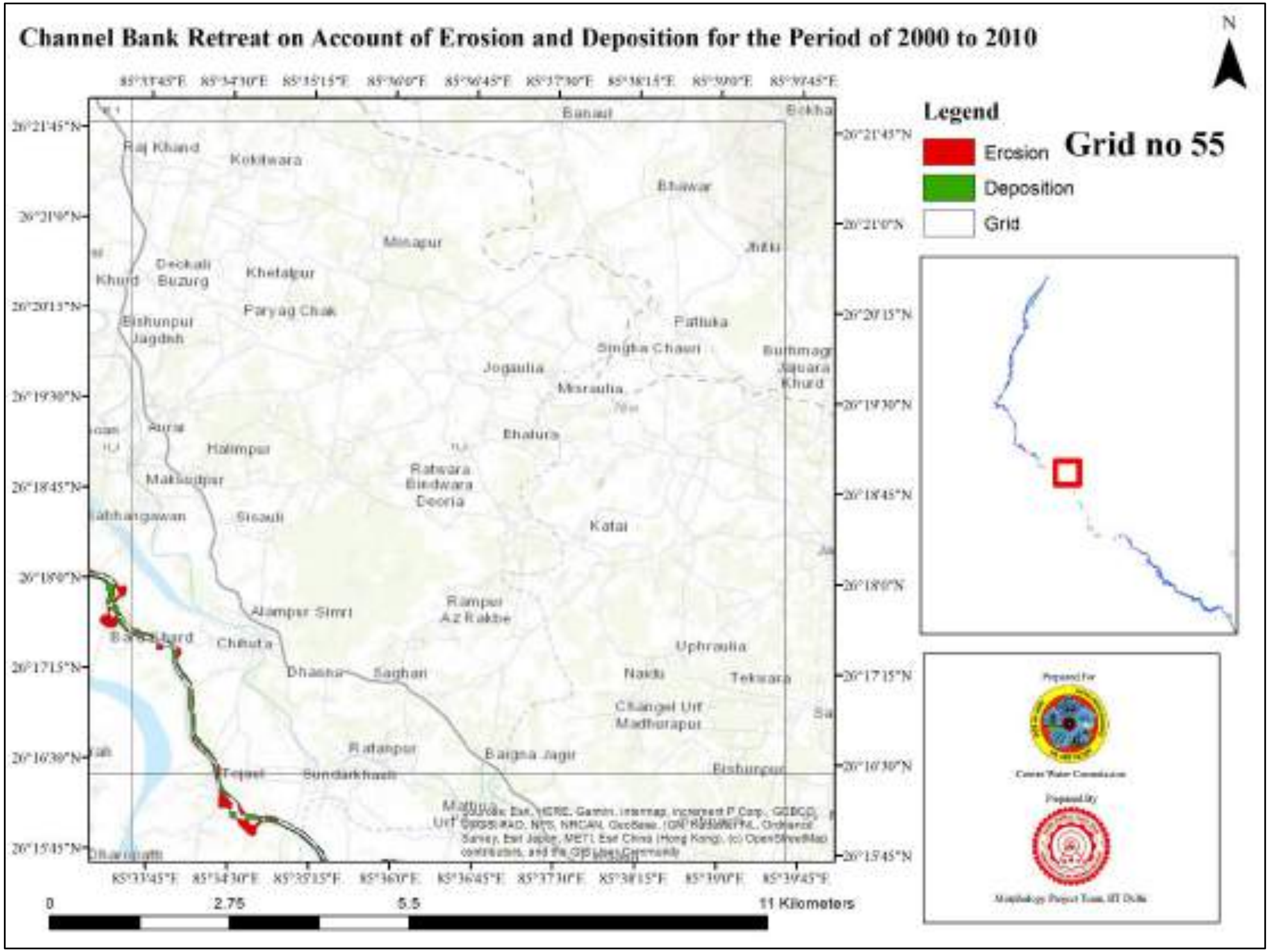



Figure **Error! No text of specified style in document.**-57: Erosion/Deposition Map of Bagmati River for Grid 55 for year (2000-2010)

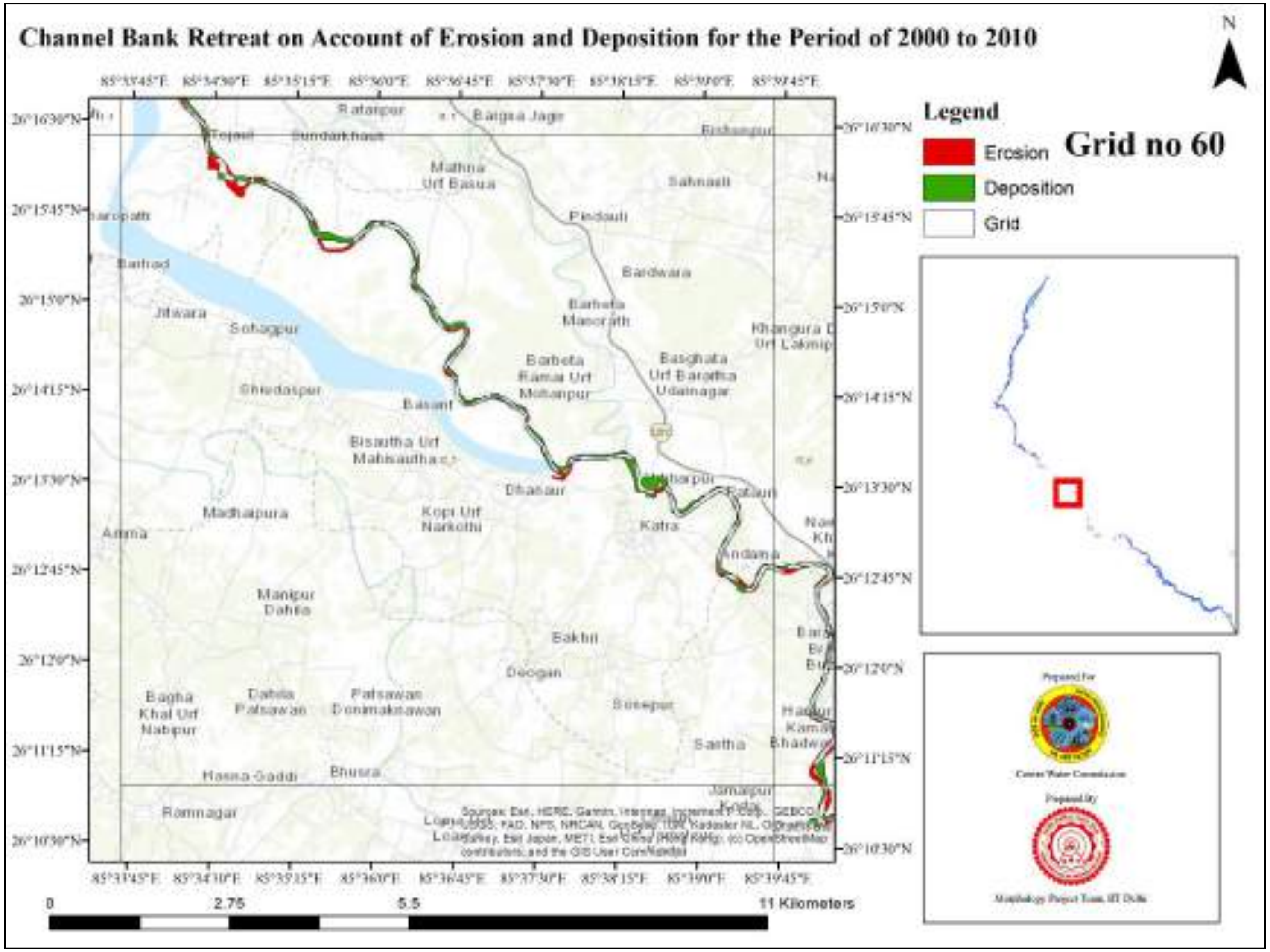



Figure **Error! No text of specified style in document.**-58: Erosion/Deposition Map of Bagmati River for Grid 60 for year (2000-2010)

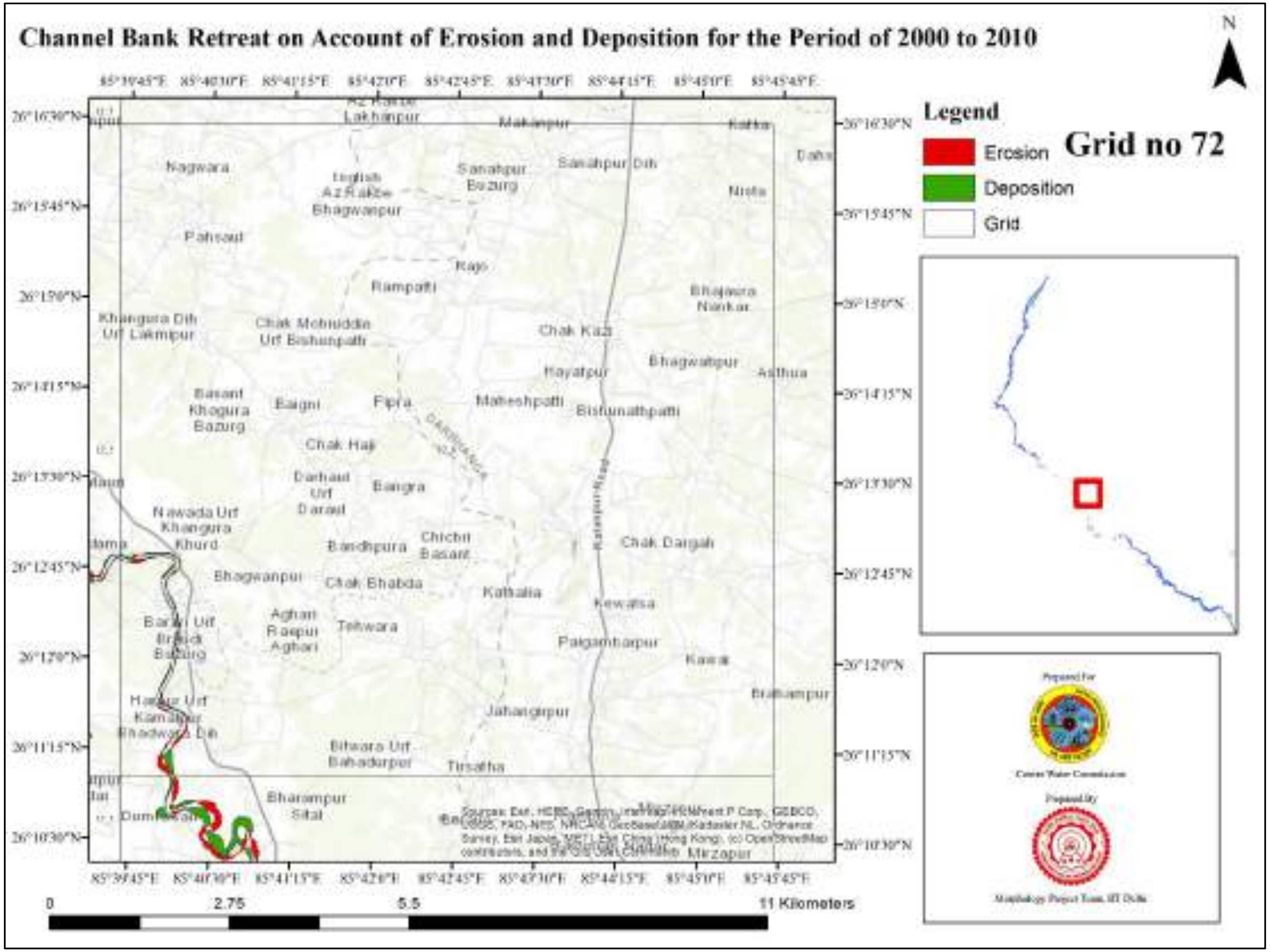



Figure **Error! No text of specified style in document.**-59: Erosion/Deposition Map of Bagmati River for Grid 72 for year (2000-2010)

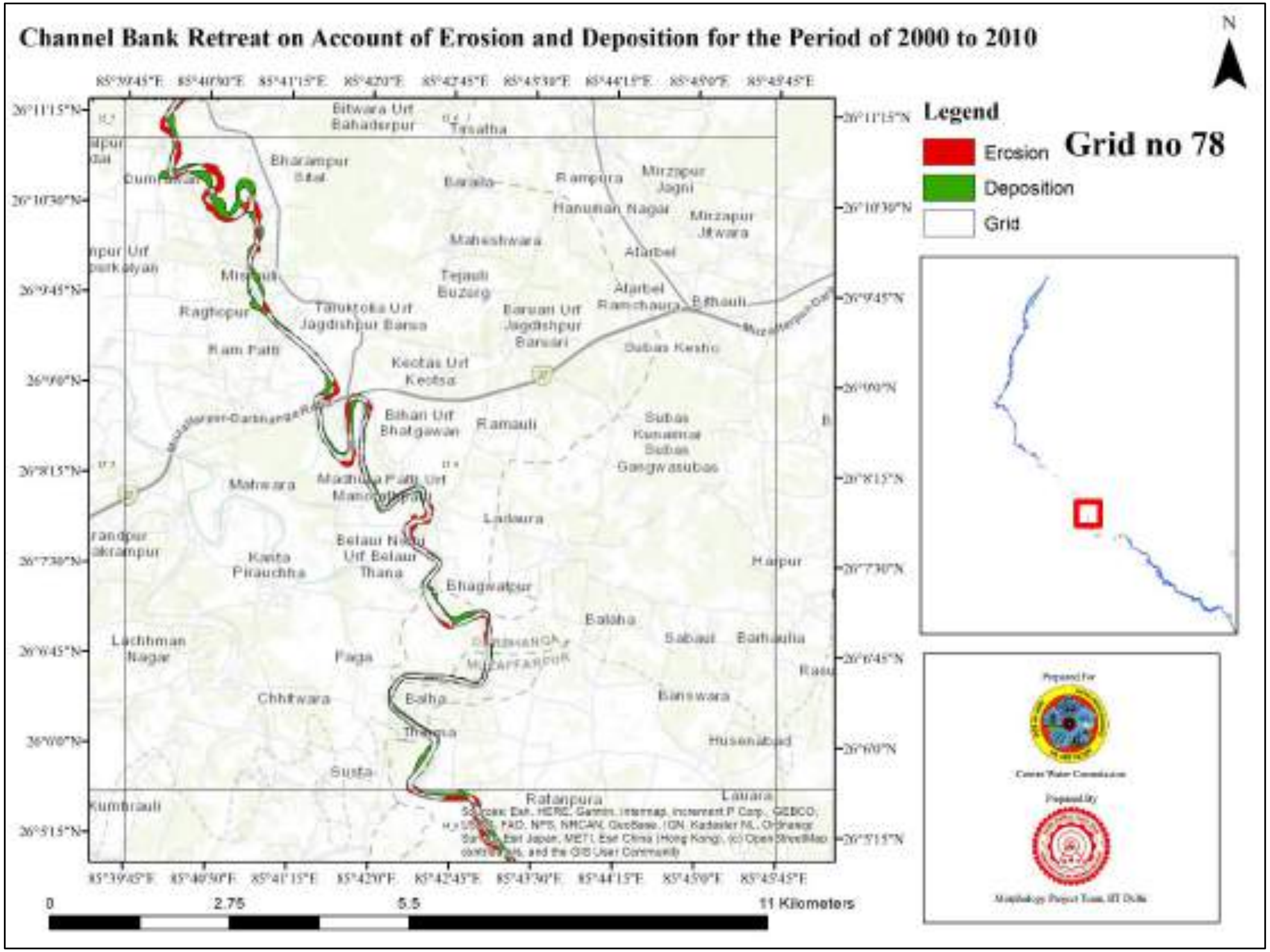



Figure **Error! No text of specified style in document.**-60: Erosion/Deposition Map of Bagmati River for Grid 78 for year (2000-2010)

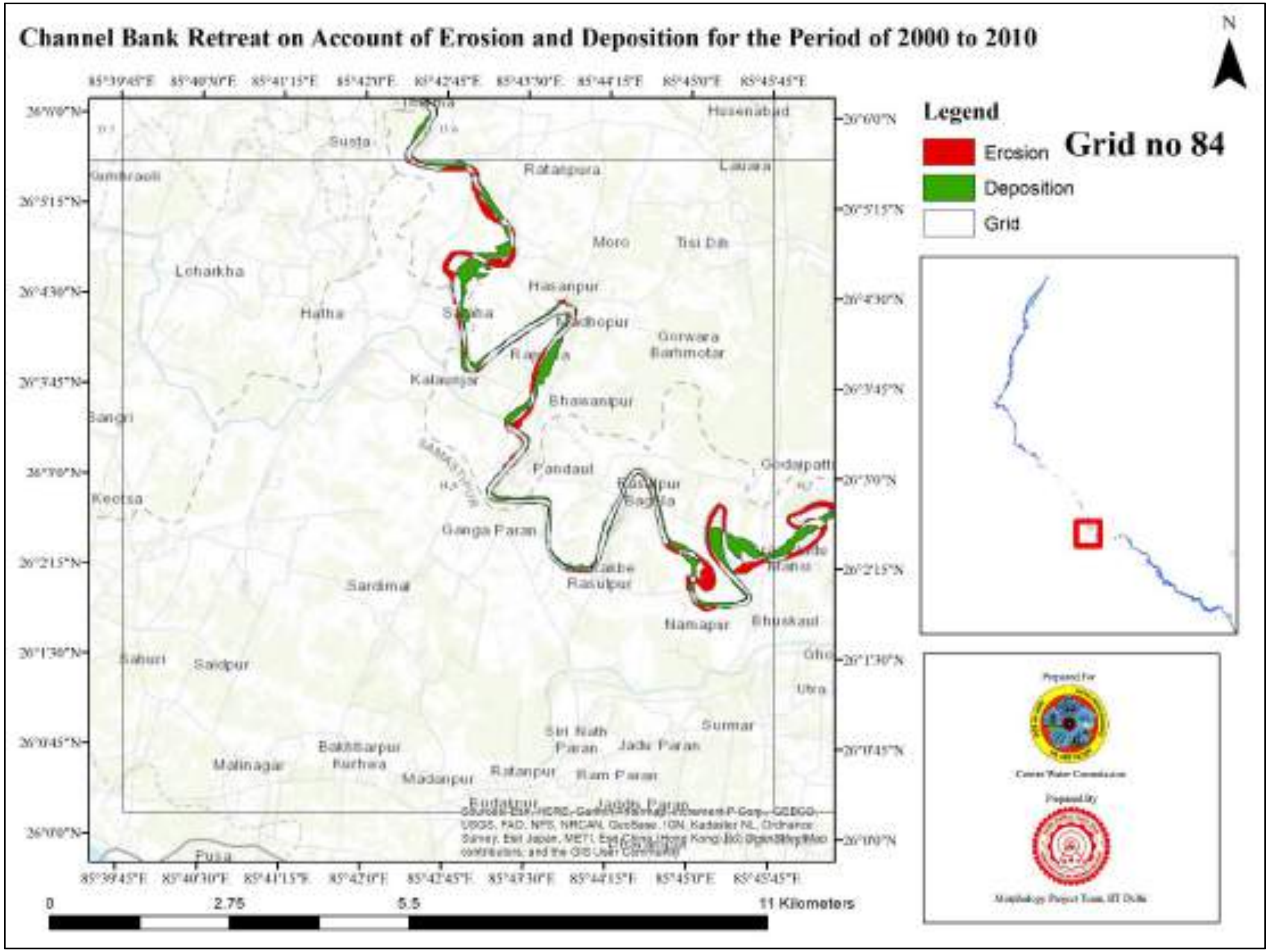



Figure **Error! No text of specified style in document.**-61: Erosion/Deposition Map of Bagmati River for Grid 84 for year (2000-2010)

