Morphological Study of Kosi River

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List of Abbreviations

(In Alphabetical Order)

Abbreviation	Expanded Form
AHP	Analytical Hierarchical Process
BI	Braiding Index
CGWB	Central Ground Water Board
CWC	Central Water Commission
DEM	Digital Elevation Model
ETM+	Enhanced Thematic Mapper Plus
FCC	False Colour Composite
FMISC	Flood Management Improvement Support Centre
GESD	Generalized Extreme Studentized Deviate
GIS	Geographic Information System
GTS	Great Trigonometrical Survey
IIT	Indian Institute of Technology
IRS	Indian Remote Sensing
KMf	Kosi Megafan
LISS	Linear Imaging Self Scanning Sensor
LULC	Landuse/Landcover
MBT	Main Boundary Thrust
MCM	Million Cubic Metre
MCT	Main Central Thrust
MoU	Memorandum of Understanding
MSS	Multispectral Scanner System
MW	Mega Watt
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIH	National Institute of Hydrology
NRSC	National Remote Sensing Centre

OBIA	Object-Based Image Analysis
PFI	Plan Form Index
PFI	Plan Form Index
SoI	Survey of India
SR	Sinuosity Ratio
SWIR	Short-Wave Infrared
TM	Thematic Mapper
USA	United States of America
USGS	United States Geological Survey

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 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 the ground, it helps in developing a sound physical understanding of the natural system. However, the spatial and temporal scale of observation is limited for such observations. On the other hand, the remote sensing technique provides observations on a spatial and temporal scale depending on availability and recording of data through satellite. In both the 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 a 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. However, ground survey-based observation is obligatory for detailed modelling exercises.

The present study evaluates erosion, deposition and shifting characteristics of the Kosi River using satellite data in the Geographic Information System (GIS) framework. For analyzing the complete reach of Kosi from its origin to its outfall, various river features like channel area, active water area, sandbars and water bodies have been extracted from satellite data at an interval of about 10 years depending on availability of cloud-free data. Four years identified for the comparative analysis are 1977, 1990, 2000, 2010 and 2016.

The study confirms that at specific locations in Kosi River, rates of erosion and deposition are high, and significant shifting in channel centerline is also observed across the river. Detailed results of the analysis have been presented in the report. Most importantly, an 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 the field of river morphology and have not been defined objectively in previous reports of morphological studies in the Indian context.

Chapter 1: Introduction

1.1 Background

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, etc. 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 also in response to human-induced changes in such behaviour (Chang, 2008). While natural states are different; human interactions with different rivers are also unique on account of their geographical extents, hydrological enormousness and various demographic, socio-economic factors. This makes a morphological study of each individual river basin more critical and a precise 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 ultimately alter the water levels significantly. 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 on account of the need for involvement of knowledge of related sciences such as physics and geology, hydraulic engineering and hydrology, climatology and landscape ecology, etc. (Mangelsdorf et al., 1990). Own impulses of hydraulic engineering experiments obligate the 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 prerequisite of flood management issues; morphological studies are essential for sustainable river management and also for restoration activities.

1.2 Dynamic transformation hypothesis of Kosi river

The report presents an understanding of the morphological and some notable morphodynamic aspects of Lower Kosi River Basin confined to the plains of North Bihar. For a contextual understanding, river Kosi emerges from the confining influence of the Himalayan ranges at Chatra Gorge (Nepal) and enters India just downstream of Kosi barrage. In addition to receiving contributions off its Western bank from catchments drained by smaller rivers including Tiljūga river, river Kosi has first major confluence with river Bagmati and further downstream, the combined system of river Bagmati and Kosi joins with river Ganges at Kursela.

In terms of morphological attributes, Kosi exhibits various planforms at different spatial scales of observations. For example, at the reach scale braiding, anabranching, and meandering planforms are observed. On a larger basin scale, the river exhibits an asymmetric morphometry which lands the basin off its Eastern flank a signature pattern which is different from the corresponding patterns as observed off its Western flank. While the Western side of the basin has a distinctive tributary structure, the Easten side of the river Kosi shows evidence of a predominantly distributive structure across it and it is further characterised by presence of a distributary network of paleochannels. These asymmetric features therefore are incongruous with the signature patterns that are typically associated with the symmetric signature patterns of a typical “Megafan”.

Over the past 150 years, the Kosi River corridor has migrated westward by approximately 120 kilometres, from the predominantly N-S, Araria-Purnia-Katihar axis to its present-day confluence with Bagmati near Baltara, indicating an average daily shifting rate of around 2 meters. The shifting Kosi Corridor has another distinct characteristic. It primarily catches tributary flows only on its western face, while the eastern face features a largely abandoned distributary paleosystem (Parmar and Khosa, 2017; Parmar, 2022).

The unidirectional nature of shifting of the Kosi River was studied by various investigators notably Wells and Dorr, 1987; Agarwal and Bhoj, 1992. Subsequently, Parmar and Khosa, 2017; Parmar, 2022 revisited the problem and proposed the concept of a river corridor. In the aforementioned studies both the autocyclic processes and tectonic (allocyclic) processes were suggested as plausible triggers behind the observed shifting of the Kosi River course and according to Parmar and Khosa, 2017; Parmar, 2022 of the underlying dedicated Kosi river corridor. The orientation of the river corridor and faults in the region has undergone significant changes over time. Before the 1730s, the corridor followed a northwest to southeast direction, aligned with the Malda-Kishenganj Fault. In the 1890s, the corridor shifted to a north-south direction, aligned with the Bhawanipur Fault. Post-1920s, the corridor assumed a northeast-southwest direction, aligned with the Begusarai Fault, as presented in Figure 1-1.

Figure 1-1: Criss-crossing of Faults in Kosi-Bagmati basin (Srivastava, 2002)

The asymmetry of the Kosi River basin is evident through its historical course changes, as depicted by Figure 1-2. Before the 1730s, the river flowed in a northwest-southeast direction, discharging into the Mahananda River, while its tributaries were mainly situated along the eastern flank. By the 1890s, a significant shift occurred as the Kosi River altered its course to a north-south orientation, resulting in tributaries joining it along both banks. However, in the post-1920s period, a further reconfiguration took place, with the Kosi River adopting a northeast-southwest direction and tributaries becoming concentrated exclusively along its western face. Notably, this shift also led to the Kosi River becoming a tributary itself, contributing to the smaller Bhagmati River. These changes highlight the dynamic nature of the Kosi River basin and the evolving asymmetry in its drainage pattern over time.

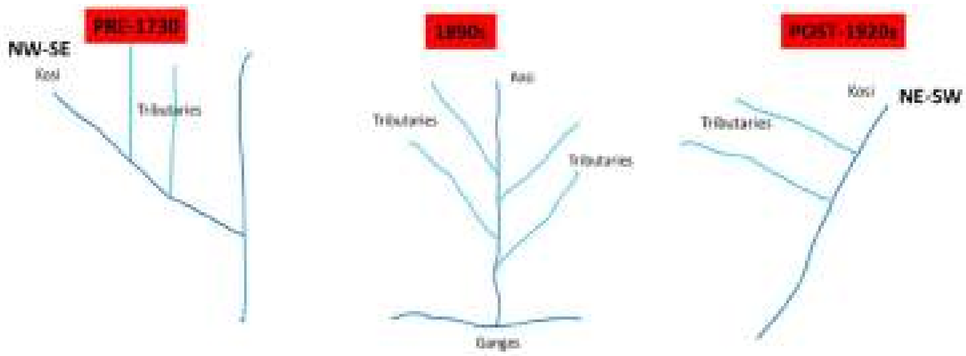


Figure 1-2: Historical Variation of Kosi river course

The Kosi basin exhibits a west-east convex-up profile, as presented by Figure 1-3, and the river corridor's migration seems to defy the principles of physics related to energy states. The observed movement from lower to higher potential energy states during the epoch from year 1736 to year 1926 contradicts the plausibility of natural course migration alone. This suggests that there must be external morphological forces at play.

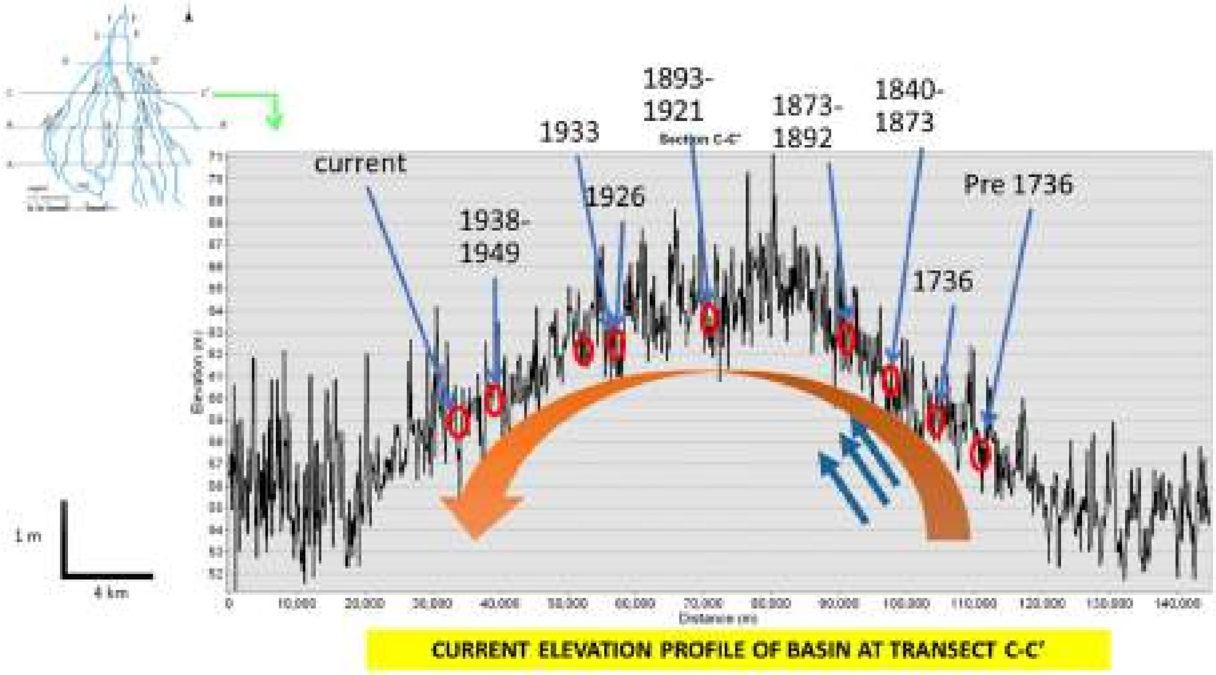


Figure 1-3: East-West Convex Up Elevation profile of Kosi river basin

The drainage pattern across the two flanks of the Kosi River is significantly dissimilar. Converging, tributary systems are predominantly found on the western side, while traces of abandoned, diverging (branching) distributary networks can be discerned off the eastern flank. The morphometric asymmetry in the drainage pattern challenges the notion of a "Megafan" and highlights the limitations of autocyclic physical processes in explaining these observations. The atypical morpho-ergodynamics of the Kosi Corridor violate energy principles unless there is an external, morphologically driven force acting on the river corridor. Literature suggests the presence of crisscrossing faults, aided by plate tectonics, in the Kosi Basin (Agarwal and Bhoj, 1992; Srivastava, 2002). The region is tectonically active, with earthquakes and aftershocks occurring approximately once every fifty years, including major events in 1833, 1837, 1883, 1897, 1934, and 1988 (Chaulagain et al., 2018). Further investigation is needed to establish a more precise correlation between this theory and its impact on morphological behaviour.

In conclusion, the overlapping of scales involves both geodynamics and fluvial dynamics. the shifting of the Kosi River Corridor in the Lower Kosi River Basin is influenced by both autocyclic fluvio-morphodynamic processes and external forces related to plate tectonics. Autocyclic processes alone cannot explain the observed preferential unidirectional shifts and the dissimilar drainage patterns on the two flanks of the river. The presence of crisscrossing faults, aided by plate tectonics, contributes to the morpho-ergodynamics of the Kosi Corridor, allowing for the westward migration and overlapping interactions between geodynamics and fluvial dynamics.

1.3 Remote Sensing and GIS for Morphological Study

Changes in river morphology can be studied with the use of 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 that are 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 in a quick and cost-effective manner, 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 particular advantage, areas that may be inaccessible for data collection can also be studied using 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 using the remote sensing data in morphological studies.

General Guidelines for Preparing River Morphological Reports, prepared in April 1991 have now been revised to incorporate remote sensing as an advanced technology in morphological computations (CWC, 2009). Several river morphological studies incorporating the use of satellite-based data are 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 the use of aerial photography and United States Geological Survey (USGS) quadrangle maps. Mohammadi et al., 2008 determined the morphological changes of Gorganrud River in Iran using satellite images of Landsat and Enhanced Thematic Mapper Plus (ETM+). Legleiter, 2010 studied the morphology of Snake River in Wyoming, United States of America (USA). Other case studies of different morphological aspects like coastal effects, aquatic habitat conditions, anthropogenic effects on morphology of river etc., studied using remote sensing and Geographic Information System (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 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 on morphological behaviour of Indian rivers are also based on 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.

1.4 Objectives of Current Study

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

A. Study morphological behaviour of the River Kosi
B. Estimate erosion and deposition (areal retreat) on a decadal time scale
C. Study the dynamics of the river course
D. Identify stable and critical reaches in the river

Chapter 2: Literature Review

2.1 Overview

Several processes are responsible for complex and time-varying phenomena of river evolution which in turn drives river morphology. Among these, processes such as sediment transport and erosion-deposition are predominant and carry much weightage than others. Multiple methodsare 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 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 Kosi River system.

2.2 Morphological Indices

2.2.1 Meandering Parameters

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 and deposition is greater than vertical erosion and 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.

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.

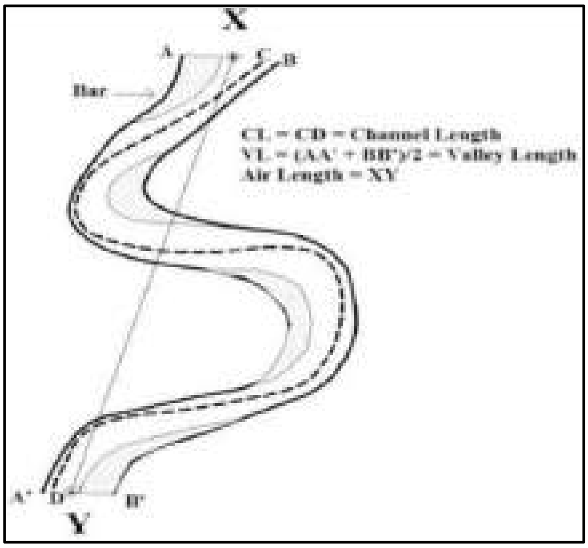


Figure 2-1: Mueller's Sinuosity Index

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

VL = Valley length along a stream, the length of a line that is everywheremidway between the base of the valley walls

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

CI (Channel Index) = CL / Air Length

VI (Valley Index) = VL / Air Length

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

Sinuosity Index (Friend and Sinha, 1993): Sinuosity Index 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 asits valley), while the higher this ratio is above 1, the more the river meanders. It is possible to estimate this index using aerial photographs and satellite images.

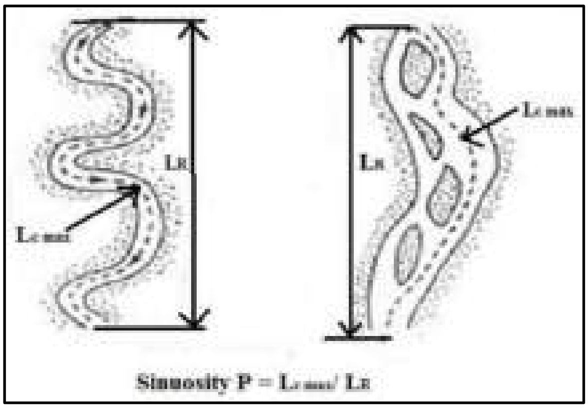


Figure 2-2: Sinuosity Index (Friend and Sinha, 1993)

According to Friend and Sinha, 1993, the sinuosity parameter P is defined as:

$$P = \frac{L_{cmax}}{L_r}$$

Where, L_r = Overall length of the channel belt

L_{cmax} = Mid-channel length for same reach or mid-channel length of the widest channel

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 definitionsof 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 barsor 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.

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

Braiding Index is defined by Friend and Sinha, 1993 as:

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

Where, L_{ctot} = Sum of mid-channel lengths of all the segments of the primary channel in a reach

L_{cmax} = Mid-channel length of the widest channel through the reach

Plan Form Index developed by Sharma, 1995 focusses on the degree of braidingin 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.

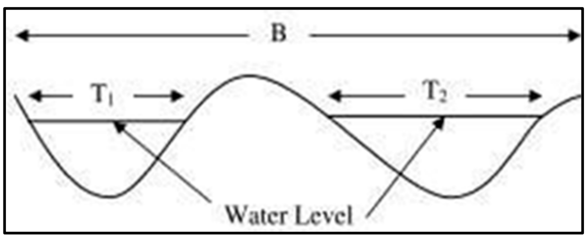


Figure 2-3: Plan Form Index (Sharma, 1995)

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

Where, T= Flow top width (T1+T2)

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 thesestudies 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 Thematic Mapper (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-BrahmaputraPlains. 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 Indian Remote Sensing (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 Multispectral Scanner System (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 areais 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 Linear Imaging Self Scanning Sensor-II (LISS-II) images. It was reported that overall trend indicates the intense shift of the river towards northwarddirection 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 more than100 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 and 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, TM and 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 fora period of eighteen 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 Kosi River

The morphological study of the Kosi channel and megafan region was first presented by Singh et al., 1993 based on the analyses of lithological facies. Based on the channel patterns and sediment deposits, the author classified the river into 04 distinct zones: gravelly-sandy braided, sandy braided, straight and meandering.

Sinha and Friend, 1994 examined the Himalayan rivers of Bihar based on their origin, channel hydraulics and planform characteristics. The authors concluded that the Himalayan rivers, Kosi and Gandak, carry high discharge and sediment, and are highly braided.

Sinha, 1995 did an account of sedimentological characteristics such as grain size distribution, clay mineralogy, sand mineralogy and magnetic susceptibility of the alluvial sediments in the interfan area between the Gandak and Kosi megafan in the north Bihar plains. He found mud-dominated intervals in the fluvial sedimentation process in the north Bihar plains. Clayey silt and silty clay were found to be the most dominant units in the flood plain sediments.

Sinha, 2009 presented an account of Kusaha beach and avulsion of Kosi in 2008. The satellite images were studied to develop strategies for integrated management of basin.

Chakraborty et al., 2009 studied theoretical considerations, insights from simulation studies, results of laboratory experiments and comparisons with other megafans. They concluded that there is no evidence in favor of the existing notion of unidirectional shifting of the Kosi River from the eastern to western margin of the megafan. On the contrary, for most of the time, the Kosi channels were occupying a narrow zone in the east-central part of the megafan. The channel position used to oscillate randomly within this zone.

Sinha et al., 2014a performed sedimentological study of the Kosi Megafan (KMf) region. They observed upward fining sequences in the medial and distal parts of the KMf. Sinha et al., 2014b studied the upper reach of Kosi River based on the avulsion threshold index proposed by the authors to identify the critical sections prone to avulsion. The avulsion threshold index was derived using various topographic (Slope ratio, super elevation, flow depth, etc.) and planform indicators (Channel area ratio, bar area ratio, etc.) using Analytical Hierarchical Process (AHP). The study found that the river was prone to avulsion in the reach upstream of the Kosi barrage.

2.5 Conclusion

The review of pertinent literature indicates that river morphology has been 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 Kosi River have been carried out, 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 upwith more rational approach for understanding the morphological behavior of river at the basin scale.

Chapter 3: Salient Features of Kosi River

3.1 Physiography

The Kosi River drains the northern slopes of the Himalayas in the Tibet Autonomous Region and the southern slopes in Nepal. From a major confluence of tributaries north of the Chatra Gorge onwards, the Kosi River is also known as Saptakosi for its seven upper tributaries. These include: the Tamur Kosi originating from the Kanchenjunga area in the east, Arun Kosi from Tibet and Sun Kosi from the Gosainthan area farther west. The Saptakosi crosses into northern Bihar where it branches into distributaries before joining the Ganga River near Kursela in Katihar district.

The Kosi Basin is bounded on the north by the Himalayas, on the east by the Mahananda basin, on the west by the Burhi Gandak basin and on the south by the River Ganga. The salient features of the Kosi Basin as taken from Flood Management Improvement Support Centre (FMISC) Bihar have been tabulated in Table 3-1. The study area is shown in Figure 3-1.

Table 3-1: Salient Features of Kosi Basin

(Source: FMISC, Bihar)

S. No.	Feature	Details
1	Tributaries	Bagmati (R), Kamla Balan (R), Bhuthi Balan (R), Trijuga (R), Fariani Dhar (L), Dhemama Dhar (L)
2	Total Drainage Area	74,030 km^2
3	Drainage Area in Bihar	11,410 km^2
4	Water Resources	52,219 MCM
5	Average Annual Rainfall	1,456 mm
6	Total Length of Main River in Bihar	260 km
7	Cropped Area in Bihar	8,694 km^2
8	Population in Bihar	66.55 lakh

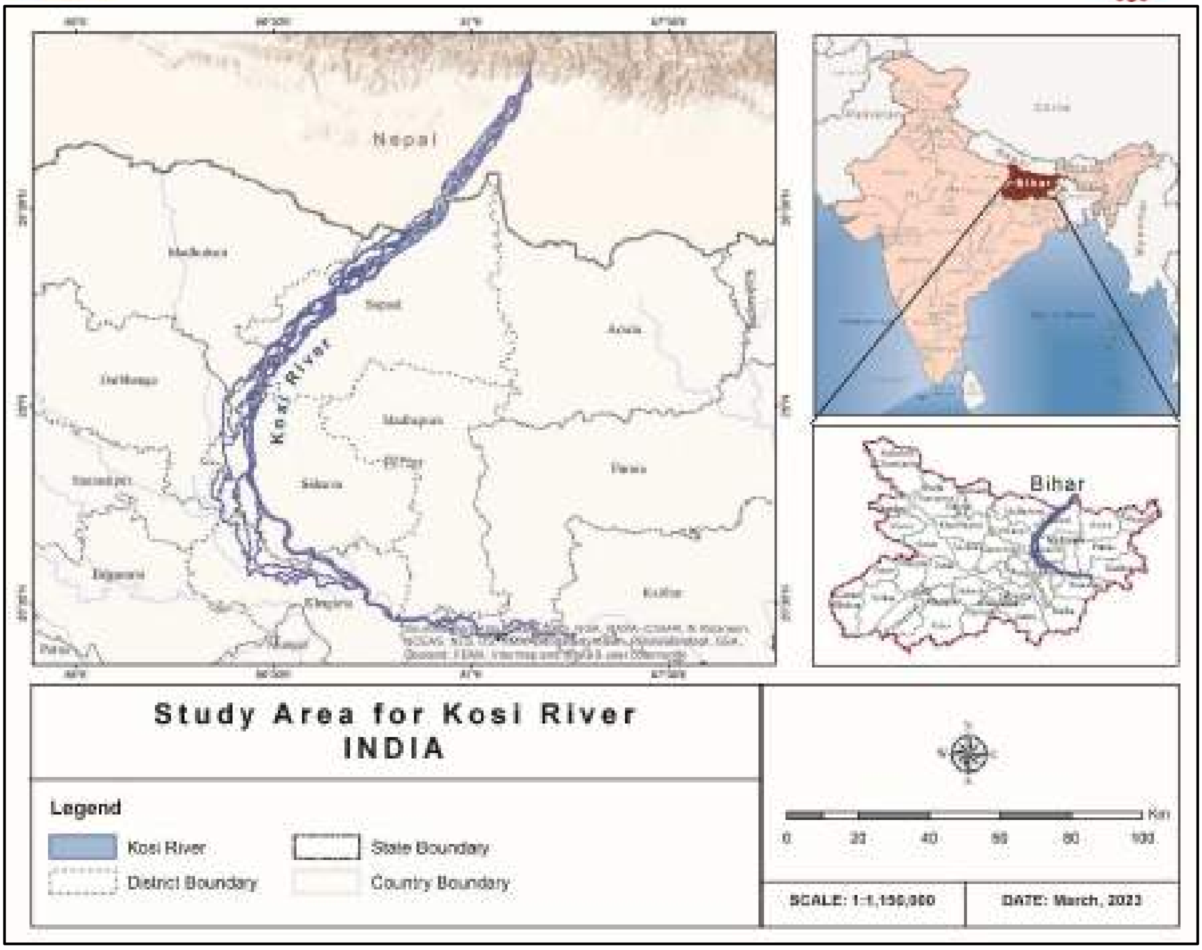


Figure 3-1: Map of Study Area (Kosi River)

3.2 Topography

The Kosi Basin has huge variation in its elevation profile. The basin shows two distinct topographical characteristics. On the one hand, it has the world's highest peaks in its upper reach in Nepal and on the other hand, flat flood plains when it enters Bihar, India. There is an abrupt change in its elevation on its entry in India, and it branches into several channels. The Digital Elevation Model (DEM) of the Kosi Basin is shown in Figure 3-2 below. The slope map of Kosi can be seen in Figure 3-3.

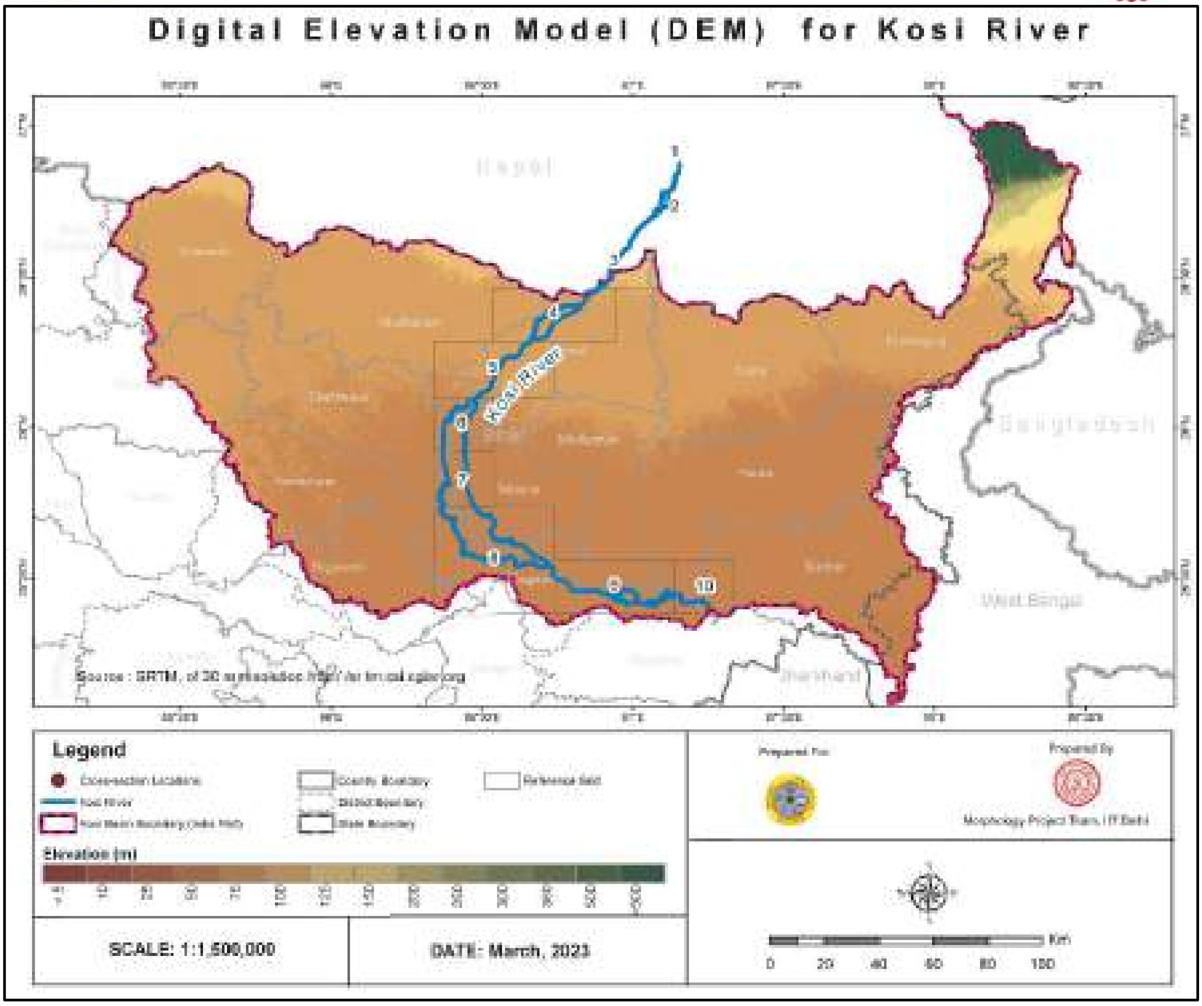


Figure 3-2: Digital Elevation Model of Kosi Basin

The topographical characteristics of the Kosi Basin are indicated in Table 3-2.

Table 3-2: Topographical Characteristics of Kosi Basin

Area (km^2)	32,166.39
Minimum Elevation (m)	22
Maximum Elevation (m)	2,913
Mean Slope (Degree)	1.81

Figure 3-3: Slope Map of Kosi Basin

3.3 Weather and Climate

The Kosi Basin in India forms part of the Gangetic plains and is 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 of June to October. The intensity decreases from east to west and from north to south. It is therefore the catchment in Nepal that contributes a major portion of the runoff in the Kosi and the Adhwara group of rivers.

3.4 Soils

The rocks in the Kosi Basin consist of Pliocene and Pleistocene deposits which are incredibly fragile rocks. Therefore, the river incises and disintegrate these fragile young rocks quickly, and carry a considerable amount of sediment of the valley. The coarsest material, the boulders and the gravels, drop off from the Himalaya foothills. The terraces in the Terai comprise of clay, sand and gravels. The hills at the flanks comprise conglomerates and thick beds of sand, rock and shoals.

Being part of the Gangetic plain, there is a thick alluvial deposit. By and large, it can be said that the geology of the Kosi 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 formations.

3.5 Major Settlements

The major cities and towns located within 15 km from the Kosi River can be seen in Figure 3-4.

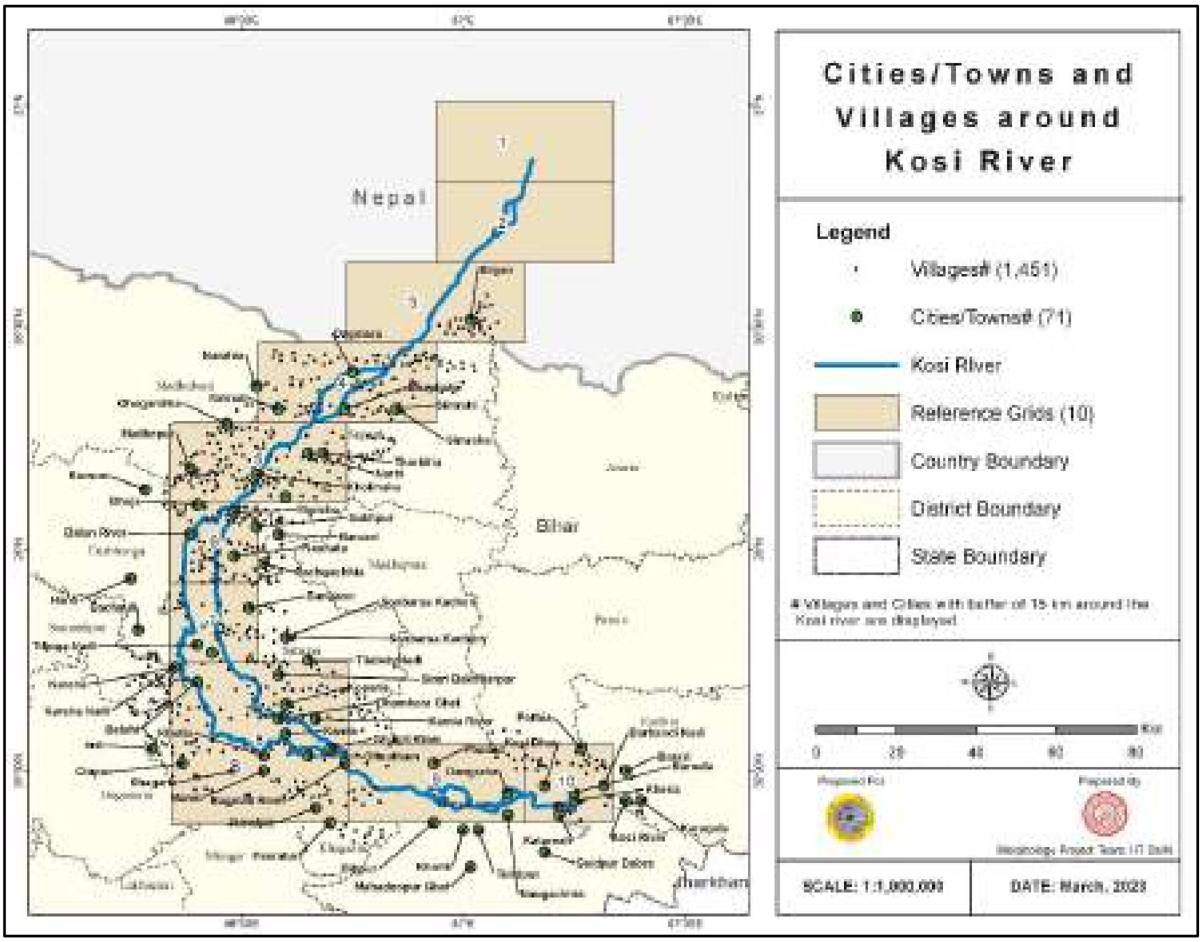


Figure 3-4: Major Settlements Along Kosi River

3.6 Water Resources Development

The Kosi Barrage, commissioned in 1963, is an irrigation, flood control and hydropower generation project in the Bhimnagar district of Bihar on the Kosi River built under a bilateral agreement between Nepal and India: The Eastern Canal and the Western Canal taking off from the barrage, were designed for a discharge capacity of 455 m^3/s to irrigate 6,125 km^2 and 210 m^3/s to irrigate 3,566.10 km^2, respectively. The Western Kosi Canal provides irrigation to 250 km^2 in Nepal. A hydropower plant has been built on the Eastern Canal, at a canal drop (3.6 km from the Kosi Barrage), to generate 20 MW. An inundation canal taking off at Chatra, where the Kosi debouches into the plains, has been built to irrigate a gross area of 860 km^2 in Nepal. The easiest way one can think to tackle flood situation is construction of embankment along the channel. And that is what is being done since last 50 years under various irrigation and flood control schemes. As can be seen in Figure 3-5, Kosi has embankments on both sides. However, construction of embankment is a controversial issue. In August, 2008, breaching of the eastern embankment of the Kosi River took place at Kusahaha around 12 km upstream of the barrage, and the river made an eastward jump of several kilometres for around nine months. The resulting flood left thousands of people homeless in Nepal and millions in India (Devkota et al., 2012).