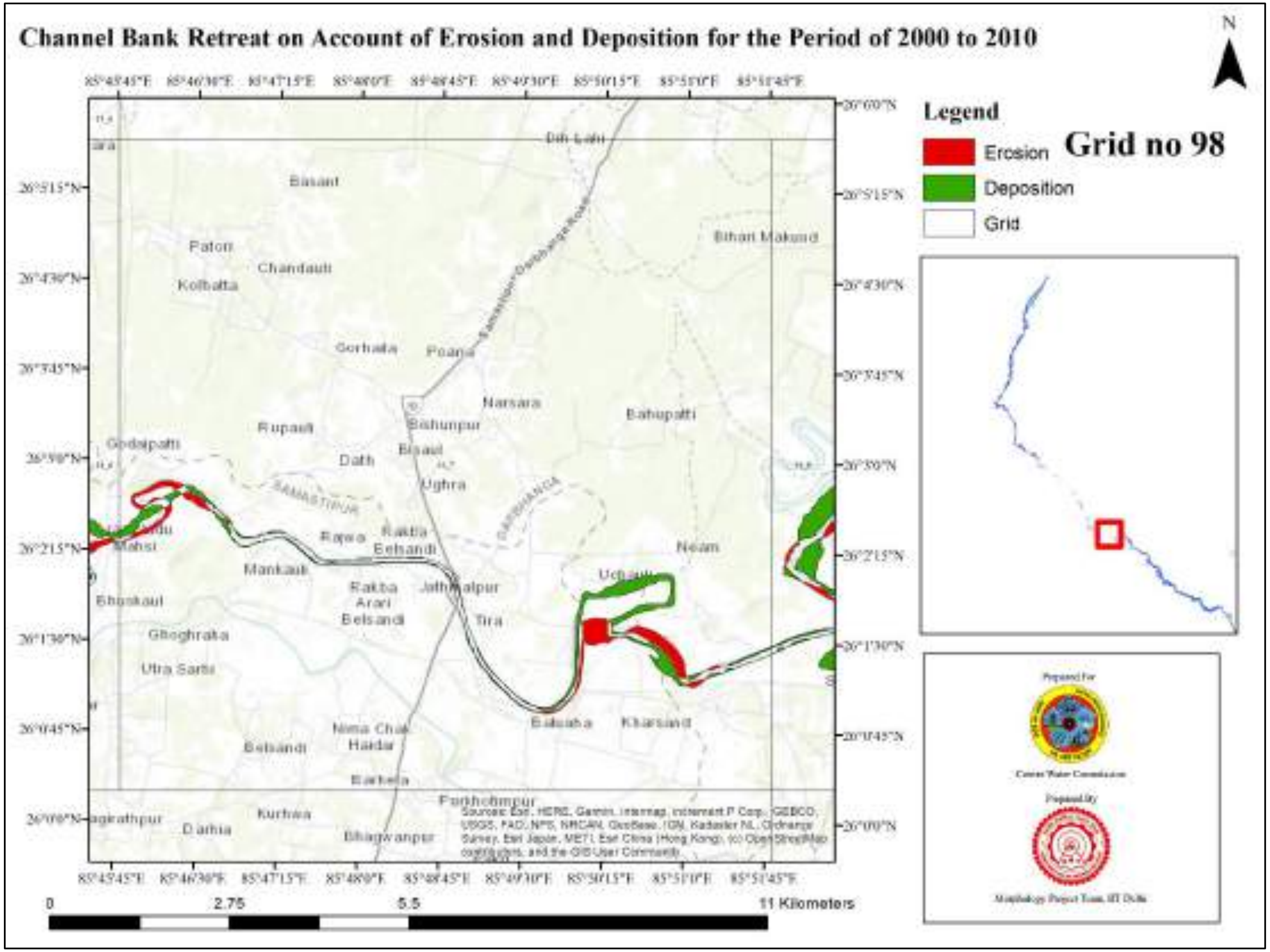



Figure **Error! No text of specified style in document.**-62: Erosion/Deposition Map of Bagmati River for Grid 98 for year (2000-2010)

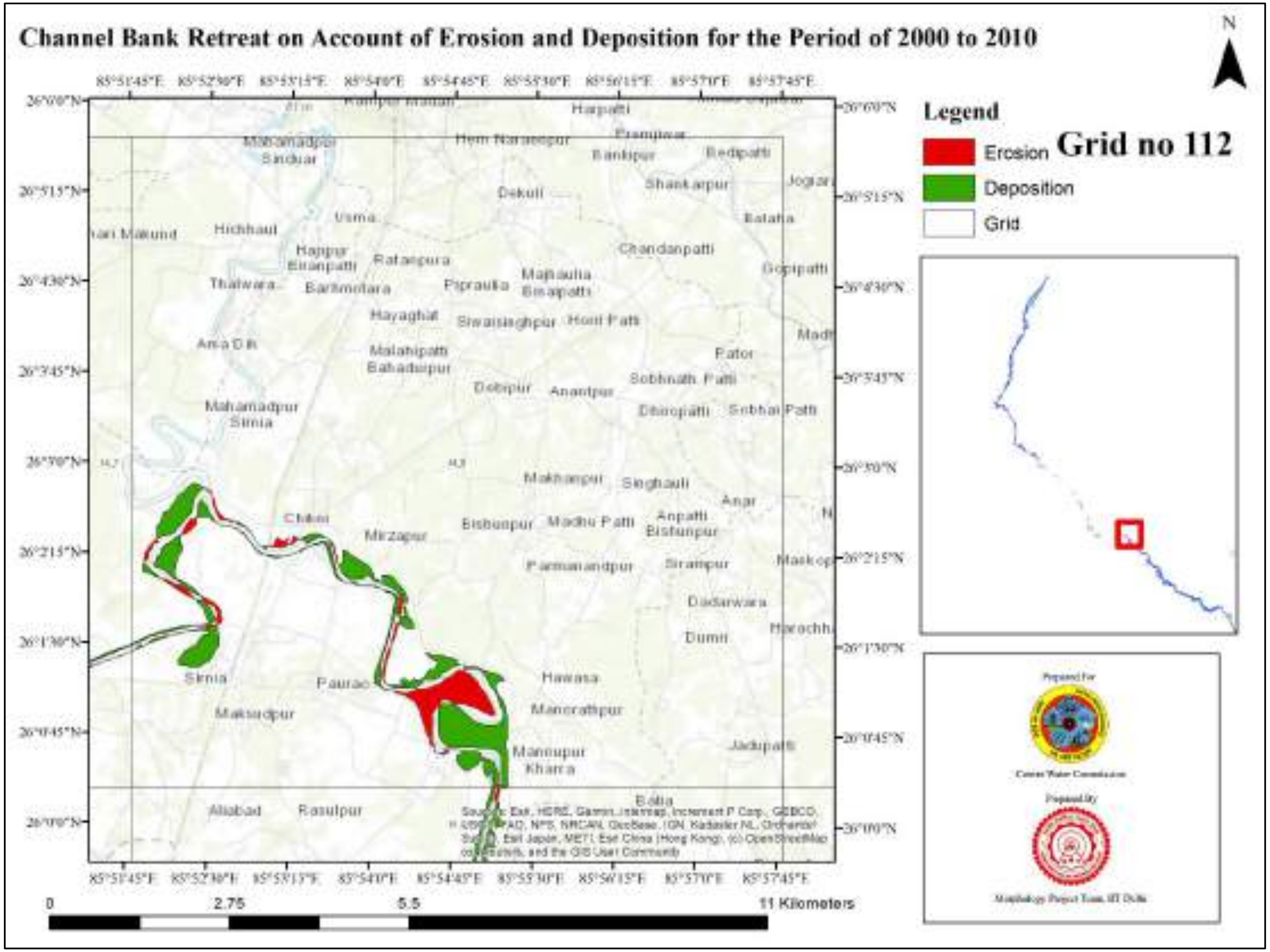



Figure **Error! No text of specified style in document.**-63: Erosion/Deposition Map of Bagmati River for Grid 112 for year (2000-2010)

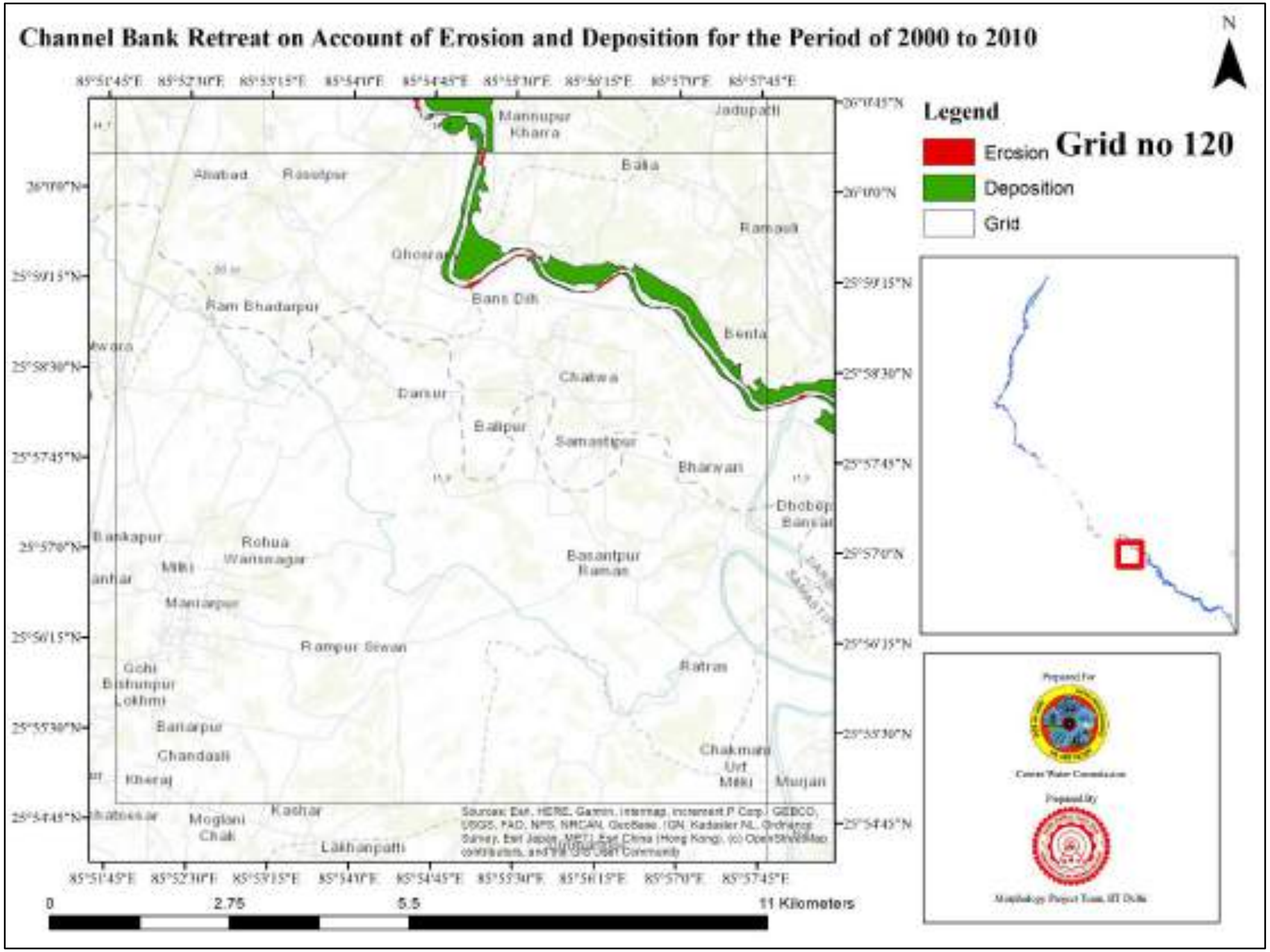



Figure **Error! No text of specified style in document.**-64: Erosion/Deposition Map of Bagmati River for Grid 120 for year (2000-2010)

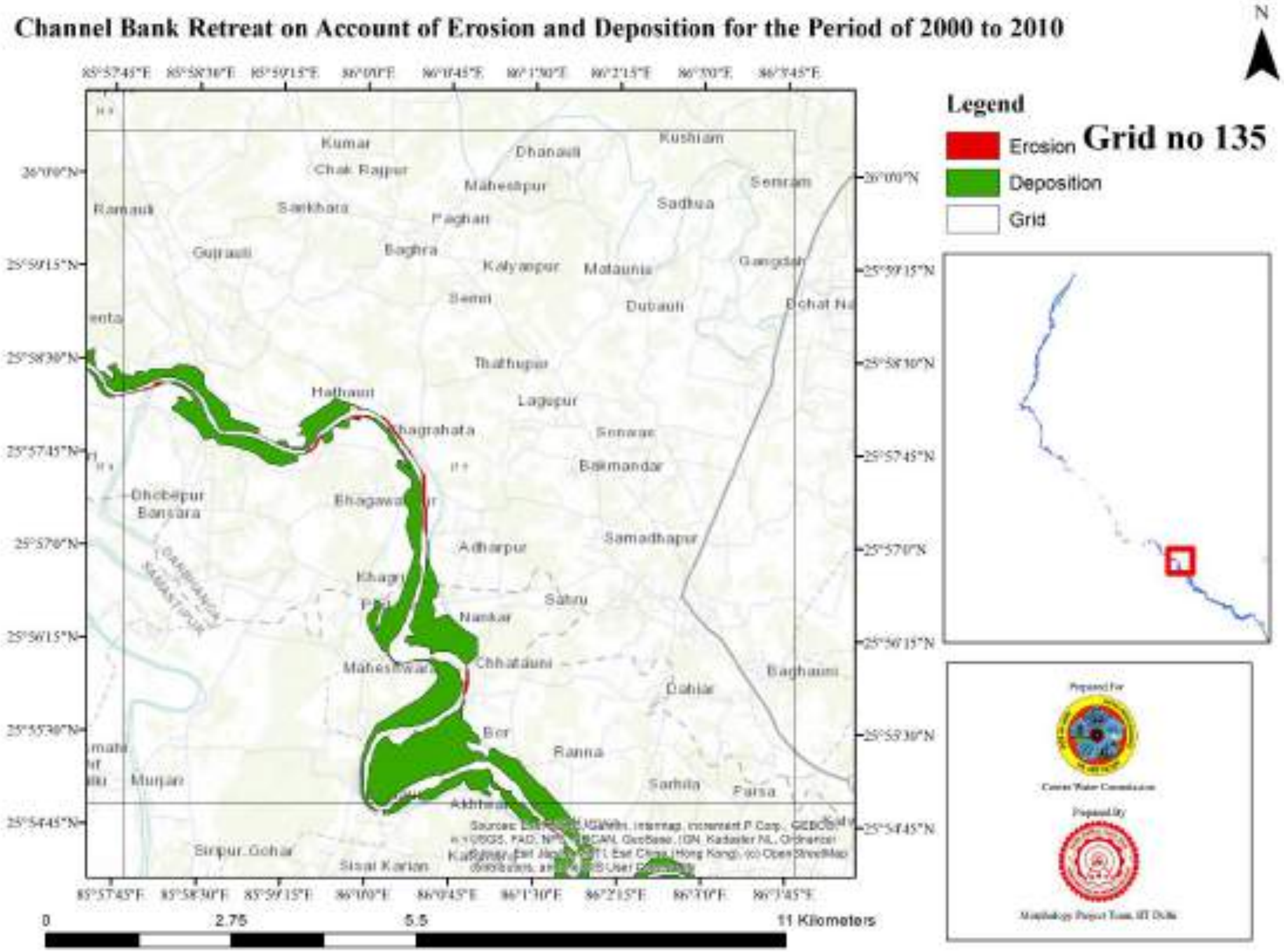



Figure **Error! No text of specified style in document.**-65: Erosion/Deposition Map of Bagmati River for Grid 135 for year (2000-2010)

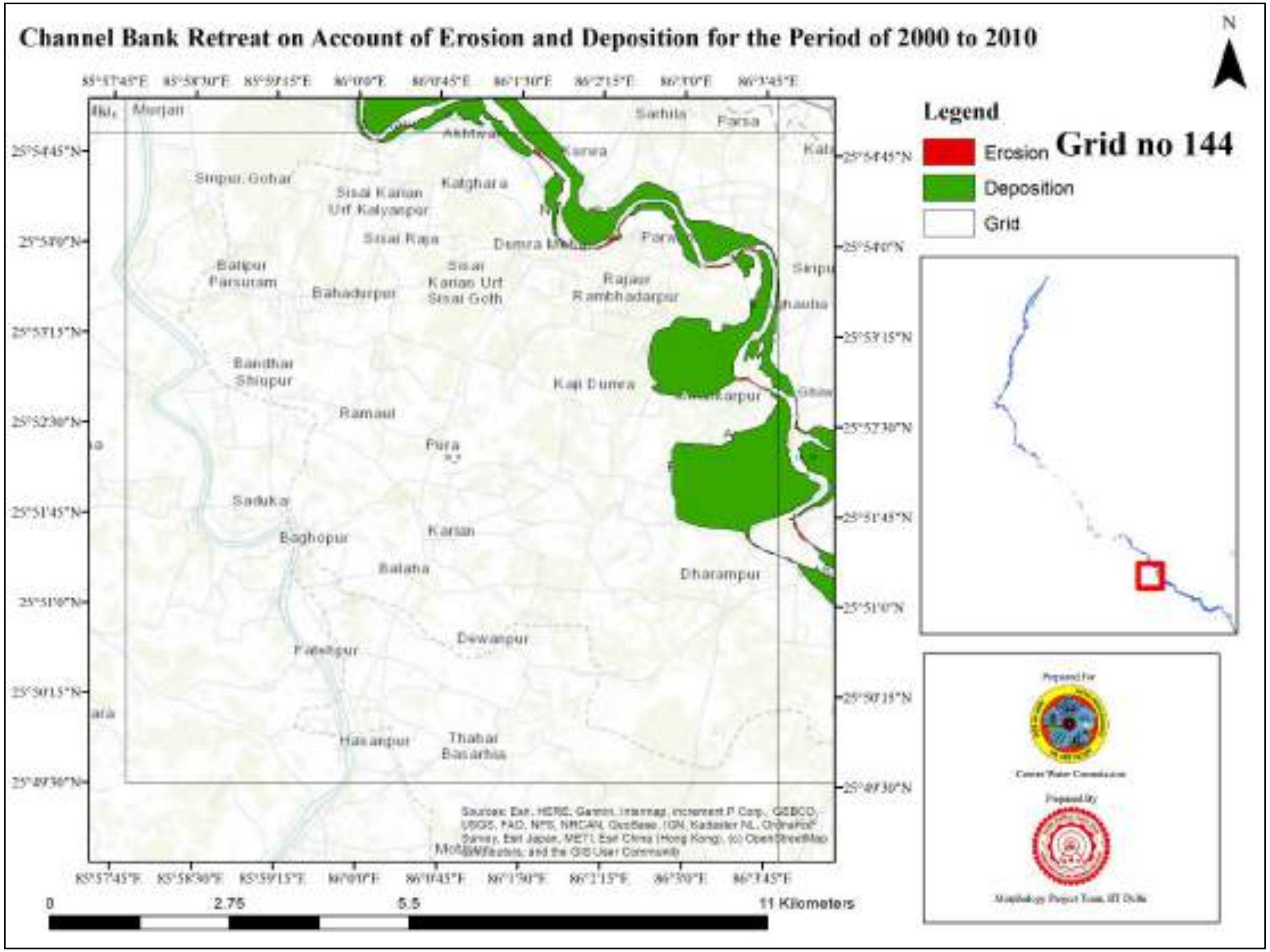



Figure **Error! No text of specified style in document.**-66: Erosion/Deposition Map of Bagmati River for Grid 144 for year (2000-2010)

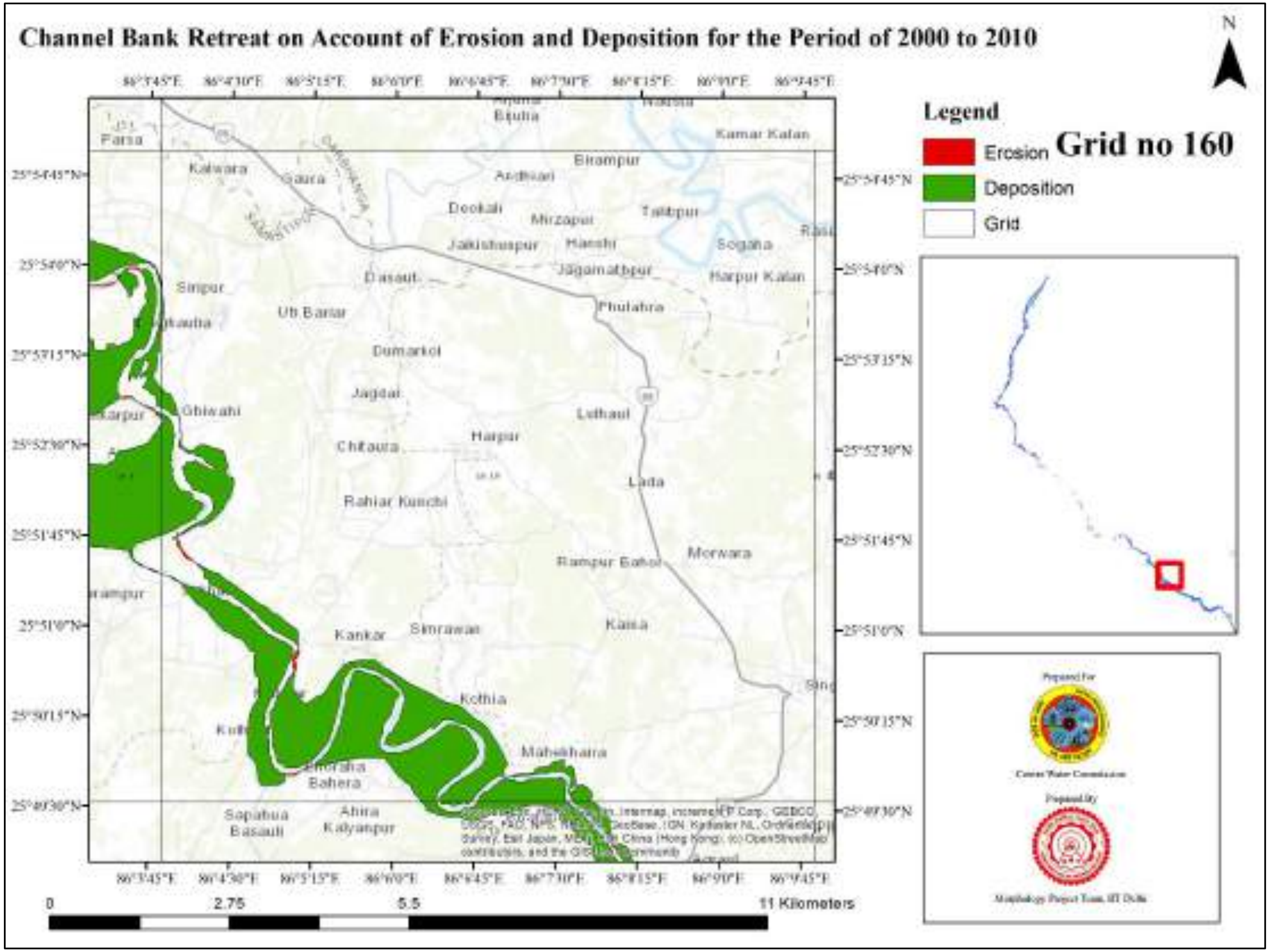



Figure **Error! No text of specified style in document.**-67: Erosion/Deposition Map of Bagmati River for Grid 160 for year (2000-2010)

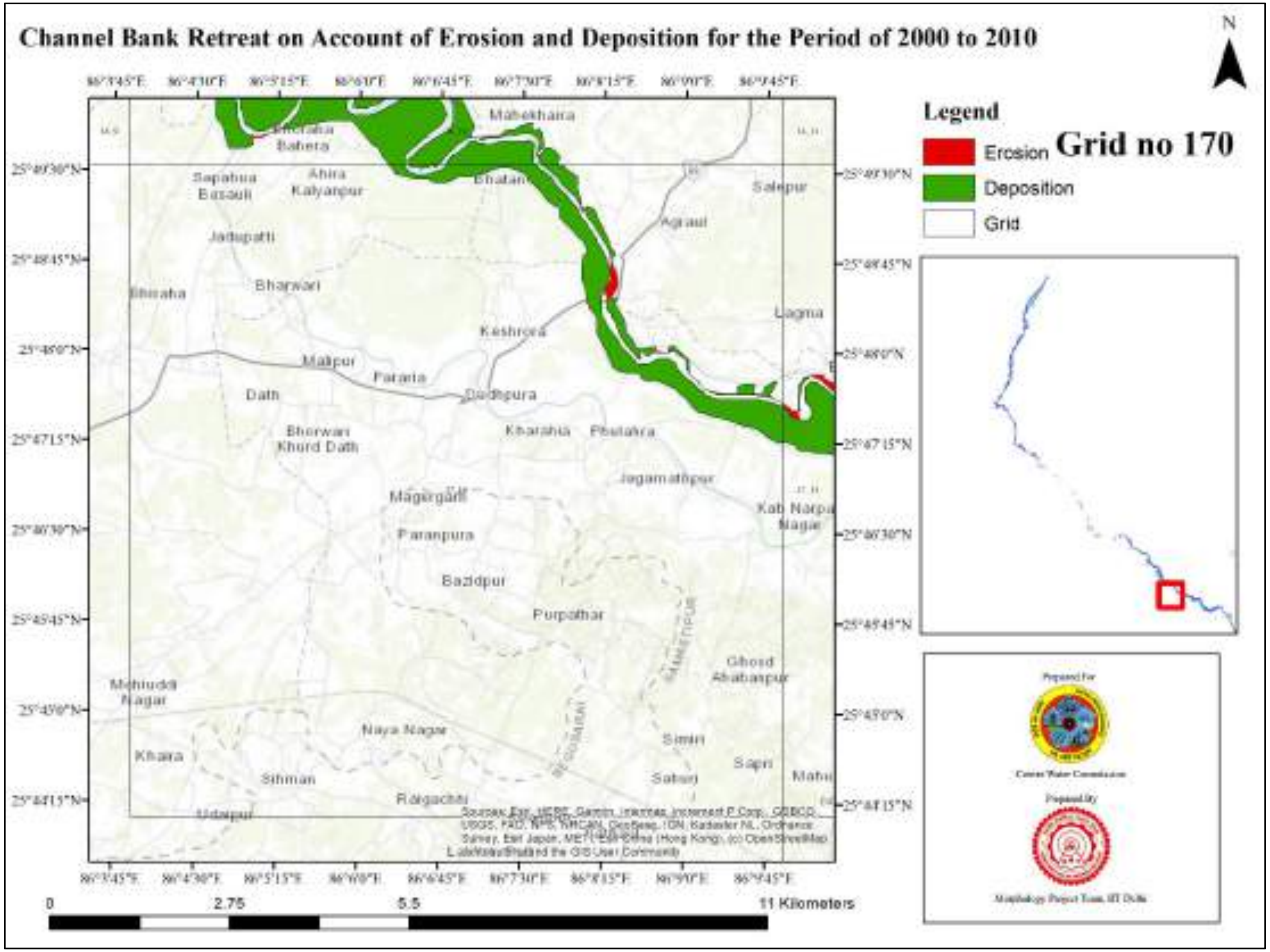



Figure **Error! No text of specified style in document.**-68: Erosion/Deposition Map of Bagmati River for Grid 170 for year (2000-2010)

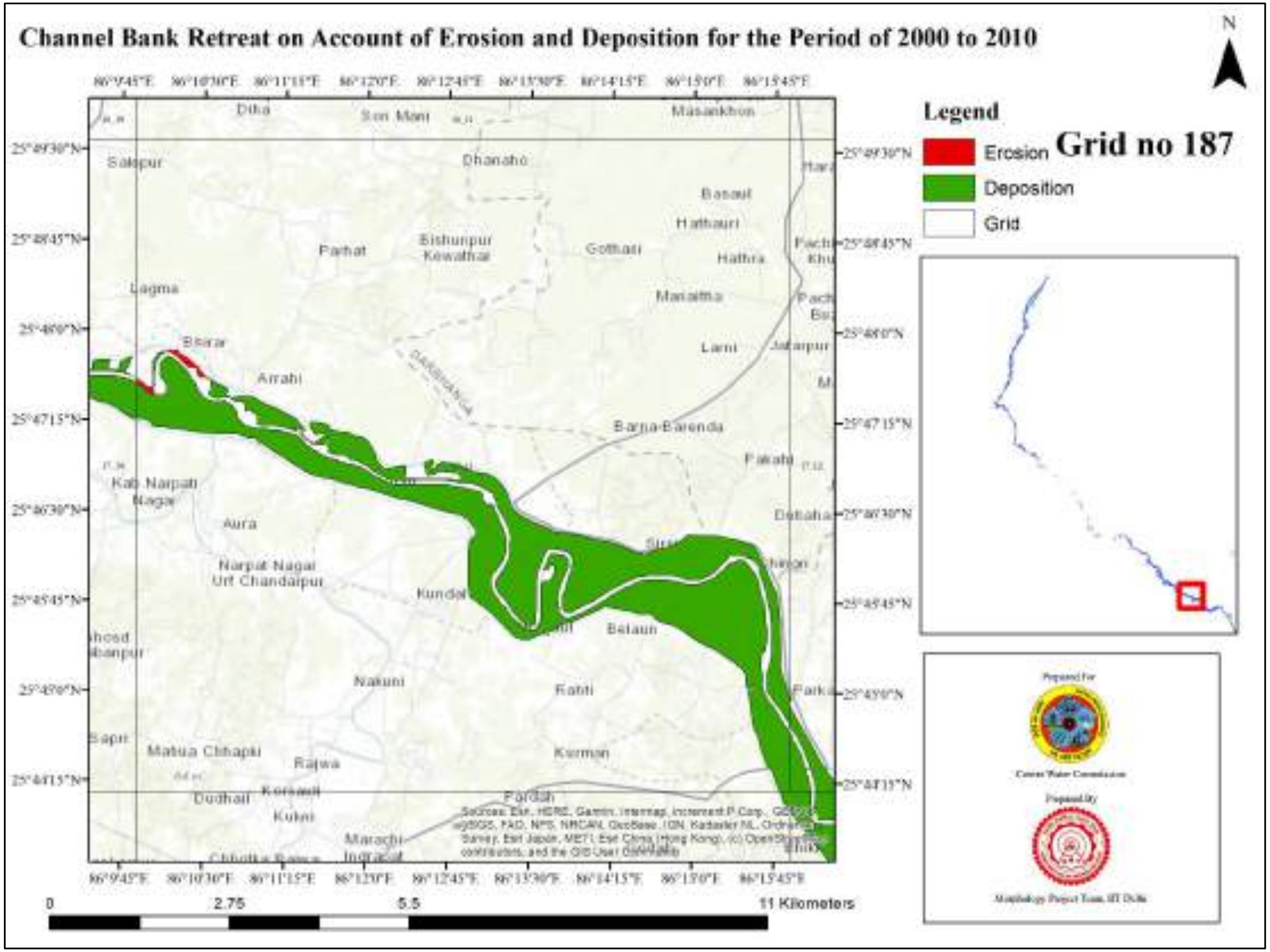



Figure **Error! No text of specified style in document.**-69: Erosion/Deposition Map of Bagmati River for Grid 187 for year (2000-2010)

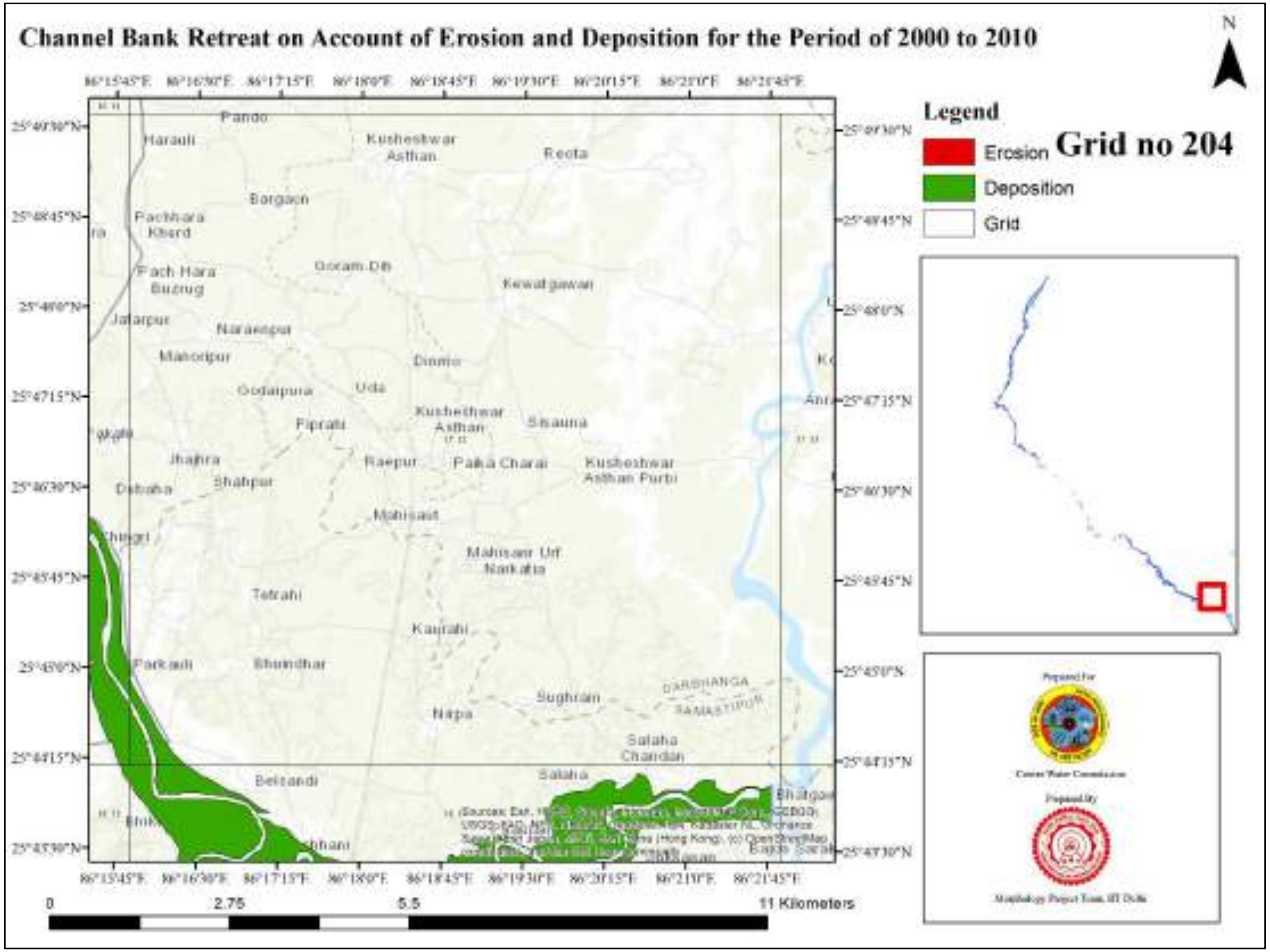



Figure **Error! No text of specified style in document.**-70: Erosion/Deposition Map of Bagmati River for Grid 204 for year (2000-2010)