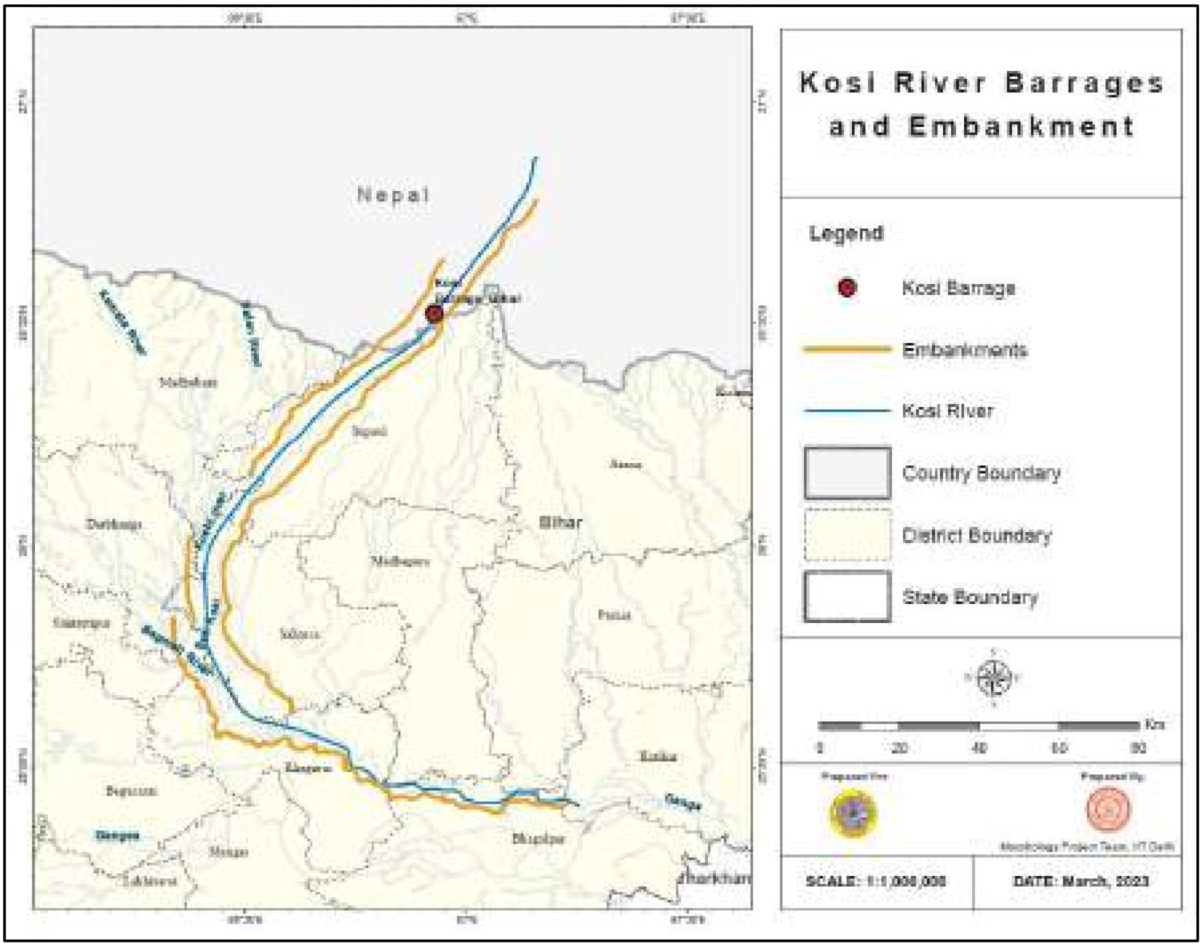


Figure 3-5: Existing Embankments along Kosi River

3.7 Reported Issues

Major issues reported in the Kosi Basin are related to frequent floods and quality of water. The topography of the catchment in India is very flat, and the river carries heavy sediment load particularly in the monsoon season, thereby subsequent deposition in the bed and flood plains of the river. This results in the spillage of flood waters 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. Then either 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 situations, it submerges surrounding villages.

Chapter 4: Geology of Kosi Basin

This chapter analyses the Kosi Basin's prominent geomorphology, geology and their variations across the spatial domain. These parameters are vital for watershed management, flood and drought estimation/management, erosion estimation/mitigation, identification of recharge zones, hydropower planning, and other structural development.

4.1 Geomorphology

As seen in Figure 4-1, the basin consists of different morphological features, including a small extent of highly and moderately dissected hilly and valleys regions, active and older floodplains, alluvial plains, lakes, ponds and rivers. The alluvial plain covers 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. River carry coarse sediments and deposit the same on both sides in their flood plain. The frequent flood incidences in the basin occur due: (1) flat terrain, (2) alluvial cover, which can be easily carved by the river course, (3) dense drainage network, and (4) floodplains.

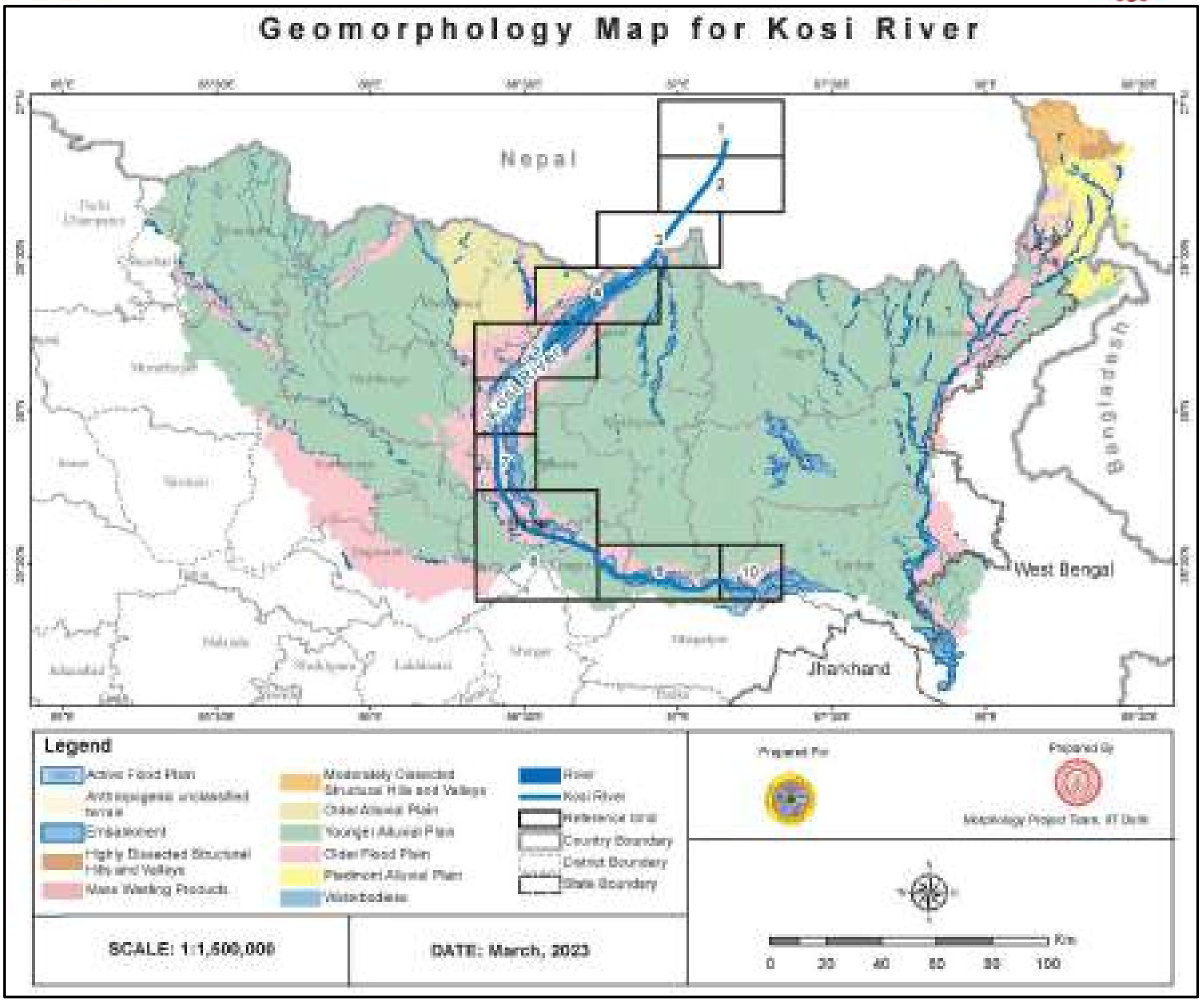


Figure 4-1: Geomorphology Map of Kosi Basin

4.2 Geological Formations

The geological formation of the Kosi Basin can be categorized into Proterozoic, Permian, Quaternary and Pliocene-Pleistocene as shown in Figure 4-2.

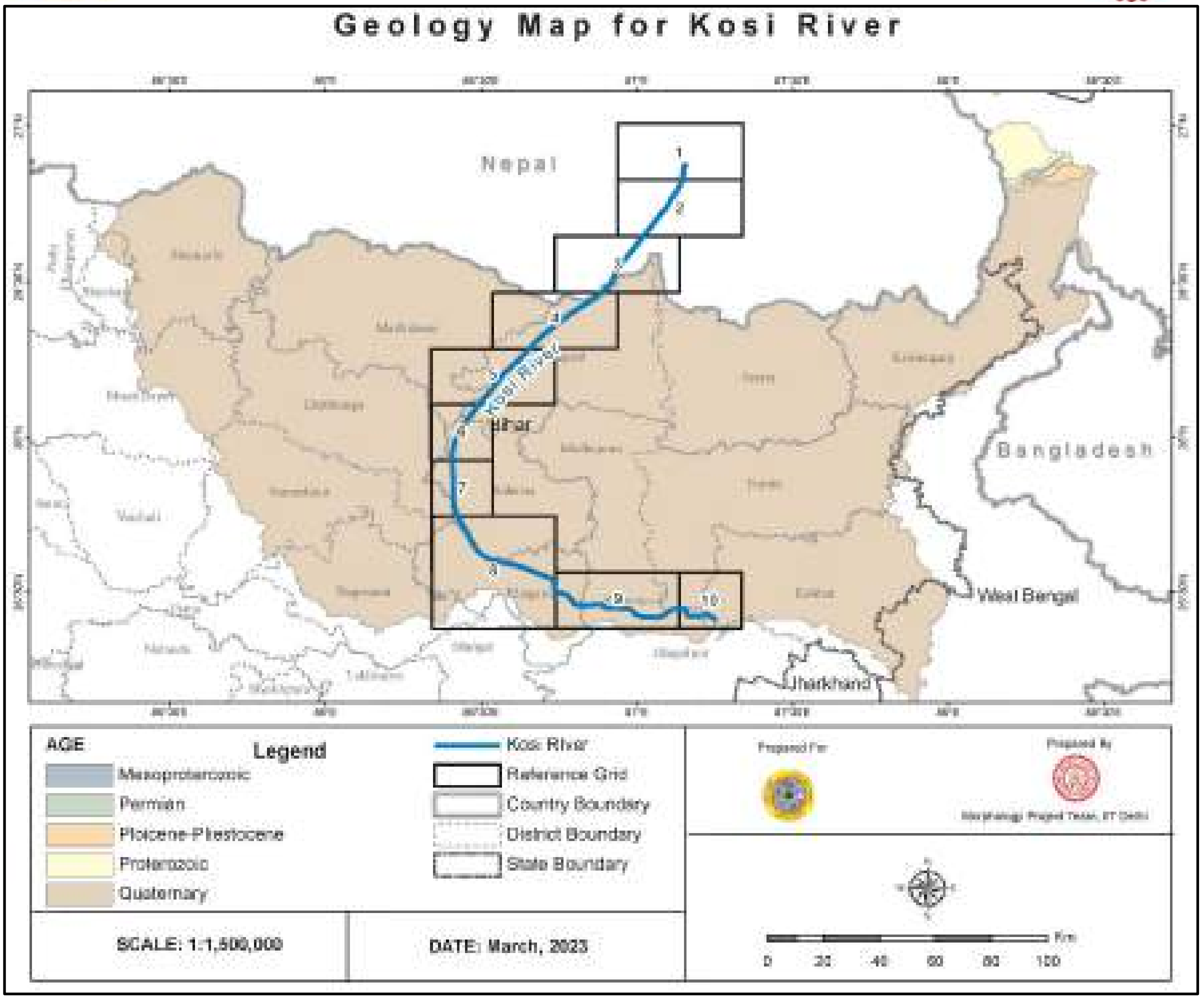


Figure 4-2: Geology Map of Kosi Basin

The details of the formations 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 Bihar'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 (CGWB) has confirmed the thickness of sedimentary deposits in North Bihar plain as more than 300 m. 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.

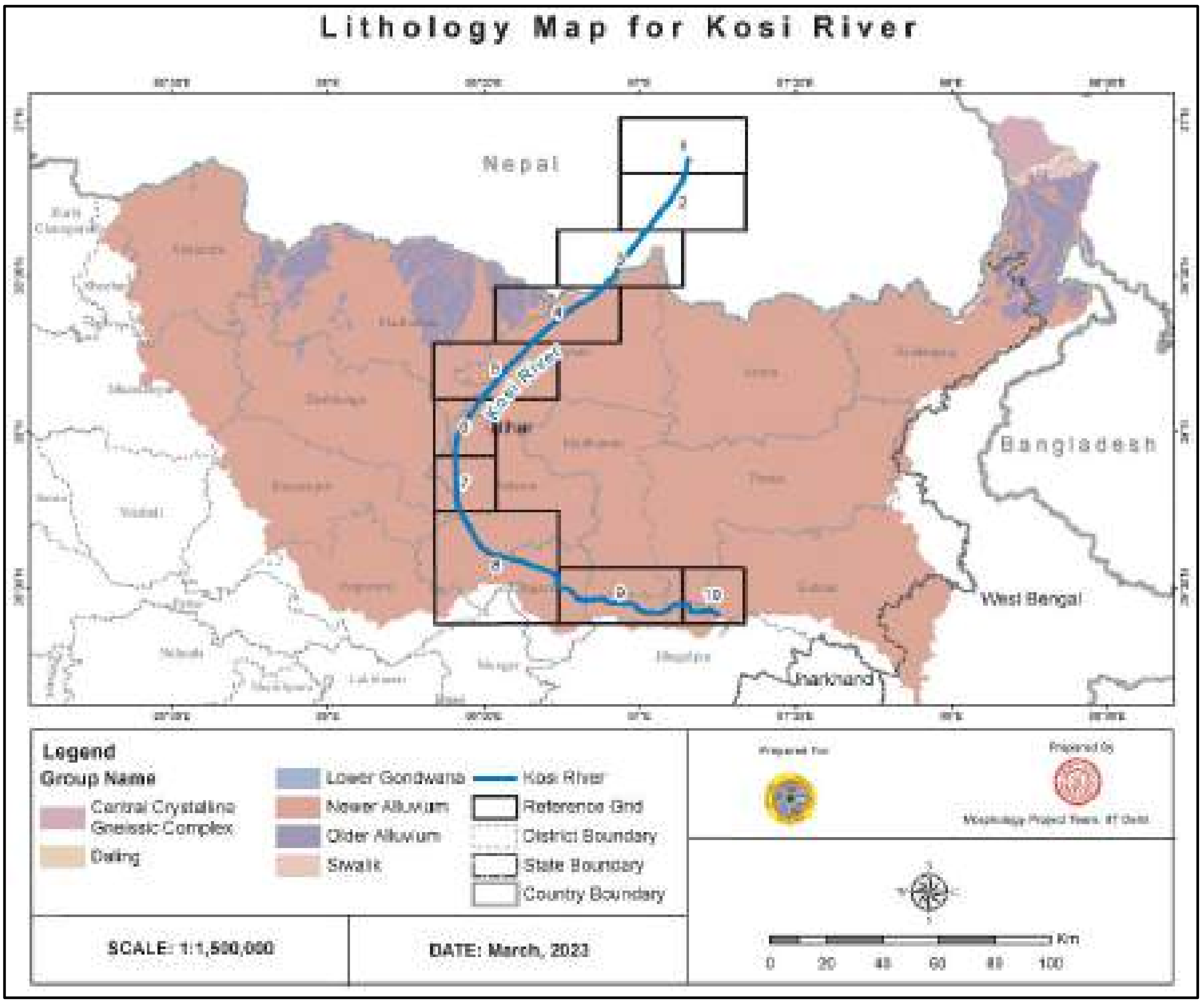


Figure 4-3: Lithology Map of Kosi Basin

4.3 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 sub-surface fault lines moving towards the Gangetic planes in four directions. As can be seen in Figure 4-4, the study area consists of several strike-slip faults.

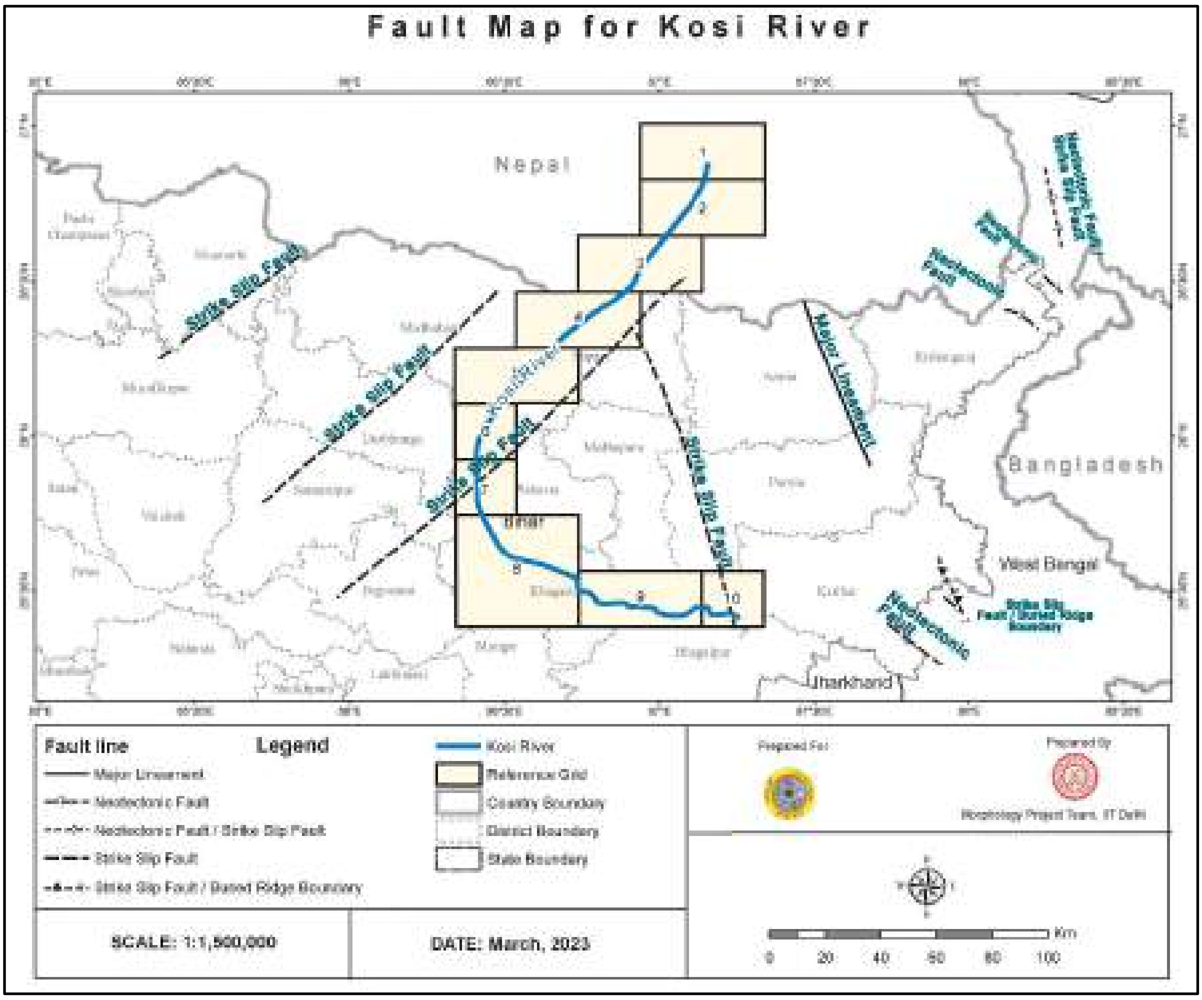


Figure 4-4: Fault Map of Kosi River

The Himalayan tectonics influences the upstream part of the Kosi River in the Kathmandu region. As can be seen in Figure 4-5, besides Main Central Thrust (MCT) and Main Boundary Thrust (MBT), the Kathmandu Himalaya is traversed by several other faults like Bhimpedi-Kathmandu fault, Motihari-Gourisankar fault and Motihari-Everest fault which are seismically active faults (Valdiya, 1976). Most epicenters reported after 1961 are concentrated in a 50 km wide zone between MBT and MCT (Dasgupta et al., 1987).

Mohindra et al., 1992 inferred that the flood basin between the Burhi Gandak River and the Kosi River is tectonically active and rapidly subsiding.

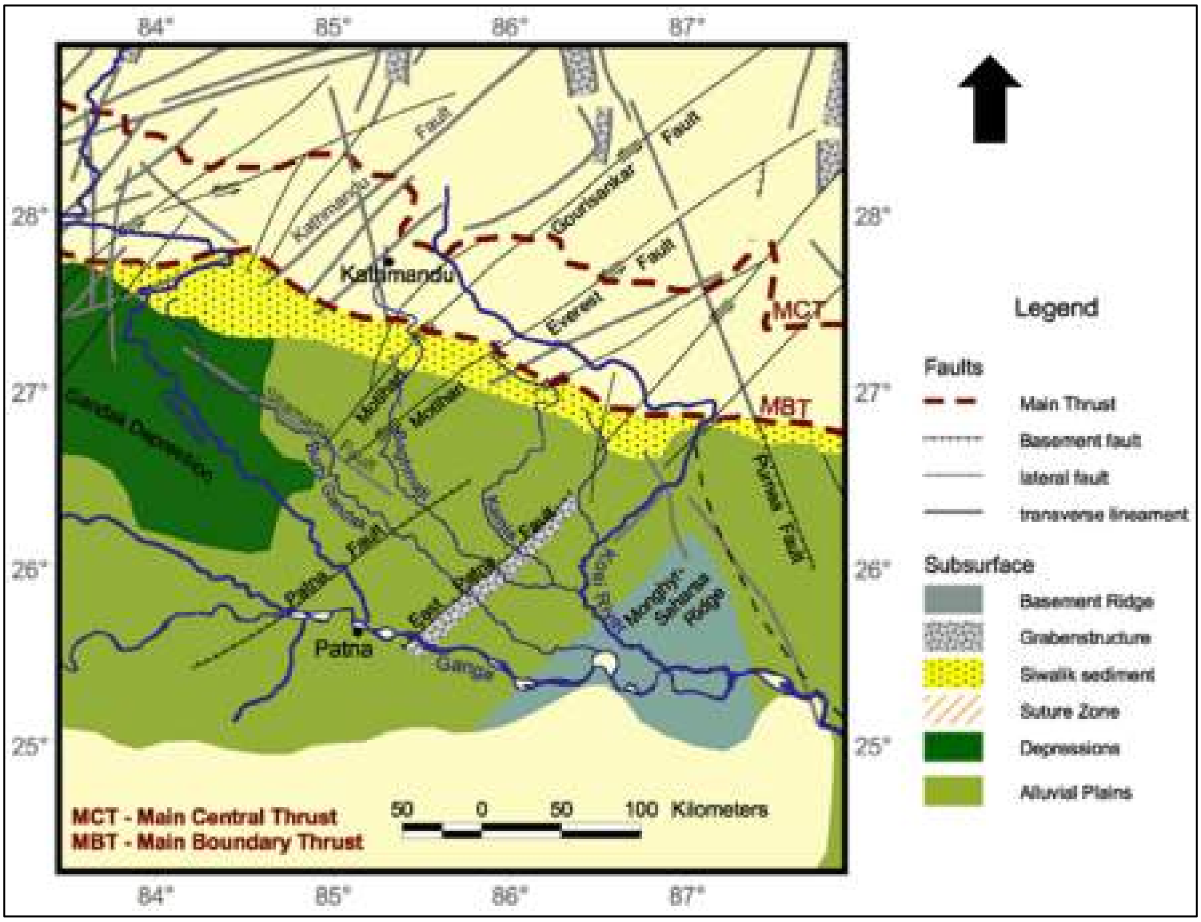


Figure 4-5: Lineament Map of Kosi-Bagmati Region

(Source: http://www.iitk.ac.in/gangetic/interfan/interfan_area_geol_litho_files/structec_bagh.htm)

In the north Bihar region, the important faults are West and East Patna faults in the East Ganga Basin and the Monghyr–Saharasa Ridge with its bounding faults, one passing through Rajgir and Barauni towards the north-east direction and the other from east of Bhagalpur towards north.north-west. These faults are known as transverse faults as the trend of these faults is transverse to the trend of Himalayan faults (Valdiya, 1976). These transverse faults in the Himalayan region vary in direction from north-west to north-east direction and form a set of conjugate faults. Dasgupta et al., 1987 interpreted that the northward movement of Indian plate is causing the activation of these sub-surface transverse faults and added that a substantial part of convergence of Indian plate is accommodated by strike-slip motion across the Himalaya, in addition to normal faulting in certain areas.

Frequently, the strains within the range are invested due to the over-turning of the folds and their dislocation. Features of such up-heavals bringing the older beds above the younger, characterize the whole length of the outer Himalayas. The present relief of high peaks and deep valleys has been carved by three principal agents of denudation, namely, wind, water and snow. The resulting products of disintegration of mountains are swept over the sub-mountainous tract as the rivers debouch into the plains. The terrain and the plains at the foot of the Himalayas assumed their present form after the final up-heavals of the range and consist of almost horizontal layers of unconsolidated sand, silt, pebbles and gravel. Igneous, metamorphic rocks are the varieties available all along the range, which are commonly known as Darjeeling gneiss and are composed of mica, schists and gneiss. The sedimentary variety of Darjeeling contains minerals such as garnet, sillimanite, kyanite etc., the presence of which indicates that the rocks were subjected to high temperature and pressure.

Due to lack of instrumentation, the details of seismic activities in the Kosi Basin are limited. However, the region's history of large earthquakes suggests that it is at high risk for future earthquakes. The Kosi Basin is characterized by tectonic activity with seismic events and aftershocks of magnitude 7 or higher happening approximately once every 50 years. Notable earthquakes have occurred in the area in 1833, 1837, 1883, 1897, 1934, and 1988, as documented by Chaulagain et al., 2018. The 1833 earthquake in Nepal was a magnitude 7.6 event that caused significant damage in the Kathmandu Valley. The 1934 Bihar-Nepal earthquake was a magnitude 8.4 event that caused widespread damage in Nepal and Bihar, India. It was the deadliest earthquake in Nepal's history, with an estimated death toll of over 8,000. The 1988 Udayapur earthquake was a magnitude 6.5 event that caused significant damage in eastern Nepal.

Earthquakes can have a significant impact on the morphology of rivers. They can cause the river to change its course, the riverbanks to erode or deposit sediment, and the riverbed to deform. These changes can lead to a variety of other changes in the river, such as the river becoming wider, deeper, shallower, narrower, or even changing its flow direction.

According to Mukherjee, 2008, the structure contour map at the basement and Neogene-Quaternary level suggests a regional tilt from east to west along the Malda-Kishanganj fault, which got accentuated in the recent past due to reactivation along the faults/lineaments resulting in westward migration of the river. Srivastava, 2002 (Refer Figure 4-6) suggested that Quaternary faults associated with Begusarai faults, regional E-W tilt of the basement towards the Madhubani depression and subsidence due to the basement faults on their peripheral region, helped Kosi river in maintaining its continuous westward migration.

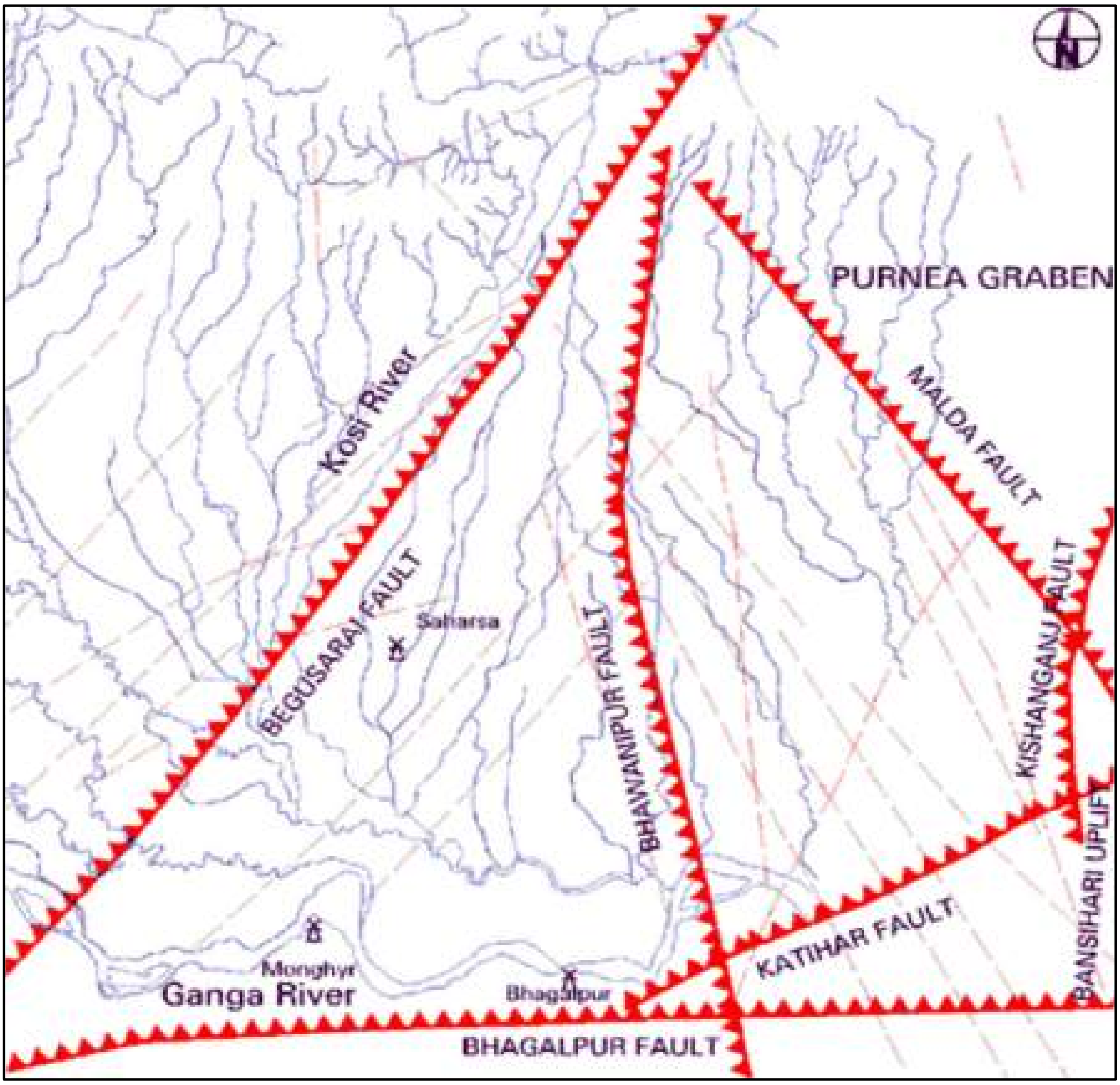


Figure 4-6: Lineament Map of Kosi River

(Source: Agarwal and Bhoj, 1992)

Chapter 5: Input Data Used

In this chapter, different types and sources of datasets related to the Kosi River Basin have been discussed. These datasets have been procured from the concerned agencies, preprocessed using different tools and then analyzed for this study. The details of the data used in this study are discussed in the subsequent section.

5.1 Hydrological Data

The various hydrological observation sites maintained by Central Water Commission (CWC) on the Kosi River can be seen in Figure 5-1.

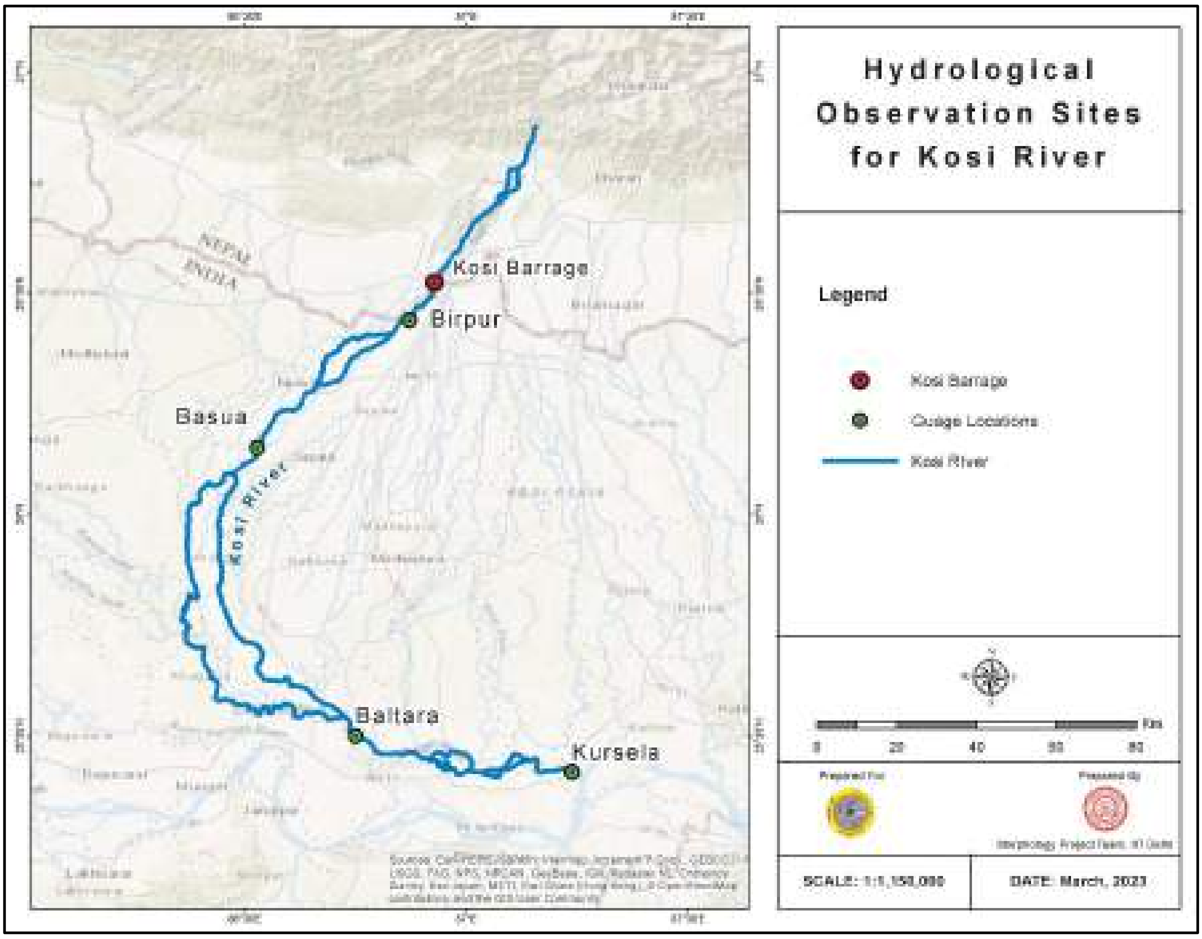


Figure 5-1: Hydrological Observations Sites on Kosi River

5.2 Satellite Data

Satellite data for five different years (1977, 1990, 2000, 2010 and 2016) have been obtained from National Remote Sensing Centre (NRSC) and United States Geological Survey (USGS) website. They have been used to extract features like active water area, bank lines, stream centerline, sandbars, channel area and islands.

5.2.1 NRSC Data

For 1990, 2000 and 2010, images from NRSC have been procured (Refer Table 5-1).

Table 5-1: Issues in NRSC Data Procured for Kosi River Analysis

Year	Product and Resolution	Issues	Solution
2010	LISS 3, 23.5 m	Translation errors (Lateral shifts in x and y-direction)	Corrected for further use
2000	LISS 3, 23.5 m	Lateral shifts (About 20-25 km) and geo-referencing errors	USGS images of 2000 (30 m multispectral and 15 m panchromatic) used
		Some scenes missing	
1990	LISS 1, 72.5 m	Few scenes missing	USGS images of 1990 (30 m resolution) used
		Without geo-referencing	

5.2.2 USGS Data

In the absence of NRSC images, data from other sources like USGS has been used to attain project objectives (Refer Table 5-2 and Table 5-3).

Table 5-2: Issues in USGS Data Downloaded for Kosi River Analysis

Year	Product and Resolution	Issues	Solution
2010	LANDSAT 7 and LANDSAT 5, 30 m	Translation errors (Lateral shifts in x and y-direction)	NRSC images of 2010 (23.5 m resolution) used
2000	LANDSAT 5, 30 m	Lateral shifts (About 20-25 km) and geo-referencing errors	Corrected for further use

1990	LANDSAT 5, 30 m	Geo-referencing errors	Corrected for further use
1977	LANDSAT 1 and 2 MSS, 60 m	Image resolution is coarse (60 m) and river is very thin, so challenging to delineate river	Toposheets used for rectification and digitization

Table 5-3: Description of USGS Data Used for Kosi River Analysis

Year	Product and Resolution	Path	Row	Date
2016	LANDSAT 8, 30 m multispectral	140	41	2016-01-04
		140	42	2015-12-19
		141	41	2015-12-26
		141	42	2015-12-26
2000	LANDSAT 7 ETM+, 30 m multispectral and 15 m panchromatic LANDSAT 5 TM, 30 m multispectral	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
1990	LANDSAT 5 TM, 30 m multispectral	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
1977	LANDSAT 1 and 2 MSS, 60 m multispectral	150	42	1977-05-12
		151	42	1979-10-21

5.3 Toposheets

Survey of India (SoI) toposheets (1:50,000 scale) have been used to digitize features for preparation of the baseline data. However, the unavailability of toposheets for a complete stretch of the river surveyed in the same year led us to use the satellite data. Satellite imageries of the year 1977 and the features extracted from those imageries have been considered as baseline in the present study. Details of available toposheets are given below in Figure 5-2.