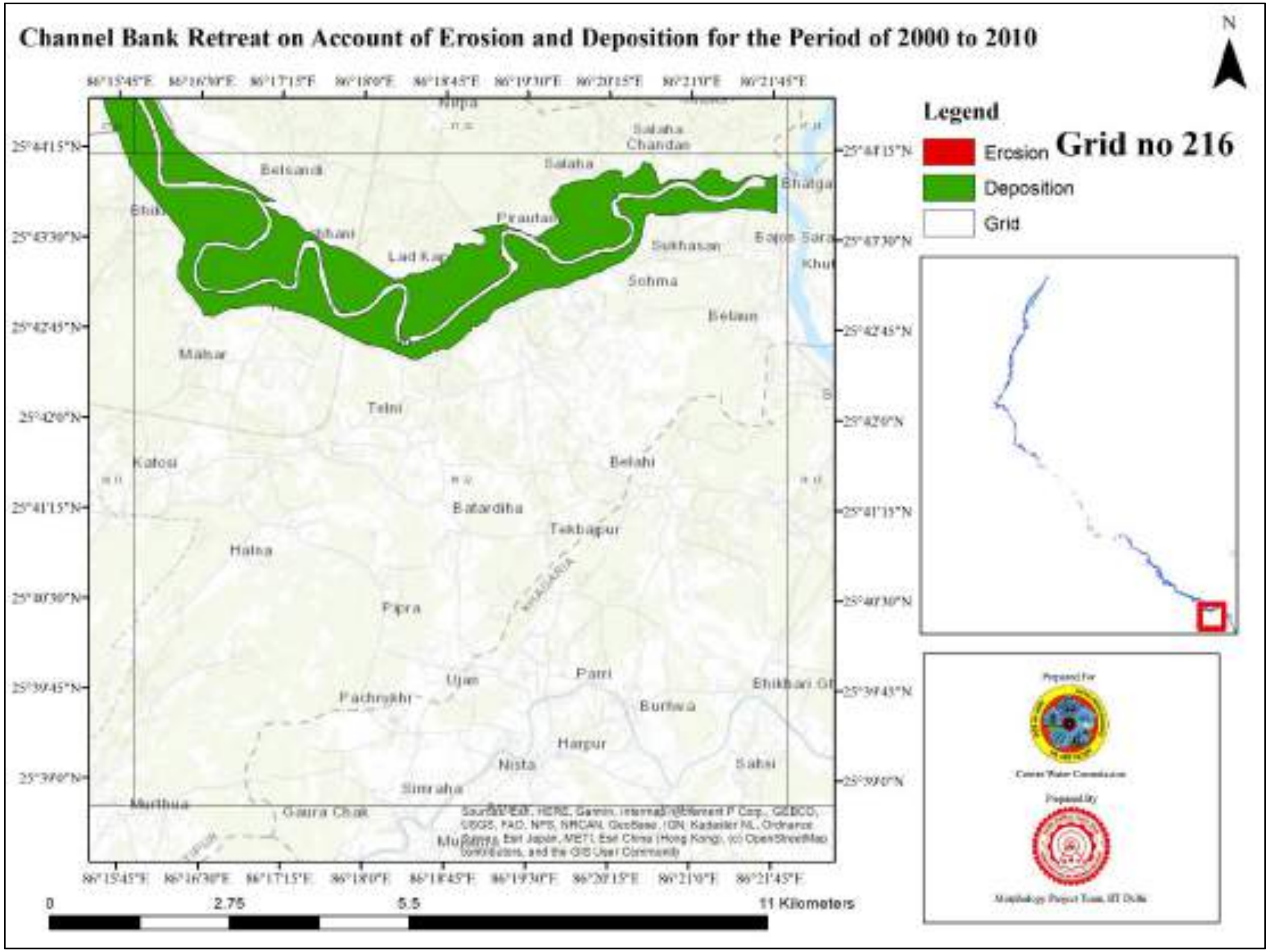



Figure **Error! No text of specified style in document.**-71: Erosion/Deposition Map of Bagmati River for Grid 216 for year (2000-2010)

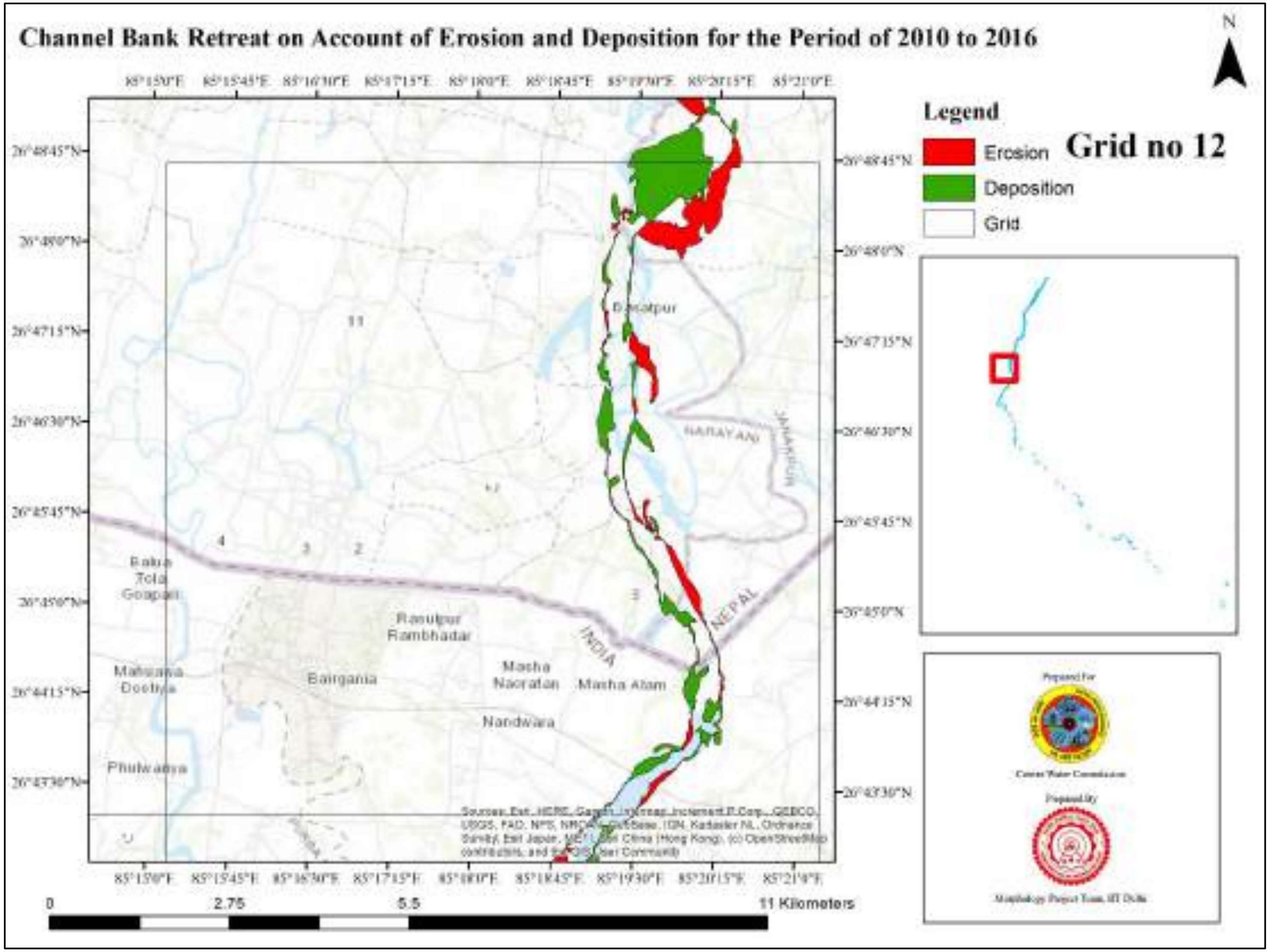



Figure **Error! No text of specified style in document.**-72: Erosion/Deposition Map of Bagmati River for Grid for Grid 12 year (2010-2016)

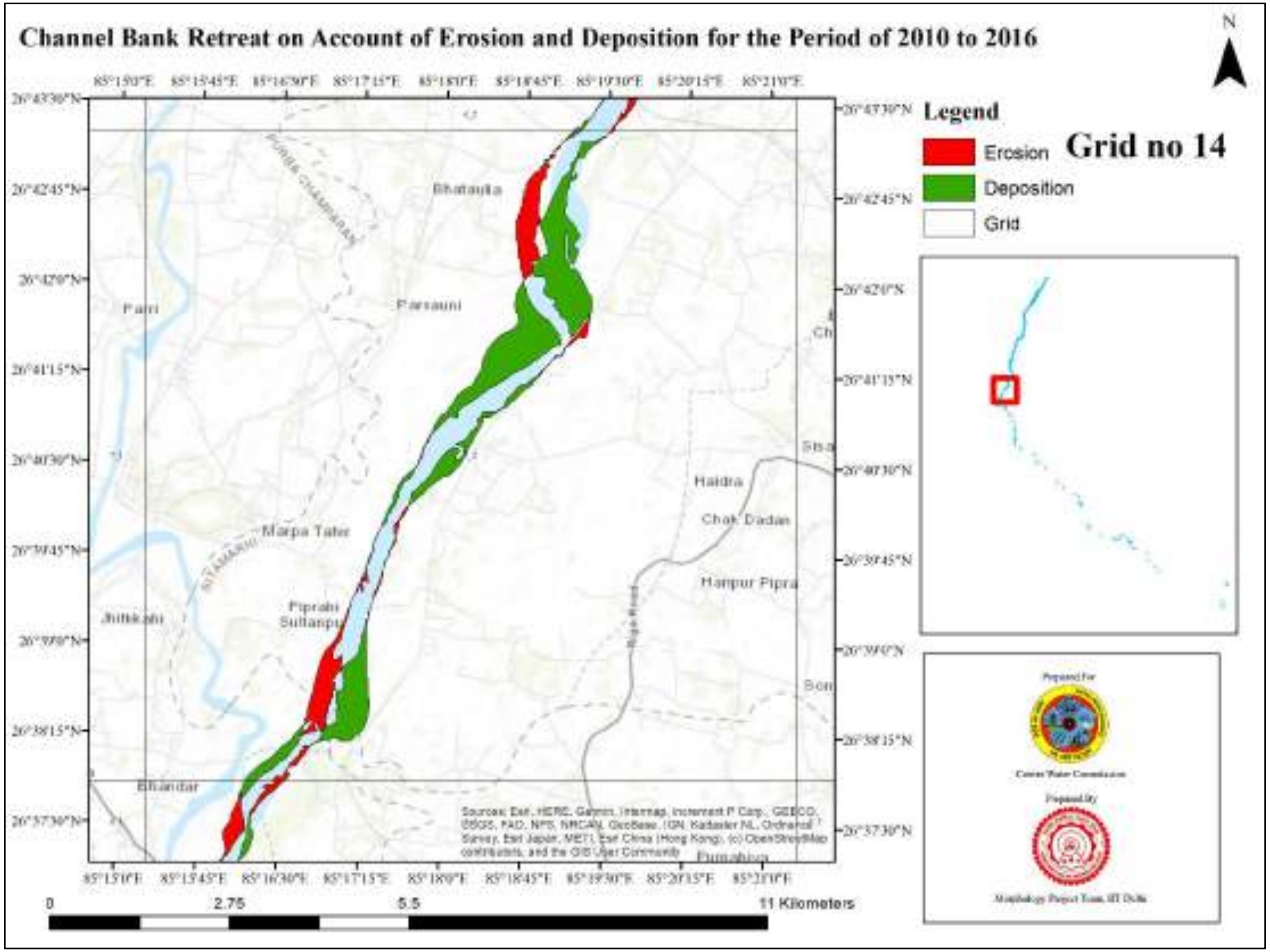



Figure **Error! No text of specified style in document.**-73: Erosion/Deposition Map of Bagmati River for Grid 14 for year (2010-2016)

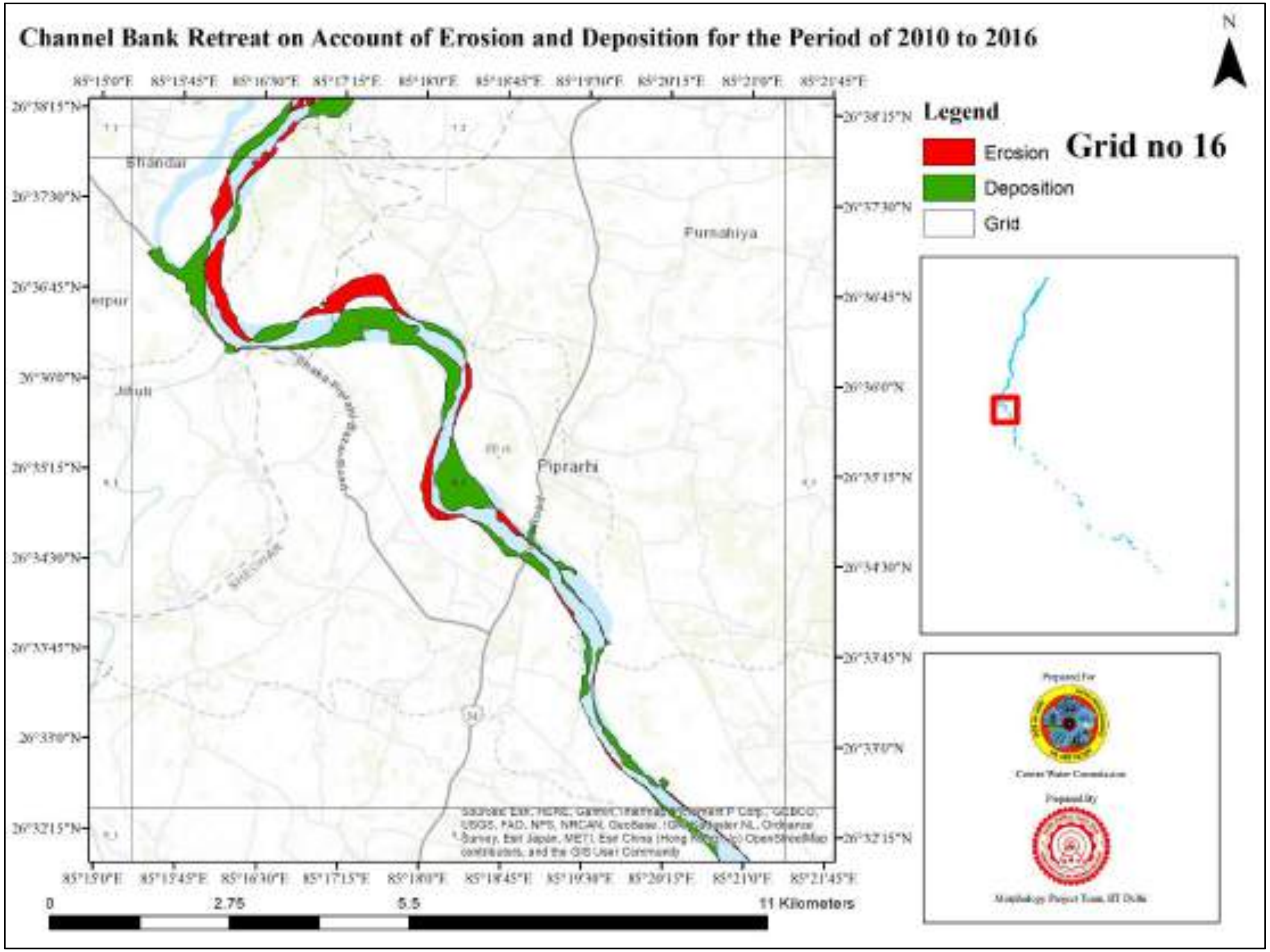



Figure **Error! No text of specified style in document.**-74: Erosion/Deposition Map of Bagmati River for Grid 16 for year (2010-2016)

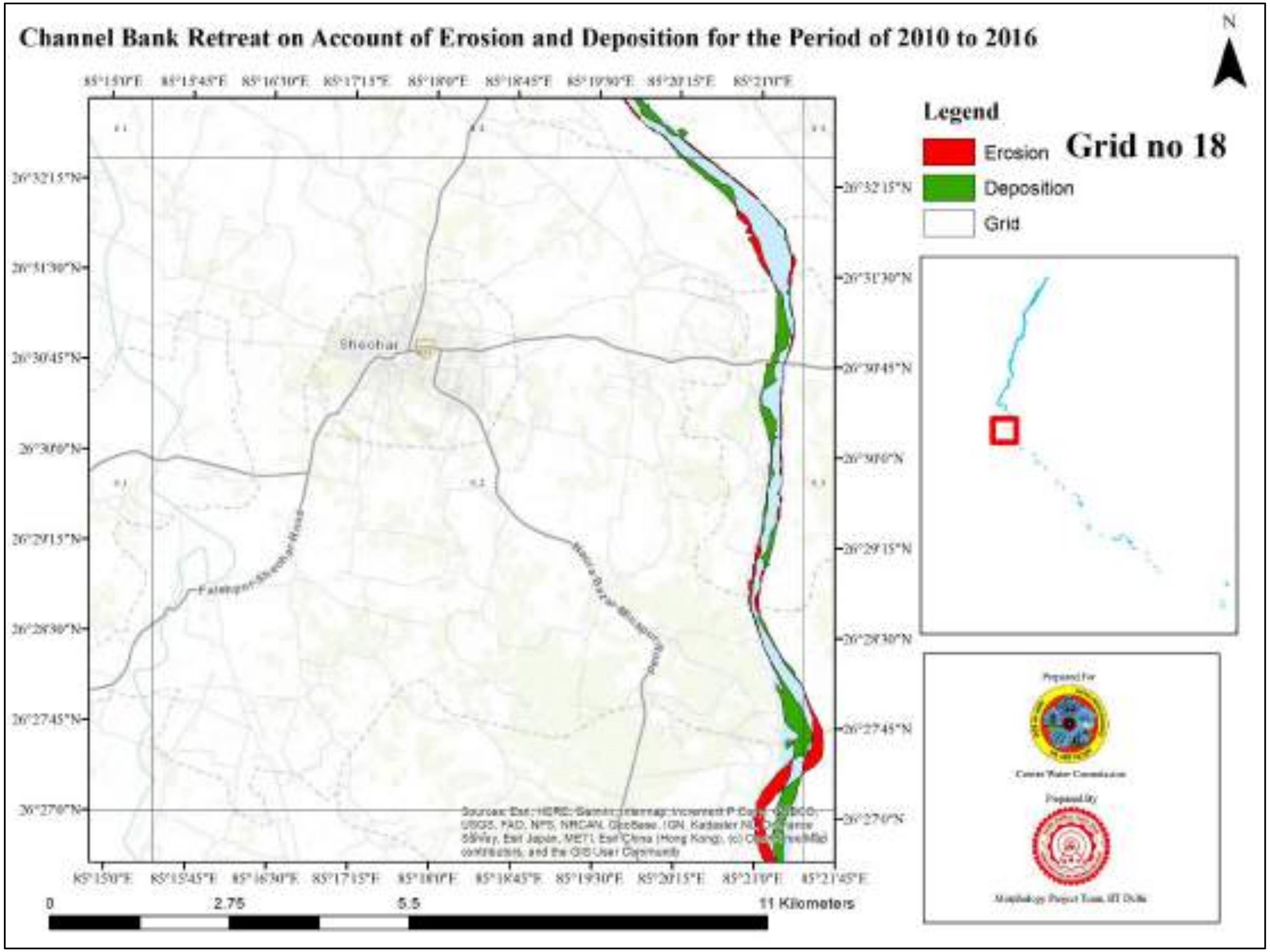



Figure **Error! No text of specified style in document.**-75: Erosion/Deposition Map of Bagmati River for Grid 18 for year (2010-2016)

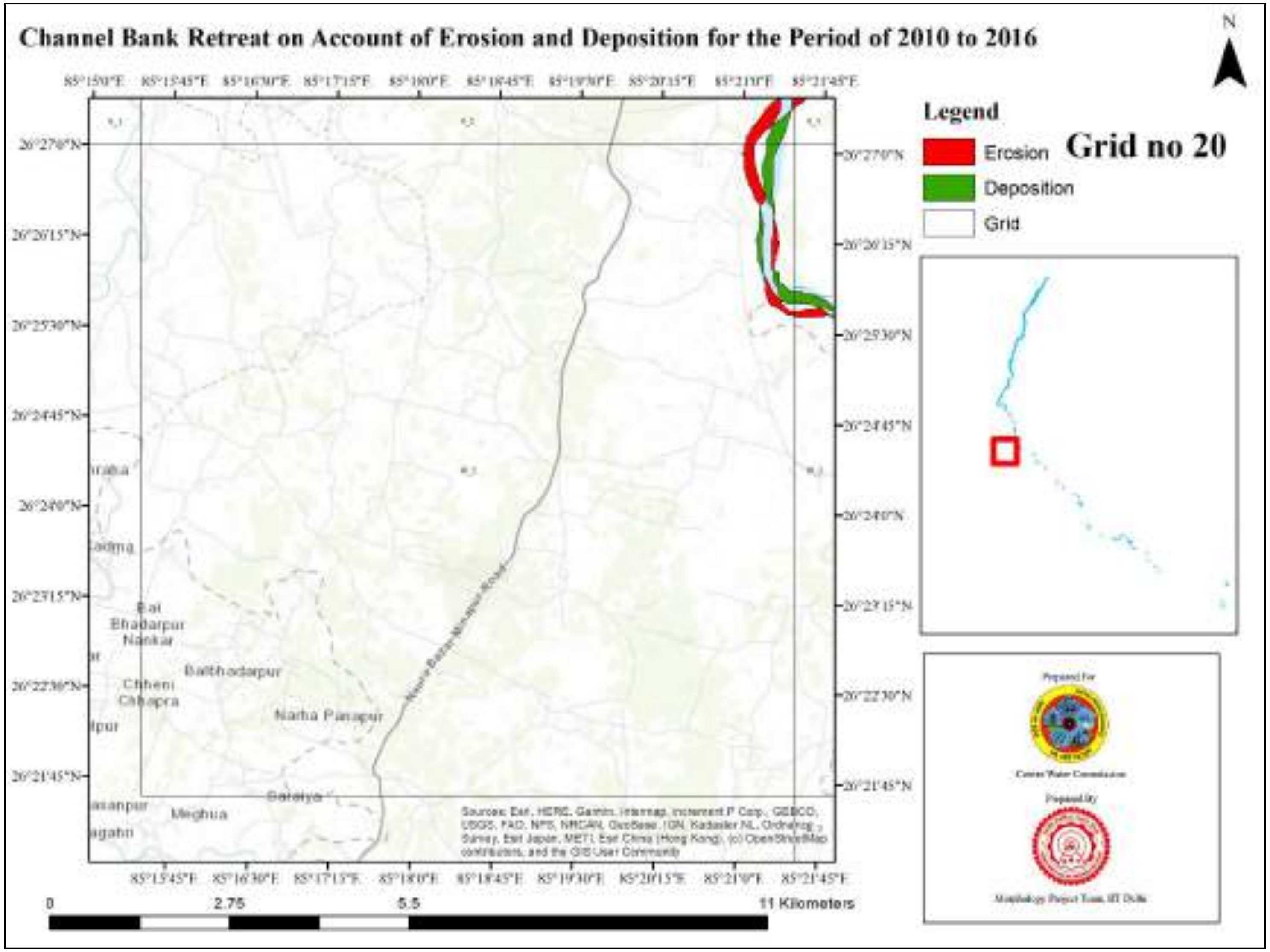



Figure **Error! No text of specified style in document.**-76: Erosion/Deposition Map of Bagmati River for Grid 20 for year (2010-2016)

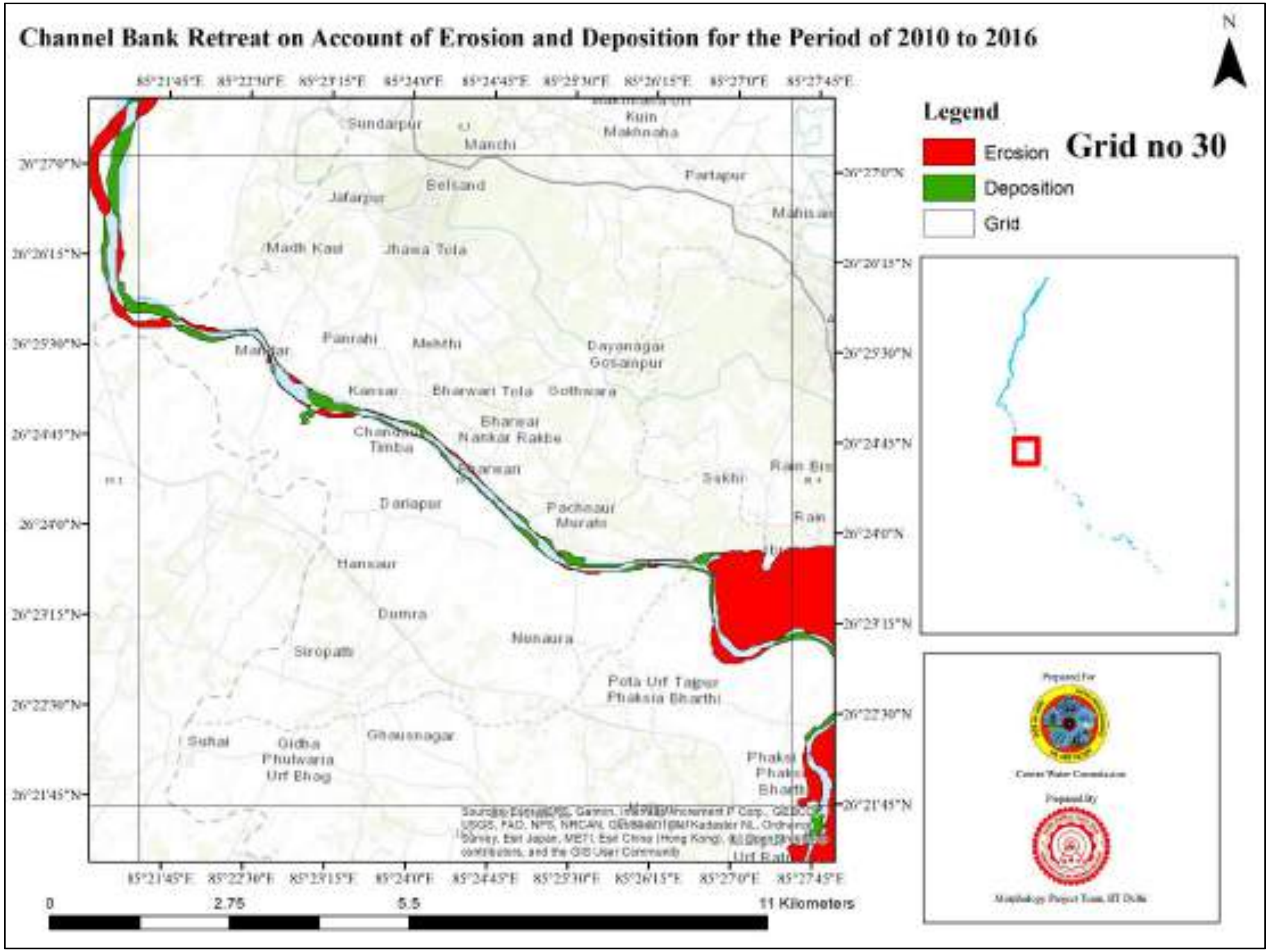



Figure **Error! No text of specified style in document.**-77: Erosion/Deposition Map of Bagmati River for Grid 30 for year (2010-2016)

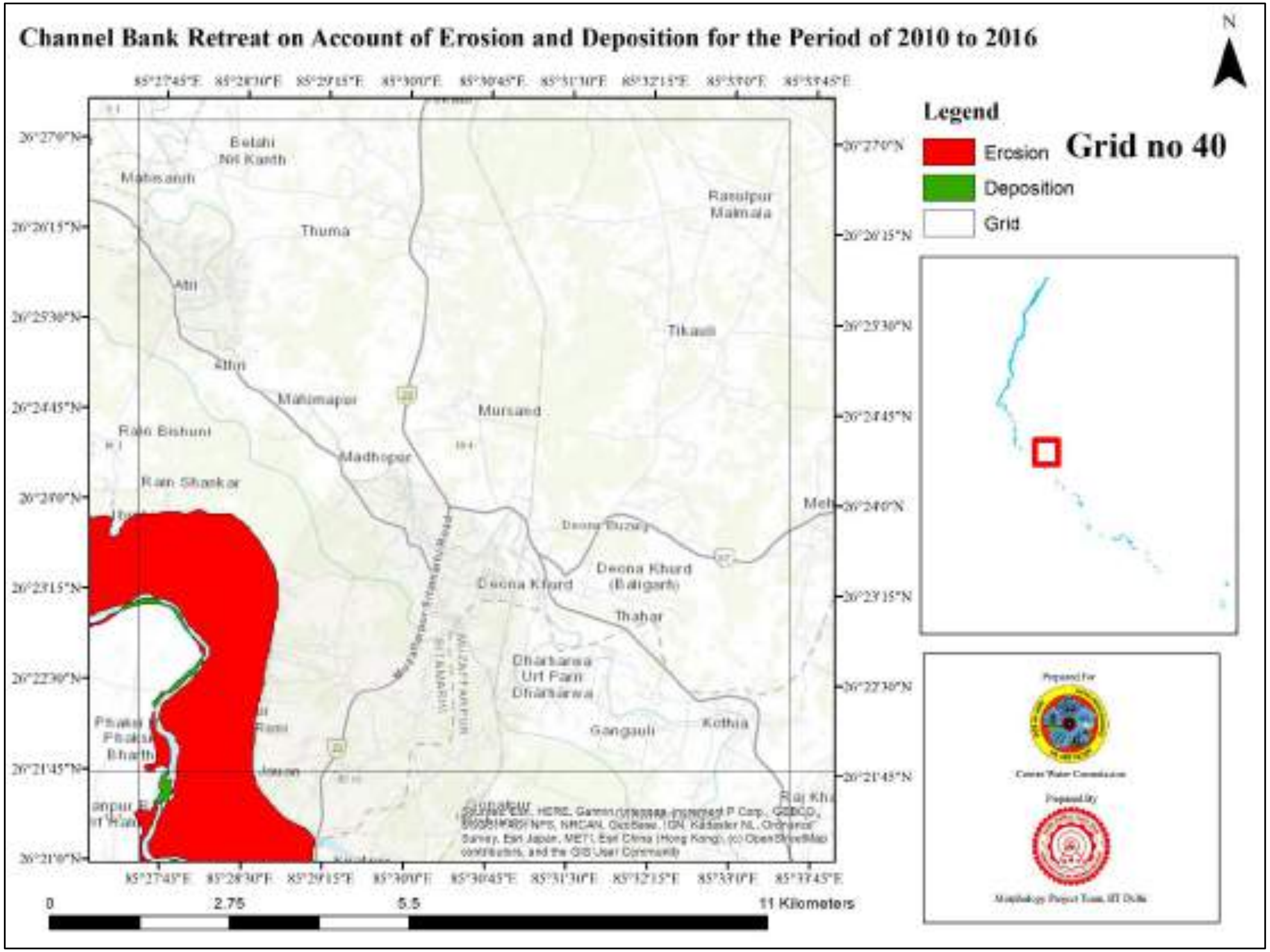



Figure **Error! No text of specified style in document.**-78: Erosion/Deposition Map of Bagmati River for Grid 40 for year (2010-2016)

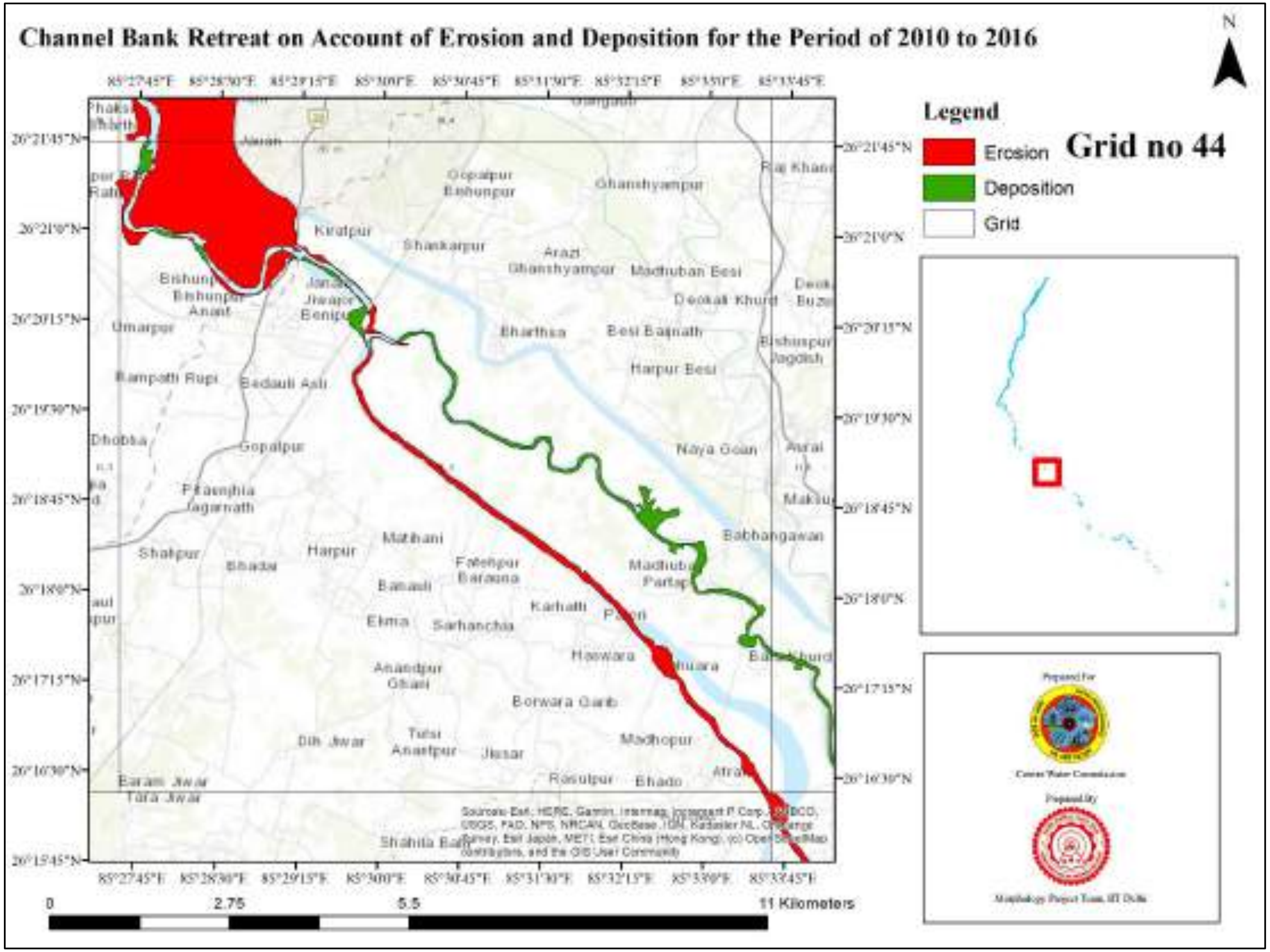



Figure **Error! No text of specified style in document.**-79: Erosion/Deposition Map of Bagmati River for Grid 44 for year (2010-2016)

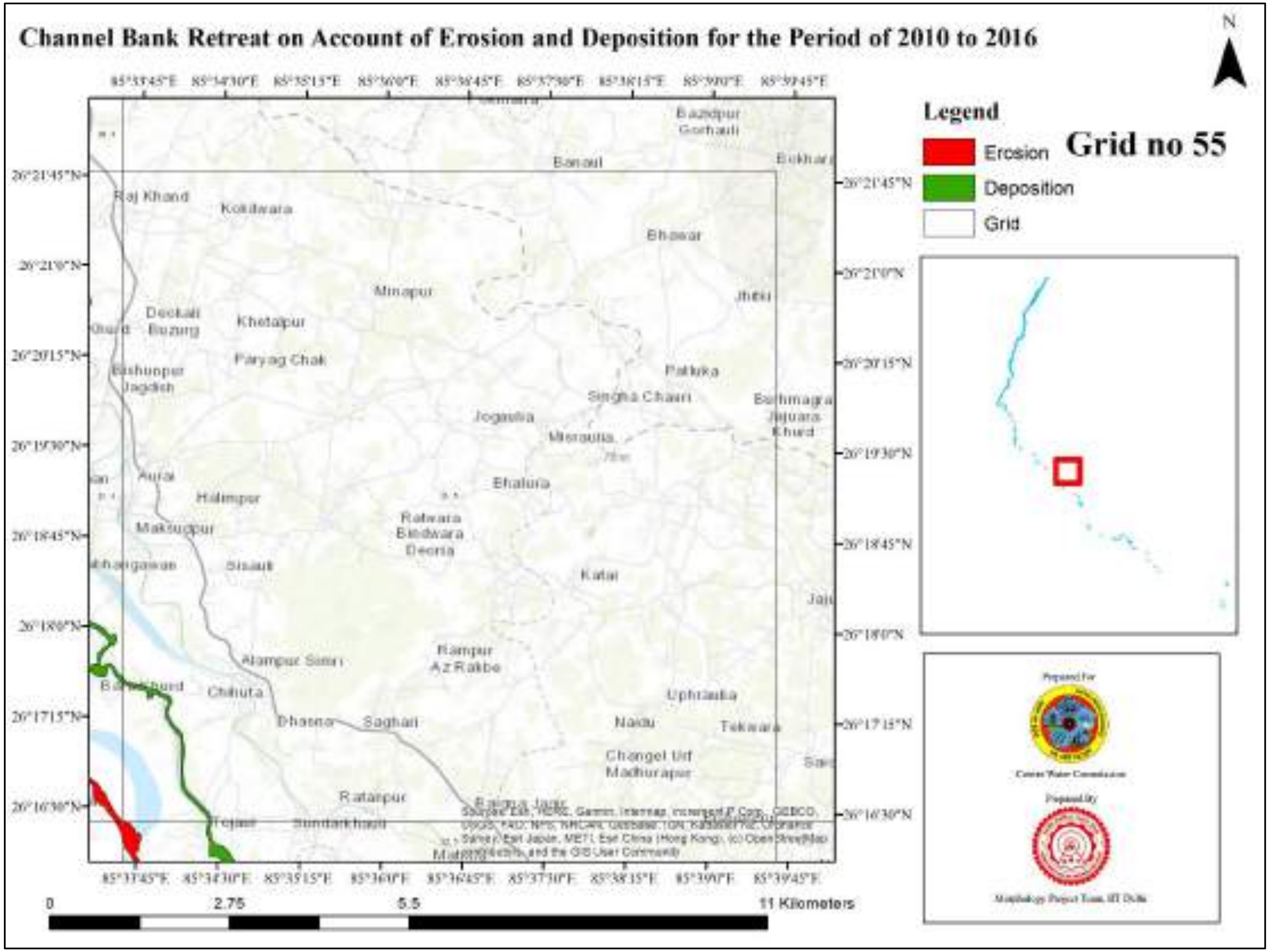



Figure **Error! No text of specified style in document.-**80: Erosion/Deposition Map of Bagmati River for Grid 55 for year (2010-2016)