Figure 5-2: Available Toposheets for Kosi River

5.4 Other Data

Apart from the datasets discussed above, the data presented in Table 5-4 have been used for various analyses.

Table 5-4: Other Datasets Used in Kosi River Analysis

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

5.5 Tools Used

The following software have been used for activities related to this project:

A. ERDAS Imagine: Satellite data processing

B. ArcGIS/QGIS: Data digitisation and GIS operations

C. Microsoft Office: Documentation and data analysis

Chapter 6: Methodology

6.1 Terminologies

The terminologies related to river morphology that have been used in the present study are explained in the subsequent sections, along with their adopted definitions.

6.1.1 Channel Area

The channel area of a river refers to the part of the river that is defined by the banks on either side. It is essentially the area of the river bed that is occupied by flowing water, and can be represented by a polygon layer with a boundary defined by the right and left banks. The channel area can be affected by various factors, including sediment transport, channelization, and human activities such as damming or dredging. The Figure 6-1 depicts the method employed to extract the channel area from the imagery used in this study.

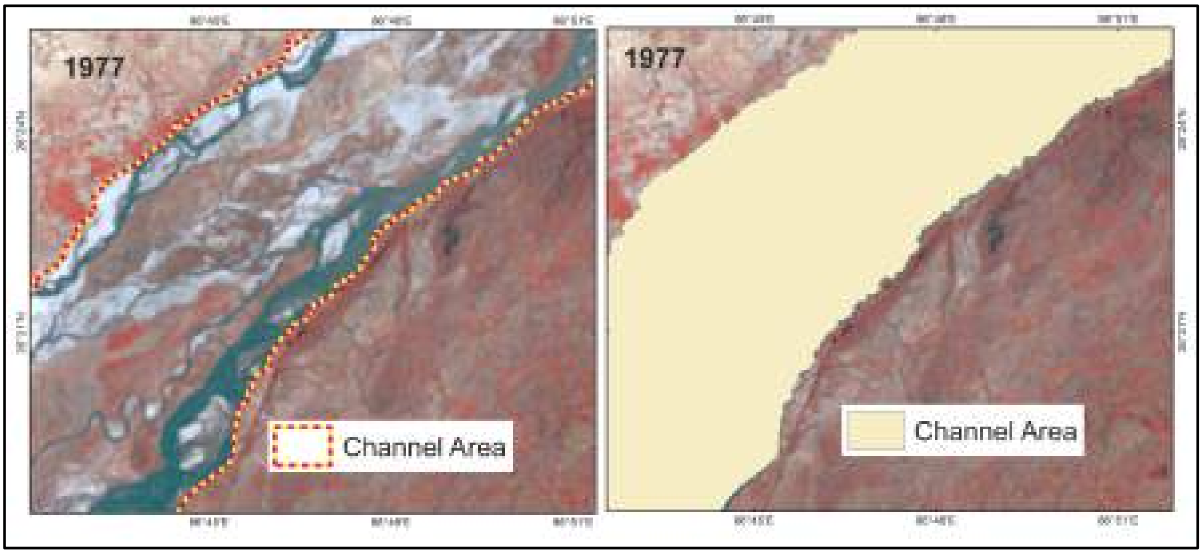


Figure 6-1: Extraction of Channel Area of Kosi River from Imagery

The channel area of a river is not a static feature and can be influenced by a range of factors over time. Natural factors that can contribute to channel area changes include erosion, sediment deposition, and fluctuations in water flow. For example, during periods of heavy rainfall or snowmelt, a river may experience increased water flow, which can erode its banks and alter the shape of the channel. Similarly, sediment deposition can occur when the river's flow slows down, leading to the creation of sandbars or other sediment deposits that can change the shape and size of the channel.

Human activities can also contribute to changes in channel area. For example, dredging or channelization can alter the course of the river and change the shape of its channel. Additionally, the construction of dams or other infrastructure can alter water flow and sediment transport, leading to changes in the channel area downstream. The changes in the channel area of Kosi river from 1977 to 2016 are presented in Figure 6-2.

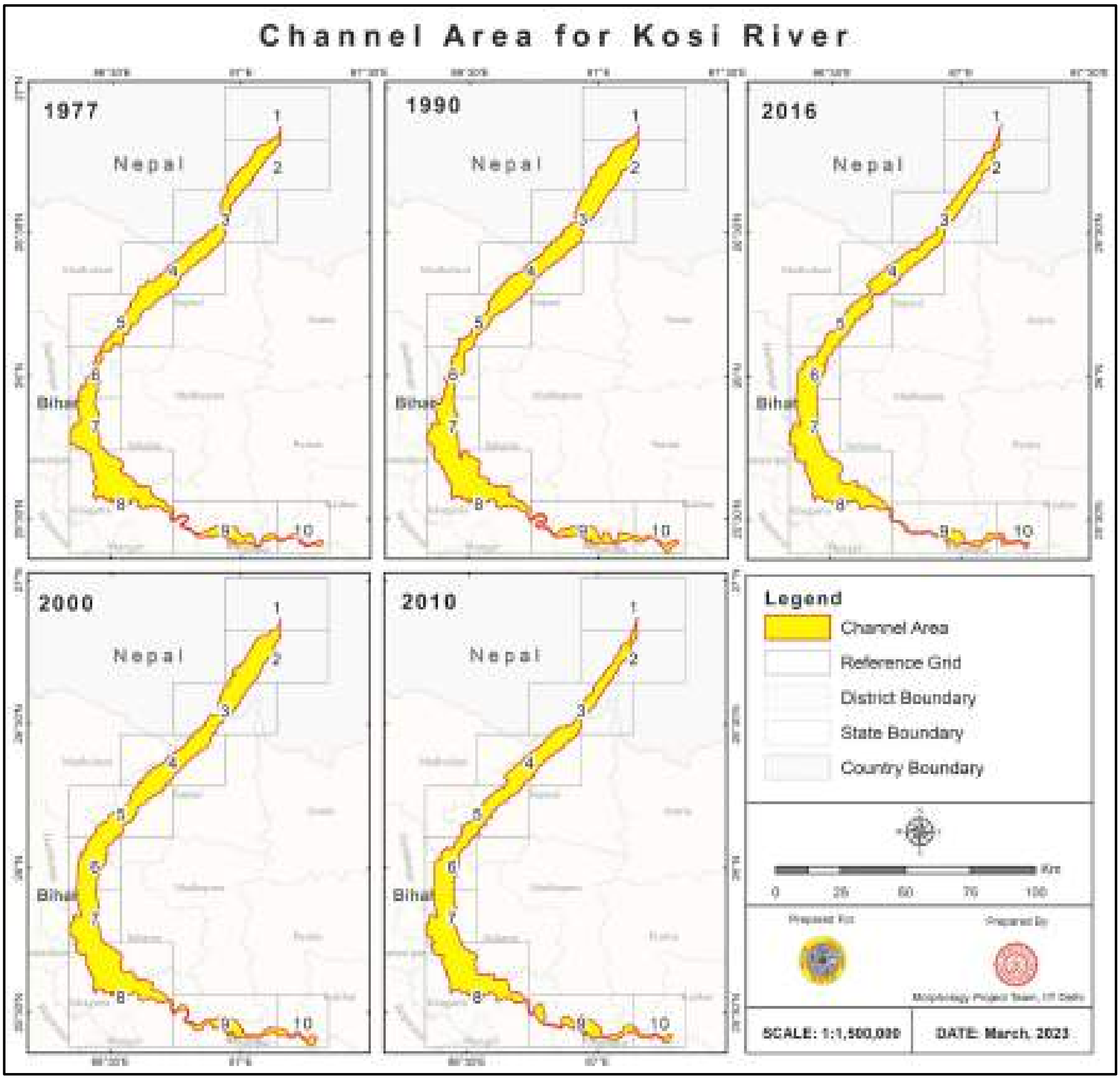


Figure 6-2: Variations in Kosi River Channel Area Across Different Years

6.1.2 Active Water Area

The active water area is that part of a river channel which represents actual flowing water at that time. The active water area in the monsoon season is different from that in the lean season. Moreover, in some cases, the active water area might be disconnected in the lean season on account of different interactions between surface water and groundwater at different locations. Figure 6-3 depicts how active water area has been extracted from the imagery.

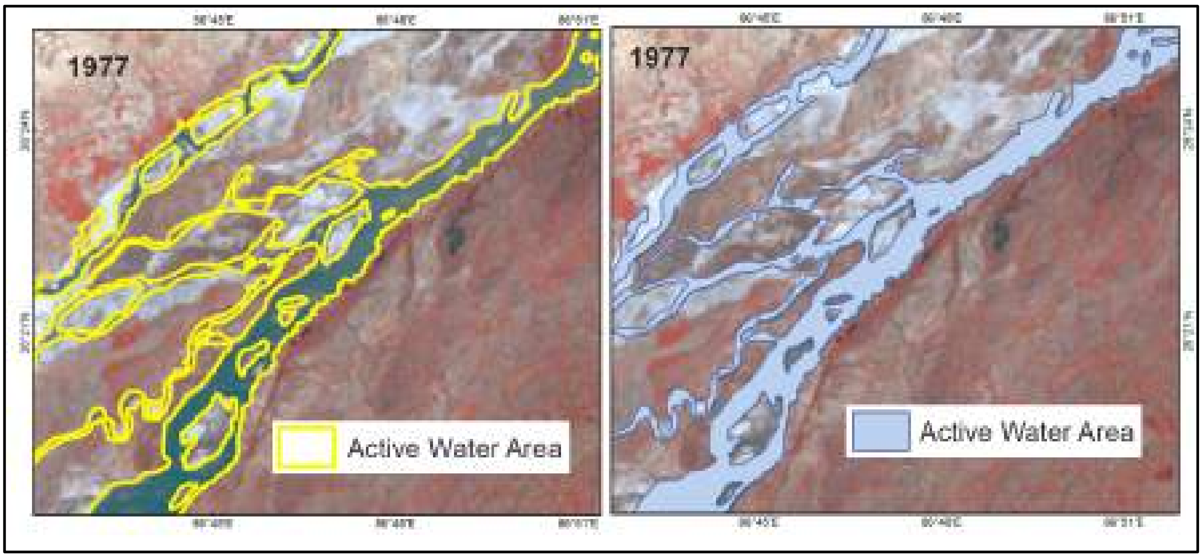


Figure 6-3: Extraction of Active Water Area of Kosi River from Imagery

In the present study, the active water area at varying time scales (1977, 1990, 2000, 2010 and 2016) have been marked using the satellite images of the respective years. Though the river shows significant channel changes during the monsoon period due to the occurrence of high flows, but the imageries of the monsoon months have large discrepancies due to cloud cover. Hence, lean season (December to February), which has significant impact on channel geometry, has been selected for marking the active water area. Figure 6-4 illustrates the active water areas in the channel of Kosi River in various years.

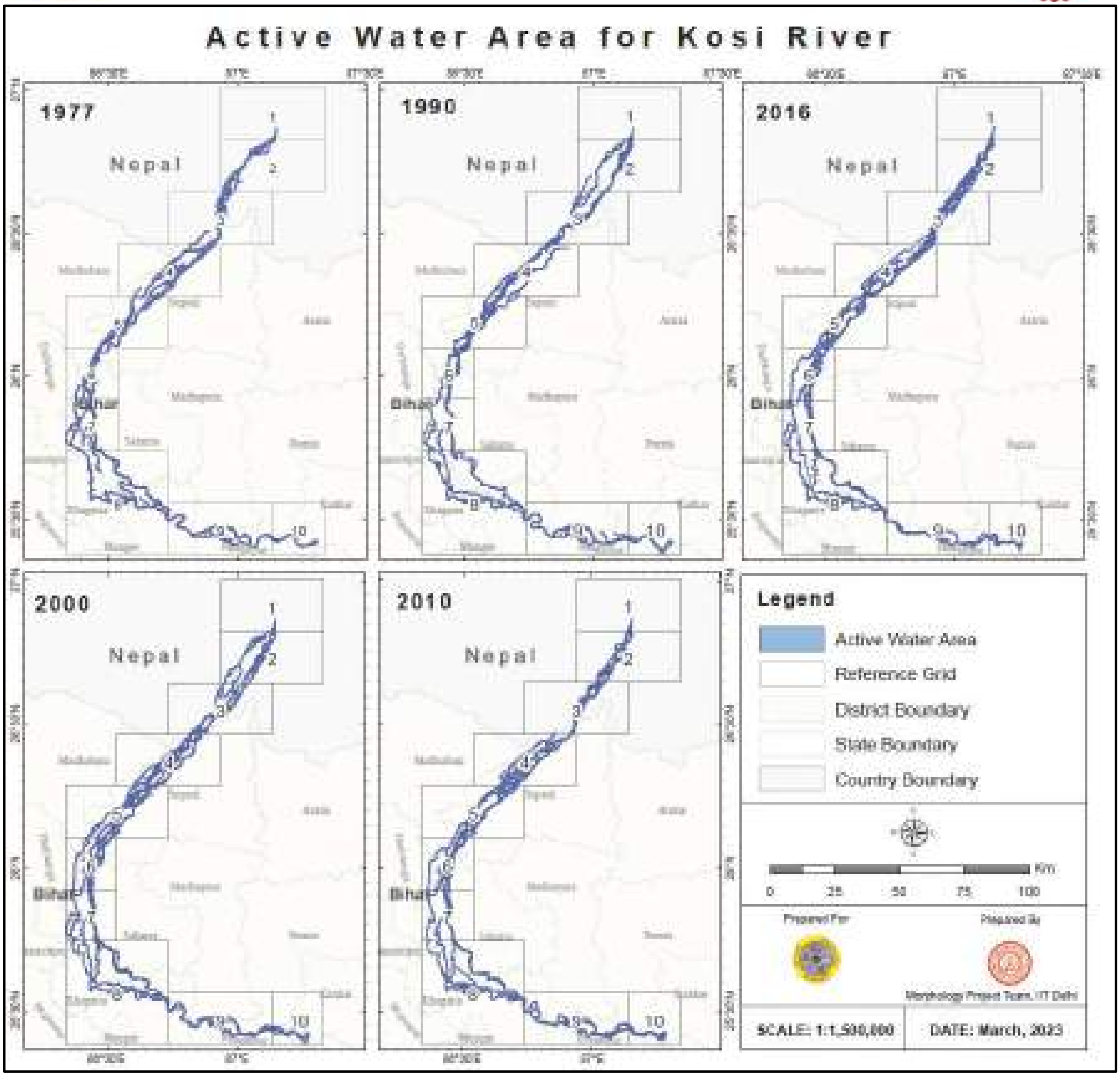


Figure 6-4: Variations in Active Water Area for Kosi River Across Different Years

6.1.3 Sandbars and Islands

The Kosi river dynamics and sedimentation patterns have resulted in the formation of numerous sandbars and shifting river channels. These sandbars are often temporary and can change in size and shape over time due to the river's flow and the deposition and erosion of sediment. The floods scour the sediments at the river bottom and when the floods recede, these sediments get deposited in different parts of the river channel in the form of sandbars.

While the Kosi Basin is known for its extensive sandbars, it does not have permanent islands in the traditional sense. The sandbars may appear as islands during certain seasons or when the water level is low, but they are subject to constant changes due to the dynamic nature of the river. The shifting sandbars and channels contribute to this dynamic nature of the river.

Sandbar is an elevated region of sediments deposited by the river flow and is not inundated at certain flow depth. Types of sand bars include mid-channel bars (Also called braid bars and common in braided rivers), point bars (Common in meandering rivers) and mouth bars (Common in river deltas). The locations of bars are determined by the geometry of the river and the flow through it. The bars reflect sediment supply conditions, and show where the sediment supply rate is greater than the transport capacity. Sandbars play a key role in the maintenance of the 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 create eddies where fish and other fauna feed (Hoeting, 1998; O'Neill and Thorp, 2011). Sandbars also serve as important habitats for reptilians in the riverine environment which use them for basking and nesting. Figure 6-5 depicts how sandbars look on the imagery.

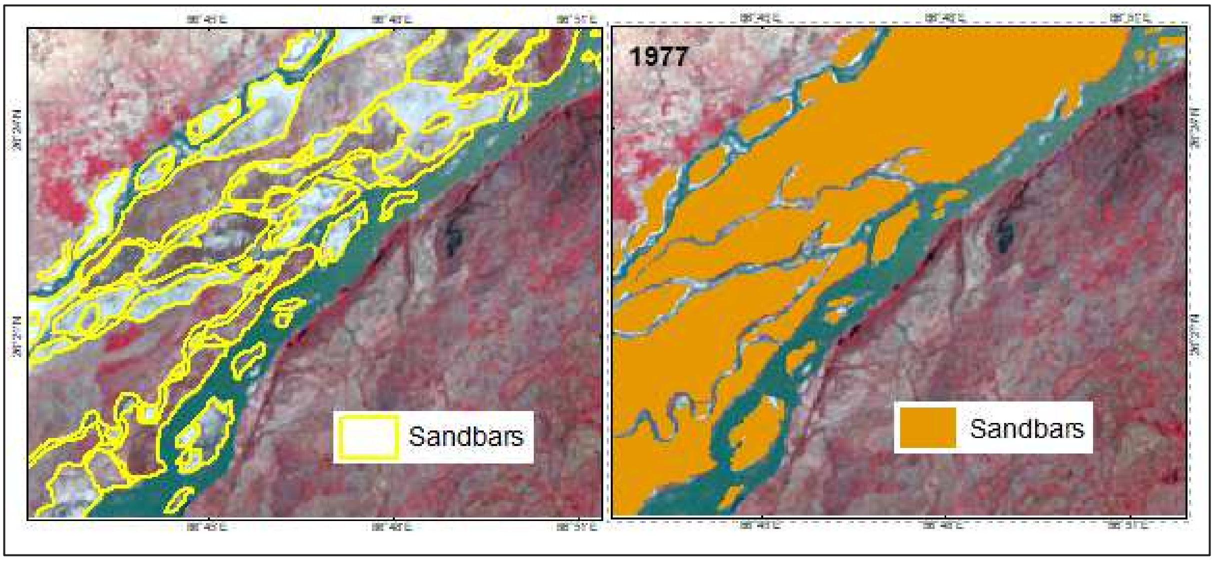


Figure 6-5: Mapping of Sandbars of Kosi River Using Satellite Imageries

In the present study, only mid-channel bars (braid bars) that are altering active water area computations have been considered. Point bars have been considered as part of the channel area. The variations in the areal retreat of sand bars have been assessed on a decadal scale for estimating erosion and deposition. Figure 6-6 illustrates the sandbar areas in the channel of Kosi River in various years.

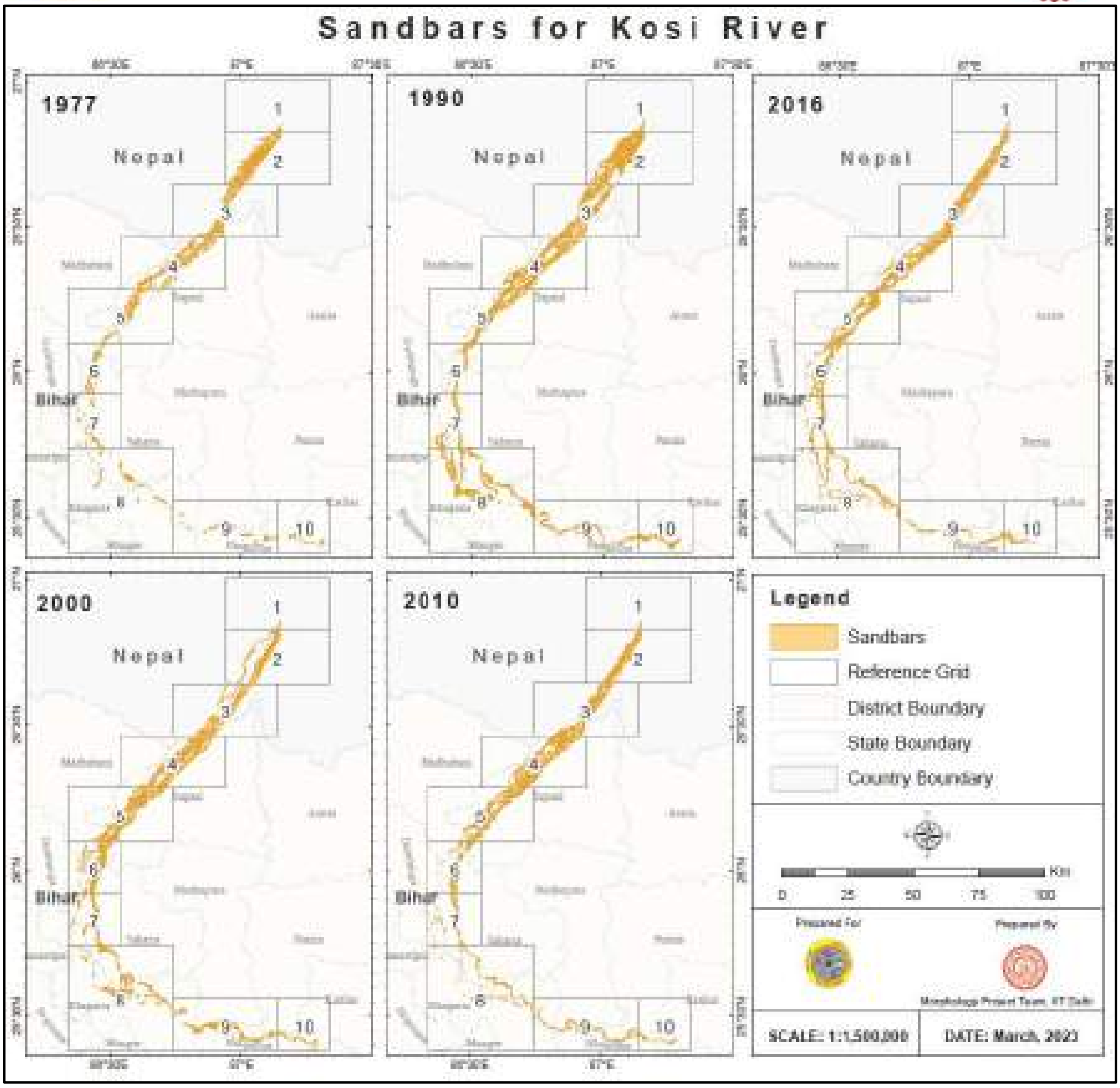


Figure 6-6: Variations in Sandbar Area for Kosi River Across Different Years

6.1.4 Water Bodies

Water bodies (Refer Figure 6-7) have been identified in the present study as independent water areas that are not part of the channel area. Generally, water bodies are oxbow lakes, swamps and small wetlands around the river course. Changes in waterbody area around rivers can have significant impacts on the surrounding ecosystem, including on water quality, habitat availability, and human activities such as agriculture or recreation. Understanding the factors that influence these changes is important for effective management and conservation of these ecosystems.

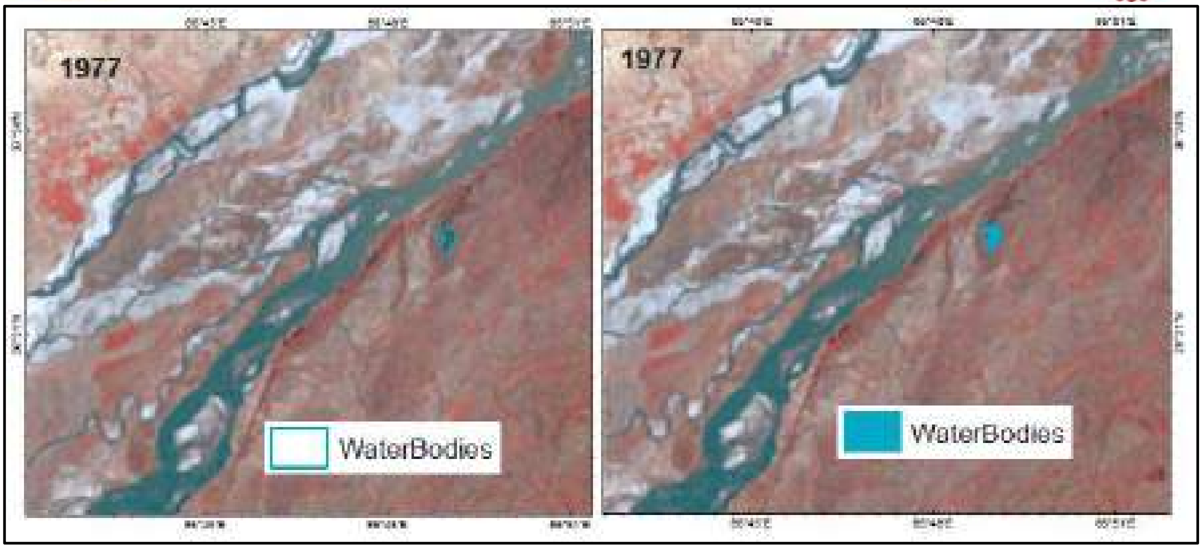


Figure 6-7: Mapping of Waterbodies of Kosi River Using Satellite Imageries

Waterbody area around rivers can change significantly over the course of decades due to a variety of factors, both natural and human-induced. Some factors that can influence changes in waterbody area include:

Climate change: Changes in precipitation patterns, temperature, and other climate-related factors can affect the water flow and volume in rivers and surrounding waterbodies. For example, if a region experiences prolonged drought, the waterbody area around a river may shrink due to decreased water availability.

Land use changes: Human activities such as agriculture, urbanization, and deforestation can lead to changes in the amount and quality of water flowing into a river, which in turn can affect the waterbody area around the river. For example, increased agricultural activity may lead to higher levels of runoff and erosion, which can cause sediment to accumulate in waterbodies and decrease their size.

Hydrological changes: Alterations to the river channel or water flow regime, such as the construction of dams or other water control infrastructure, can also affect the waterbody area around a river. For example, a dam can regulate the flow of water downstream and lead to changes in the waterbody area.

Natural events: Natural disasters such as floods or landslides can cause significant changes to the waterbody area around a river. For example, a flood may cause sediment to accumulate in a river or surrounding waterbodies, which can change the waterbody area.

Figure 6-8 depicts the changes in waterbody area in the Kosi River for various years.

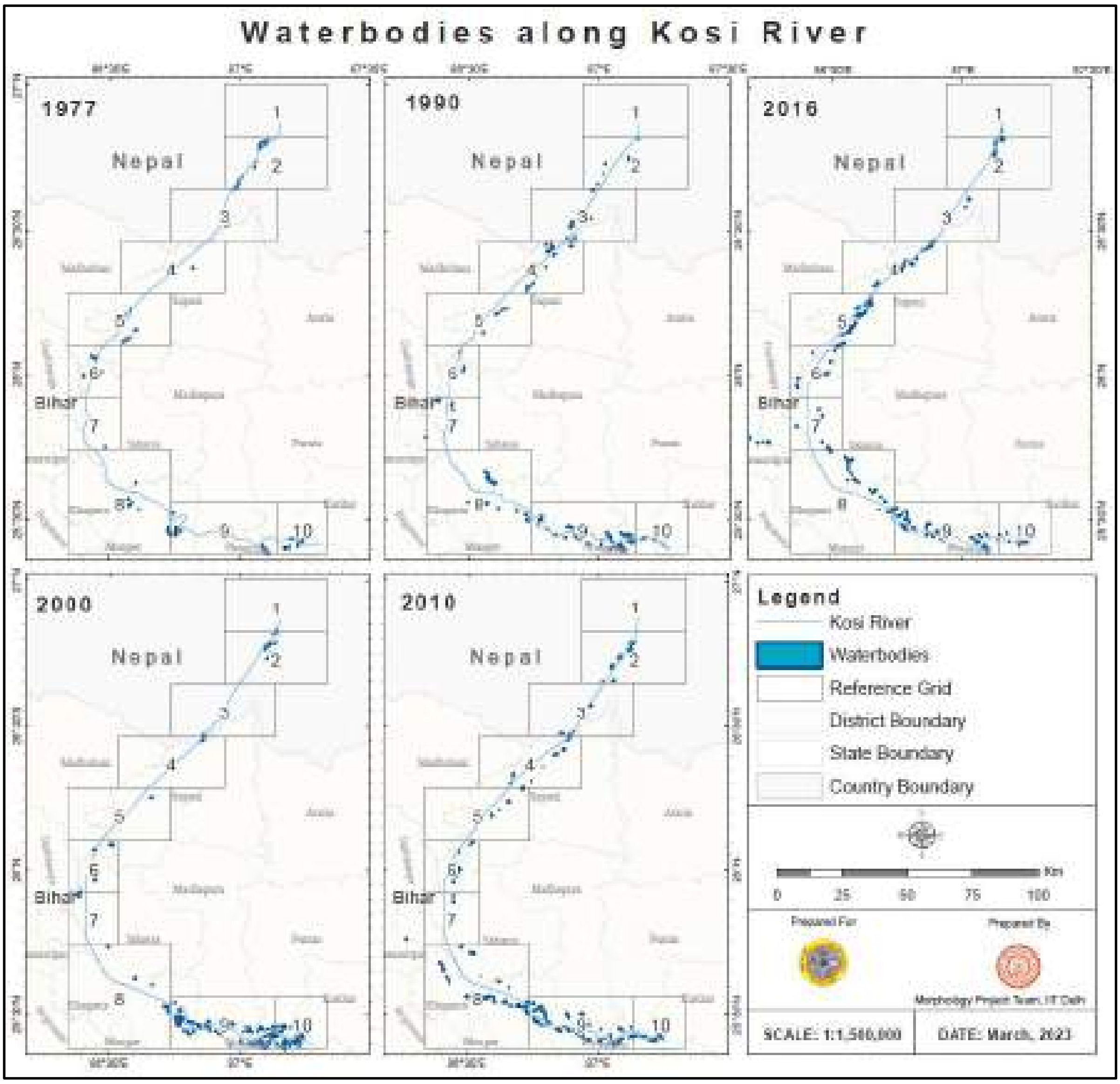


Figure 6-8: Variations in Waterbody Area for Kosi River Across Different Years

6.1.5 Center Line

There are various ways in which river centre line may be defined, and as a result, the concept of the river centre line 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 channel. It is also called as thalweg. It can also be defined as the centerline of active water area. In some of the modeling approaches, the centerline is defined as the channel centerline, irrespective of depth variation within the channel.

It is not possible to capture thalweg from remote sensing data because most of the remote sensing products are based on reflectance from the ground surface, and only very few of them (E.g. InSAR and Lidar datasets) are able to 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 not possible.

It is important to note that the center line based on active water area may vary from season to season. Most importantly in dynamic rivers where releases from hydel projects, dynamics in opening of gates, and natural variability in flows within and across seasons has significant impact on water depth. The centerline may not exist at few locations where the channel is not carrying any water.

Figure 6-9 shows the channel centerline delineated for a reach of Kosi for different years. Shifting of the Kosi River is calculated on the basis of center line of year 1975. Center line of year 1975 is perpendicularly bisected at a regular interval of 1 km. The shift of left bank, right bank and center line in left and right directions have been computed for the years 1990, 2000, 2010 and 2016 with respect to year 1977.

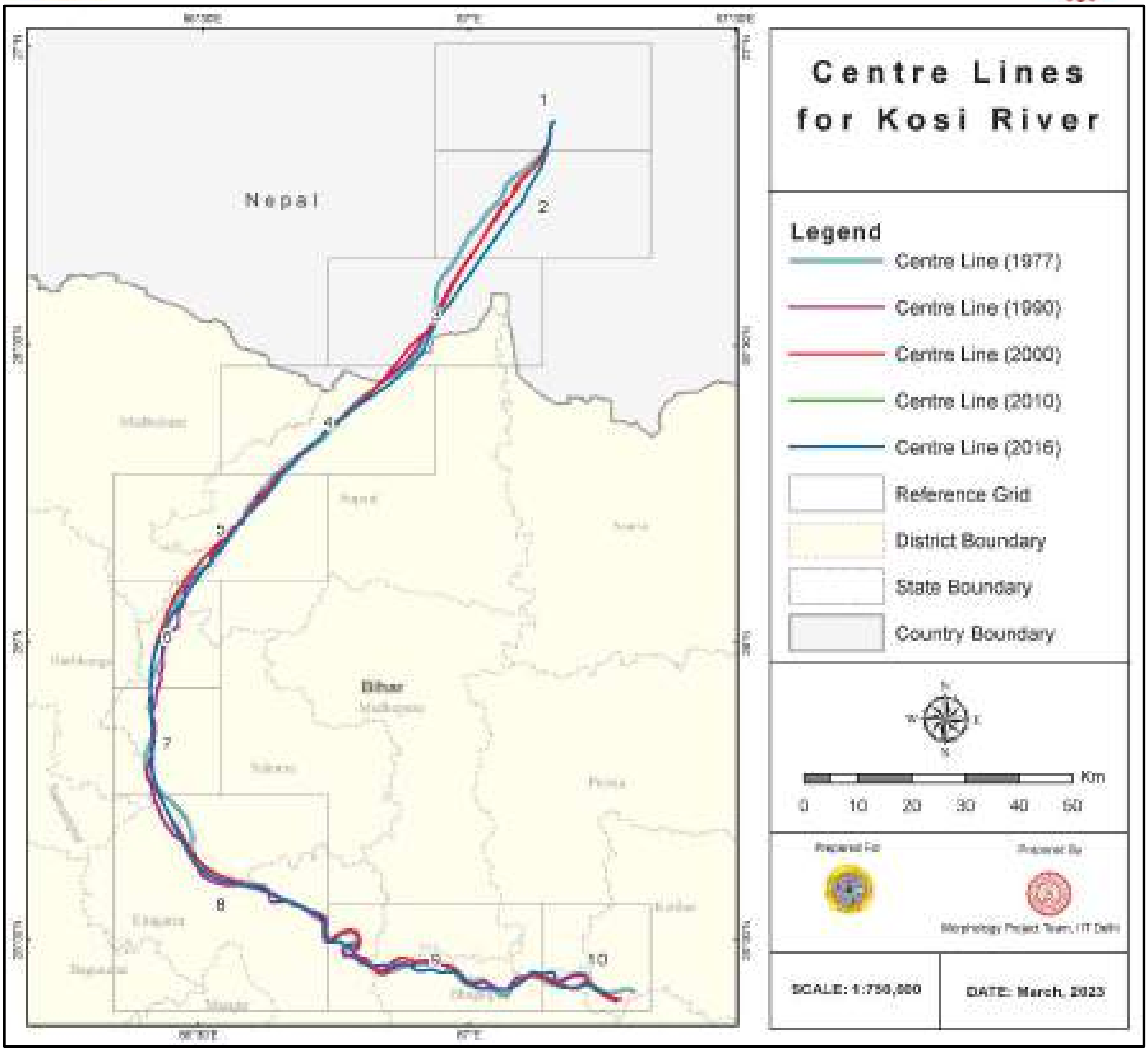


Figure 6-9: Centreline of Kosi River in Different Years

6.1.6 Sinuosity Index

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 claimed that the streams for which this ratio is equal to or greater than 1.5, are the true meandering streams. Friend and Sinha, 1993 modified Sinuosity Index for Indian rivers with multi-channel situations. Higher the value of Sinuosity Index, 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. Coarse sediments deposited during high flow become a barrier during low flow seasons 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 such rivers which 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 processes such as erosion and deposition. Braiding is typically referred to as the splitting of channels around bars or islands, which are contained within a dominant pair of floodplain banks.

As discussed in the literature review section, various types of braiding indices have been proposed. In the present study, Braiding Index suggested by Friend and Sinha, 1993 has been adopted.

6.1.8 Plan Form Index

For a more logical and quantitative description of braiding phenomena, Sharma, 1995 introduced a Plan Form Index (PFI) for identifying the level of braiding in a highly braided river. PFI indicates the river landform disposition with respect to a given water level. Lower value of PFI indicates higher degree of braiding. For classification of the braiding intensity, Sharma and Ashagrie, 2012 proposed following threshold values for PFI: Highly Braided: PFI < 4, Moderately Braided: 19 > PFI > 4 and Low Braided: PFI > 19. For calculating PFI, the entire reach of the river is subdivided into 1 km intervals, and the bed width, channel width and number of channels of the river are computed for each 1 km.