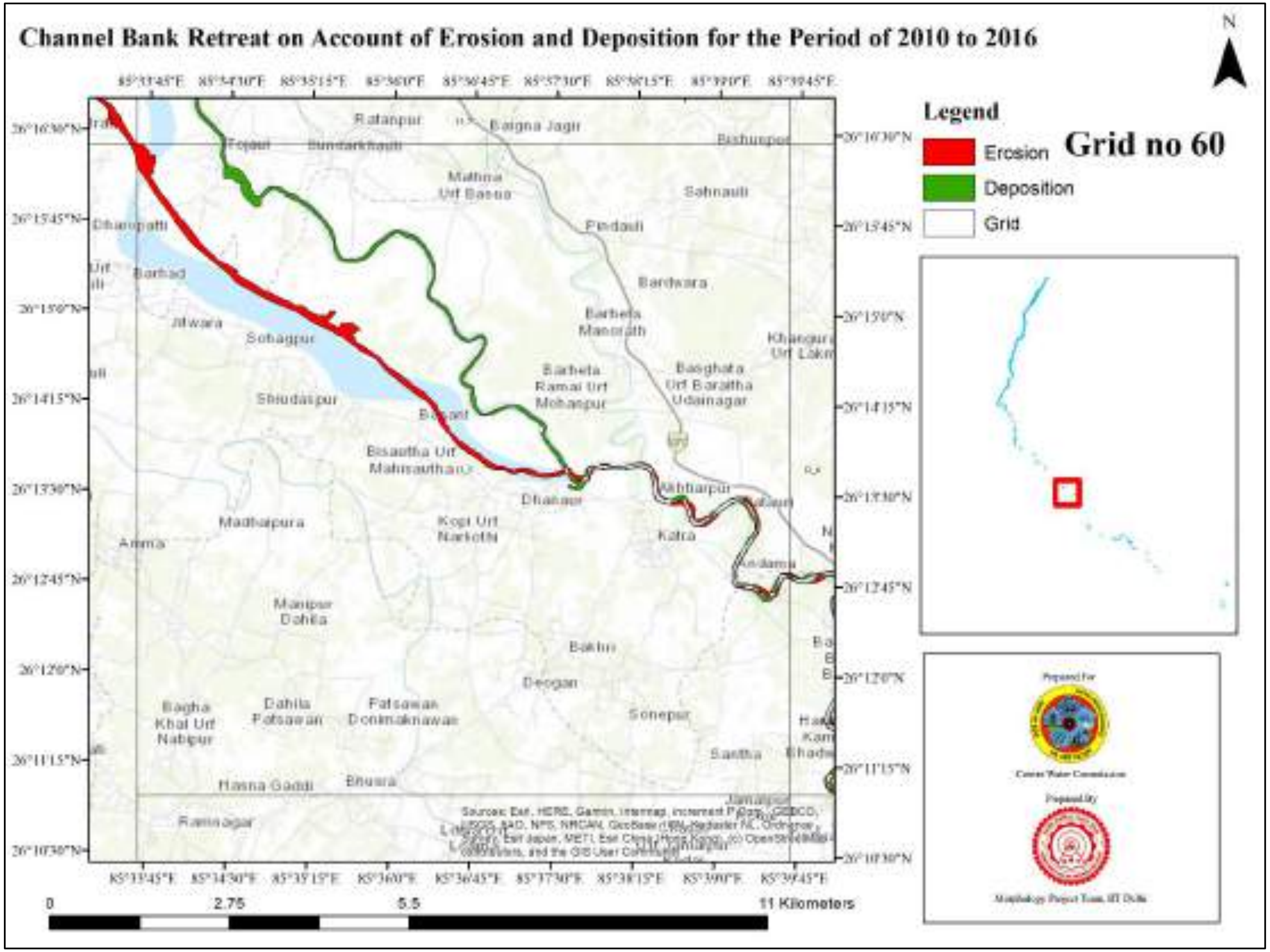



Figure **Error! No text of specified style in document.**-81: Erosion/Deposition Map of Bagmati River for Grid 60 for year (2010-2016)

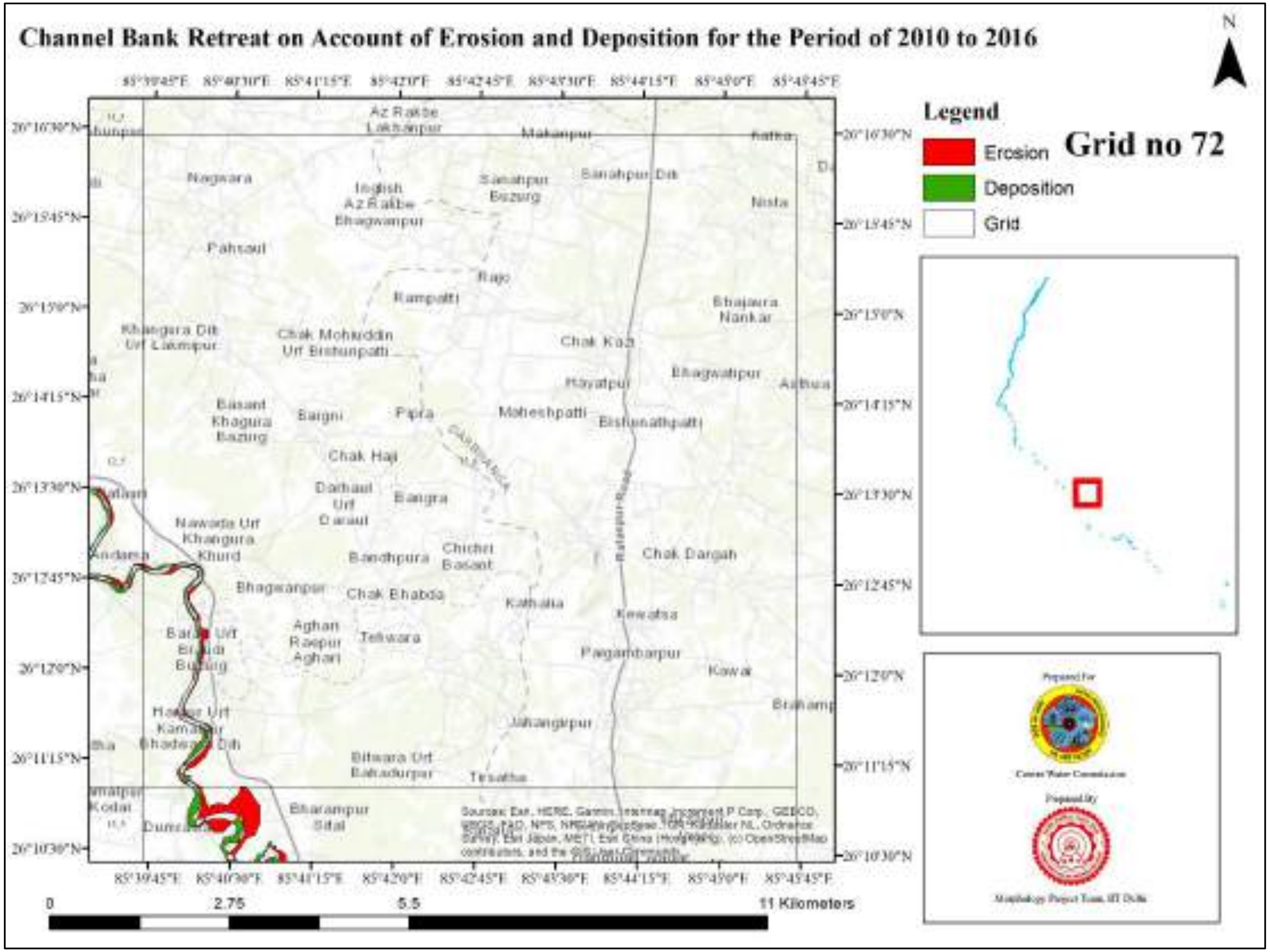



Figure **Error! No text of specified style in document.**-82: Erosion/Deposition Map of Bagmati River for Grid 72 for year (2010-2016)

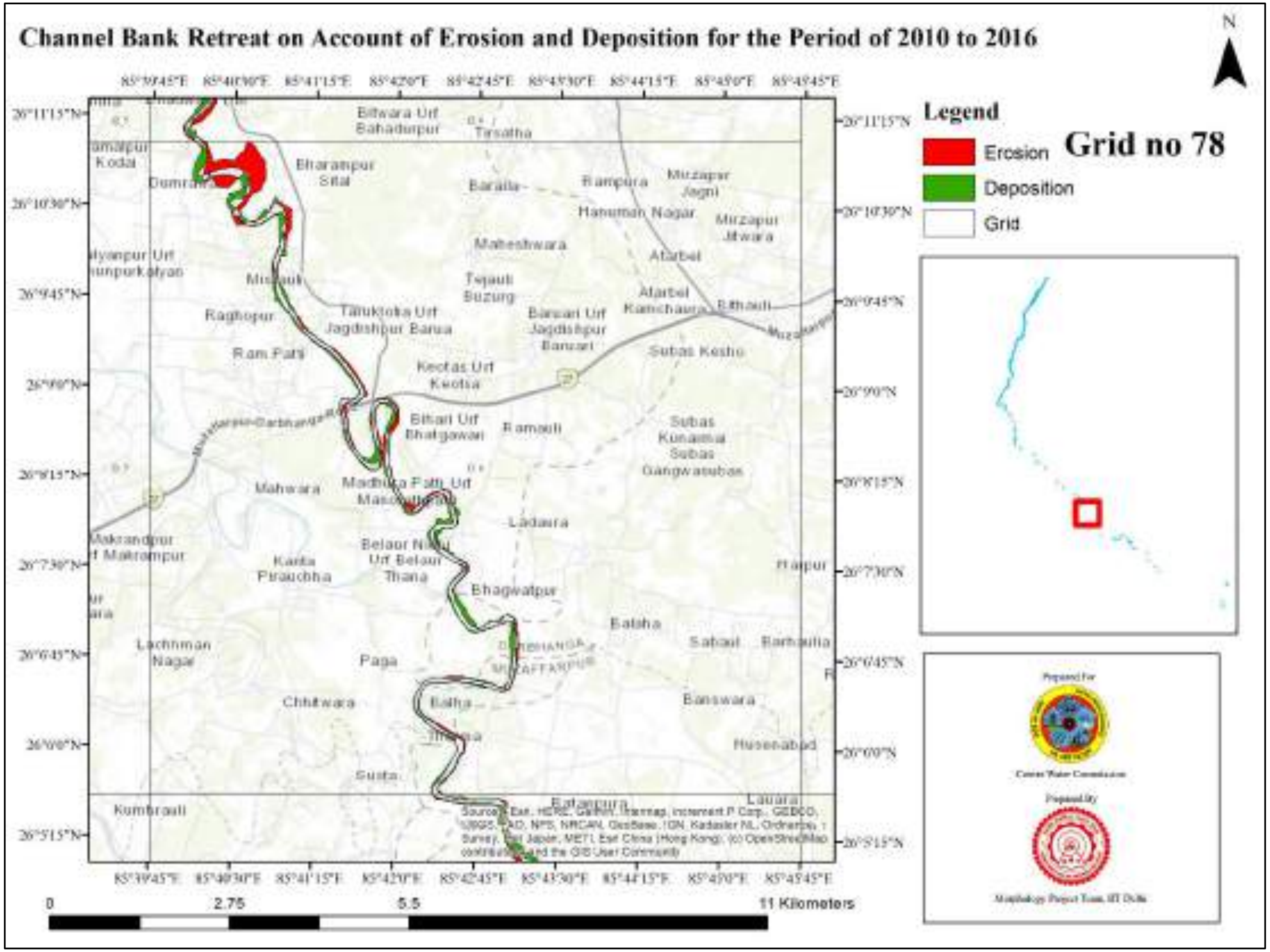



Figure **Error! No text of specified style in document.-**83: Erosion/Deposition Map of Bagmati River for Grid 78 for year (2010-2016)

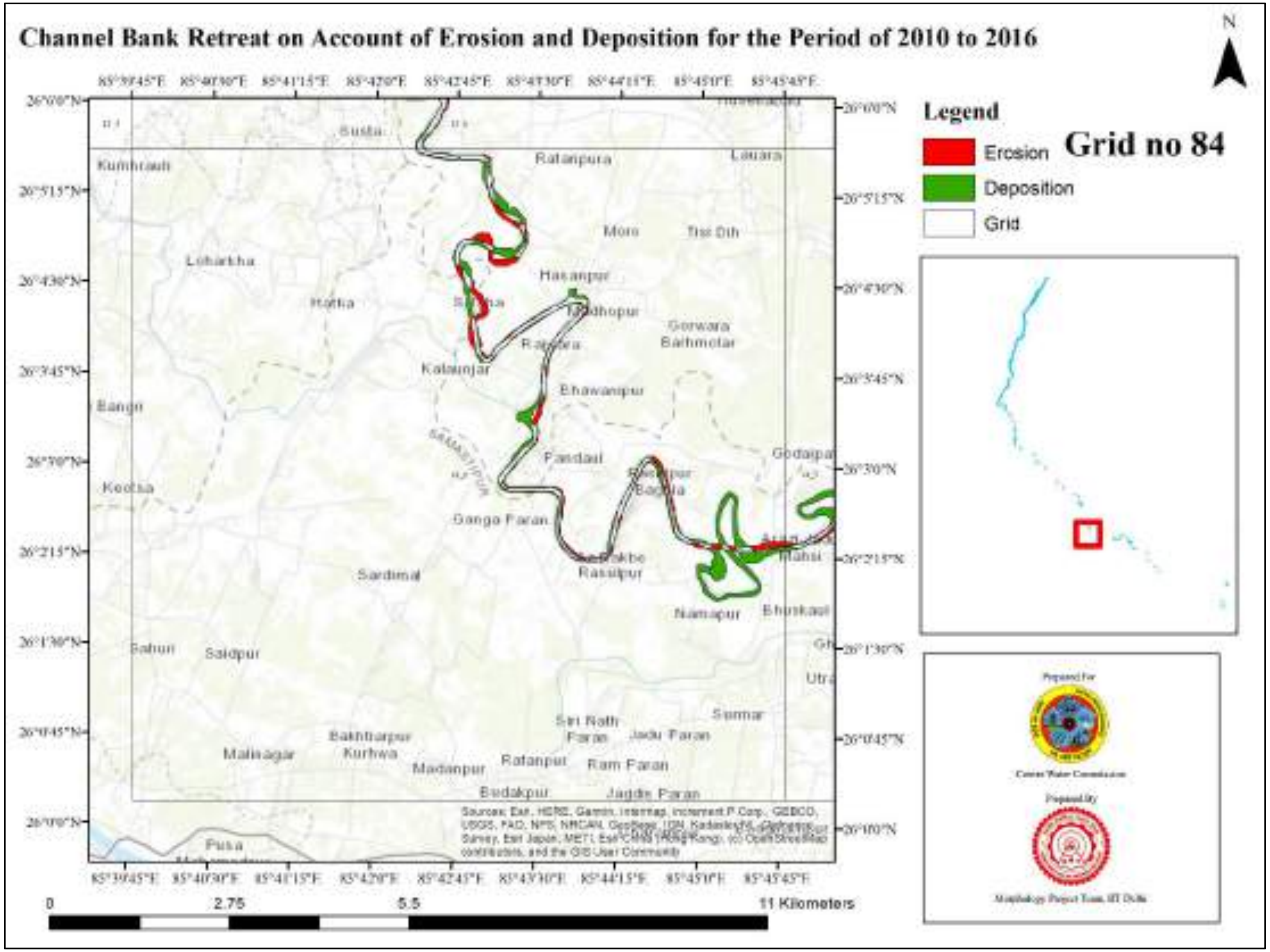



Figure **Error! No text of specified style in document.-**84: Erosion/Deposition Map of Bagmati River for Grid 84 for year (2010-2016)