6.1.9 Critical and Stable Reach

Understanding the concept of critical and stable reach is important for the identification of 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 literature for identification of critical or stable reaches which can be generalized for different river systems of the world. Moreover, wide range of parameters are available to analyze the stability of the systems. Not only these parameters, but 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; whereas ecologist may identify particular fragment of 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, expert's background and his judgement are most important variables in declaring a reach as critical. It is important to note that, stability or criticality of a reach is also function of temporal and spatial scales of study. The scale on which observations are made also plays an important role in defining the stability or criticality of the reach under study.

Our understanding of natural systems suggests that river system in unregulated flow scenario should be considered as reference to discover changes occurred in the system over a temporal domain. In the present study, system observed in 1975 has been considered as the reference condition. Various features as explained above have been marked on 1975 image and used as the reference. Distance between bank lines (End points of channel area as observed in non-monsoon season) has been used to obtain location of centerline and channel width. If shifting of centerline between various years is more than width of channel in that particular stretch, it has been analyzed further to understand the dynamics of river functioning. The rate and scale of erosion-deposition and river course shifting have been used to identify a critical reach. If the shifting of river is limited to channel width, it has been considered as natural phenomena of river hydraulics and not attributed as a critical reach.

6.2 Remote Sensing Data Processing

Image processing has been performed prior to feature extraction. Image processing operation mainly involves geo-referencing and mosaicking of data. While using the temporal satellite data, it is required to geo-reference the imageries of different dates. So, in the present study, clearly identifiable stable features like road crossings, railways, canals, bridges, barrages have been selected as control points. The data prepared after image processing has been checked for its consistency and the error in geo-referencing has been estimated to be less than one pixel. After geo-referencing, the scenes have been combined together to incorporate entire reach of the river course. Mosaic False Colour Composite (FCC) image of Kosi River system after correction, for the year 2010, is shown for representation purpose in Figure 6-10.

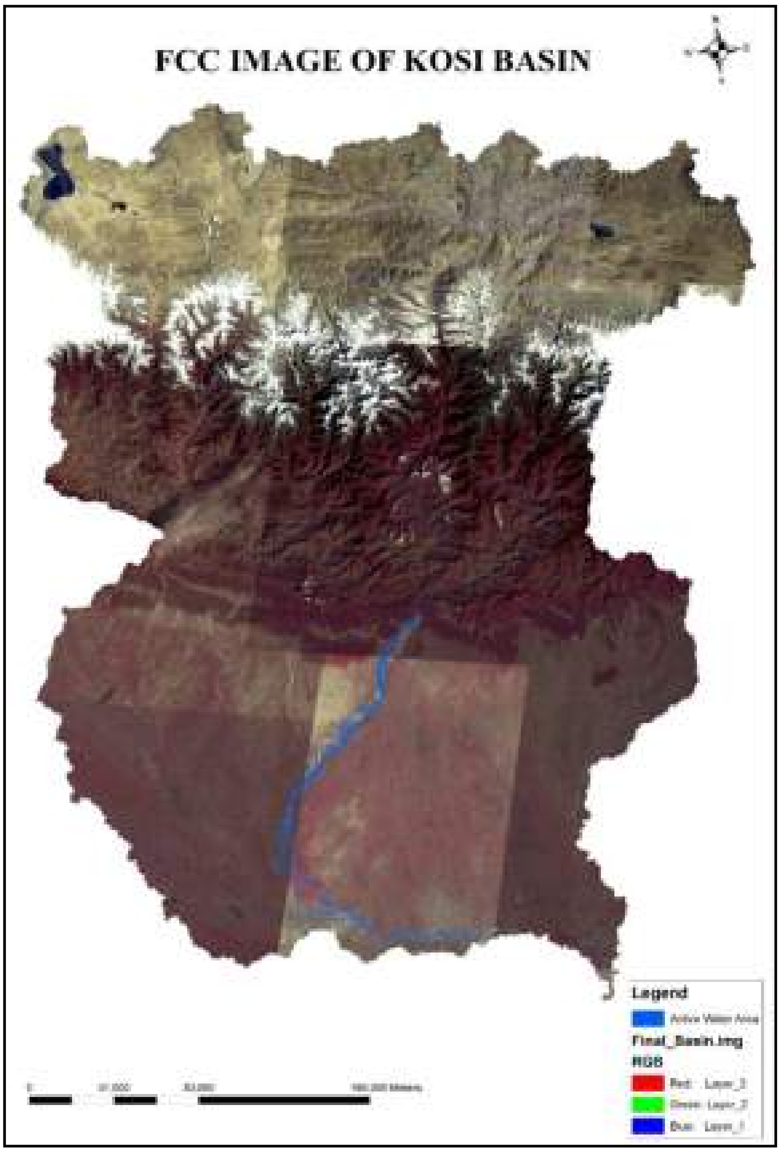


Figure 6-10: Mosaic FCC Image of Year 2010 for Kosi

The channel area, active water area, sandbars, water bodies and centre line have been obtained from digitization of the satellite imageries. All objects pertaining to these classes have been obtained using the appropriate products for the desired years, viz., 1977 (Landsat MSS data considered as baseline), 1990 (Landsat TM), 2000 (Landsat ETM+), 2010 (LISS III) and 2016 (Landsat 8). A representative reach of Kosi with these features is shown in Figure 6-11.

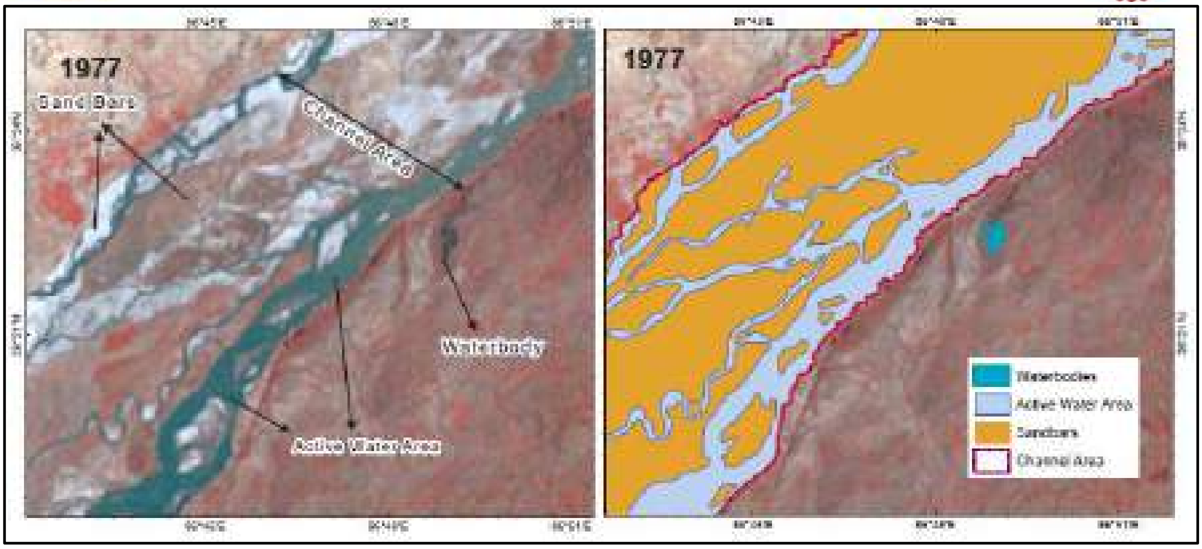


Figure 6-11: Mapping of Morphological Features of Kosi River using Satellite Imageries

6.3 Scale of Study

As per the Memorandum of Understanding (MOU) signed between CWC and IIT Delhi, river stretch had 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. The decision was made to set the grid size at 10 km in order to capture more precise details. However, it has been observed that some of the grids contained only a small length of river which made it difficult to analyze them individually. As a solution, a few of these grids have been combined to create a larger grid. Table 6-1 below illustrates the grid sizes used in the current study. Figure 6-12 shows the actual grid template used for analysis of the Kosi River system.

Table 6-1: Grid Index for Study Area

Grid No.	Dimension (Km)	Average River Length in Grid (Km)
1	10 X 20	6.40
2	10 X 20	24.70
3	10 X 20	24.40
4	10 X 20	30.40
5	10 X 20	26.30
6	10 X 10	23.80
7	10 X 10	20.60
8	20 X 20	45.40
9	10 X 20	50.10

10	10 X 10	16.20

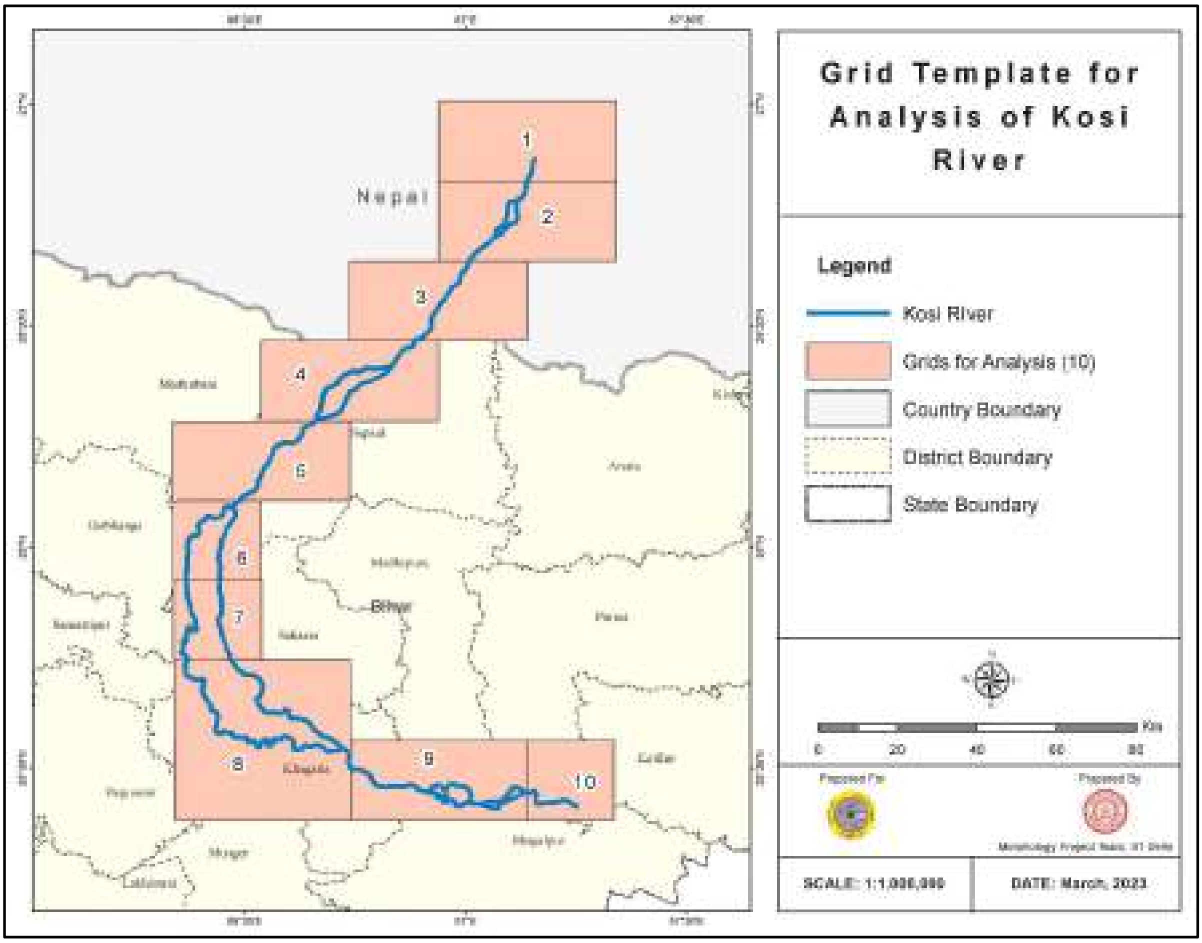


Figure 6-12: Grid Template Used for Kosi River Analysis

6.4 Estimation of Channel Bank Retreat

Areal retreat (In km^2) of erosion and deposition has been computed from digitized features. The differences in channel area, sandbars and water bodies based on their tonal variations as observed in the satellite images, have been considered for the estimation of erosion and deposition. Figure 6-13 shows erosion and deposition in a sample reach of Kosi River.

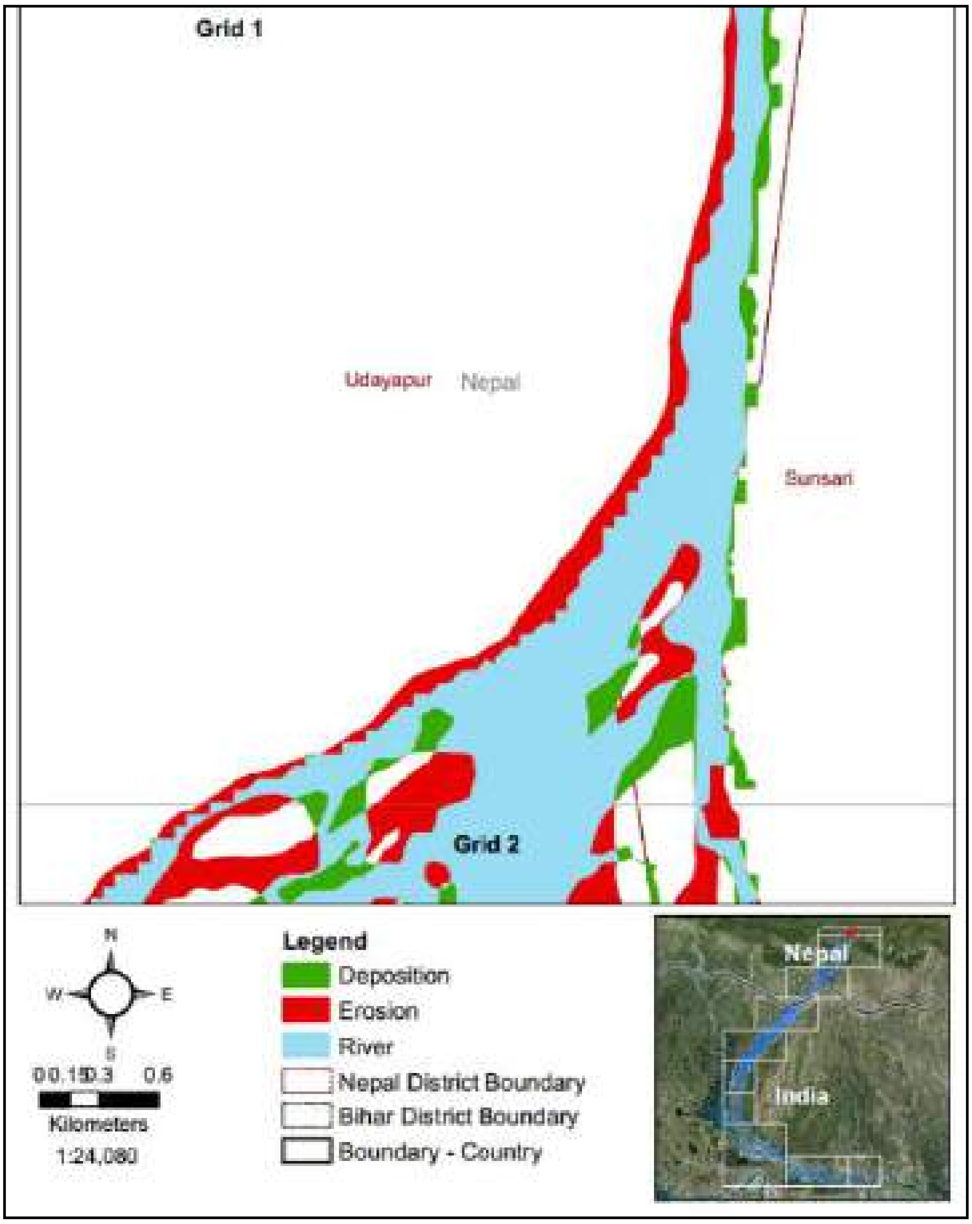


Figure 6-13: Erosion/Deposition Computation in Sample Reach of Kosi River

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, 2022. Therefore, when the river course dynamics is limited to the swing zone, it should not be considered as shifting of the river course. 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, it represents 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 shifting of river course has been studied and analyzed for all grids in a sequential manner. For all the years, centrelines have been considered for shift analysis. The procedure followed for shifting analysis has been explained hereunder:

A. Based on the centerline of the year 1975, the reference line has been created by converting the centerline into a single straight line for each grid by removing vertices and retaining end points at the grid boundary (Refer Figure 6-14).

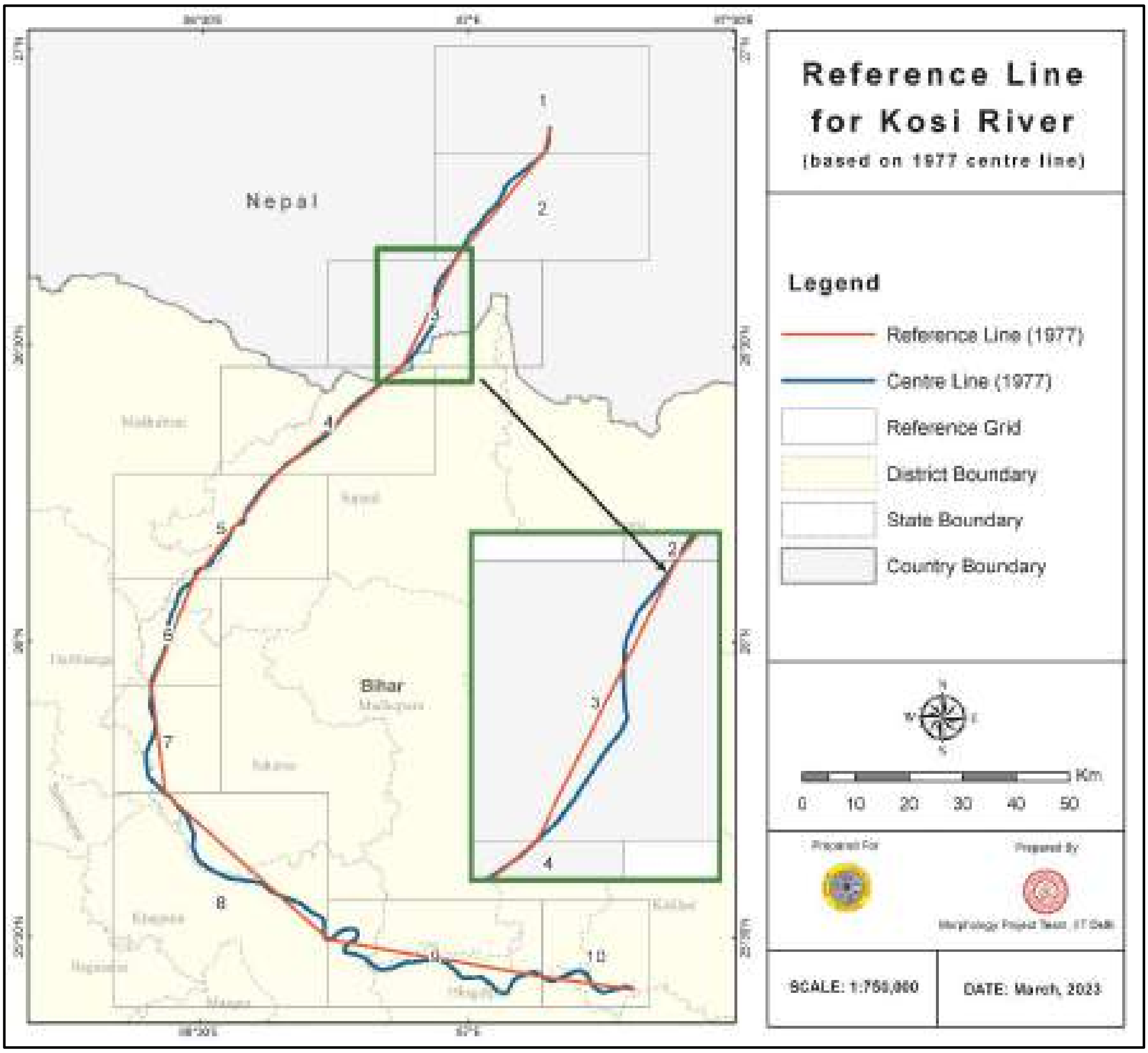


Figure 6-14: Reference Line Based on 1977 Centreline of Kosi River

B. Next, perpendiculars have been drawn to the reference line from the centerline at an interval of 1 km (Refer Figure 6-15). The intersection points of perpendiculars and reference line have been referred to as chainage.

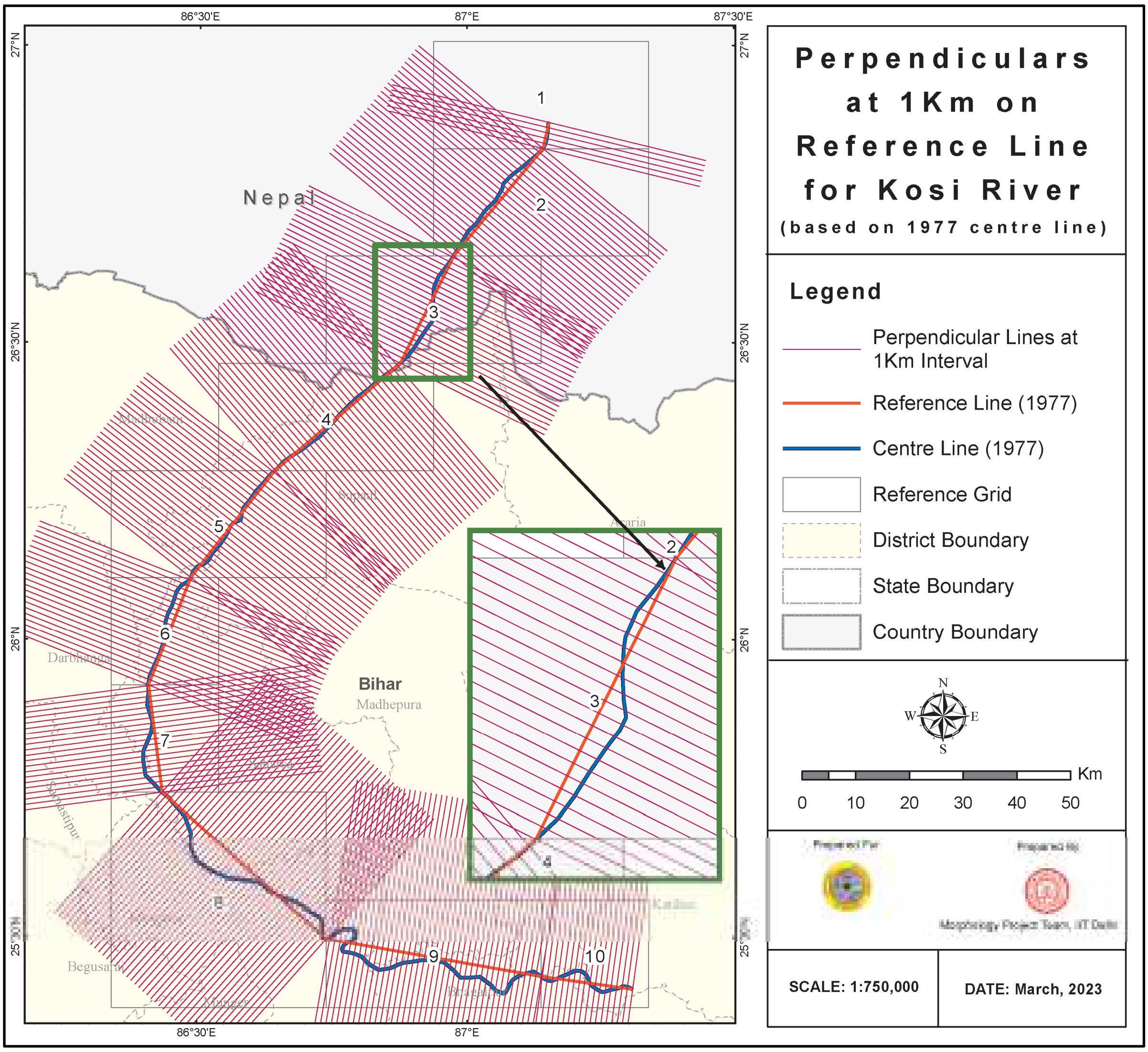


Figure 6-15: Perpendiculars Drawn at 1 km Interval on Reference Line for Kosi River

C. These perpendiculars have been extended such that they intersect with the centerlines of other respective years and the distance between the centerline and the reference line has been estimated for each time frame. When observing from upstream to downstream, distances to the left of the reference line (in the direction of flow) have traditionally been denoted with a negative sign (-), while distances to the right side of the reference line have been represented with a positive sign (+) (See Figure 6-16).

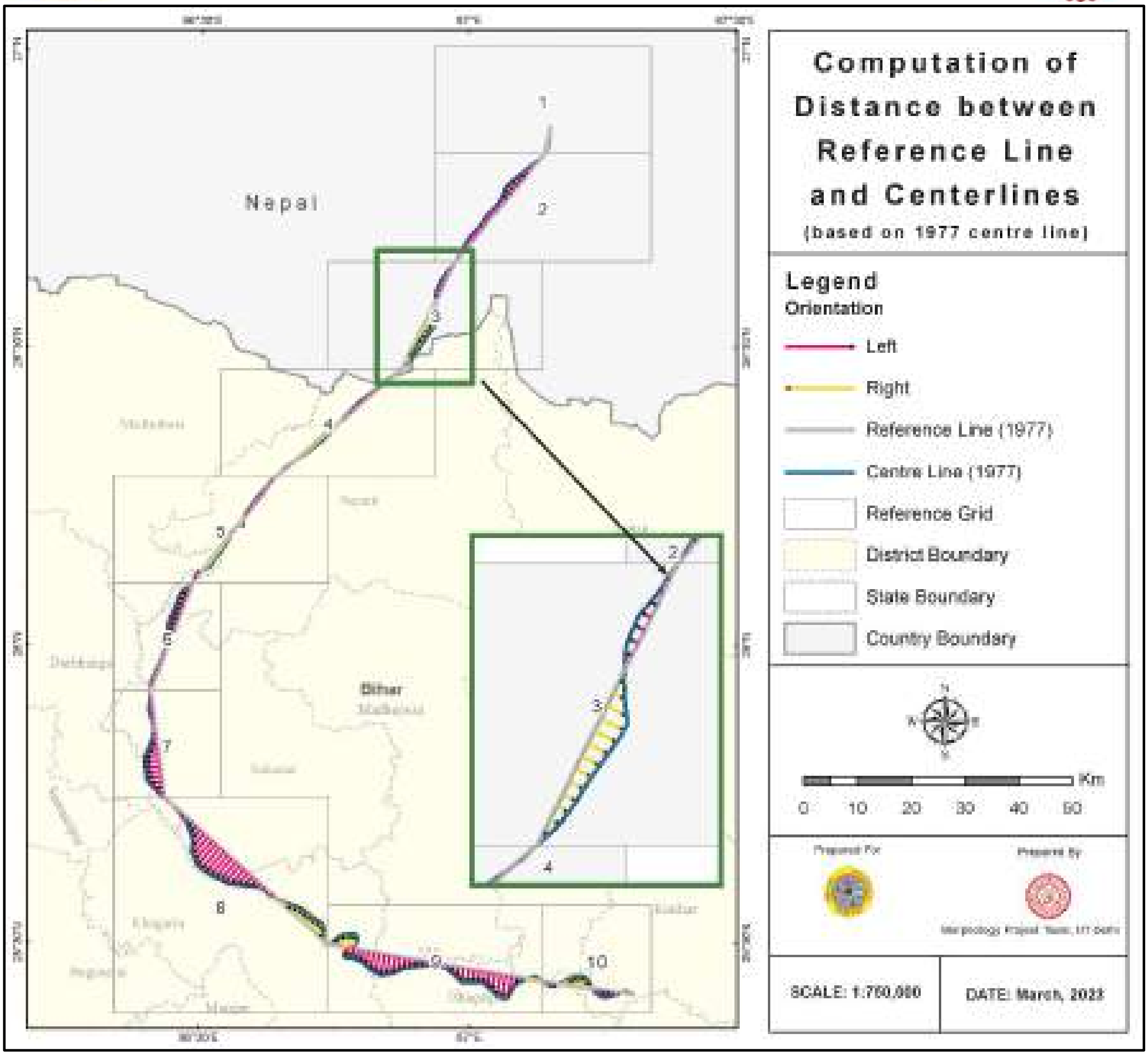


Figure 6-16: Computation of Distance Between Reference Line and Centerline for Kosi

D. The differences between these distances obtained for two consecutive years of study have been considered as shifting of river course within that time frame (Refer Figures 6-17 and 6-18).

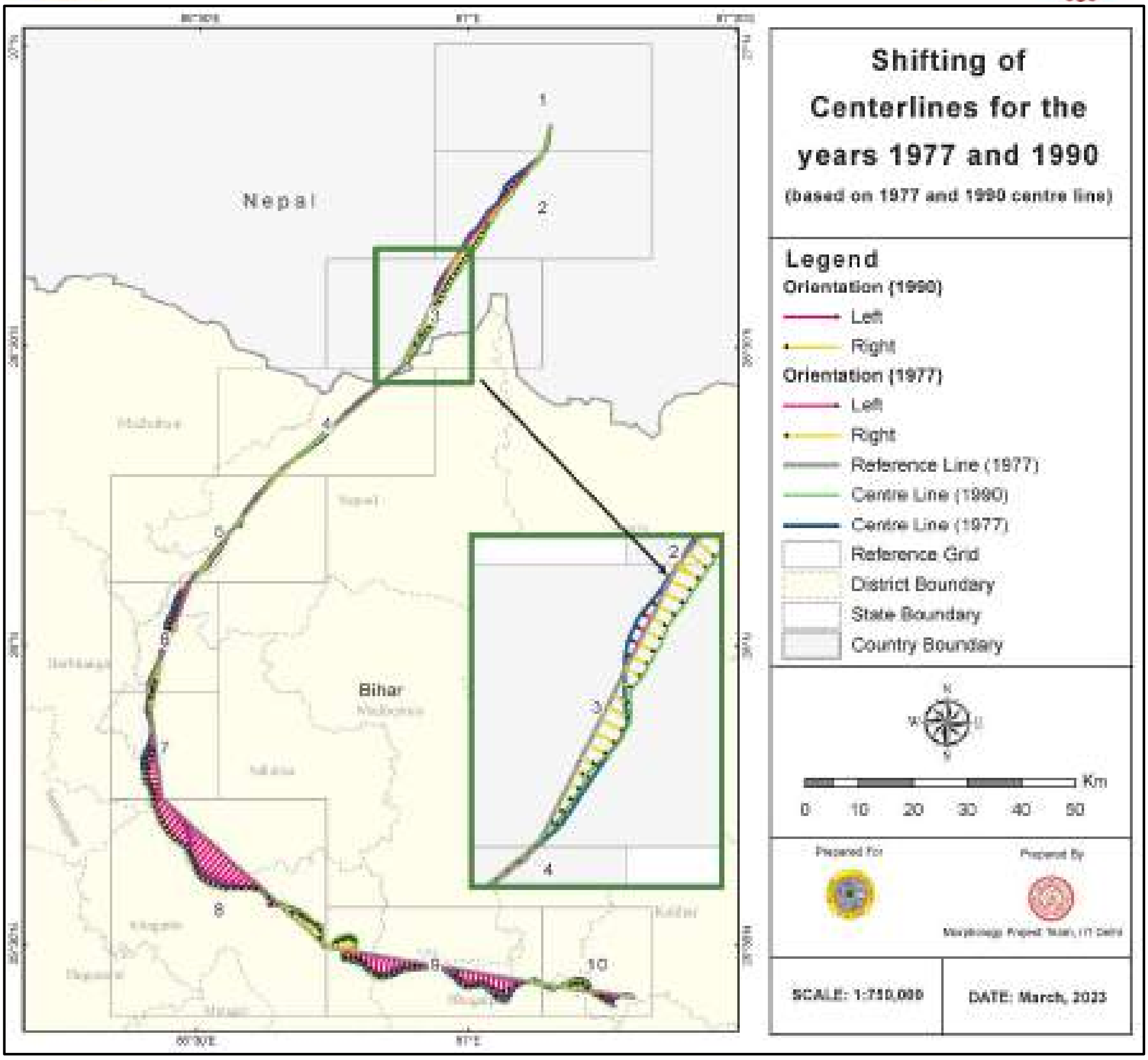


Figure 6-17: Shifting of Centerlines in Kosi River for Years 1977 and 1990

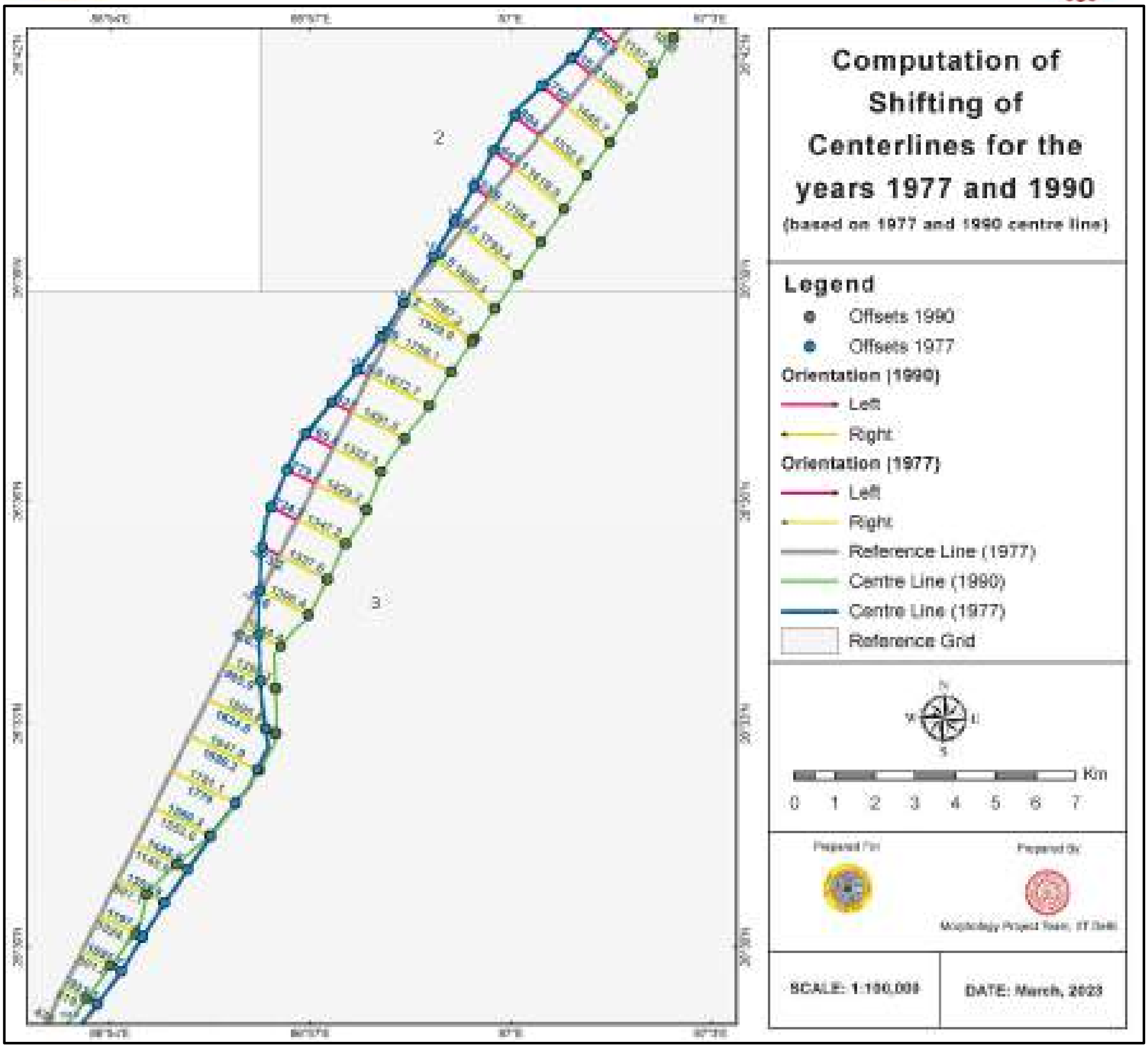


Figure 6-18: Shifting of Centerlines in Grid 3 of Kosi River for Years 1977 and 1990

Chapter 7: Landuse/Landcover Changes

7.1 Introduction

Land use can have a significant impact on river morphology. Human activities such as agriculture, urbanization and deforestation can alter the natural flow of water in rivers, and change the shape and form of river channels. Here are some specific impacts of land use on the river morphology:

A. Urbanization can increase the impervious surfaces such as pavement and buildings, which reduce the amount of water that infiltrates into the ground and increase the amount of runoff that enters rivers. This can lead to higher peak flows and more frequent flooding, which can cause erosion and alter the shape of the river channel.

B. Agricultural practices such as tillage and irrigation can increase erosion and sedimentation in rivers, which can lead to changes in the river's cross-sectional area, channel width, and channel depth.

C. Deforestation can increase sedimentation and erosion in rivers. It can also reduce the amount of shade along the riverbank, leading to increased water temperatures and changes in aquatic habitat.

D. Construction of dams and levees can alter the natural flow of water in rivers. Dams can also alter the sediment transport downstream, leading to changes in the river's bedload and channel morphology.

So, a comprehensive understanding of the land use of the entire Kosi basin is necessary to accurately study and analyse the geomorphological features of Kosi as it helps in identifying potential sources of sediment and pollutants that may affect the river's geomorphology. By studying the land use of the entire basin, areas that are particularly prone to erosion, sediment deposition or other geomorphological changes, can be identified.

7.2 Landuse Classification

The land use classification has been performed on satellite images obtained from various sources. The motive of classification is to categorize all pixels of a digital image into several land cover classes or themes. The Object-Based Image Analysis (OBIA) method has been used in the study.

7.2.1 Object-Based Image Analysis v/s Pixel Based Classification

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 were 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 these 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 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. 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 as it allows to differentiate several levels of object categories.

OBIA is very useful in the current study as: 1) Most of the built-up area falls into the category of rural, and visually, spectral properties of barren land and built-up area (rural) are 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 Normalized Difference Vegetation Index (NDVI) can help to extract them separately. 2) The basin includes several small tributaries, which are challenging to extract using the conventional methods, but by applying geometrical rules such as length/width, the tributaries can be extracted with much accuracy. 3) Indices such as Normalized Difference Water Index (NDWI) can be used to extract the water bodies such as river and oxbow lakes.

7.3 Image Analysis Methodology

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

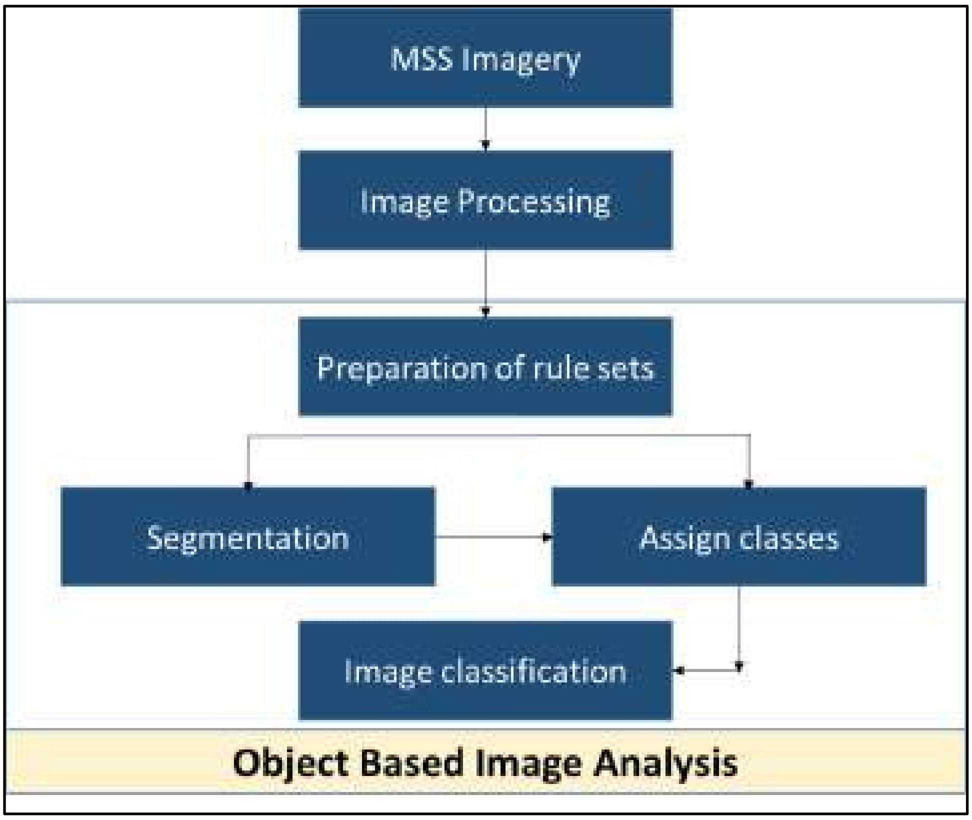


Figure 7-1: Framework for Image Analysis

7.3.1 Hierarchical Segmentation

For segmentation, various parameters given in Table 7-1 have been applied to the satellite imageries. The rules have been applied on the basis of homogeneity, colour and shape criteria.

The 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 to which the 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 of compactness gives it a relative weighting against smoothness. The scale parameter can also be modified according to the feature of interest. The higher values for the scale parameter result in larger image objects and vice versa.

Table 7-1: Segmentation Parameters Used in Analysis

Segmentation	Scale Parameter	Shape	Compactness
Level 1	45	0.1	0.2

7.3.2 Classification

After creating class hierarchy, different image objects have been assigned by applying parameters and different rulesets. Table 7-2 shows the various spectral and geometrical characteristics used to classify image objects into different classes. The 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 created classes are: Built-up, Snow and Glacier, Water Bodies, Barren Rocky, Fallow Land, Forest, and Vegetation. Indices such as NDWI and NDVI have been used to extract water bodies and green cover, respectively.

Table 7-2: Characteristics Used to Classify Images

Spectral	Mean, brightness, max. different layer values
Shape	Area (sq. m), length (m), length/width, rectangular fit, density, shape index, roundness
Indices	NDVI = $\frac{(NIR-Red)}{(NIR+Red)}$ NDWI = $\frac{(NIR-SWIR)}{(NIR+SWIR)}$

7.4 Landuse/Landcover Pattern

The proportionate spatial coverage of each Landuse/Landcover (LULC) in different years are 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 (Figures 7-3 to 7-6). The maps indicate 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 1977-2000 periods due to the population outburst. The images belong to the post-monsoon and winter season (November, December and January). 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 the images taken for the analysis are different for 1977 and 1980 years (Landsat MSS and Landsat TM). NDWI used to extract water bodies requires a Short-wave Infrared (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 digitized from Google Earth have been incorporated in the analysis.

A drastic increase in the built-up class can result from the following: (1) Change of the image resolution. For 1977, the satellite image's resolution is 60 m, while it is 30 m for other years. (2) According to NITI Aayog, 90% of the basin population resides in the rural areas. Hence, the material used to build the structures may not necessarily be 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 a coarse resolution.

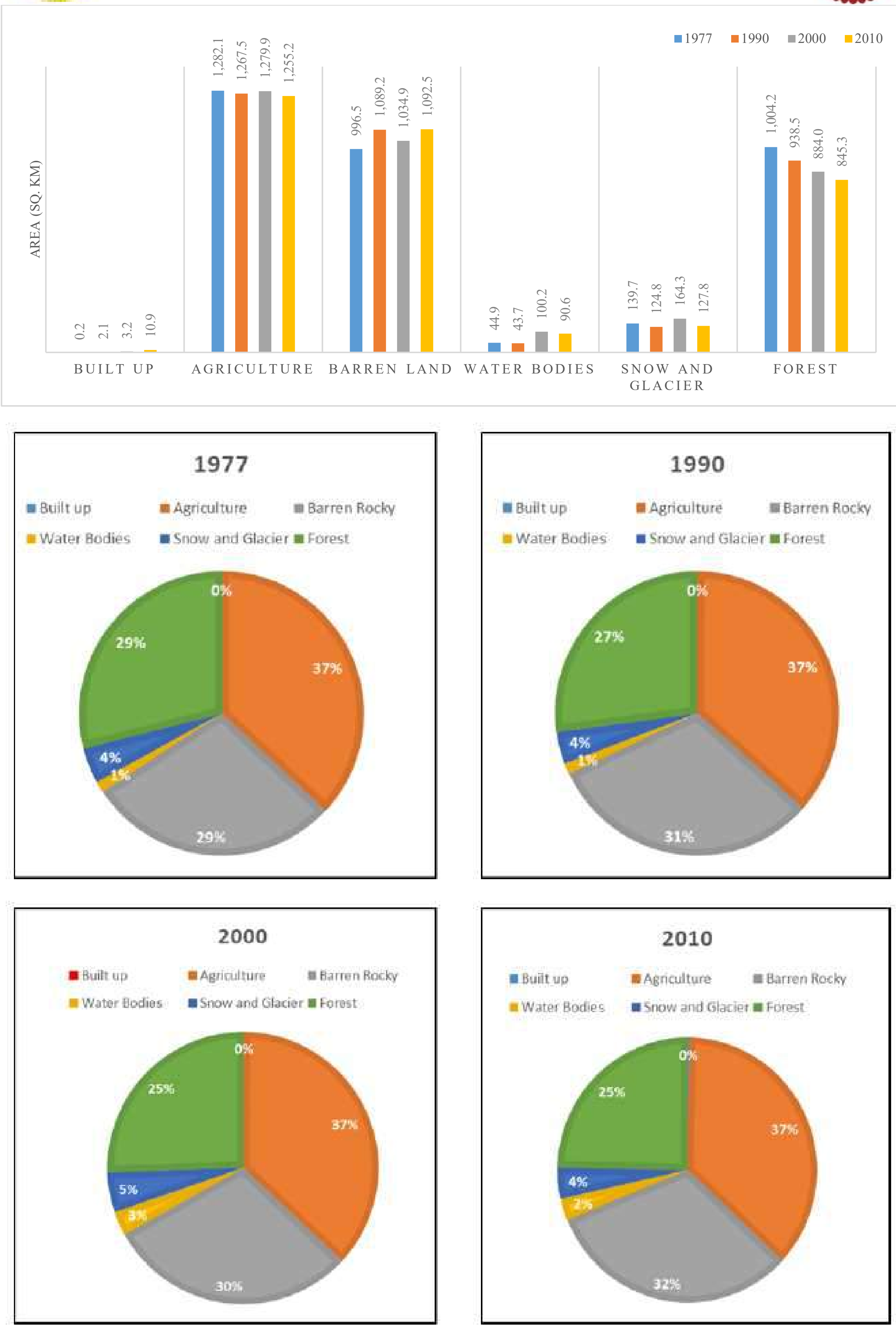


Figure 7-2: Change in LULC of Basin between Years 1977-2010

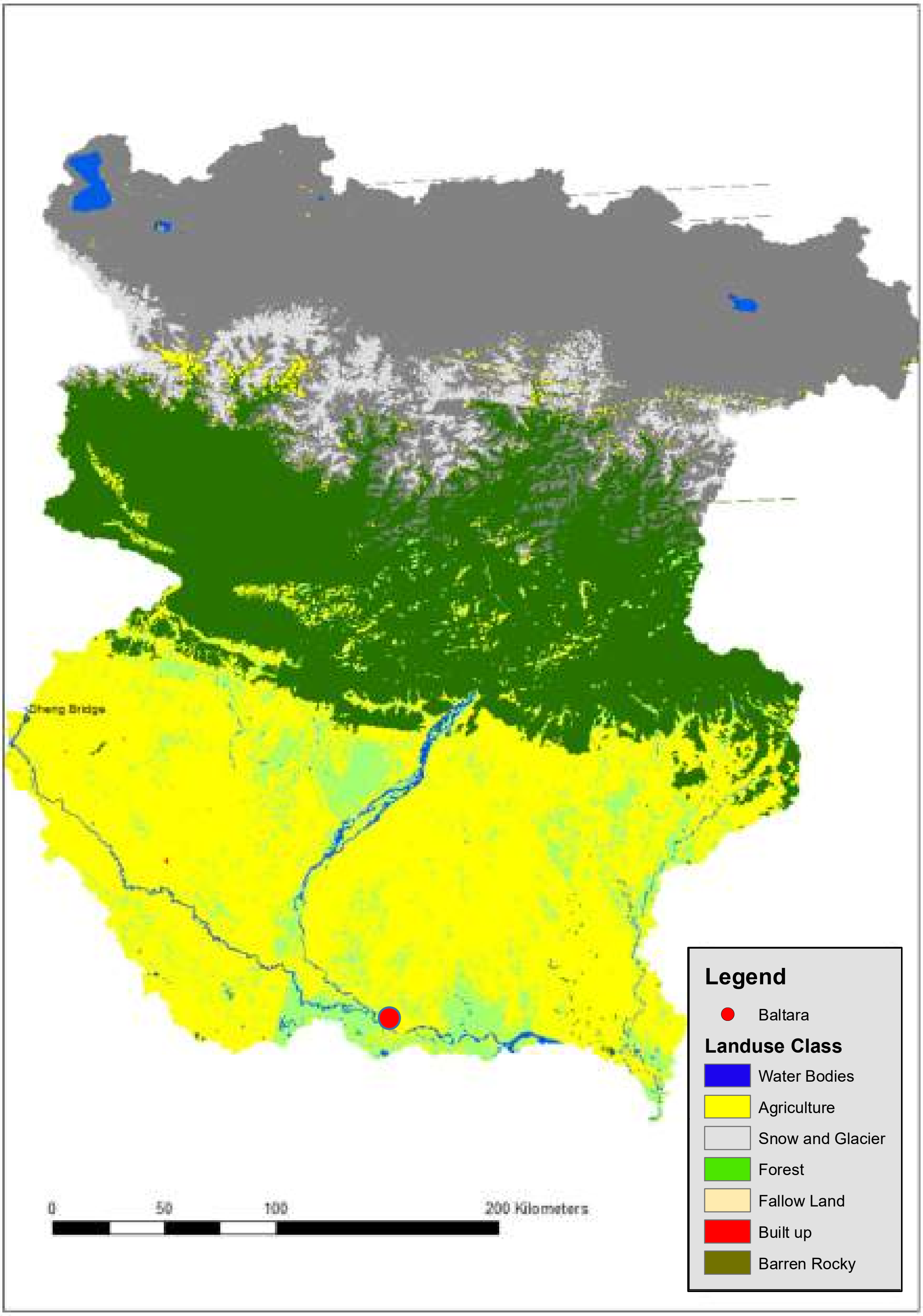


Figure 7-3: Landuse Map of Kosi River for Year 1977

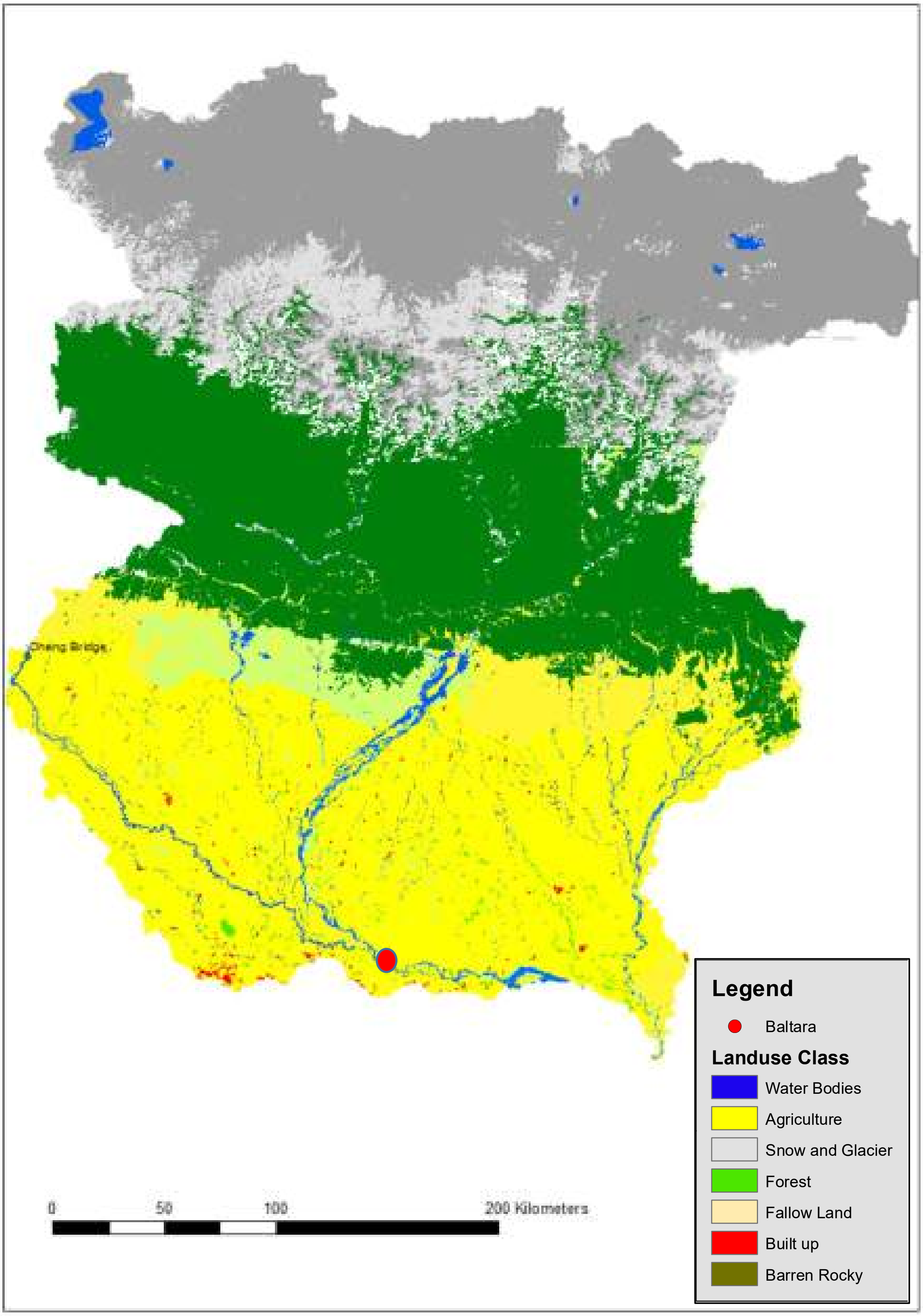


Figure 7-4: Landuse Map of Kosi River for Year 1990

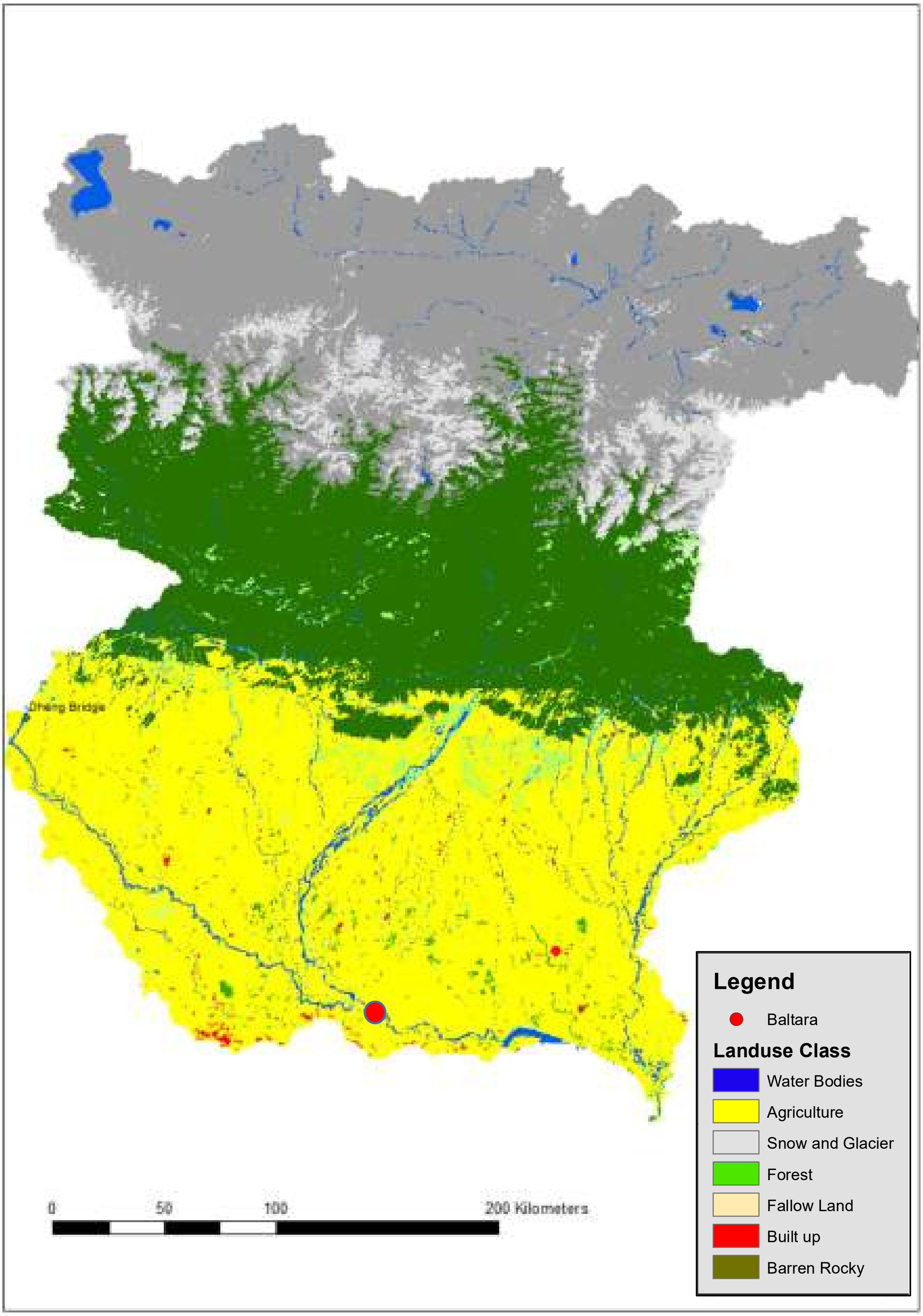


Figure 7-5: Landuse Map of Kosi River for Year 2000

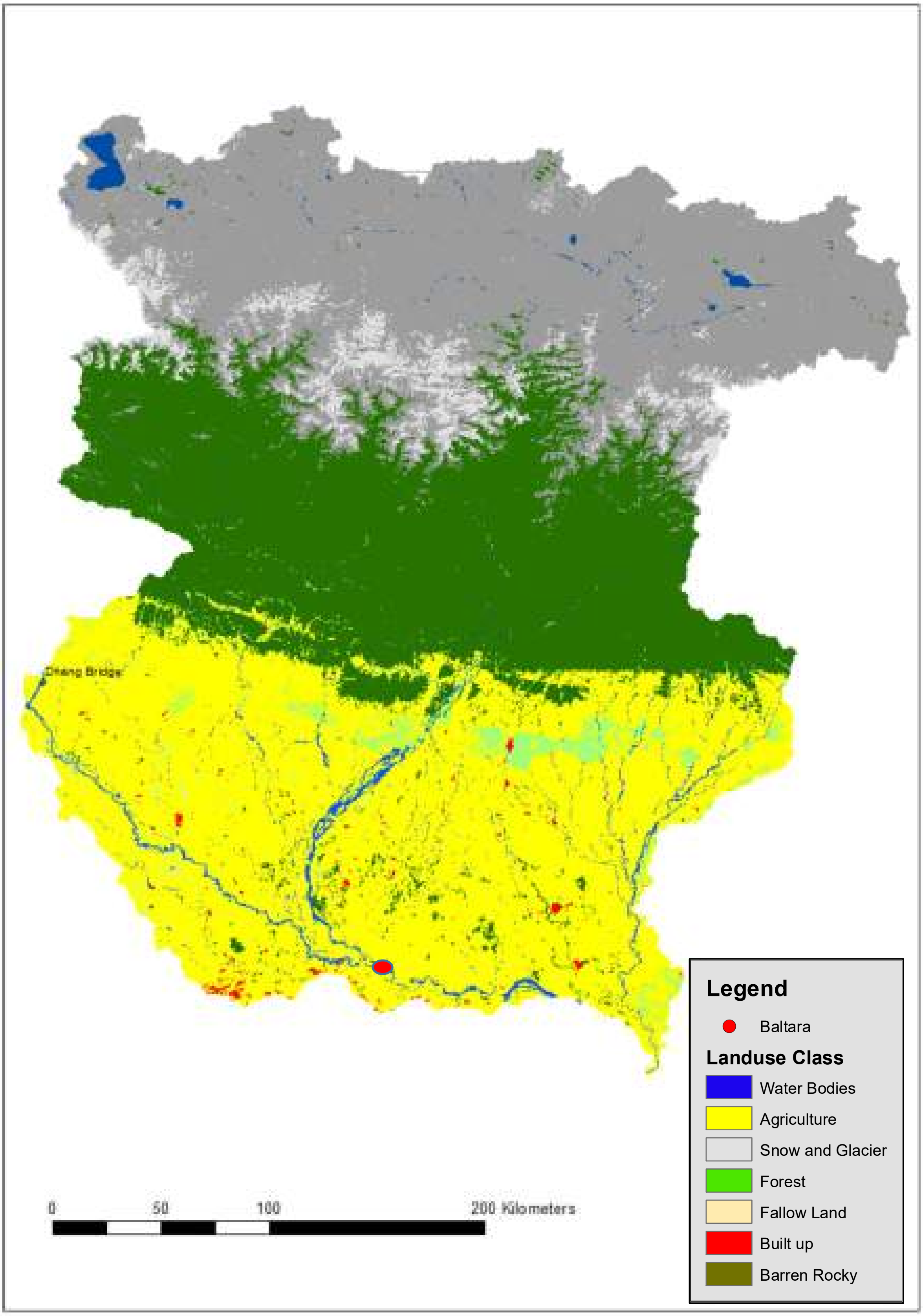


Figure 7-6: Landuse Map of Kosi River for Year 2010

7.5 Effect of Landuse Change on Channel Morphology

This section presents few studies on the impact of the change in the LULC on the Kosi 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 Kosi basin and found that despite a positive contribution from urban area increase, decreasing river discharge from the upper catchment is mainly dependent on the 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 with the extent of human activities, especially urbanization. Lamichhane and Shakya, 2019 have concluded that change in the Kosi basin's water balance and the hydrological process was mainly due to the climatic variables (Precipitation and temperature). The increase in rainfall and river discharge is a result of projected change in climate and LULC. Jha and Mishra, 2007 have found increase in the agricultural land and built-up land and decrease in forest class, has led to the rise in the surface runoff in the Kosi basin between 1992-2001.

7.6 Conclusions

Following conclusions may be drawn:

A. Based on land use of the year 2010, it can be said that the major part of the basin is covered with agriculture accounting for 36.19%, followed by barren/fallow land (31.5%), forest (24.37%), snow/glaciers (3.7%), water bodies (2.6%) and built-up land (0.341%).

B. The growing agriculture and deforestation in most areas of the Kosi-Bagmati basin may have led to soil erosion on the one hand and accentuated flooding on the other. Most of the forest tracts within the basin are degraded because of overexploitation.

C. 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 all these factors jointly affect the river morphology, isolating land-use change from other factors is not possible. However, landuse 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 of Study Area

This chapter presents the details of field visits undertaken to various locations of the Kosi River basin by the IIT Delhi team. 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.

8.1 Embankment Protection

A team from IIT Delhi visited several embankments near the Kosi-Ganga confluence. The team noticed significant damage to the embankments, indicating a pressing need for comprehensive repairs and maintenance. The condition of the embankments is illustrated in Figure 8-1 below. The team also observed the implementation of protective measures such stone pitching and use of sandbags to manage local flooding (Refer Figure 8-2).

Figure 8-1: Condition of Embankments Observed in Kosi River

Figure 8-2: Embankment Protection Measures Observed in Kosi River

8.2 Landslide Prone Areas

Landslides introduce large sediment volumes, thereby altering sediment load and transport. Channel blockage affects flow dynamics, velocity and overall morphology. Landslide deposition can cause aggradation or incision, thus raising flood risk or causing deepening of riverbeds. Overall, landslides significantly alter sediment dynamics, obstruct channels and trigger erosion, thus impacting floods, habitats and infrastructure.

The landslides have been observed in the Kosi basin upstream of India-Nepal boundary near Barahkshetra (Nepal) (Refer Figure 8-3).

Figure 8-3: Landslides Observed in Upper Reaches of Kosi River

8.3 Expansion of Riverbanks

The Kosi River has experienced expansion in its riverbanks at various locations. During periods of high flow, the water breaches its boundaries through bank cutting. Figure 8-4 illustrates the bank expansion near Sattour, Bihar.

Figure 8-4: Expansion of Kosi Riverbanks Near Sattour, Bihar

8.4 Confluence Zone and Anabranches

The confluence of the Kosi River with the Bagmati River in Bihar is a significant geographical feature. The interaction between these two rivers results in variations in river dynamics that influence the flow patterns, sediment transport and overall morphology of the area.

One notable consequence of the formation of anabranching channels is the shifting of confluence zones. Anabranching refers to the development of multiple interconnected channels within a river system. Figure 8-5 depicts one of these anabranches of the Kosi River near Mahua and Figure 8-6 shows its confluence with the Kamla River near Jagmohra. The figure highlights an important characteristic of these anabranches: their shallow depth. This feature has implications for water flow, sediment deposition and ecosystem dynamics within these channels.

Figure 8-5: Anabranch of Kosi River Near Mahua, Bihar

Figure 8-6: Confluence of Kosi River With Kamla River Near Jagmohra

8.5 Elevated Railway Lines

During the reconnaissance survey, it has been observed that the railway lines are strategically elevated at certain locations to create a significant height difference from the main channel of the Kosi River. This elevation played a role in the formation of ox-bow lakes. Figure 8-7 depicts the elevated railway track in the east-west corridor near Itahari, Bihar.

Figure 8-7: Elevated Railway Line Near Itahari, Bihar

8.6 Bridges

Bridges impact river morphology in various ways. They can cause channel constriction, thereby narrowing the river and increasing flow velocity which can result in erosion or deposition downstream. Bridge piers and abutments can induce scour which can erode sediment around the supports and affect riverbed stability. Bridges can impede sediment transport, causing accumulation upstream and potential erosion downstream, altering sediment dynamics and forming bars or islands. Additionally, bridges modify water and sediment flow onto floodplains, affecting their dynamics, water storage and natural processes.

Figure 8-8 showcases the BP Mandal highway bridge, an impressive structure spanning approximately 950 m across the Kosi River in Dumari, Bihar.

Figure 8-8: BP Mandal Bridge on Kosi River

Figure 8-9 shows the Badlaghat railway bridge near Dighri, Bihar. The water level staff on this bridge indicates a notable accumulation of sediment around the bridge piers. Such sediment deposition can potentially affect the reliability of using the level staff to measure the actual depth of water in that area.

Figure 8-9: Badlaghat Railway Bridge on Kosi River

8.7 Varying Particle Size of Sediment

Based on the survey and slope calculations using existing data, it is evident that the upper region of the Kosi-Bagmati Basin contains coarse-grained sediments. As the Kosi River enters the Indian territory, the slope decreases, leading to the deposition of coarse sediments. Upstream of the Kosi barrage, particularly near the Barahkshetra village, coarse-sized sediments are prevalent, as seen in Figure 8-10. Silt and fine sand are observed downstream of Kosi barrage. This observation aligns with the topographic and flow characteristics of the basin, highlighting the dynamic nature of sediment distribution in the Kosi-Bagmati Basin.

Figure 8-10: Particle Size Variation in Upper and Lower Zone of Kosi River

8.8 2008 Kosi River Breach

Figure 8-11 illustrates the precise spot where the Kosi River breached near Tapu in Nepal leading to a catastrophic flood in Bihar in 2008.

Figure 8-11: Location of 2008 Kosi River Breach in Nepal

8.9 Cultivation in Active Floodplain

Prominent agricultural activities have been observed in the active floodplain areas on both sides of the Kosi riverbanks. When these cultivated lands are exposed to flood events, soil loss occurs in certain areas, while deposition takes place in others. Figure 8-12 depicts the agricultural activities taking place in the active floodplain area of Kosi. It also illustrates the marking of water depth resulting from the flood. The picture of flood mark on the tree, was captured in November, 2019.

Figure 8-12: Agricultural Activity on Kosi River Active Flood Plain

8.10 Oxbows

Abandoned oxbows are remnants of former meander loops on river geomorphology. They represent areas where the river has changed its course, leaving behind curved or horseshoe-shaped depressions. These abandoned oxbows provide insights into the dynamic nature of rivers, sedimentation patterns and historical channel migration. During field survey, many abandoned ox-bows formations have been observed surrounded by agricultural land and built-up area. Figure 8-13 shows the present condition of an ox-bow formation near Kursela, Bihar upstream of Kosi-Ganga confluence. Figure 8-14 depicts the ox-bow formation near Naugachia, Bihar.

Figure 8-13: Ox-Bow Formation Near Kursela, Bihar

Figure 8-14: Ox-Bow Formation Near Naugachia, Bihar

8.11 Kosi Barrage

During the visit to the Kosi barrage, several hydraulic and structural features were observed. Figure 8-15 showcases the ongoing dredging work to remove sediments and silts downstream of the Kosi barrage. This activity is crucial for maintaining proper water flow. In Figure 8-16, the water depth monitoring at the Kosi barrage is depicted. Additionally, the figure illustrates a divide wall spanning approximately 220 m across the Kosi barrage. Figure 8-17 reveals interesting differences between the left and right sides of the eastern canal of the Kosi barrage. Deposition is noticeable on the left side, while the right-side exhibits vegetation. One plausible reason for this distinction could be the operational system of the gates, affecting water flow and sediment distribution. These observations provide valuable insights into the ongoing activities and conditions at the Kosi barrage, highlighting the importance of sediment management, water depth monitoring and gate operations for maintaining the functionality of the barrage system.

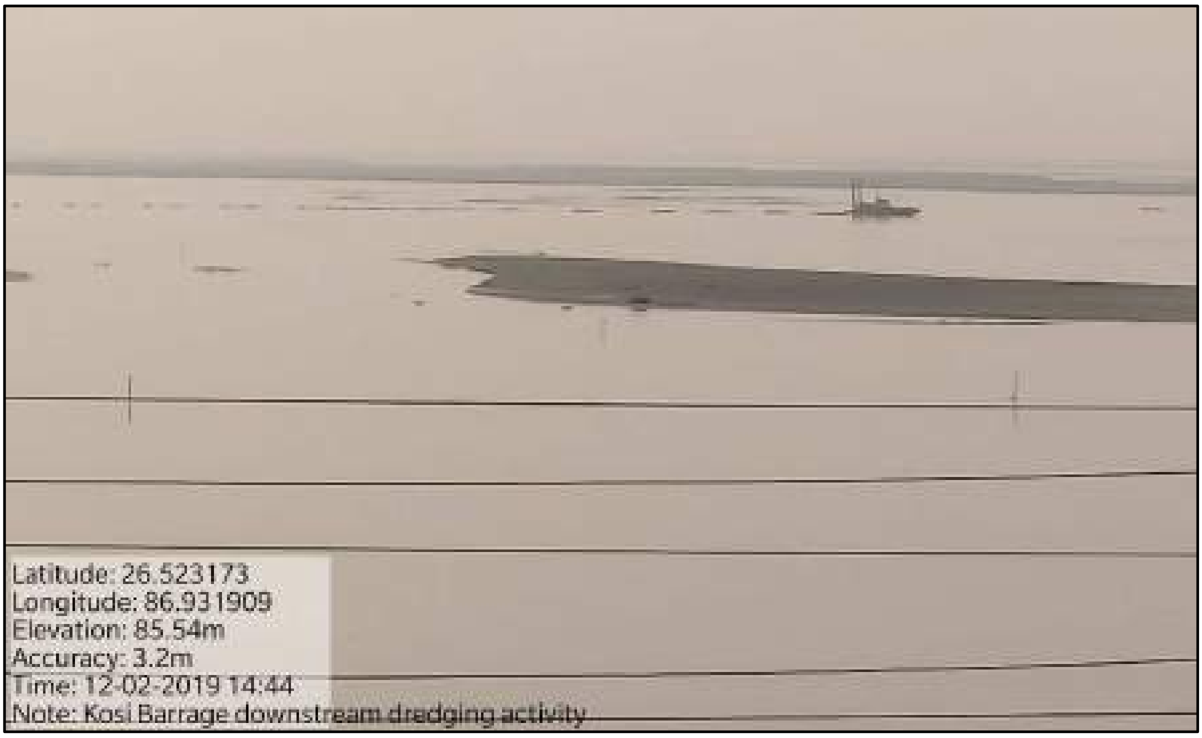


Figure 8-15: Dredging at Downstream of Kosi Barrage

Figure 8-16: Kosi Barrage Gate System

Figure 8-17: Eastern Canal From Kosi Barrage

8.12 Accumulation of Water in Channels Outside 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 have been considered here as active water channel outside the traditional network. During the visit, such water accumulation or saturated areas have been observed in non-monsoon season at various places in the Kosi basin. 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 have resulted in the formation of channels in the areas where soil is loose on account of agriculture and construction activities. This may result in deterioration of road conditions in the region (Figure 8-18).