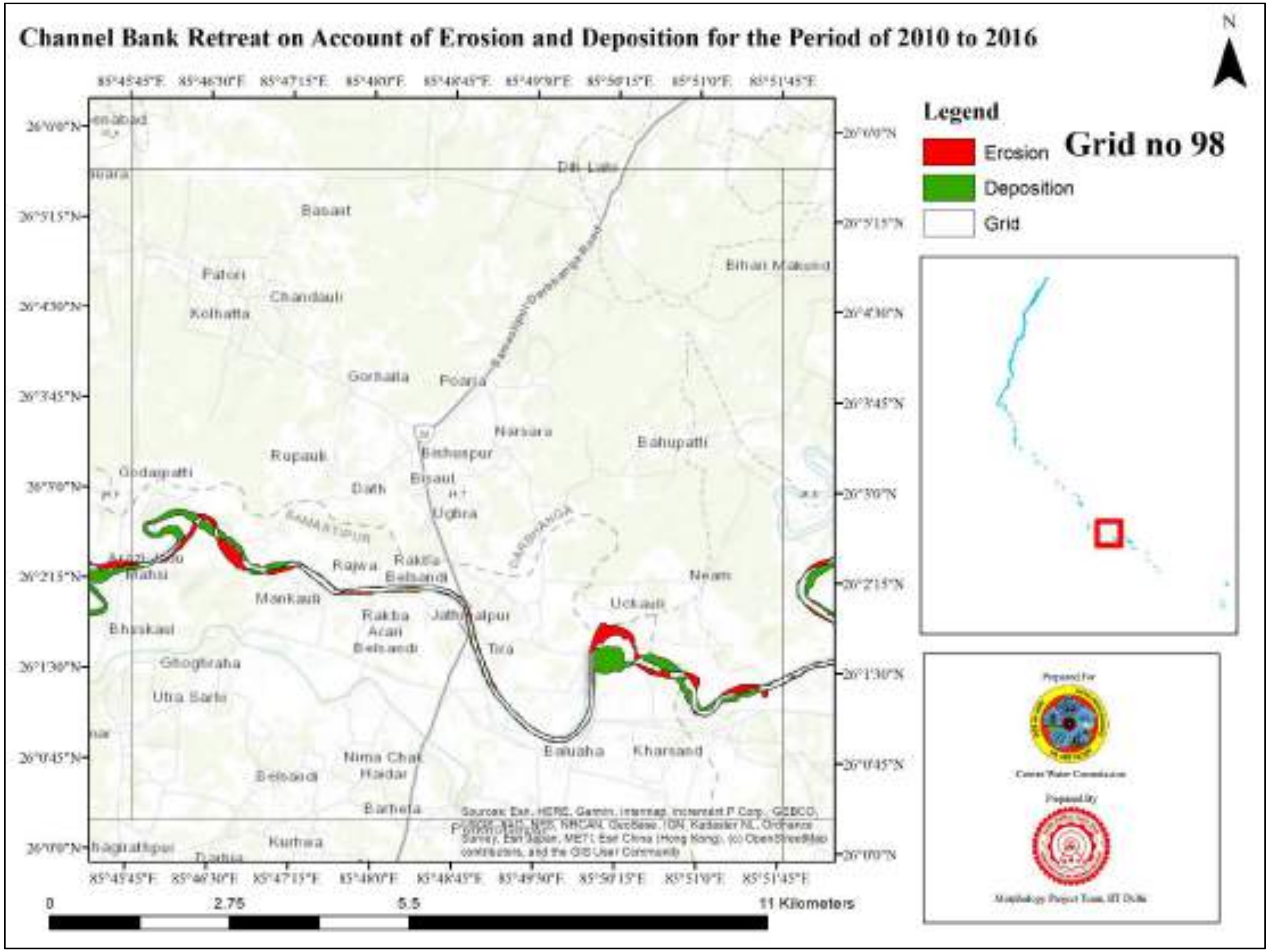



Figure **Error! No text of specified style in document.**-85: Erosion/Deposition Map of Bagmati River for Grid 98 for year (2010-2016)

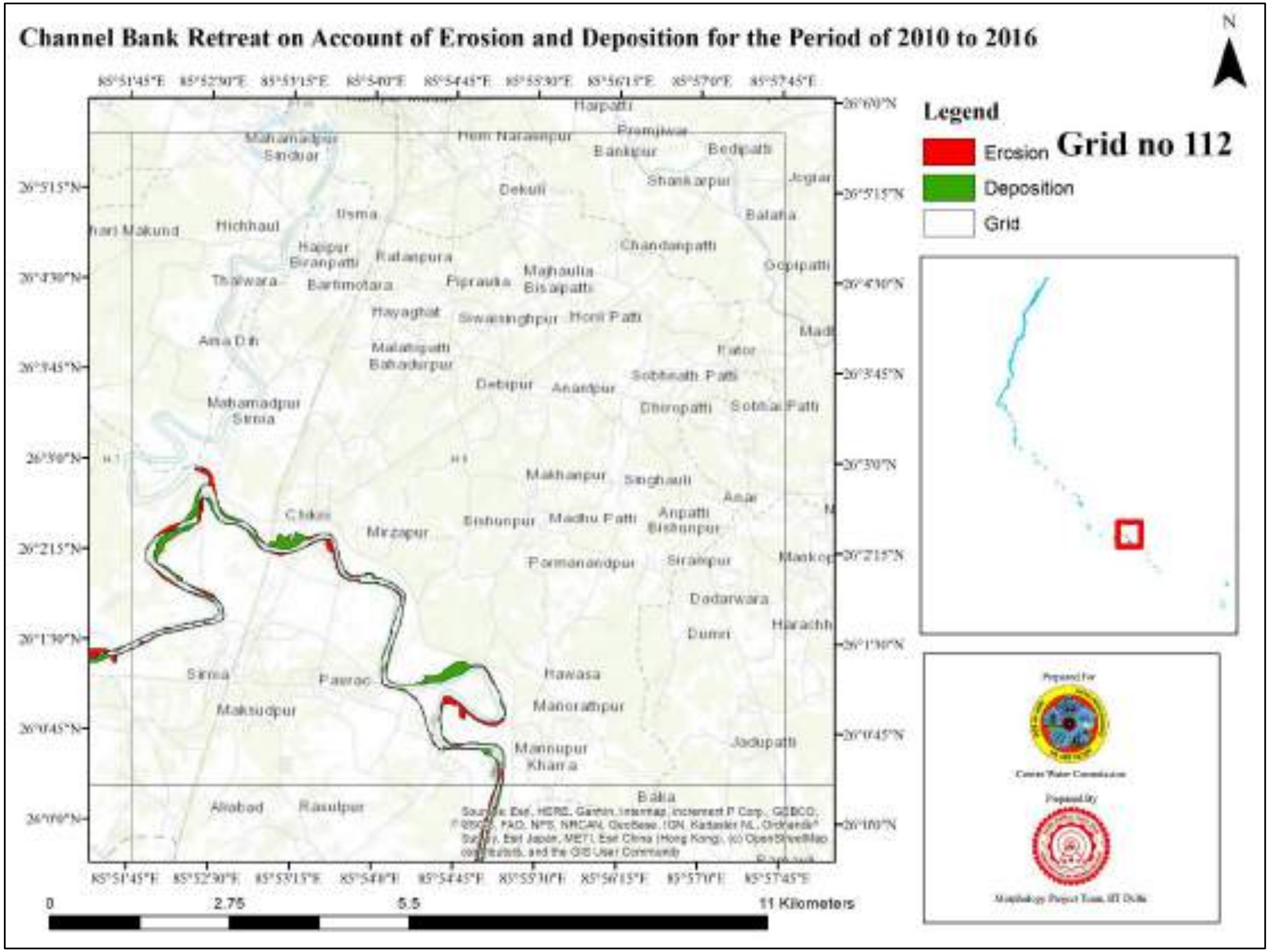



Figure **Error! No text of specified style in document.**-86: Erosion/Deposition Map of Bagmati River for Grid 112 for year (2010-2016)

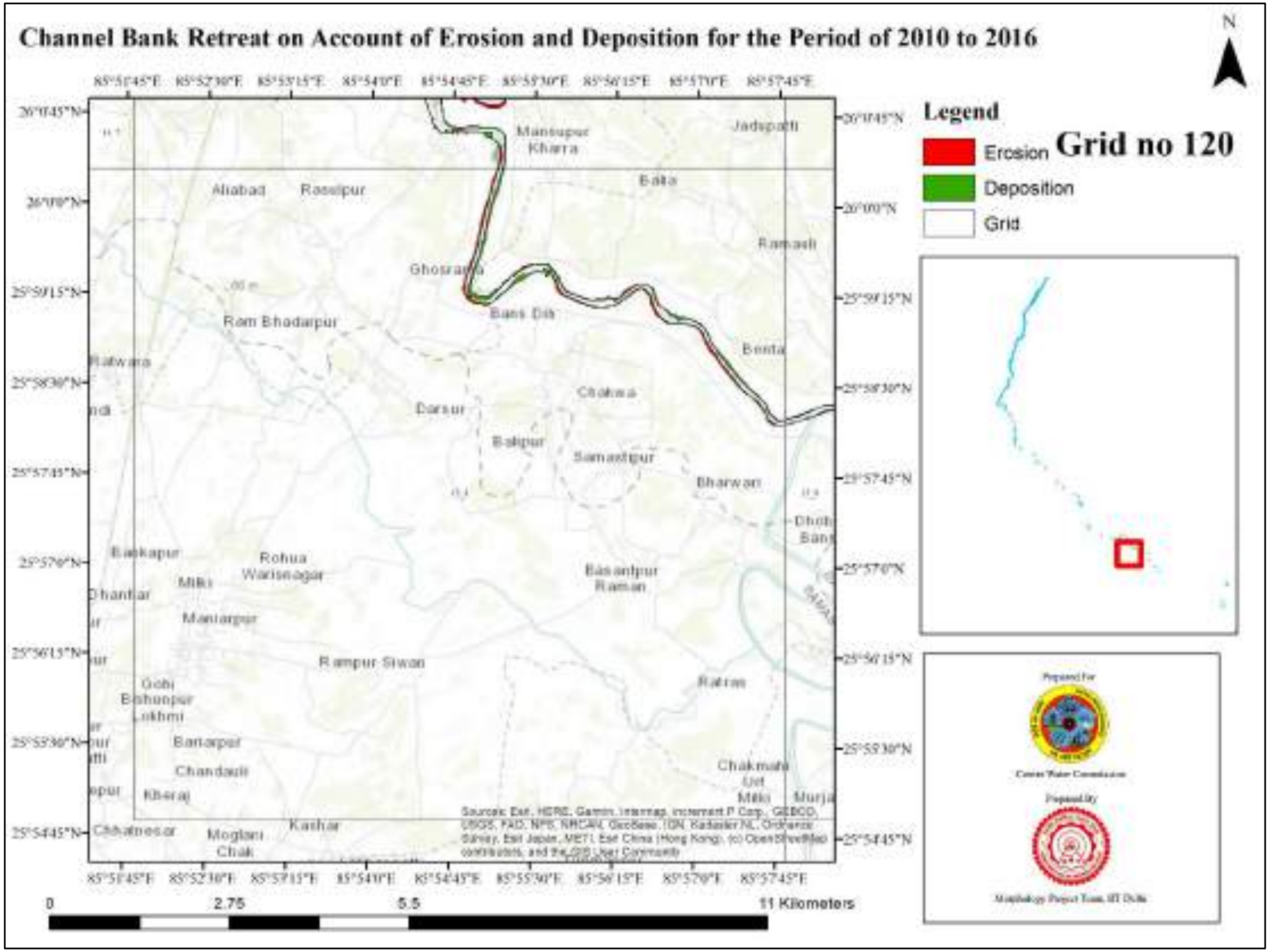



Figure **Error! No text of specified style in document.**-87: Erosion/Deposition Map of Bagmati River for Grid 120 for year (2010-2016)

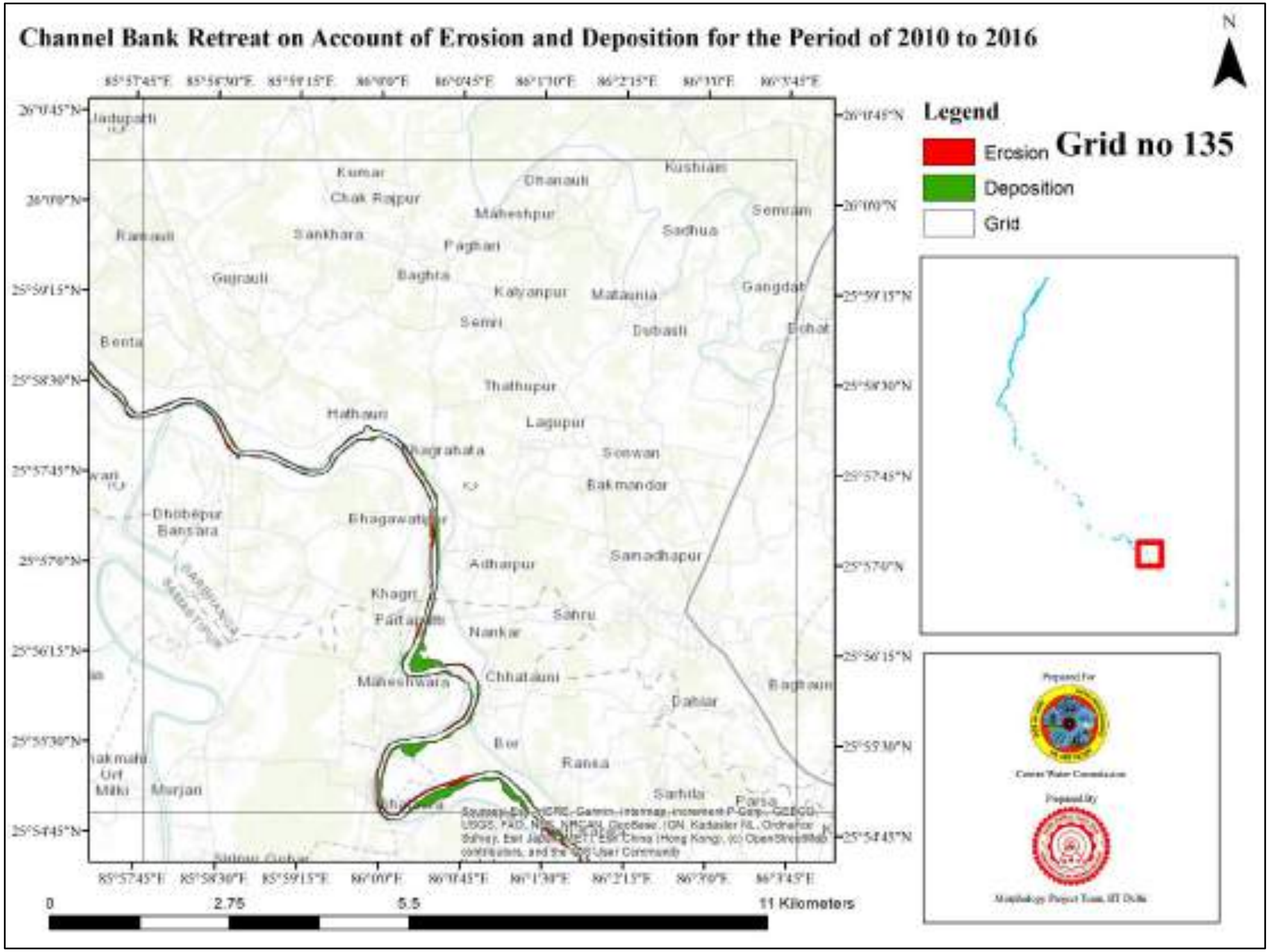



Figure **Error! No text of specified style in document.**-88: Erosion/Deposition Map of Bagmati River for Grid 135 for year (2010-2016)

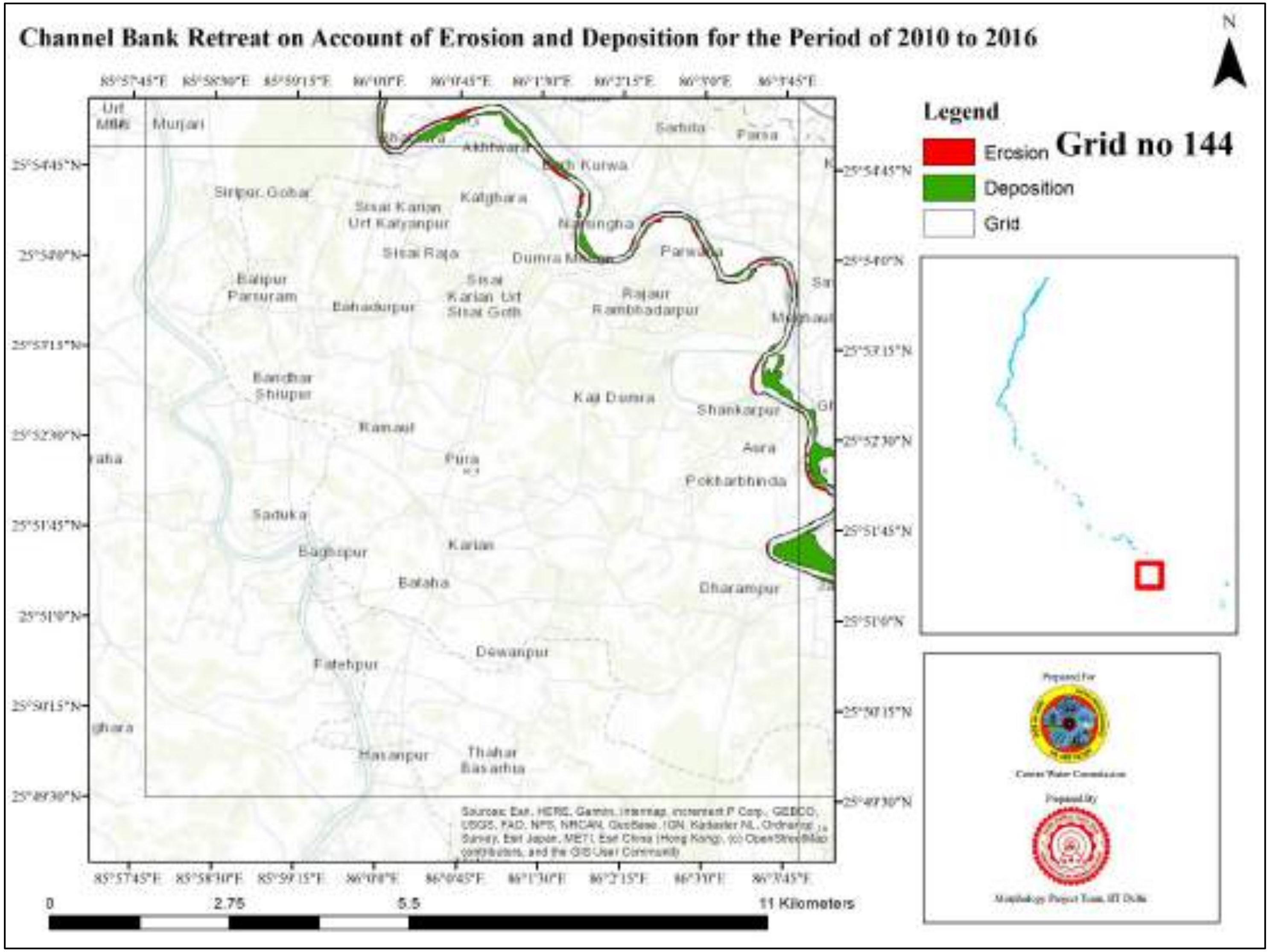



Figure **Error! No text of specified style in document.**-89: Erosion/Deposition Map of Bagmati River for Grid 144 for year (2010-2016)