Figure 8-18: Accumulation of Water Along Roadside in Kosi Basin

8.13 Ecological Perspective

In the ecological landscape of Nepal, particularly near the Kosi region, an important aspect is the presence of the pure Lime breed of buffalo (Figure 8-19). This breed is believed to have originated from the wild Arna and has been domesticated for centuries in Nepal. The Lime buffalo holds significant value and is estimated to make up around 35 percent of the total indigenous buffalo population in the hills and mountains of the country. This indigenous breed plays a crucial role in the local ecology, providing livelihood support to communities and contributing to the biodiversity and cultural heritage of the region.

Figure 8-19: Native Lime Breed Buffalo Seen in Kosi Region of Nepal

8.14 Other Issues Related to Risk to Life and Property

On most occasions, small boats and wooden rafts are being used for connecting islands with mainland. Two-wheelers, goods, food items, cylinders, etc. are being 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. Figure 8-20 shows one of the loaded boats that are being used to connect islands/bars to mainland.

Figure 8-20: Crowded Boat Being Used for Navigation Across Kosi River

Observations have revealed infrastructure activities in the form of road-bridge establishment and construction of a railway bridge within the active floodplains of the river. While it is challenging to determine the precise distance of these establishments from the riverbank, it appears that they are situated and operational within the active floodplain area. Additionally, a significant number of inhabitants were found residing in this floodplain zone, necessitating their relocation prior to any flood event to minimize the risk of casualties. It is important to note that severe flood events have the potential to inflict damage upon these infrastructures, as well as pose threats to properties and human lives.

Figure 8-21: Infrastructure in Active Floodplain of Kosi River

8.15 Conclusions

Following are the key observations from the reconnaissance survey:

1. Despite sandbags and stone pitching, Kosi 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.
2. Upper regions of Kosi experiencing landslides greatly impact river morphology by introducing large sediment volumes and altering sediment load, transport, and flow dynamics.
3. Kosi riverbanks have expanded at various locations with water breaching boundaries through bank cutting, even during low flow.

4. The Kosi River's confluence with the Bagmati River causes variations in dynamics, flow patterns, sediment transport, and morphology. Shifting confluence zones and shallow depths result from anabranching channels.
5. Bridges impact river morphology by constricting channels, altering flow patterns, inducing scour, impeding sediment transport, and modifying water and sediment flow onto floodplains.
6. Abandoned oxbows and former meander loops have been observed amidst agricultural land and built-up areas.
7. Observations at the Kosi barrage included ongoing dredging, water depth monitoring, and differences between the eastern canal's left and right sides.
8. 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.
9. Agricultural activities in active floodplain areas lead to soil erosion and deposition during floods. Such 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.
10. Risks to life and property from crowded boat transportation and infrastructure activities within active floodplains has been observed, so there is a need for relocation and mitigation measures.

Chapter 9: Analysis of Hydrological Data

9.1 Introduction

In this chapter, available discharge data at Baltara station on Kosi River has been analyzed. Exceedance probability curves have been drawn at Baltara gauging site with the use of the available daily average discharge data. Discharges corresponding to 1.5 and 2-years return periods have been obtained. Further, peak discharges corresponding to 5, 10, 20, 50 and 100-years return period have been obtained considering Gumbel, Log-normal and Log pearson type-III distribution for available data using frequency analysis.

9.2 Hydro-Meteorological Data

Various gauging sites on the Kosi River are shown in Figure 9-1. It may be noted that data gaps have been noticed for some of the gauging stations.

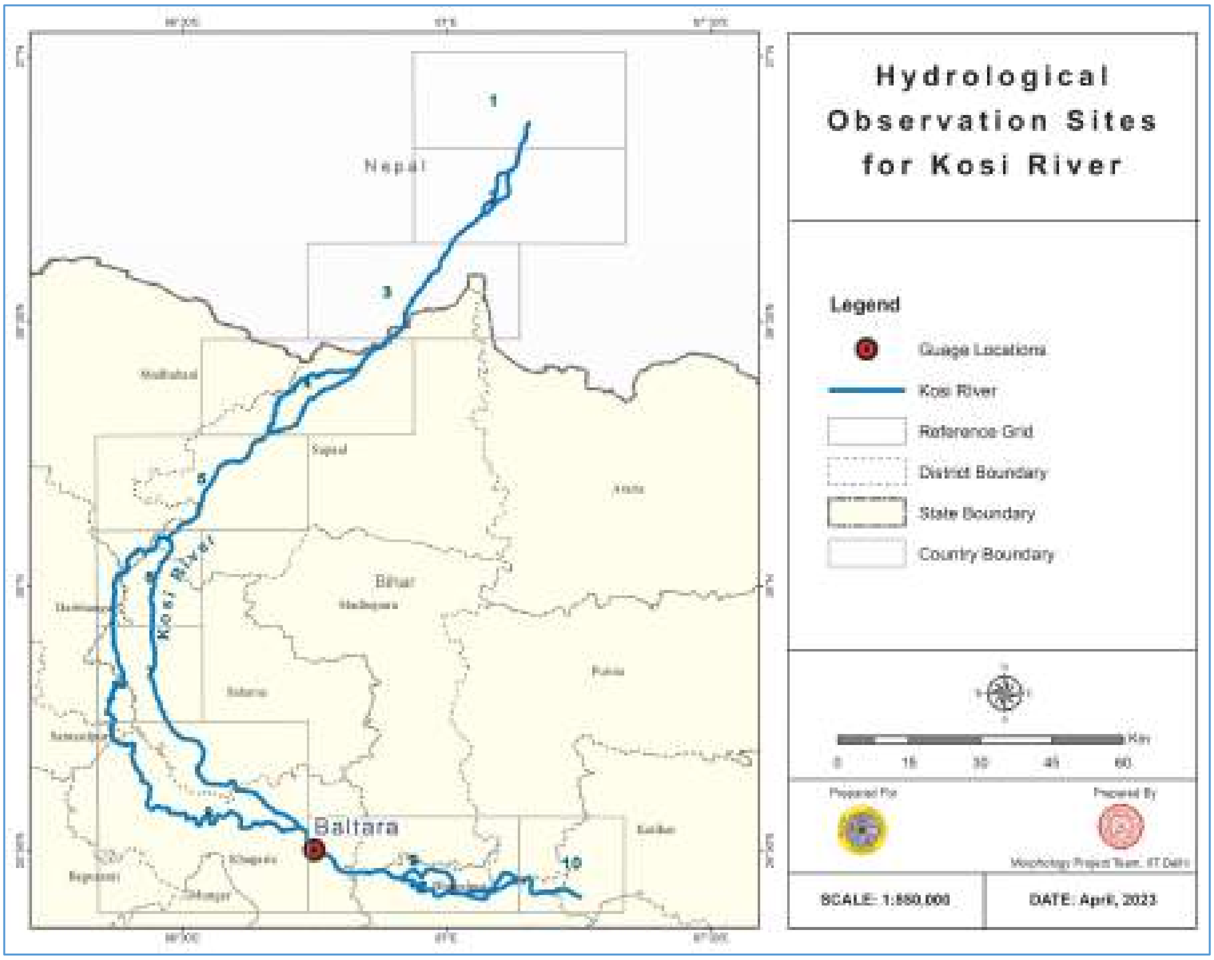


Figure 9-1: Hydrological Data Sites in Kosi River

9.2.1 Flow Duration Curves

The measured streamflow at a gauging site is the surface outflow of the watershed above that specified point on the stream. Thus, the streamflow assimilates the effects of physiography, climatic variability, anthropogenic activities and provides the distribution of runoff both in time and in magnitude. The streamflow observations are arranged according to the frequency of occurrence, and a curve is plotted, indicating the chances of a flood reaching or exceeding a specific magnitude. A curve with a steep slope throughout denotes a highly variable stream where the flow is largely driven by direct runoff, whereas a curve with a flat slope reveals the presence of storage, which tends to equalize the flow. The slope of the lower end of the flow duration curve shows the characteristics of the perennial storage in the drainage basin; a flat slope at the lower end indicates a large amount of storage, and a steep slope indicates a negligible amount of storage. Streams whose high flows come largely from snowmelt tend to have a flat slope at the upper end (Searcy, 1959).

The objective of flood frequency analysis is to infer the probability of exceeding all possible discharge values using the observed discharge data. This process is accomplished by selecting a statistical model representing the relationship of discharge magnitude and exceedance probability for the parent population. The Weibull graphical method is adopted herein to estimate discharges for 1.5 and 2-years return periods. The maximum annual discharge data are arranged in descending order, and rank is assigned to each data. The highest flood data is assigned a rank 1, second highest two and so on. This data arrangement estimates the exceedance probability. That is, the probability of a value is equal to or greater than the ranked value. The Weibull formula calculates the probability of data being equaled or exceeded. The decreasing chronological order of the discharge values is ranked from 1 to N, where N is the sample space. The return period for each value is simulated using the Weibull formula:

$$T = \frac{N + 1}{m}$$

Where, T = Return period for each discharge

N = Number of years for which discharge data is observed

m= Rank of each value of discharge

Chapter 11: Analysis of River Morphology

11.1 Introduction

A remote sensing-based morphological study for Kosi River has been performed in this study. For this purpose, processed satellite data for 1977, 1990, 2000, 2010 and 2016 have been used. Various features like active water area, channel area, sandbars and channel centerlines have been digitized using GIS software. Methodology as explained in Chapter 6 has been used for deriving these features. These features have been then used to find out sinuosity, radius of curvature, plan form and braiding indices.

11.2 Sinuosity Index

Leopold and Wolman, 1960 considered a Sinuosity Ratio (SR) of 1.5 to differentiate sinuous river from the meandering river. If the value is higher than 1.5, it is considered meandering, as shown in Figure 11-1.

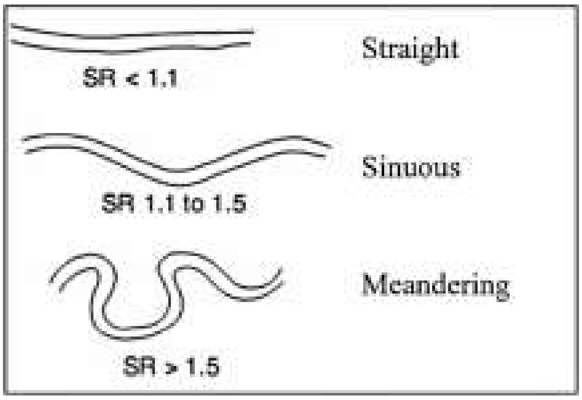


Figure 11-1: Channel Patterns for Different Sinuosity Ratio

The sinuosity of Kosi River is computed grid wise to understand the meandering behaviour of the system. Table 11-1 indicates sinuosity values of Kosi River calculated on grid basis. Since there are large variations in the planform of the river for all the four considered years, it is very difficult to compare the results for each year. Hence, comparison has been done on each grid for all the years.

Table 11-1: Grid Wise Computation of Sinuosity Index of Kosi River for Different Years

Sinuosity Index 1977

Grid	Stretch	Longitude	Latitude	Sinuous Length (Km)	Straight Length (Km)	Sinuosity
1		87.15	26.92	5.07	4.98	1.02
2	A	87.13	26.74	29.15	26.58	1.1
	B			29.53	25.7	1.15
3	A	86.94	26.56	21.93	20.67	1.06
	B			13.39	11.43	1.17
4	A	86.74	26.37	29.82	28.1	1.06
	B			-	-	-
5	A	86.54	26.19	28.92	26.36	1.1
	B			32.73	28.62	1.14
6	A	86.44	26.01	-	-	-
	B			22.52	20.35	1.11
7	A	86.44	25.83	29.39	20	1.47
	B			21.75	20.27	1.07
	C			13.73	10.21	1.34
	D			-	-	-
8	A	86.54	25.56	68.14	37.99	1.79
	B			21.17	15.71	1.35
	C			46.02	38.5	1.2
	D			-	-	-
9		86.84	25.47	60.16	40.53	1.48
10		87.13	25.47	21.29	17.33	1.23

Sinuosity Index 1990

Grid	Stretch	Longitude	Latitude	Sinuous Length (Km)	Straight Length (Km)	Sinuosity
1		87.15	26.92	5.35	5.19	1.03
2	A	87.13	26.74	27.21	24.39	1.12
	B			23.3	22.45	1.04
3	A	86.94	26.56	25.34	24.19	1.05
	B			28.95	25.6	1.13
4	A	86.74	26.37	28.62	27.8	1.03
	B			-	-	-
5	A	86.54	26.19	28.23	26.92	1.05
	B			29.92	27.56	1.09
6	A	86.44	26.01	24.83	20.88	1.19
	B			22.55	20.83	1.08
7	A	86.44	25.83	29.46	20.23	1.46
	B			21.27	20.11	1.06
	C			12.39	9.4	1.32
	D			15.11	9.35	1.62
8	A	86.54	25.56	52.72	43.63	1.21
	B			20.05	14.26	1.41
	C			55.76	39.07	1.43
	D			-	-	-
9		86.84	25.47	57.9	40.64	1.43
10		87.13	25.47	17.05	14.25	1.2

Sinuosity Index 2000						
Grid	Stretch	Longitude	Latitude	Sinuous Length (Km)	Straight Length (Km)	Sinuosity
1		87.15	26.92	4.84	4.71	1.03
2	A	87.13	26.74	27.24	24.08	1.13
	B			23.09	22.65	1.02
3	A	86.94	26.56	27.69	26.99	1.03
	B			17.82	13.01	1.37
4	A	86.74	26.37	30.03	28.63	1.05
	B			59.65	25.88	2.31
5	A	86.54	26.19	27.89	26.68	1.05
	B			28.38	26.7	1.06
6	A	86.44	26.01	18.57	21.45	0.87
	B			-	-	-
7	A	86.44	25.83	29.95	20.27	1.48
	B			64.56	55.58	1.16
	C			14.4	9.98	1.44
	D			15.83	9.35	1.69
8	A	86.54	25.56	63.06	42.14	1.5
	B			19.69	14.23	1.38
	C			43.93	38.35	1.15
	D			35.65	22.36	1.59
9		86.84	25.47	55.85	40.55	1.38
10		87.13	25.47	16.75	15.25	1.1

Sinuosity Index 2010						
Grid	Stretch	Longitude	Latitude	Sinuous Length (Km)	Straight Length (Km)	Sinuosity
1		87.15	26.92	5.43	5.24	1.04
2	A	87.13	26.74	30.33	24.56	1.24
	B			25.54	23.31	1.1
3	A	86.94	26.56	27.48	25.58	1.07
	B			-	-	-
4	A	86.74	26.37	32.28	28.71	1.12
4b	B			31	29.19	1.06
5	A	86.54	26.19	29.59	27.21	1.09
5b	B			30.04	27.97	1.07
6	A	86.44	26.01	27.05	22.4	1.21
6b	B			22.96	21.69	1.06
7	A	86.44	25.83	26.82	20	1.34
7b	B			21.85	20.53	1.06
7c	C			15.37	10.07	1.53
7d	D			15.73	9.35	1.68
8	A	86.54	25.56	65.05	14.86	4.38
8b	B			23.57	16	1.47
8c	C			46.82	37.97	1.23
8d	D			38.31	32.54	1.18
9		86.84	25.47	56.95	40.37	1.41
10		87.13	25.47	16.41	14.95	1.1

Sinuosity Index 2016						
Grid	**Stretch**	**Longitude**	**Latitude**	**Sinuous Length (Km)**	**Straight Length (Km)**	**Sinuosity**
1		87.15	26.92	6.02	5.78	1.04
2	a	87.13	26.74	26.07	23.75	1.1
	b			11.34	9.97	1.14
3	a	86.94	26.56	24.71	23.53	1.05
	b			-	-	-
4	a	86.74	26.37	32.3	30.22	1.07
	b			26.16	21.47	1.22
5	a	86.54	26.19	29.09	26.2	1.11
6	a	86.44	26.01	22.07	20.59	1.07
	b			27.47	23.28	1.18
7	a	86.44	25.83	21.01	20.19	1.04
	b			26.6	19.94	1.33
8	a	86.54	25.56	45.95	37.96	1.21
	b			63.94	45.84	1.39
9	a	86.84	25.47	49.21	40.48	1.22
	b			8.01	6.24	1.28
	c			6.09	4.89	1.25
	d			16.51	10.42	1.58
10		87.13	25.47	15.85	12.53	1.26

For grid 1, the SR value is less than 1.1 for all the years which represents that the channel is straight in this stretch.

For grid 2, in 1977 it is observed that the river shows both braiding and meandering patterns, but predominantly braided patterns. Hence, SR of 1.096 is obtained only for the wider part of the river segment, which means the channel is straight. The river segment is braided and sinuous in 1990. The presence of a large island area in between the flowing river bifurcated the river into two parts, which later rejoined. The sinuosity for both segments are calculated. For one segment it is observed to be less than 1.1 indicating straight segment, while for the other segment, it is between 1.1 and 1.5, which means it is sinuous. In 2000, a large change is observed for the river segment. as it turns highly sinuous from highly braided. This indicates the formation of new sand deposits or islands in the river with the passage of time. The sinuosity is calculated for two segments and observed that the narrow segment is sinuous and wider part relatively is straight. Similar trends are followed in 2010 and 2016.

For grid 3, in the year 1977, the river segment is meandering rather than braiding, but the presence of some big islands divides the river into a narrow channel and a long wider channel. The sinuosity is calculated for both, and it is observed that the wider part is almost a straight segment whereas the narrow small segment is sinuous as its SR is between 1.1 and 1.5. Coming to 1990, the river has two parallel segments flowing downstream which are connected at the East-West highway bridge. Both segments are nearly straight. When looked at the imagery of 2000, a large change is observed from past years. Instead of two parallel segments, the river stretch has joined to form a wider part with a few very narrow channels connected to it. The main wider channel is straight whereas the connected narrow channels are meandering. In 2010, again the river Kosi has shown a tremendous change from past years. Presence of large number of small and large islands made the river both braided and sinuous with the SR value less than 1.1, which means channel is straight. Similar trend was observed in 2016. From the above observations, it is very clear that the part of Kosi River coming in grid no. 3 has undergone much larger changes compared to grids 1 and 2 from 1977 to 2016.

When looked at Kosi in grid 4, presence of large number of islands in the river made it more braided rather than sinuous or meandering. For all the years the SR is calculated for the wider reach of the river and it is observed to be straight for all the years except for 2010 where it has become sinuous and showed similar characteristics in 2016.

The portion of the river in grid 5 is partially braided and partially meandering. In 1977, two sinuous river segments are clearly visible, which has merged into a straight wider river segment in 1990. In 2000, some new narrow river channels are generated due to the increased rate of deposition. Even though the main channel is straight, these small channels are meandering. In 2010 the river has become nearly straight channel and showed similar sinuosity in 2016.

From grid 6 onwards, Kosi has changed into many long narrow channels due to the formation of many huge islands, and increased erosion and deposition of silts. In grid 6, only a small sinuous channel compared to the above wider segments is observed in the years 1977 and 1990. But in 2000, total channel width of the main channel has increased and many new narrow meandering channels are formed. A similar trend is followed in 2010 and in 2016 showing sinuosity index ranges between 1.05 to 1.21.

In grid 7, for all the years, the river channel has divided into many long narrow connected channels, which are highly meandering. The SR is calculated for each narrow channel to know the planform characteristics of each. It is observed that the major number of channels have SR values above 1.1 and close to 1.5, which means they are highly meandering.

In grid 8 also, a similar trend as grid 7 is observed. Compared to grid 7, more number of narrow channels are present in grid 8, which are longer. Hence for easy interpretation and analysis, grid 8 is taken with a size of 40 km × 40 km. Some major changes occurred from 1977 to 1990. There is an increase in width of the channels in 1990 compared to 1977 and few channels have turned into meandering from sinuous.

The portion of Kosi in the grid 9 shows higher SR values (above 1.4) than all other grids for all the years due to the presence sharp curves in the channel. In 2010, this sharp curve turned into an oxbow due to the increased deposition.

For grid 10, for the years 1977 and 1990, the river shows SR values above 1.1 which means they are sinuous. For 2000, 2010 and 2016, SR is reduced below 1.26. That means, the river segment has changed to relatively straight.

11.3 Radius of Curvature

Curvature is the concept in geometry that indicates the change in direction of the curve at a certain point. While the radius of curvature gives the radius of the approximate circle that matches the curve at a particular point. The radius of curvature of a river is a measure of the curvature of the river channel at a specific point. It is the radius of the circle that best fits the curvature of the river channel at that point.

The radius of curvature of a river can vary along the length of the river, depending on the shape and topography of the river channel. It can also vary with the spatial scale of measurement. In general, rivers with a wider and more sinuous channel will have a larger radius of curvature, whereas rivers with a narrower and more meandering channel will have a smaller radius of curvature. The radius of curvature of a river is an important parameter for understanding the dynamics of river systems, including how sediment is transported, how floods occur, and how rivers change their course over time.

To determine geometrical parameters associated with Sinuosity, the radius of curvature for the different years has been worked out. The river centrelines were converted into points with 500 m interval. The radius of curvature was varying from 0.5 km (most curved) to the very large value (almost straight). Hence, only the radius of curvature less than 10 km was identified considering the remaining stretch straight. The following table indicates the average radius of curvature calculated for each grid. Table 11-2 below indicates that the average radius of curvature grid wise varies from 3.1 to 7 km. Analysis of the average radius of curvature suggested non-uniform sinusoidal variation in all grids, over the past 40 years (1977 to 2016).

Table 11- 2: Gridwise Average Radius of Curvature for Kosi River (In km)

Grid No.	Year 1977	Year 1990	Year 2000	Year 2010	Year 2016
1	4.5	4.3	5.5	3.1	4.6
2	4.7	4.3	4	4.6	4.8
3	5	3.9	7	6.3	4.7
4	6.3	5.7	3.4	6.3	6.7
5	3.8	3.8	6.2	5.9	5.4
6	4.3	3.4	5.4	6.6	6.5
7	3.3	4.7	7.4	6.2	5.0
8	4.3	3.7	3.4	4.4	3.5
9	3.4	3.4	3.2	3.6	3.6
10	3.2	4.8	3.1	3.2	3.1
Total	**42.8**	**42**	**48.6**	**50.2**	**47.9**

A higher value of radius of curvature means less meandering. Meandering refers to the degree to which a path deviates from a straight line, and the radius of curvature is a measure of the curvature of that path. A larger radius of curvature indicates a more gradual and less abrupt curve, whereas a smaller radius of curvature indicates a sharper and more abrupt curve. Therefore, a path with a higher value of radius of curvature will have less meandering and will be more gradual and smoother.

11.4 Braiding Index

The Braiding Index (BI) is a measure of tendency of the channel belt to develop multiple channels in a reach. In the present study, BI as suggested by Friend and Sinha, 1993 has been adopted (Refer Figure 11-2). Here, Lc_{tot} is the sum of mid-channel lengths of all the segments of primary channels in a reach and Lc_{max} is the mid-channel length of the widest channel through the reach. If the reach has a single channel, BI will be unity.

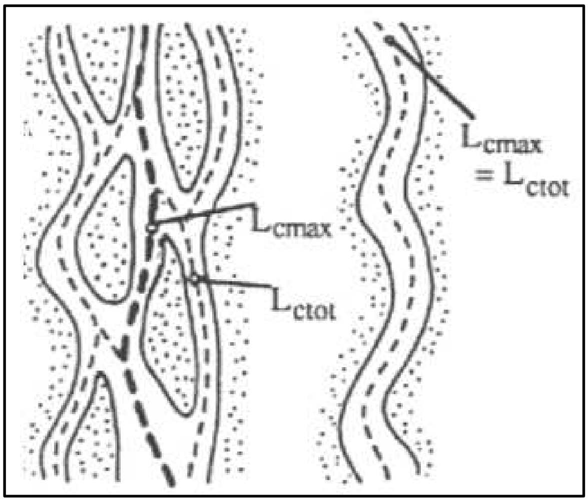


Figure 11-2: Braiding Index Suggested by Friend and Sinha, 1993

Grid wise length of total channel and length of wider channel based on digitized data of different years and decadal variation of BI are shown in Table 11-3.

BI is observed to be varying between 1.04 and 9.36. However, it is important to note that braiding is observed in only selected reaches of the Kosi River. Braiding is significantly high in a few stretches. Grid wise analysis of braiding in given in Table 11-3. Highlighted values in yellow colour show highly braided regions with high BI (BI > 6). Another significant change is observed for grid 2. In 1977 and 1990, river is braided in its entire width, whereas in 2000, 2010 and 2016, a new branching can be observed which is separately braided. Hence, for 2000, 2010 and 2016, BI is calculated separately for these branches. It is important to note that braiding is observed in all selected reaches of the Kosi River. To understand the associated plan form in a detailed manner, the planform index has been computed and discussed in further sections.

Table 11-3 Grid wise total length and length of the wider channel (in km) and Braiding Index of Kosi river for years 1977, 1990, 2000 and 2010

Braiding index 1977				Braiding index 1990				Braiding index 2000			
Grid no.	L_{max}	L_{ctot}	**BI**	**Grid no.**	L_{max}	L_{ctot}	**BI**	**Grid no.**	L_{max}	L_{ctot}	**BI**
1	5.07	8.67	1.71	1	5.49	10.85	1.98	1	4.84	31.03	6.41
2	30.42	206.15	6.78	2	23.36	218.71	9.36	2a	24.64	77.91	3.16
3	22.3	116.24	5.21	3	30.54	122.84	4.02	2b	28.2	53.95	1.91
4	29.81	209.87	7.04	4	29.14	170.11	5.84	3	27.74	92.53	3.34
5	25.67	131.83	5.14	5	26.41	119.9	4.54	4	25	216.14	8.65
6	22.93	72.45	3.16	6	23.65	70.79	2.99	5	30.71	210.24	6.85
7	21.97	21.97	1	7	21.32	24.1	1.13	6	14.52	88.86	6.12
8	68.29	75.74	1.11	8	55.73	299.36	5.37	7	20.9	24.98	1.2
9	46.32	91.76	1.98	9	58.14	72.23	1.24	8	38.94	60.39	1.55
10	21.41	35.74	1.67	10	17.36	32.86	1.89	9	55.19	96.16	1.74
								10	17.12	24.27	1.42

Braiding index 2010				Braiding index 2016			
Grid no.	L_{max}	L_{ctot}	**BI**	**Grid no.**	L_{max}	L_{ctot}	**BI**
1	5.37	11.25	2.09	1	5.33	12.53	2.35
2a	30.17	35.21	1.17	2a	27.54	137.13	4.98
2b	25.5	142.04	5.57	2b		39.74	1.44
3	28.96	146.02	5.04	3	25.57	205.56	8.04
4	35.57	248.28	6.98	4	35.60	299.55	8.41
5	29.96	174.61	5.83	5	28.66	202.76	7.07
6	22.58	93.36	4.13	6	22.89	105.41	4.60
7	21.71	37.95	1.75	7	21.51	53.64	2.49
8	46.46	51.05	1.1	8	45.59	76.87	1.69
9	56.79	90.85	1.6	9	51.82	120.41	2.32
10	16.73	23	1.37	10	18.16	18.85	1.04

11.5 Planform Index (PFI)

The Plan Form Index of Kosi River has been calculated using the approach given by Sharma, 2004. PFI is calculated as reach specific; hence the total reach of the river has been subdivided according to their respective geometric characteristics to compute the bed width, river width and the number of channels. Each chainage PFI (%) calculated for 1977, 1990, 2000, 2010 and 2016 are shown in Table 11-4.

PFI indicates the river landform disposition with respect to a given water level. A lower value of PFI indicates a higher degree of braiding. For the classification of the braiding intensity, following threshold values for PFI have been proposed by Sharma and Ashagrie, 2012: Highly Braided, PFI < 4, Moderately Braided, 19 > PFI > 4, Low Braided, PFI > 19. For calculating PFI, the entire reach of the river has been subdivided into 1 km intervals, and the bed width, channel width and number of channels of the river have been computed for each 1 km. PFI calculated for each chainage are given in Table 11-4 below.

Table 11-4. Planform Index (In %) for Kosi River for Different Years

Highly Braided PFI < 4 | Moderately Braided 19 > PFI > 4 | Low Braided PFI > 19

Grid No.	Central Latitude	Central Longitude	Chainage (Km)	1977	1990	2000	2010	2016
1	26.92	87.15	1	100	100	99.19	99	100.00
			2	100	100	99.88	100	100.00
			3	100	100	99.85	100	100.00
			4	39.63	99.98	32.69	27	23.65
			5	78.09	46.19	17.29	8	13.90
2	26.74	87.13	1	22.74	17.94	10.73	10	18.14
			2	27.21	17.6	7.11	8	20.99
			3	22.29	22.33	10.5	5	14.60
			4	10.78	16.65	13.05	4	19.55
			5	16.61	15.04	10.4	5	46.63
			6	7.2	11.09	9.15	9	32.68
			7	7.72	10.43	6.74	9	22.35

			8	11.41	21.48	6.47	6	7.19
			9	5.31	16.03	10.27	4	8.31
			10	7.7	14.28	15.39	7	17.70
			11	7.82	10.25	12.54	3	7.12
			12	7.38	14.17	12.22	7	29.41
			13	10.47	7.39	20.76	10	20.32
			14	4.85	6.56	23.09	14	15.78
			15	10.08	8.49	13.72	8	24.00
			16	9.94	9.59	16.49	20	36.86
			17	24.76	12.17	22.87	8	15.41
			18	14.56	11.54	18.66	7	14.78
			19	17.47	8.64	13.02	8	19.79
			20	11.38	7.85	13.41	10	15.98
			21	8.64	4.98	12.91	7	19.84
			22	14.17	12	9.5	18	15.60
			23	13.8	7.42	8.77	12	14.15
			24	13.76	8.48	9.64	10	18.08
			25	12.34	17.52	12.32	21	14.68
			26	21.65	17.04	7.21	12	12.37
3	26.56	86.94	1	33.51	9.28	6.53	14	14.00
			2	68.61	12.57	10.06	24	19.26
			3	80.03	8.07	10.88	33	21.05
			4	26.39	9.09	5.75	46	8.82
			5	26.12	7.15	7.96	17	11.40
			6	45.99	6.69	11.55	13	12.88
			7	29.24	11.37	15.3	35	8.61
			8	94.14	12.25	15.39	14	12.47
			9	77.37	28.49	17.12	9	16.82
			10	40.57	34.46	18.92	28	6.79
			11	28.67	37.42	22.09	15	5.93
			12	69.4	44.31	43.19	12	18.90
			13	27.52	100	98.62	20	41.16

			14	24.03	50.24	99.02	100	100.00
			15	87.36	100	100.11	100	100.00
			16	100	44.31	99.76	100	49.53
			17	21.1	44.11	31.8	100	44.97
			18	34.54	25.94	49	30	19.22
			19	15.58	17.31	45.71	13	37.86
			20	9.9	24.16	37.97	14	14.69
			1	10.47	23.9	24.89	12	10.75
			2	16.6	24.22	35.43	11	8.45
			3	16.08	39.2	36.29	13	12.00
			4	7.53	37.51	23.34	8	15.31
			5	15.09	32.61	21.3	11	21.59
			6	18.5	33.71	12.78	8	14.65
			7	17.98	17.18	13.78	9	26.73
			8	17.56	22.51	13.37	10	9.71
			9	11.97	19.25	28.7	11	9.72
			10	11.04	15.76	23.96	6	13.08
			11	10.68	21.81	23.92	11	9.60
			12	10.34	8.53	13.91	13	8.53
4	26.37	86.74	13	16.89	15.3	12.1	18	6.16
			14	22.35	25.11	30.3	33	13.40
			15	10.96	24.37	20.01	28	10.46
			16	13.86	25.75	13.09	13	6.79
			17	19.19	35.11	18.24	20	7.79
			18	13.93	42.94	25.6	15	11.95
			19	10.99	13.06	21.47	37	8.00
			20	8.01	16.23	28.81	23	10.83
			21	9.52	10.1	16.36	11	9.00
			22	8.92	23.84	13.87	11	6.79
			23	10.75	19.28	11.48	10	5.44
			24	9.23	13.84	9.16	15	6.84
			25	10.37	10.02	12.33	15	4.59

			26	9.01	9.63	14.14	7	4.96
			27	21.46	8.06	9.74	16	3.62
			28	12.79	12.77	12.25	11	4.46
			29	14.35	11.06	6.29	7	6.01
			30	8.48	4.61	8.62	10	6.55
			31	9.23	4.7	9.54	10	7.24
5	26.19	86.54	1	7.7	5.18	7.76	15	12.29
			2	8.36	5.33	13.18	18	20.73
			3	7.61	6.43	10.03	22	33.79
			4	11.63	9.57	8.52	18	34.94
			5	8.09	10.5	17.28	13	9.83
			6	11.05	8.2	13.66	13	4.30
			7	22.62	6.37	24.45	16	12.82
			8	30.17	7.6	27.29	8	12.11
			9	12.06	10.4	19.62	10	15.45
			10	17.91	8.52	41.36	8	7.83
			11	37.3	19.69	47.51	6	10.59
			12	16.62	27.43	94.81	10	12.03
			13	9.67	100	48.36	18	14.63
			14	8.61	45.85	41.8	10	12.48
			15	14.36	38.88	23.84	16	15.39
			16	15.6	100	23.54	13	8.99
			17	31.29	40.66	23.29	10	6.94
			18	21.3	41.76	18.49	7	7.40
			19	9.31	31	22.92	12	10.69
			20	15.15	41.66	19.26	21	12.21
			21	12.7	44.1	7.29	18	7.74
			22	11.78	42.37	8.85	18	8.27
			23	11.54	30.78	9.86	21	12.91
			24	16.59	40.16	5.15	5	11.02
			25	24.74	35.64	4.42	8	9.23
			26	31.86	16.62	5.22	10	13.33

			27	25.13	21.54	7.13	20	10.07
			28	22.05	13.3	5.42	13	8.33
6	26.01	86.44	1	19.81	13.9	5.57	16	12.91
			2	29.66	15.99	11.6	13	11.50
			3	36.48	24.77	11.42	10	8.47
			4	100	36.5	8.4	10	11.29
			5	100	35.78	4.14	12	13.78
			6	42.15	41.58	4.88	19	3.98
			7	100	18.9	7.42	21	3.99
			8	37.64	10.4	9.68	7	4.41
			9	43.43	13.28	5.7	5	1.57
			10	38.16	9.6	3.43	3	3.73
			11	100	10.34	5.46	3	3.83
			12	76.94	6.4	6.78	7	7.63
			13	34.63	14.39	7.84	2	3.30
			14	29.8	18.87	10.62	3	3.18
			15	9.17	26.05	12.94	3	2.56
			16	15.06	17.43	9.96	5	2.95
			17	12.61	16.82	9.31	6	2.38
			18	8.51	16.75	10.07	4	2.24
			19	16.97	16.68	10.22	7	5.94
			20	13.83	16.84	10.08	6	3.00
			21	11.04	9.89	13.44	4	3.61
			22	5.78	16	8.57	5	3.41
			23	6	15.58	8.64	3	3.00
7	25.83	86.44	1	7.01	5.9	7.68	4	2.19
			2	14.68	8.71	9.11	4	3.53
			3	9.92	17.65	9.66	4	3.32
			4	8.69	15.01	13.41	5	3.98
			5	6.4	9.16	10.38	6	4.50
			6	5.68	7.69	8.04	4	2.71
			7	5.68	7.07	8.49	5	5.29

			8	5.73	5.82	11.9	8	7.98
			9	8.62	6.29	9.46	14	2.24
			10	3.66	8.43	7.12	8	2.35
			11	4.3	2.95	3.51	5	3.05
			12	4.8	1.88	2.61	4	4.88
			13	2.44	2.68	2.49	3	2.95
			14	3.85	2.29	2.45	3	2.49
			15	4.5	2.46	2.87	2	1.12
			16	2.4	2.38	3.63	3	1.94
			17	4.78	2.36	2.64	3	3.02
			18	2.96	5.48	5.01	4	1.55
			19	5.38	5	4.31	4	2.30
			20	10.04	8.23	2.95	4	1.45
			21	8.42	6.2	5.01	3	2.45
			22	9.33	6.25	11.65	4	3.00
8	25.56	86.54	1	8.99	5.02	7.1	4	2.13
			2	6.96	4.15	3.71	3	2.31
			3	2.67	1.99	3.63	2	1.67
			4	2.85	1.36	3.69	3	2.51
			5	4.6	5.8	1.95	2	2.98
			6	1.78	1.84	1.7	2	2.92
			7	1.64	2.26	1.71	3	1.85
			8	2.16	1.97	1.69	3	2.33
			9	3.61	2.08	2.08	2	1.79
			10	6.26	4.71	2.79	2	1.13
			11	4.98	7.07	1.42	2	1.51
			12	2.88	6.12	2.87	1	2.65
			13	3.61	3.43	2.5	2	1.31
			14	2.89	8.22	1.96	2	4.93
			15	4.25	13.08	2.46	2	2.37
			16	2.81	7.72	9.11	2	2.77
			17	3.16	3.02	5.64	2	4.11

			18	5.37	6.73	9.97	3	3.26
			19	3.3	5.83	7.68	3	3.08
			20	3.36	10.85	7.3	3	4.06
			21	0	4.01	9.89	8	6.65
			22	4.13	0	6.07	4	2.52
			23	7.37	5.77	6.24	13	3.76
			24	3.93	10.79	5.15	6	2.48
			25	6.87	13.36	7.09	7	5.88
			26	18.88	9.02	3.91	7	8.40
			27	4.97	9.7	7.57	3	3.61
			28	8.26	42.19	13.6	5	4.26
			29	4.96	12.14	10.72	6	3.35
			30	7.94	29.16	17.64	10	6.63
			31	7.64	39.33	20.94	20	9.81
			32	13.29	100	11.76	20	20.78
			33	16.96	37.16	21.03	10	7.67
			34	16.34	100	26.3	7	12.81
			35	11.94	40.99	42.65	12	12.74
			36	20.04	100	99.18	23	14.90
			37	20.48	100	99.03	100	24.43
			38	17.44	100	98.97	100	100.00
			39	18.49	99.99	97.95	100	100.00
			40	22.38	41.3	96.68	9	39.33
			41	24.88	36.28	98.21	12	100.00
			42	30.5	37.53	100	14	100.00
			43	100	100	97.28	100	100.00
9	25.47	86.84	1	100	100	98.8	100	100.00
			2	100	100	32.36	8	100.00
			3	100	100	21.56	8	100.00
			4	100	48.67	39.02	19	100.00
			5	100	59.96	96.26	27	46.07
			6	100	100	97.1	100	11.79

			7	100	100	96.7	100	100.00
			8	100	41.06	97.67	100	100.00
			9	100	89.93	102.07	100	38.31
			10	100	100	99.92	100	100.00
			11	100	100	99.71	100	32.42
			12	100	100	98.88	100	100.00
			13	100	100	99.63	100	100.00
			14	52.76	18.73	99.47	100	100.00
			15	100	17.47	44.47	10	100.00
			16	100	12.5	45.65	15	100.00
			17	100	13.68	26.46	16	100.00
			18	100	11.05	33.16	29	41.42
			19	100	12.9	44.6	37	14.64
			20	21.08	28.17	99.18	18	22.57
			21	9.62	17.18	25.67	10	14.89
			22	15.18	16.99	98.64	10	12.47
			23	18.51	9.12	14.42	9	9.99
			24	20.5	9.45	22.07	4	11.92
			25	12.82	8.3	13.68	4	6.31
			26	10.33	11.82	7.34	10	6.54
			27	14.63	12.12	7.28	7	3.98
			28	14.45	8.63	10.42	14	9.89
			29	8.32	6.56	12.09	22	100.00
			30	7.38	8.09	11.55	42	100.00
			31	10.6	11.93	7.88	100	100.00
			32	7.19	25.49	10.59	100	42.90
			33	4.33	40.81	17.58	100	19.21
			34	2.61	21	17.33	100	12.34
			35	7.12	26.87	45.82	19	9.55
			36	18.44	30.91	100	17	18.76
			37	5.75	100	98.9	33	22.81
			38	12.09	100	99.76	32	10.70

			39	17.2	100	99.45	27	25.18
			40	12.62	49.53	99.95	32	42.00
			41	5.63	32.58	99.68	15	100.00
10	25.47	87.13	1	55.37	42.23	37.95	18	41.53
			2	39.04	51.75	99.11	17	100.00
			3	78.18	67.81	99.08	35	100.00
			4	100	19.32	99.19	100	25.21
			5	100	17.42	99.51	100	100.00
			6	100	100	100	35	100.00
			7	43.62	100	37.31	100	28.95
			8	15.07	100	29.62	100	100.00
			9	17.78	100	30.74	100	35.93
			10	16.01	100	30.23	100	100.00
			11	15.58	38.66	31.58	100	100.00
			12	24.19	41.92	99.66	100	100.00
			13	19.93	100	98.64	100	50.00
			14	20.79	100	99.7	100	
			15	38.28	38.12	99.31	100	
			16	100	43.94	98.99	-	
			17	100	100	99.03	-	
			18	44.27	40.79	100.24	-	
			19	31.81	36.83	100.1	-	
			20	26.65	-	98.94	-	
			21	15.52	-	99.44	-	
			22	35.43	-	99.93	-	
			23	76.82	-	100	-	
			24	36.48	-	100	-	
			25	43.54	-	-	-	
			26	100	-	-	-	
			27	100	-	-	-	
			28	80.56	-	-	-	
			29	80.45	-	-	-	

			30	100	-	-	-	

11.6 Understanding River Course Dynamics

11.6.1 Shifting Analysis

In the present study, shifting of river reach is computed on grid basis based on movement of channel centerline. Difference between distances of centerlines of two specific years (such as 1977-1990, 1990-2000, 2000-2010 and 2010-2016) using a predefined reference line drawn on the basis of 1977, is assessed at an interval of 1 km. This difference is considered as shifting of river channel during the specified period.

Figure 11-3 and Figure 11-4 indicate river course dynamics in the complete length of the river Kosi from its origin to its confluence with the river Ganga. Detailed presentation of various segments is rearranged in separate graphs (Figure 11-5 to Figure 11-14) depicting reach of the river grid-wise at a time, and Figure 15 to Figure 23 represents the grid-wise maps for shifting of Kosi centerline. The shifting in year 1977, 1990, 2000, 2010, and 2016 with reference of the predefined base line and the river course dynamics in the given interval are presented in tabular form in Table 11-5. The analysis reveal that the Kosi River is highly dynamic in nature specially from grid 3 to grid 8.

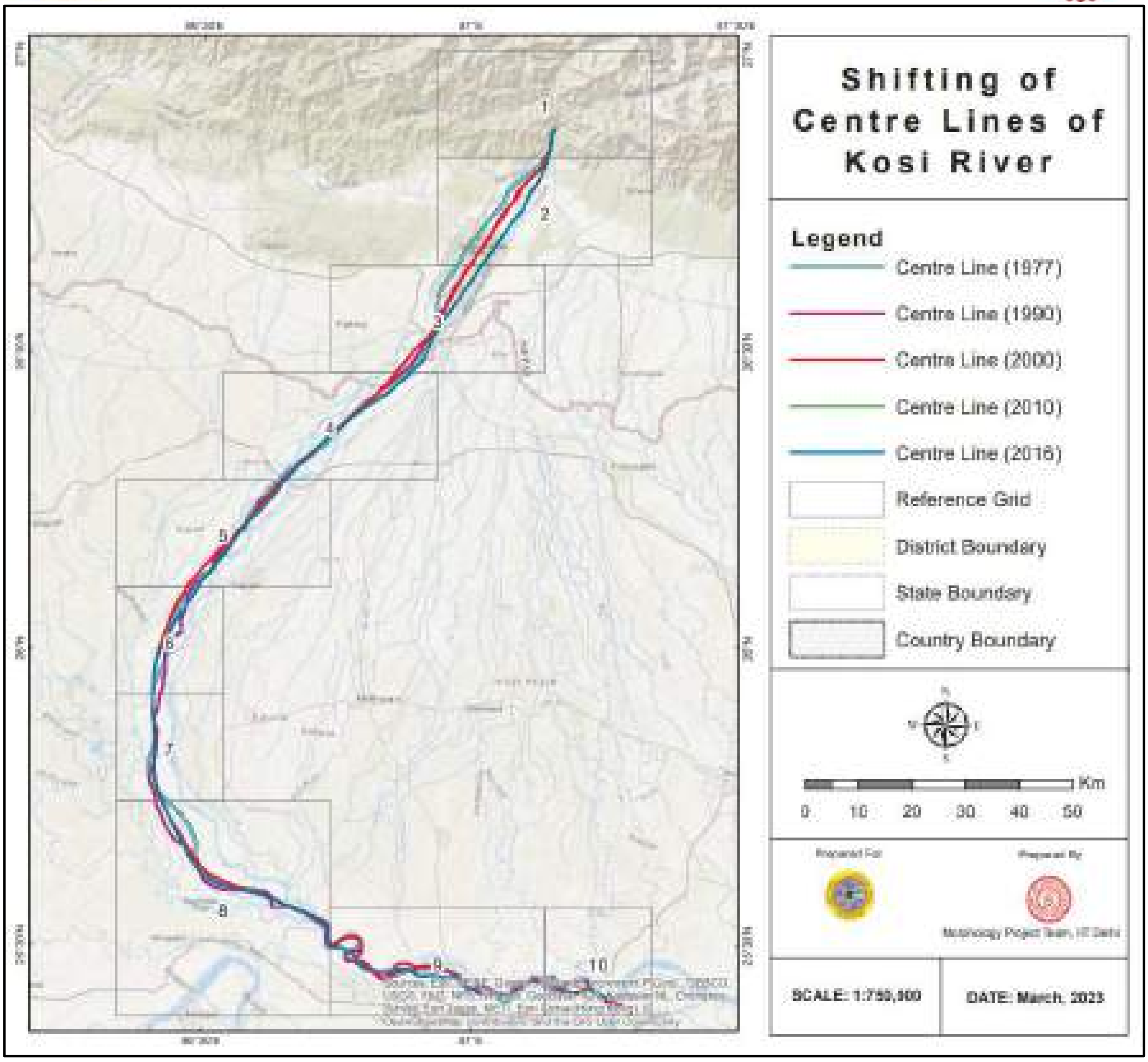


Figure 11-3: Shifting of Kosi River Centrelines in Different Years

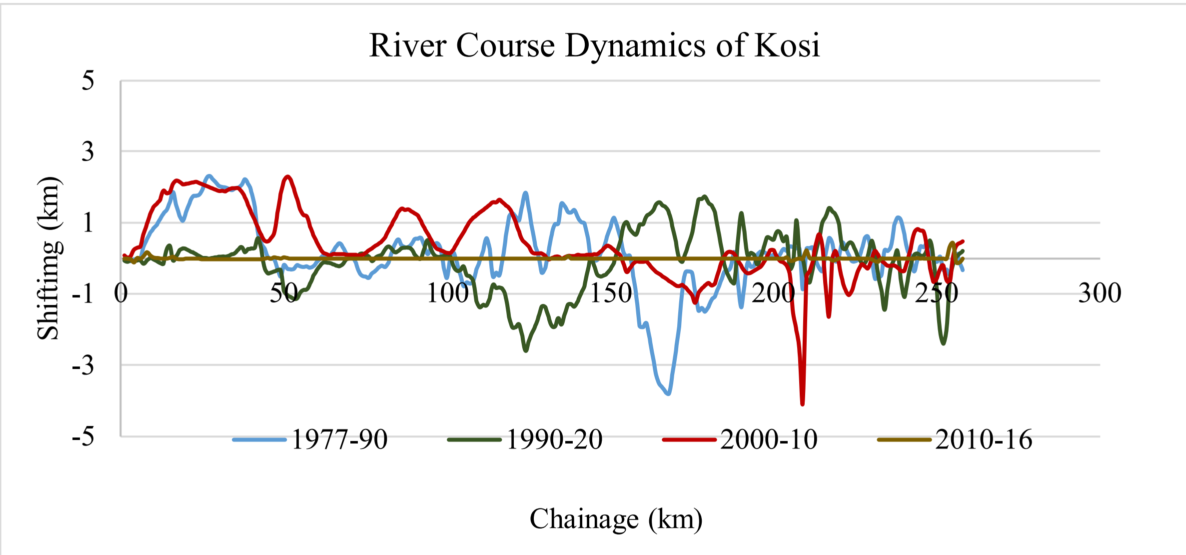


Figure 11-4: River Course Dynamics of Kosi River

Shifting analysis for the whole stretch of Kosi is carried out on grid basis and the result are presented grid wise.