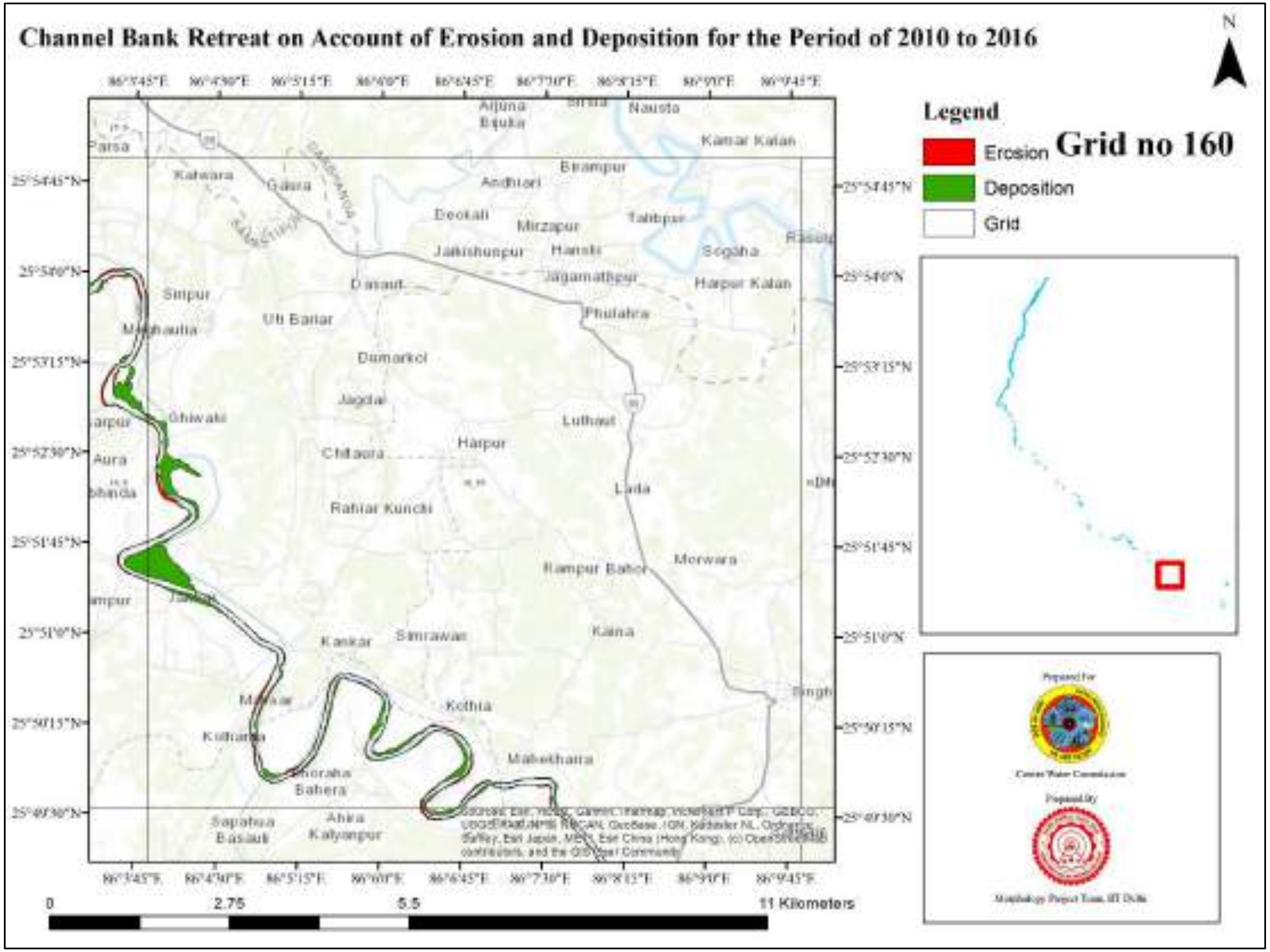



Figure **Error! No text of specified style in document.**-90: Erosion/Deposition Map of Bagmati River for Grid 160 for year (2010-2016)

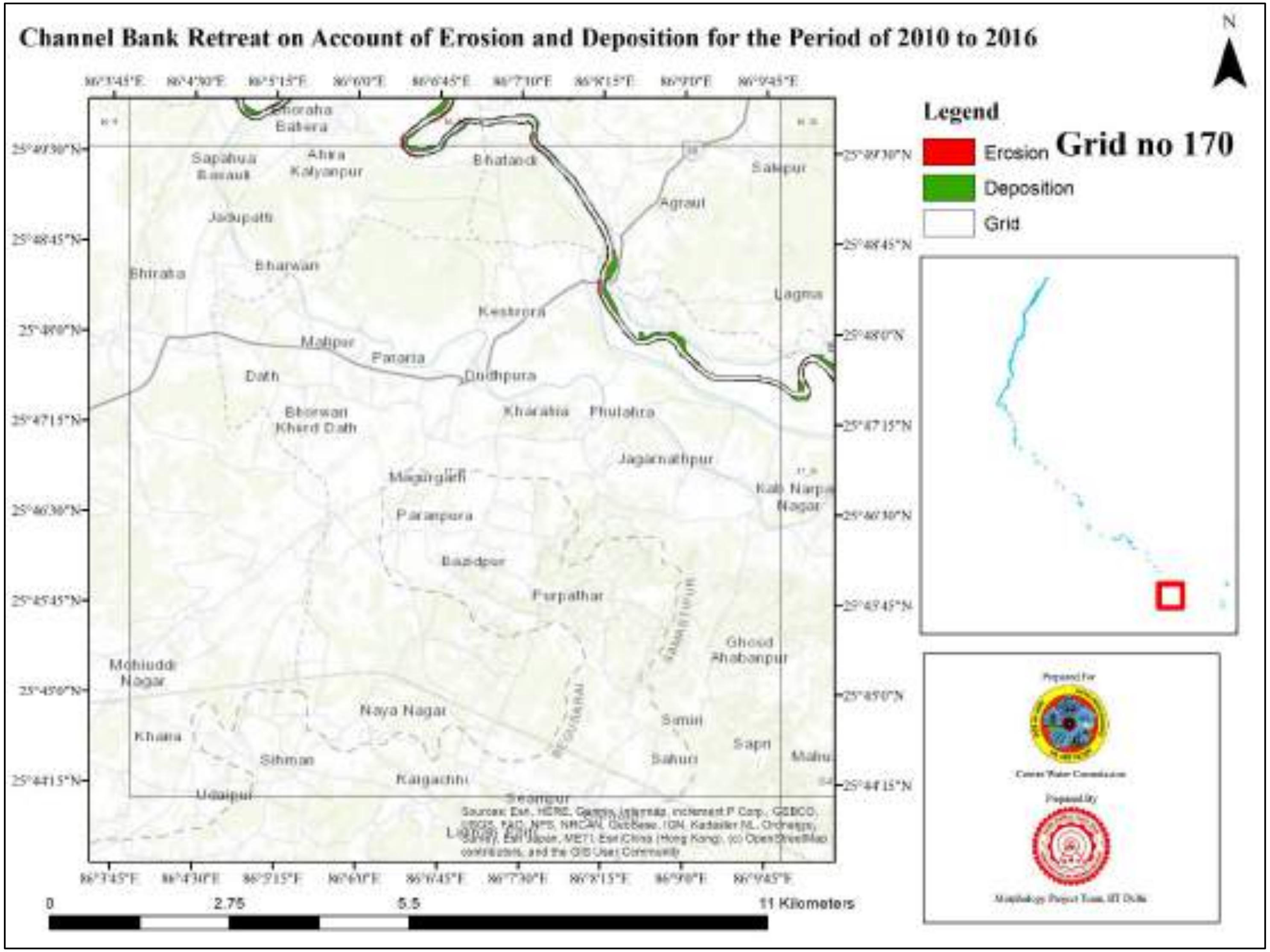



Figure **Error! No text of specified style in document.**-91: Erosion/Deposition Map of Bagmati River for Grid 170 for year (2010-2016)

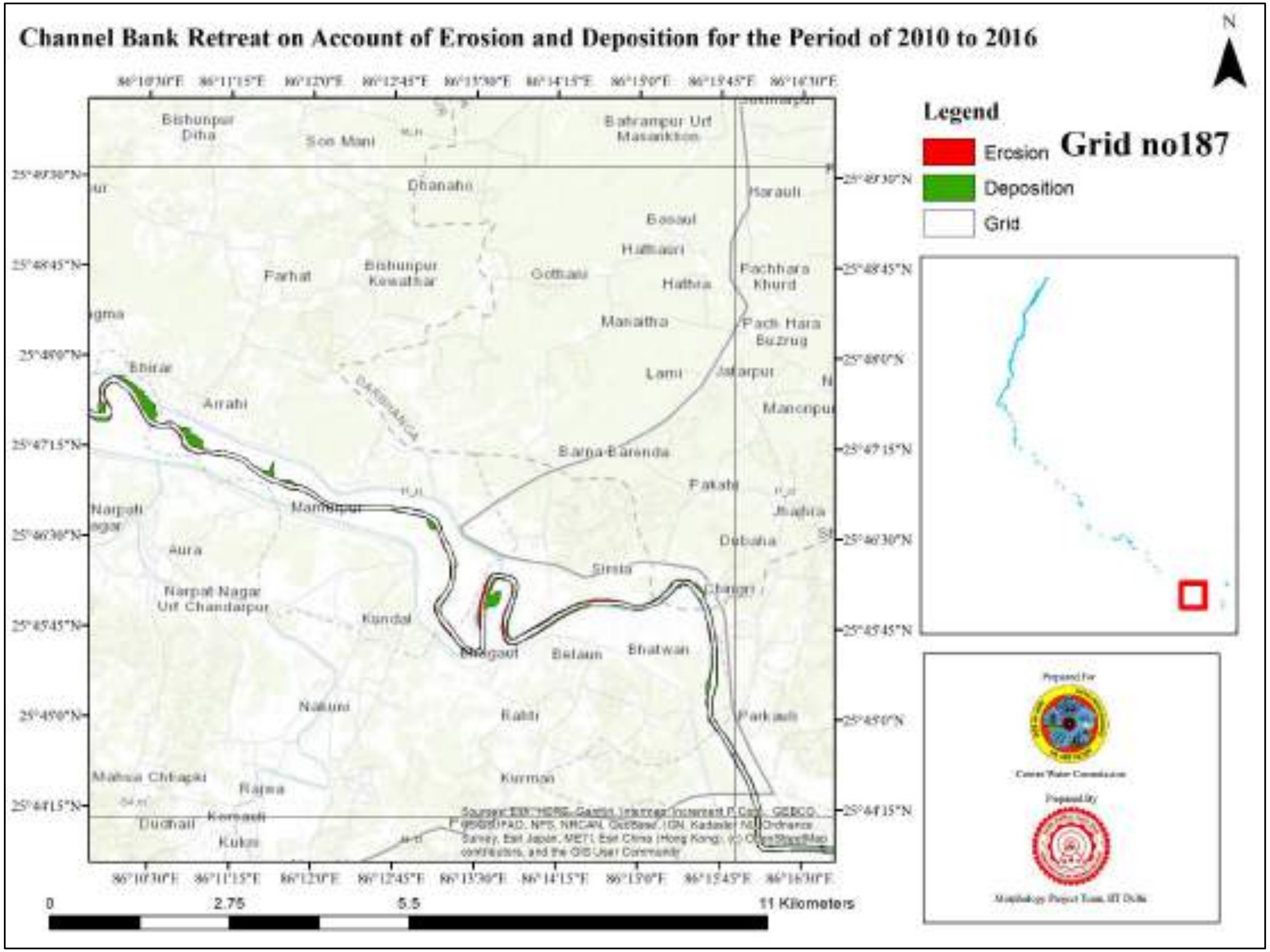



Figure **Error! No text of specified style in document.**-92: Erosion/Deposition Map of Bagmati River for Grid 187 for year (2010-2016)

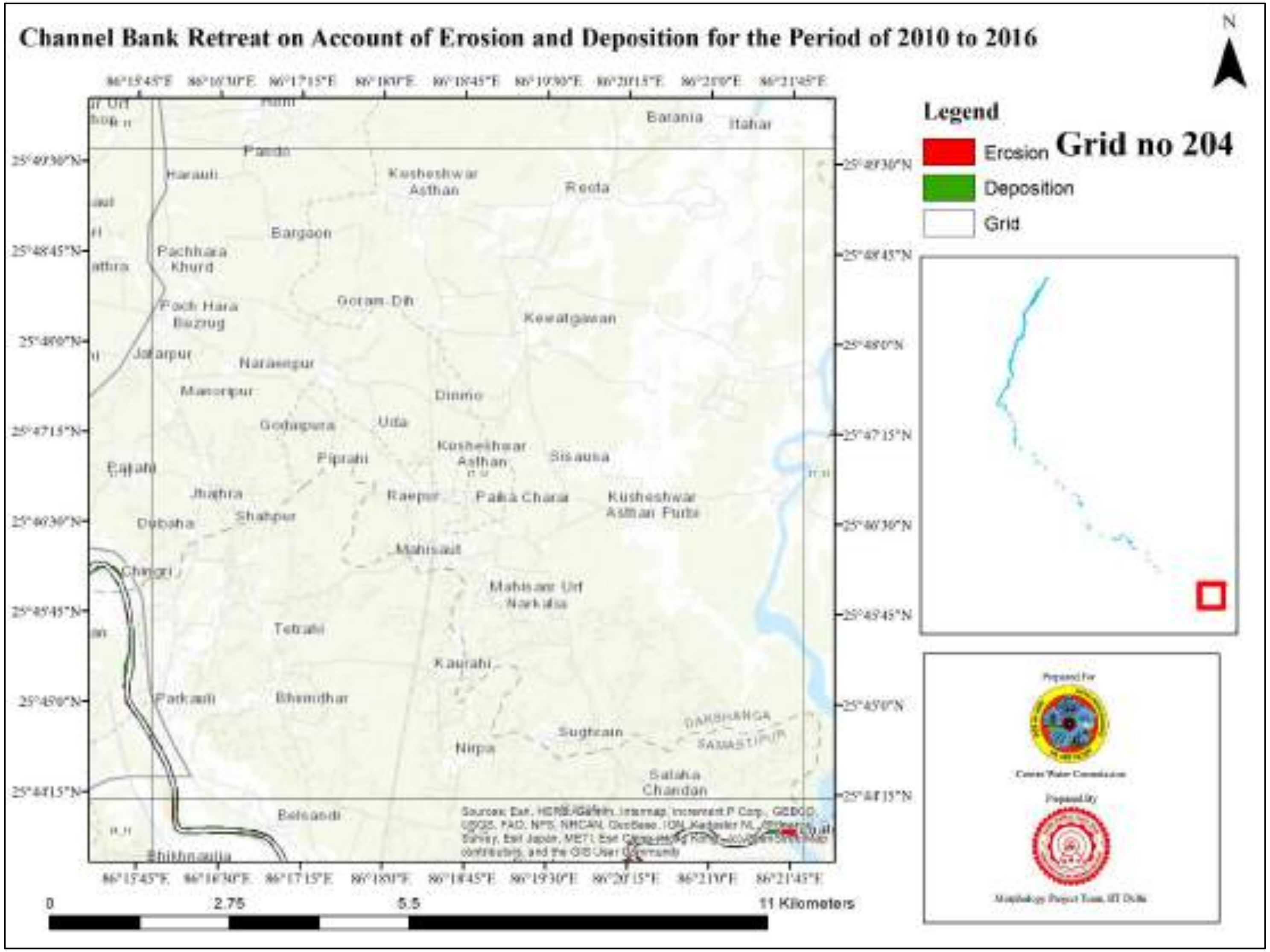



Figure **Error! No text of specified style in document.**-93: Erosion/Deposition Map of Bagmati River for Grid 204 for year (2010-2016)

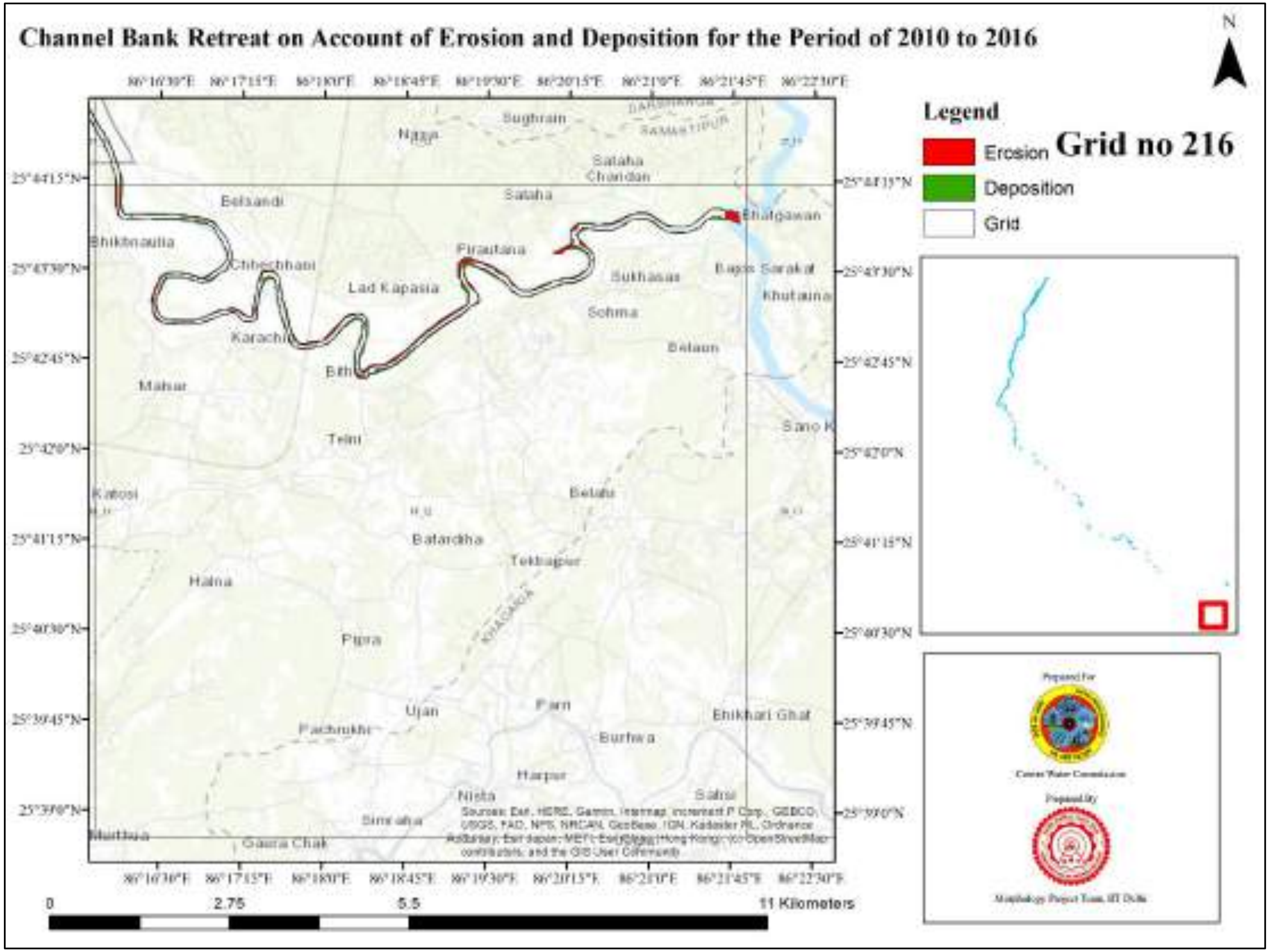



Figure **Error! No text of specified style in document.**-94: Erosion/Deposition Map of Bagmati River for Grid 216 for year (2010-2016)