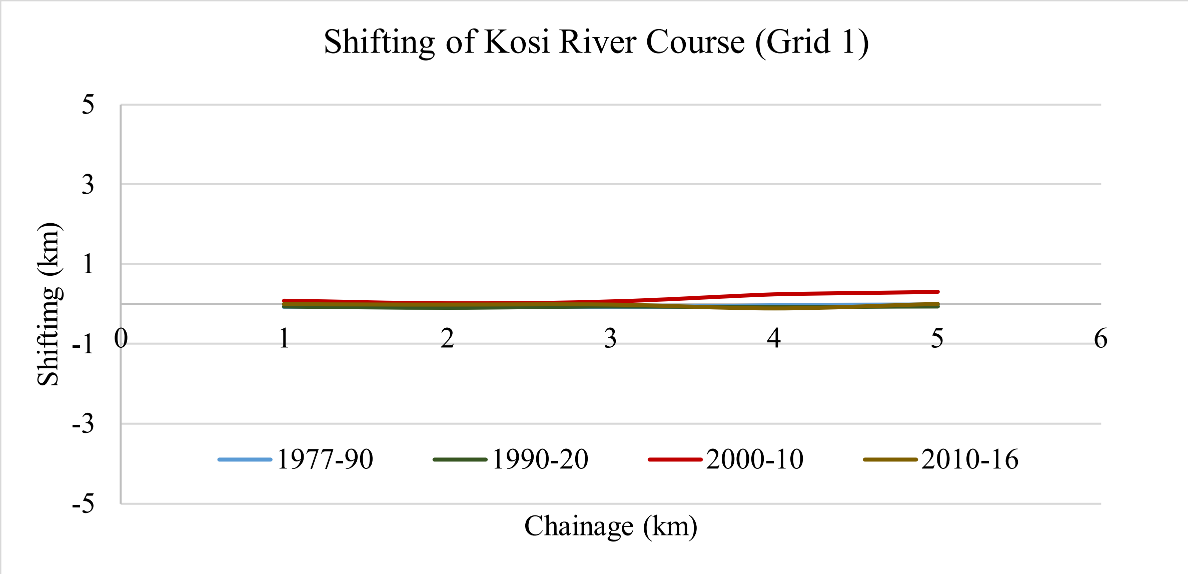


Figure 11-5: Shifting of Kosi River Reach in Grid 1

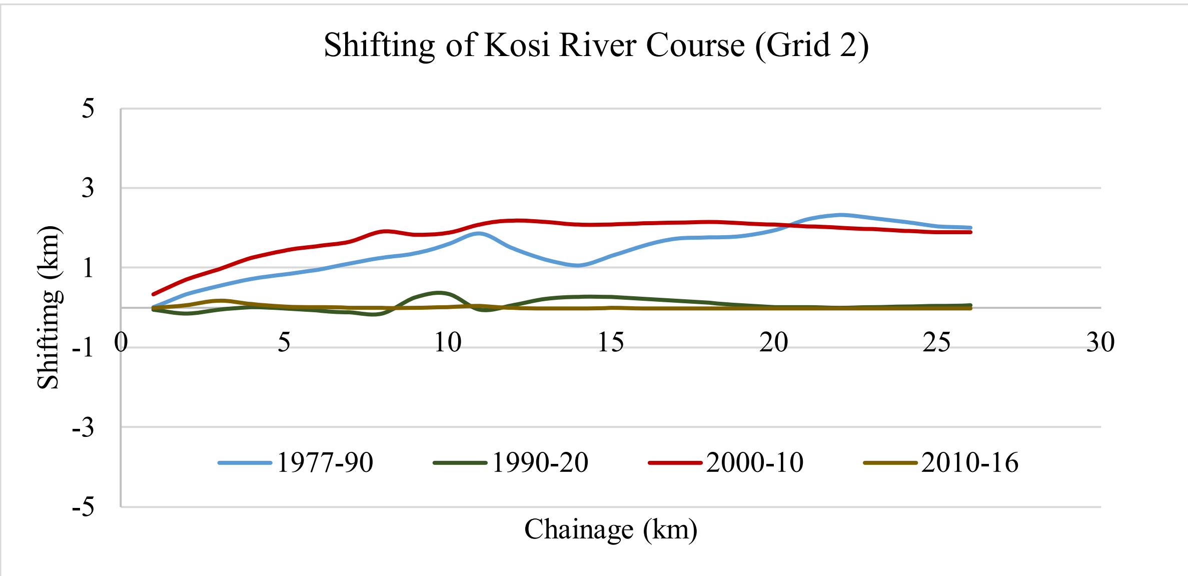


Figure 11-6: Shifting of Kosi River Reach in Grid 2

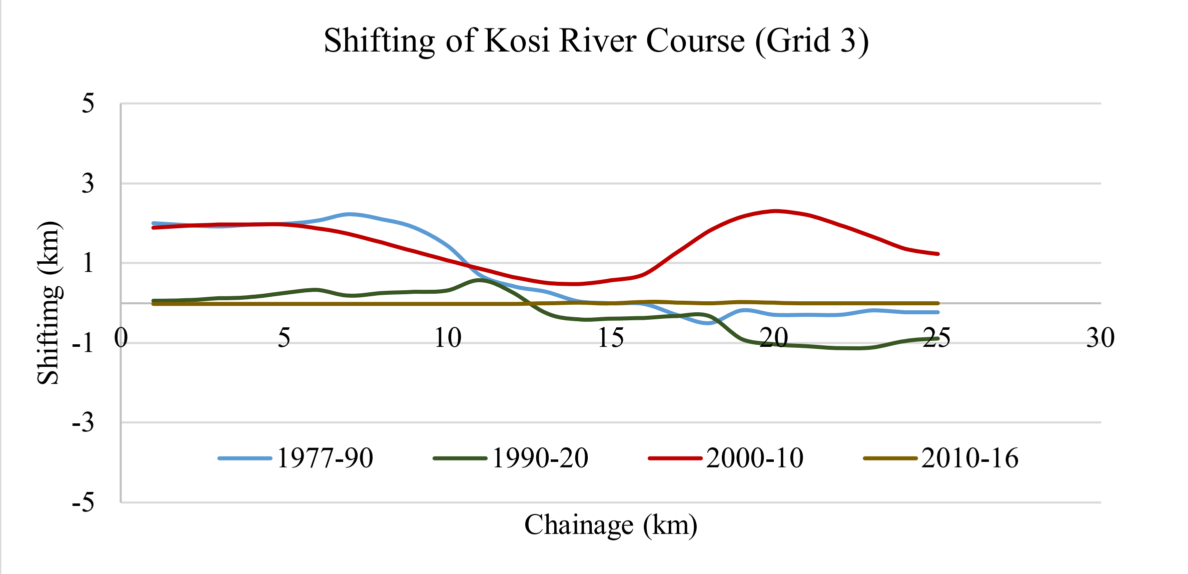


Figure 11-7: Shifting of Kosi River Reach in Grid 3

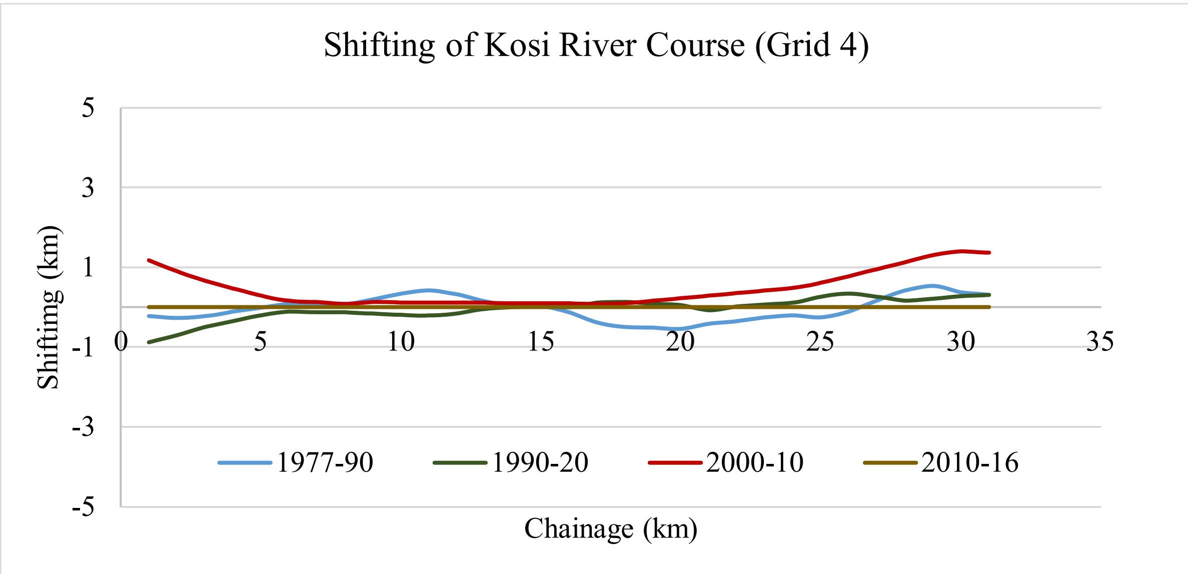


Figure 11-8: Shifting of Kosi River Reach in Grid 4

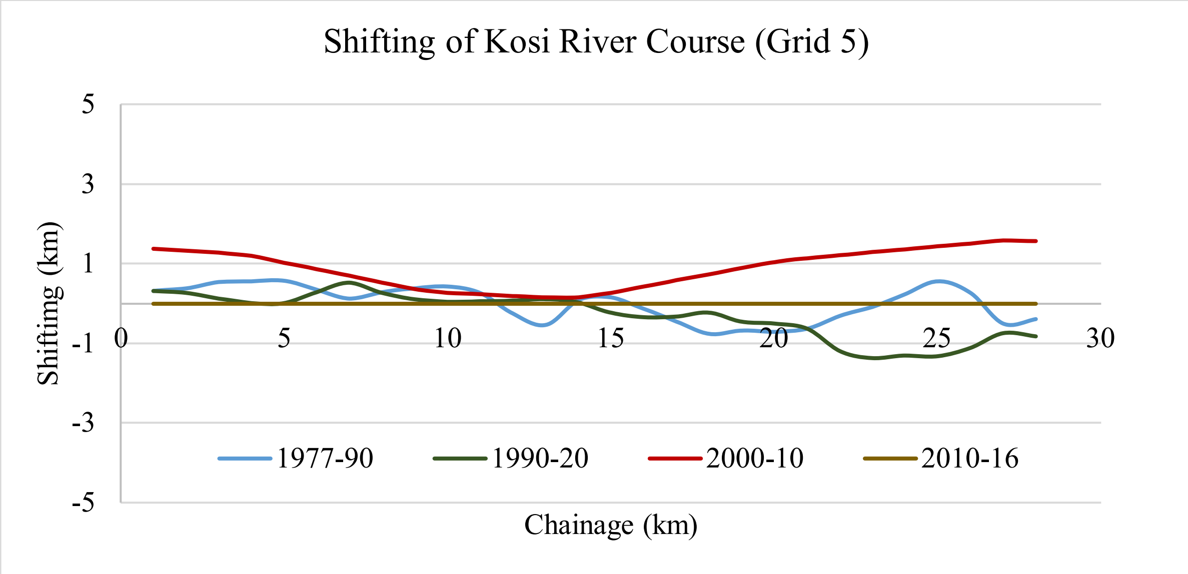


Figure 11-9: Shifting of Kosi River Reach in Grid 5

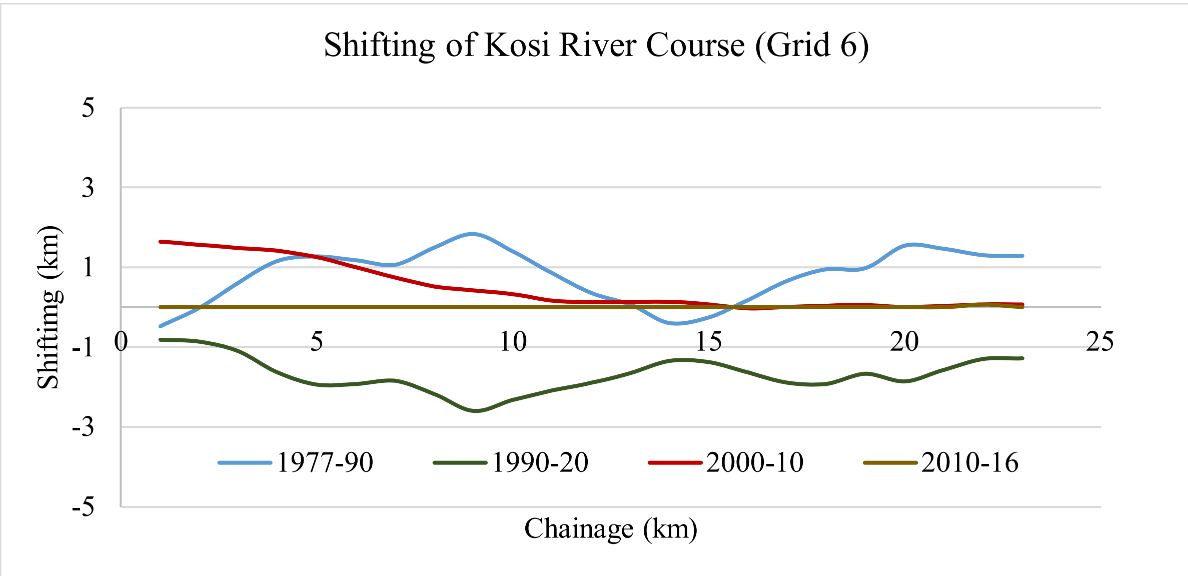


Figure 11-10: Shifting of Kosi River Reach in Grid 6

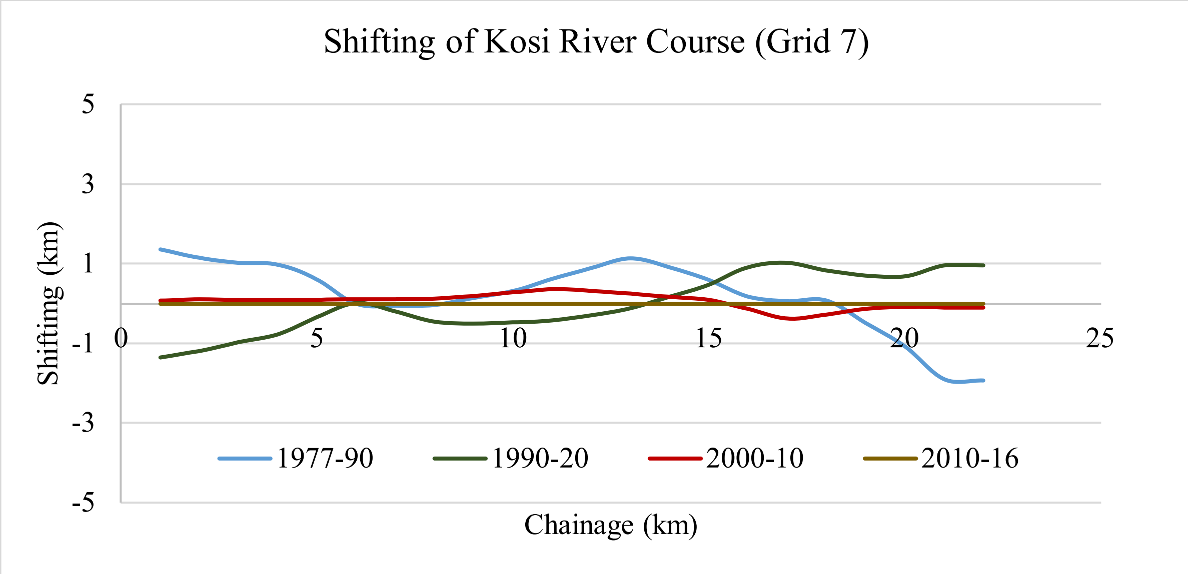


Figure 11-11: Shifting of Kosi River Reach in Grid 7

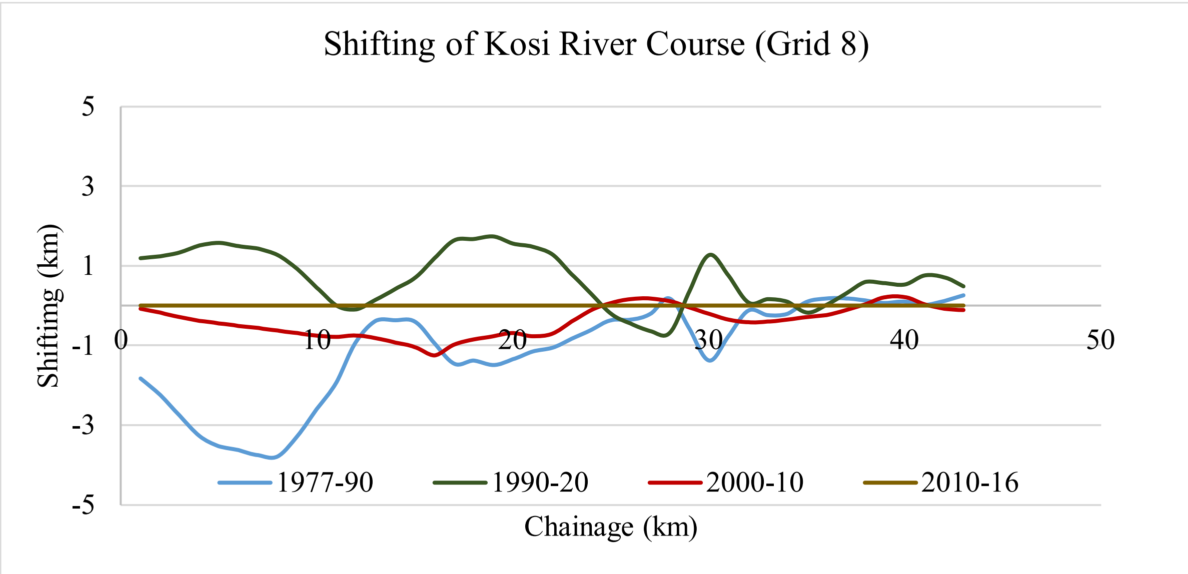


Figure 11-12: Shifting of Kosi River Reach in Grid 8

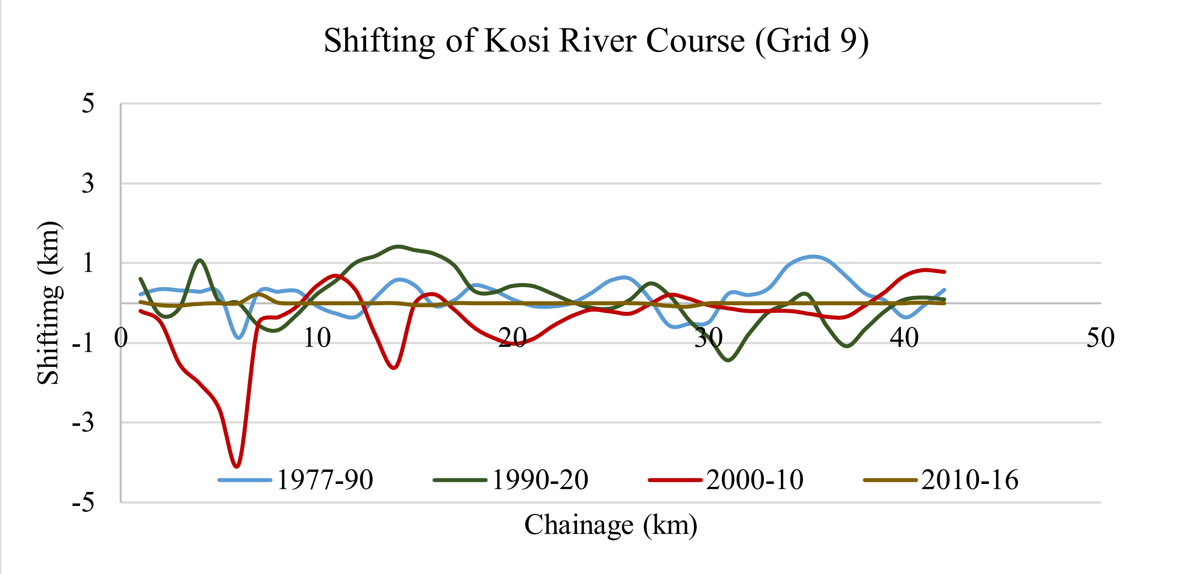


Figure 11-13: Shifting of Kosi River Reach in Grid 9

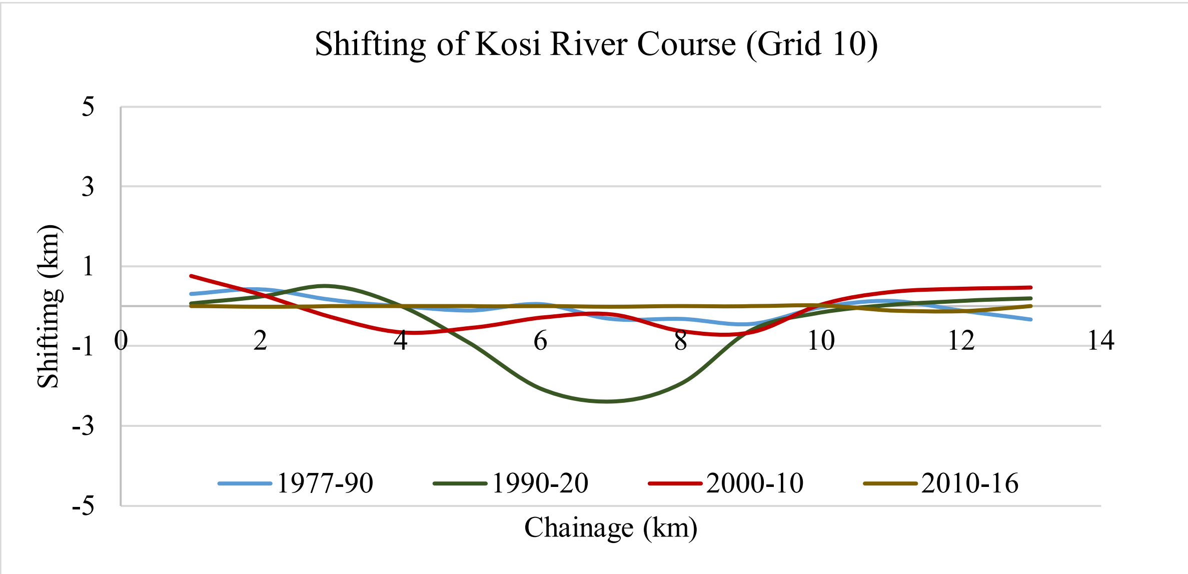


Figure 11-14: Shifting of Kosi River Reach in Grid 10

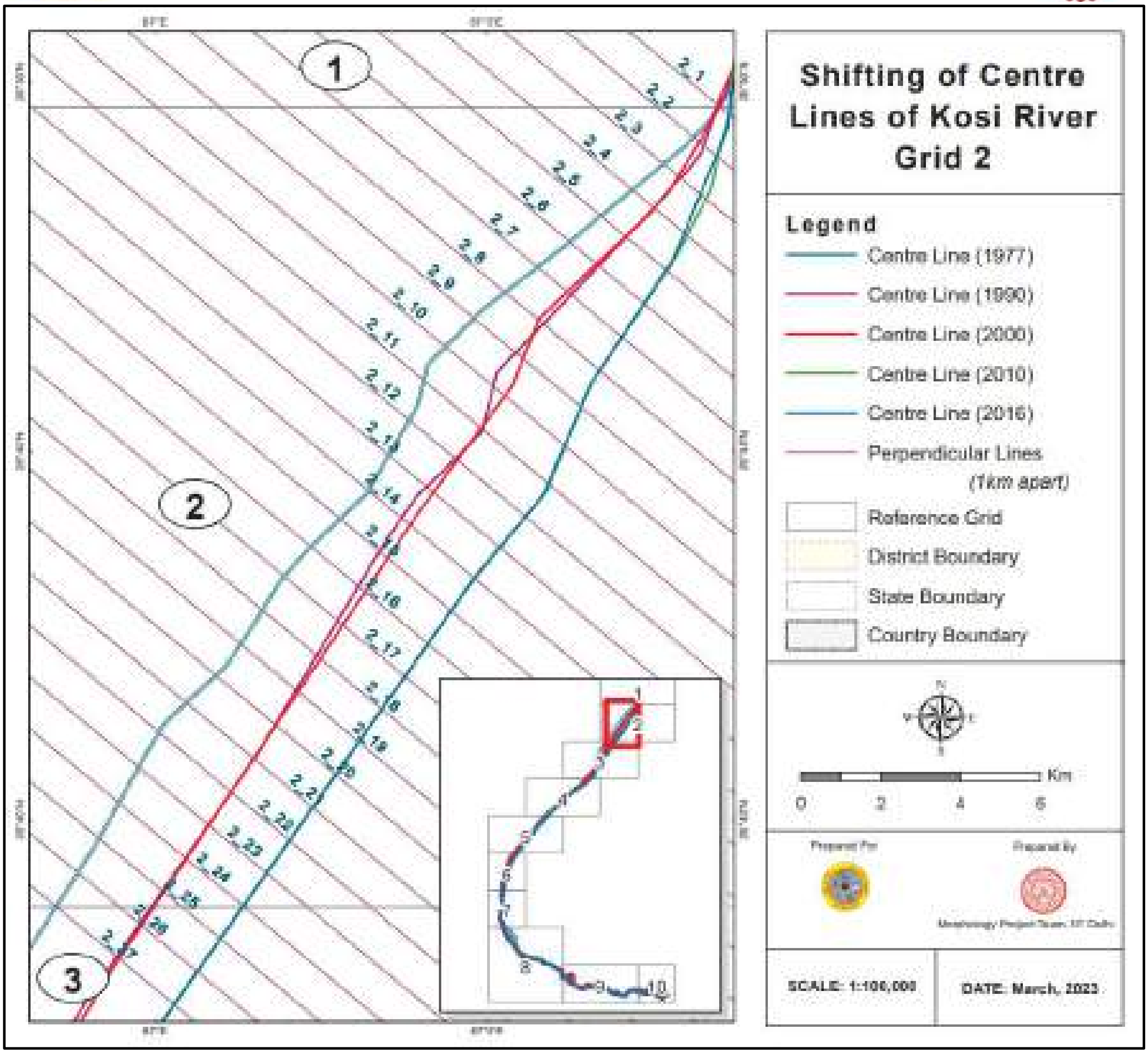


Figure 11-15: Shifting of Kosi River Reach Centreline in Grid 2

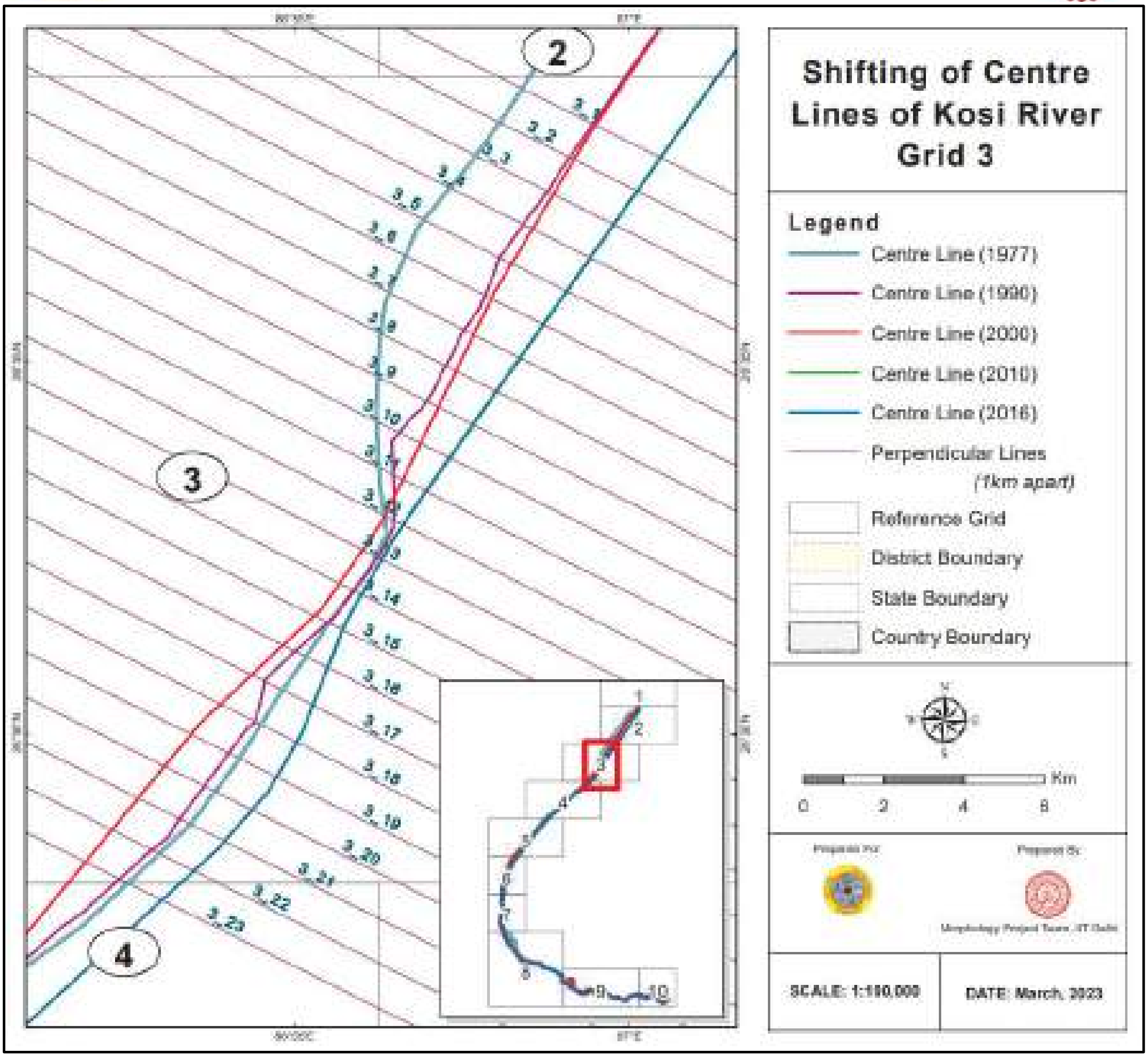


Figure 11-16: Shifting of Kosi River Reach Centreline in Grid 3

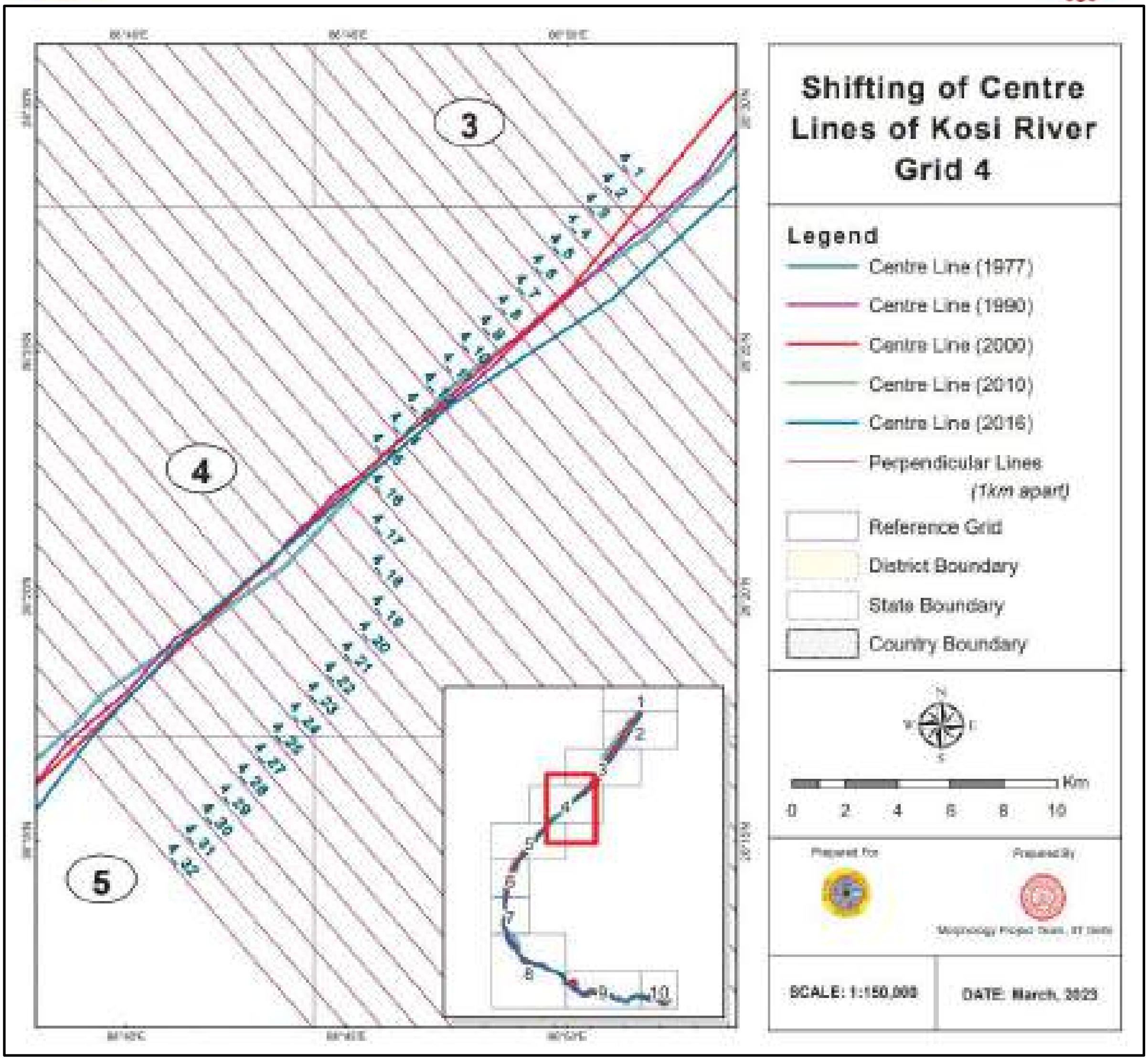


Figure 11-17: Shifting of Kosi River Reach Centreline in Grid 4

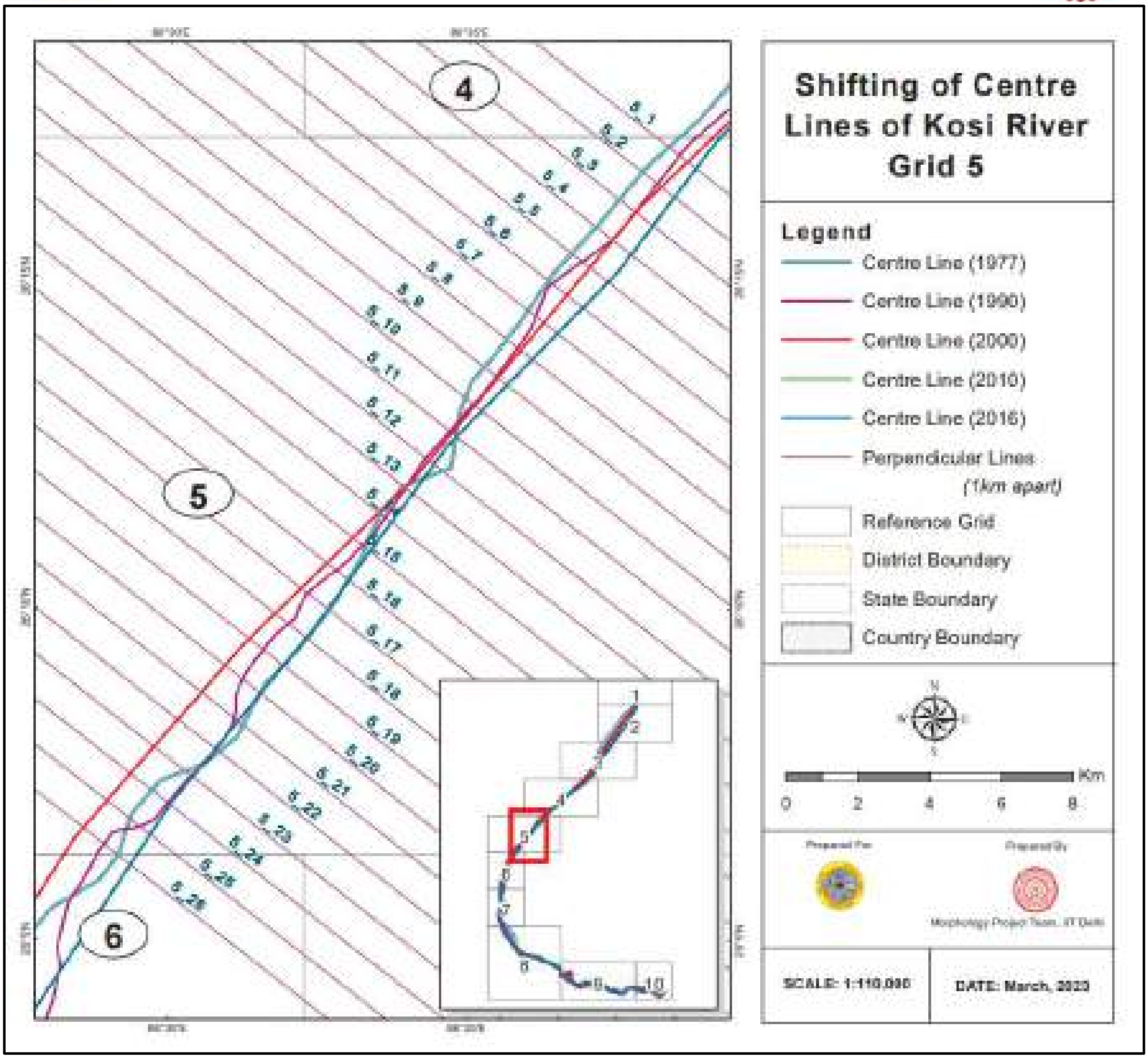


Figure 11-18: Shifting of Kosi River Reach Centreline in Grid 5

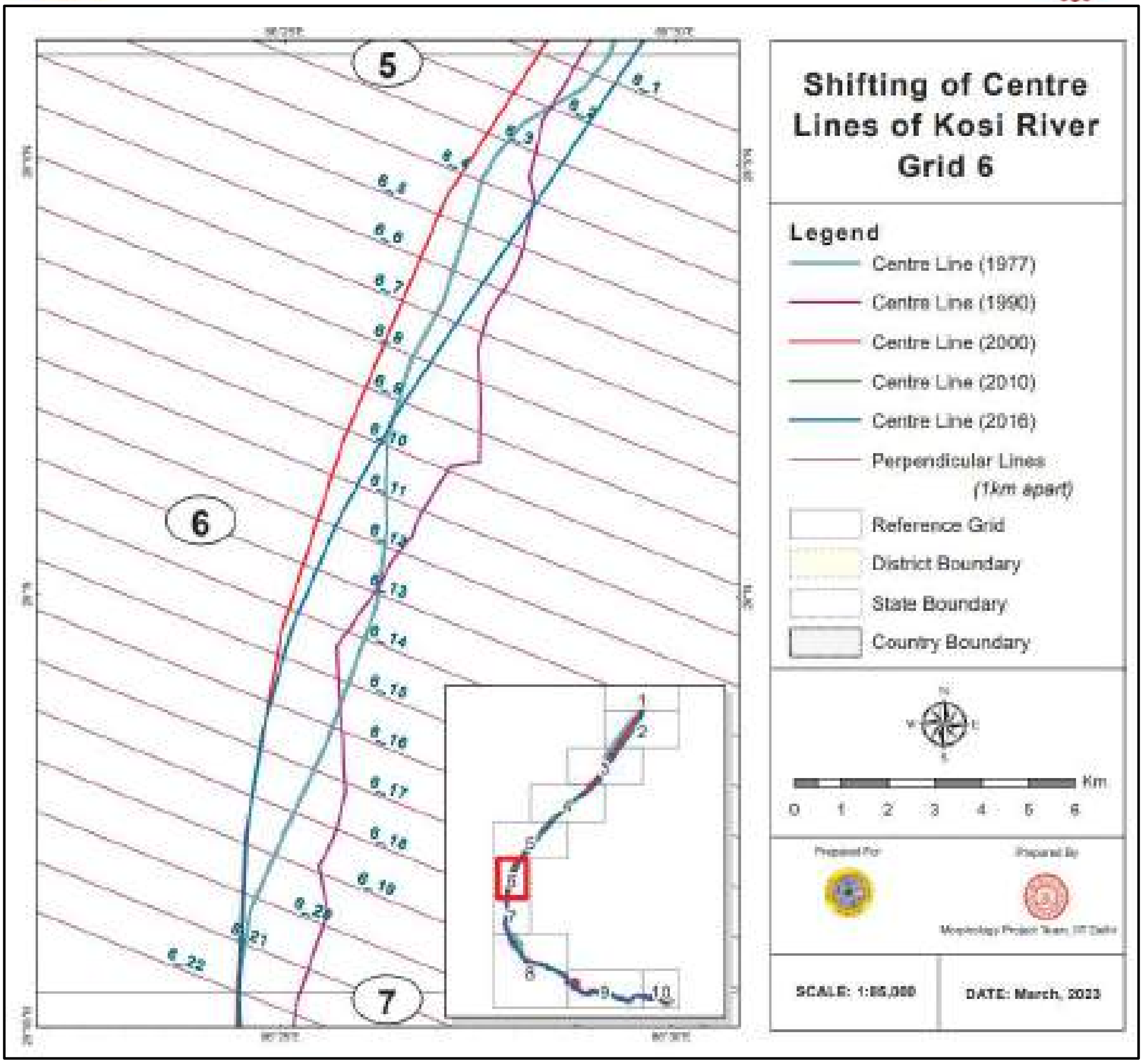


Figure 11-19: Shifting of Kosi River Reach Centreline in Grid 6

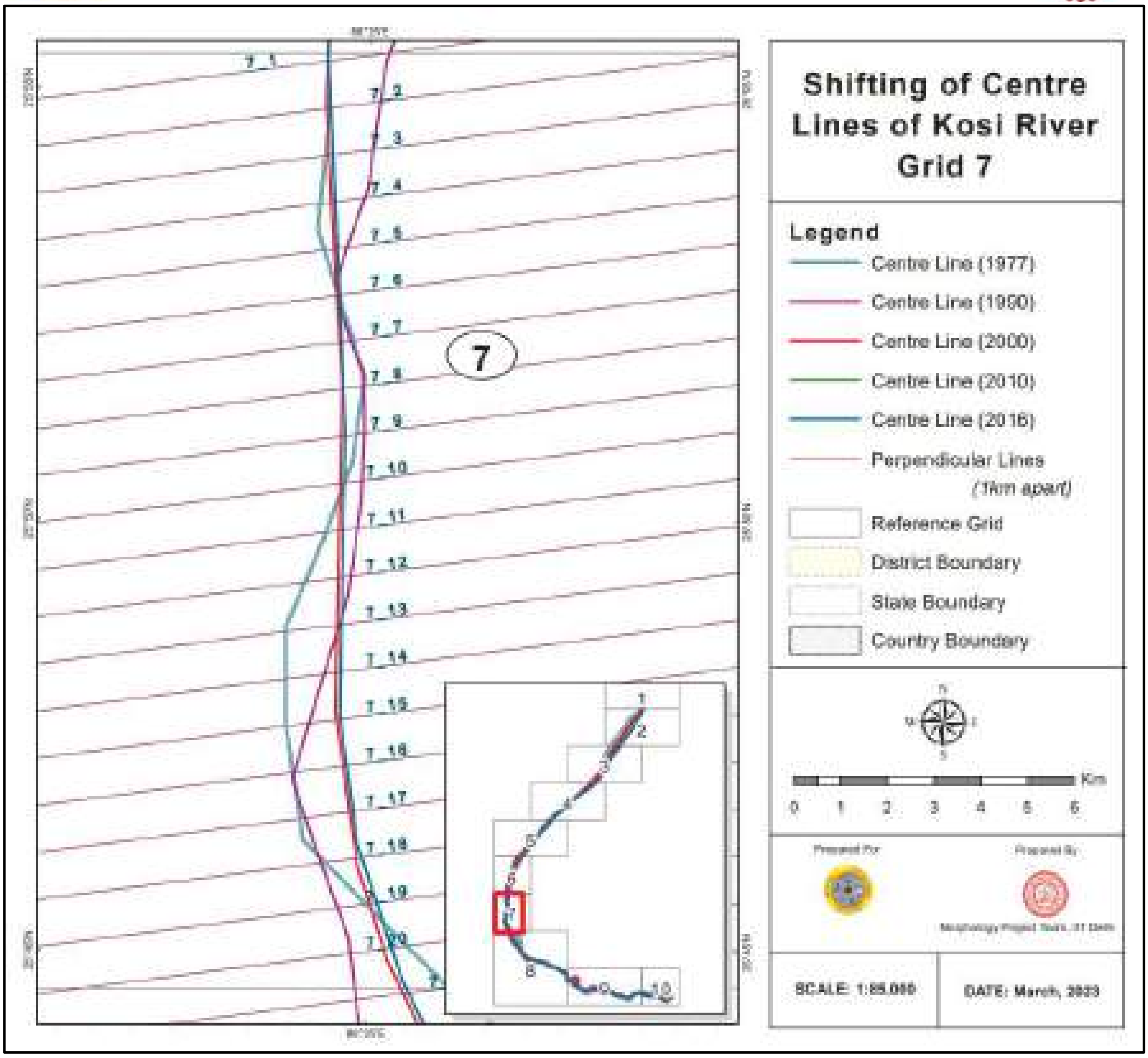


Figure 11-20: Shifting of Kosi River Reach Centreline in Grid 7

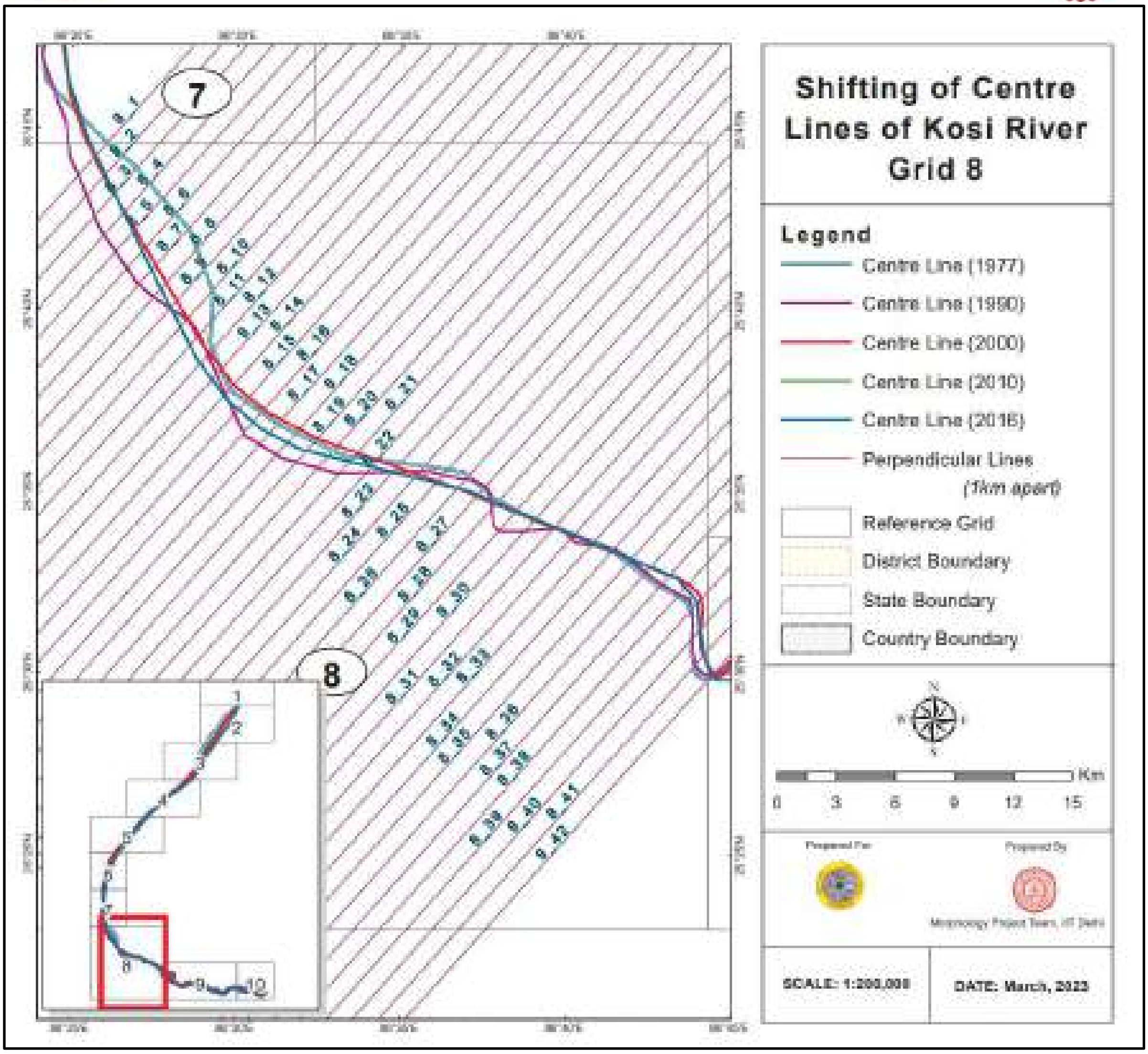


Figure 11-21: Shifting of Kosi River Reach Centreline in Grid 8

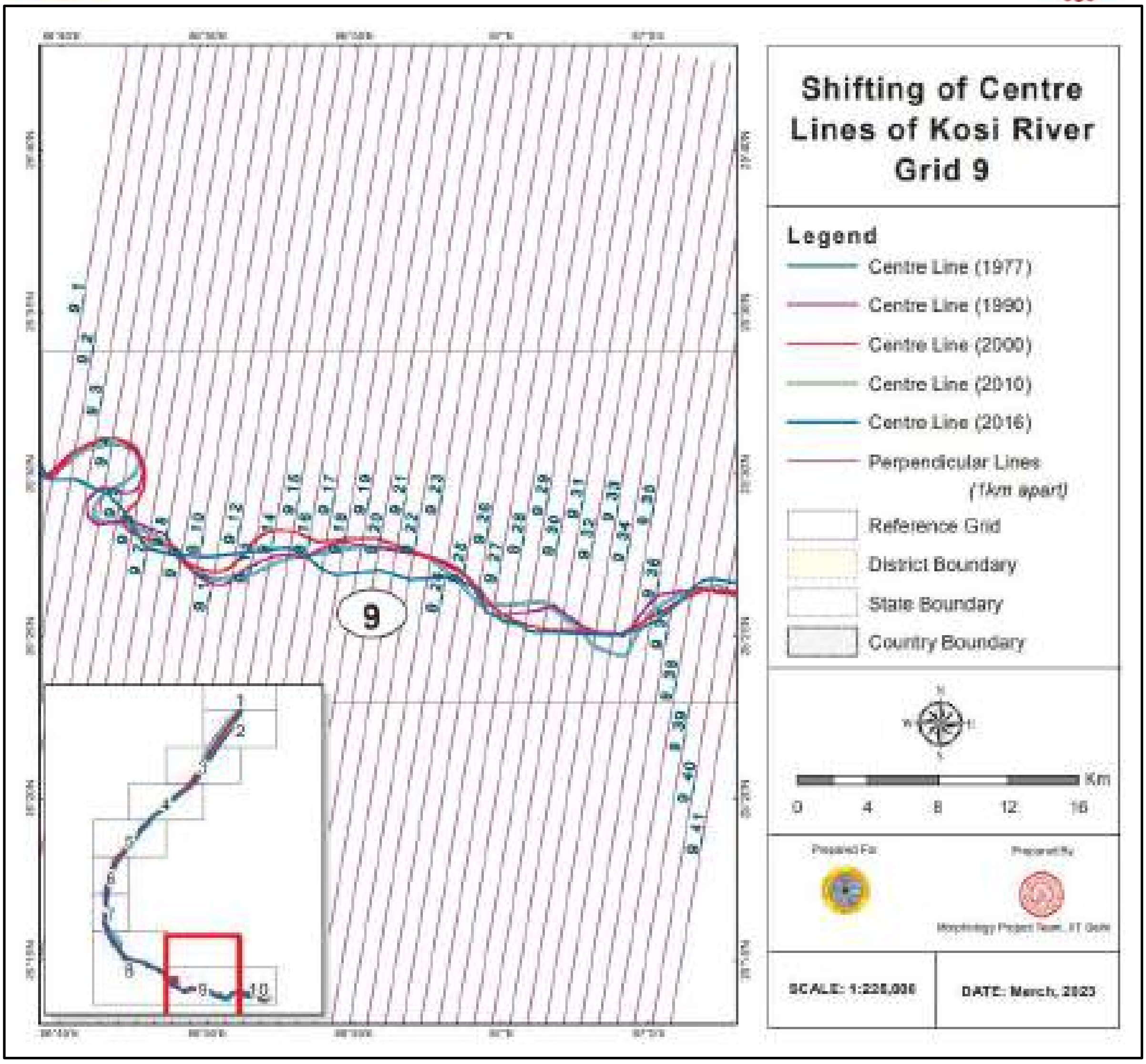


Figure 11-22: Shifting of Kosi River Reach Centreline in Grid 9

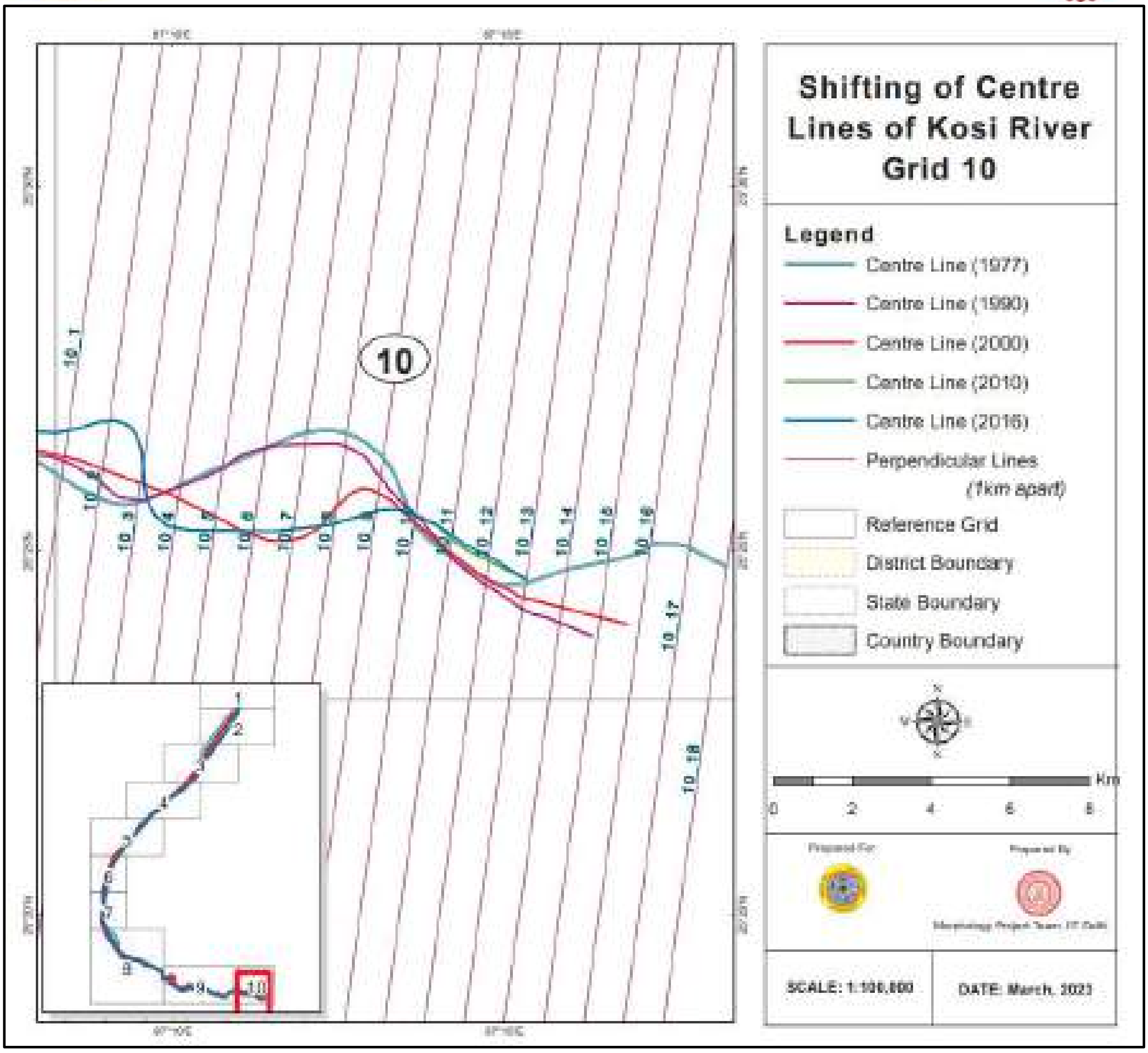


Figure 11-23: Shifting of Kosi River Reach Centreline in Grid 10

Table 11-5: Gridwise Analysis of Kosi River Course Shifting

Left of Baseline(-)/ Right of Baseline(+)										
All Indices measured perpendicular to the Baseline										
	Interval (1 km)	Distance from reference line (km)					River Course Dynamics (km)			
Grid No.	Chainage	1977	1990	2000	2010	2016	1977-1990	1990-2000	2000-2010	2010-2016
1	1_2	-0.04	0.01	0.00	0.00	0.00	0.05	-0.01	0.00	0.00
	1_3	-0.18	-0.13	-0.12	-0.12	-0.13	0.05	0.00	0.00	-0.01
	1_4	-0.30	-0.25	-0.21	-0.25	-0.26	0.04	0.04	-0.04	-0.01
	1_5	-0.22	-0.15	-0.11	-0.10	-0.20	0.07	0.05	0.00	-0.10
	1_6	0.00	0.00	0.06	-0.28	-0.27	0.00	0.06	-0.34	0.01
2	2_1	-0.01	0.00	0.06	-0.31	-0.32	0.01	0.06	-0.37	-0.01
	2_2	0.01	-0.32	-0.17	-0.79	-0.72	-0.32	0.15	-0.62	0.07
	2_3	0.16	-0.38	-0.32	-1.21	-1.03	-0.54	0.06	-0.89	0.18
	2_4	0.35	-0.36	-0.37	-1.43	-1.34	-0.71	-0.01	-1.07	0.09
	2_5	0.54	-0.29	-0.27	-1.61	-1.58	-0.82	0.02	-1.34	0.03
	2_6	0.73	-0.22	-0.14	-1.71	-1.69	-0.94	0.07	-1.56	0.02
	2_7	0.94	-0.14	-0.03	-1.81	-1.80	-1.09	0.12	-1.78	0.00
	2_8	1.16	-0.07	0.08	-1.91	-1.92	-1.24	0.16	-1.99	-0.01
	2_9	1.35	0.00	-0.24	-2.13	-2.13	-1.35	-0.24	-1.89	0.00
	2_10	1.44	-0.11	-0.49	-2.44	-2.42	-1.55	-0.37	-1.95	0.02

	2_11	1.33	-0.59	-0.54	-2.75	-2.71	-1.91	0.05	-2.21	0.04
	2_12	0.97	-0.53	-0.59	-2.80	-2.81	-1.50	-0.06	-2.20	-0.01
	2_13	0.80	-0.43	-0.65	-2.80	-2.81	-1.23	-0.22	-2.15	-0.02
	2_14	0.63	-0.44	-0.72	-2.80	-2.82	-1.07	-0.28	-2.08	-0.02
	2_15	0.73	-0.55	-0.82	-2.87	-2.88	-1.28	-0.27	-2.05	-0.01
	2_16	0.84	-0.70	-0.92	-2.95	-2.96	-1.54	-0.22	-2.03	-0.01
	2_17	0.88	-0.85	-1.02	-3.03	-3.04	-1.73	-0.17	-2.01	-0.01
	2_18	0.76	-1.01	-1.13	-3.11	-3.12	-1.77	-0.12	-1.98	-0.01
	2_19	0.65	-1.16	-1.23	-3.19	-3.20	-1.80	-0.07	-1.96	-0.01
	2_20	0.62	-1.31	-1.33	-3.27	-3.28	-1.93	-0.02	-1.94	-0.01
	2_21	0.75	-1.45	-1.43	-3.34	-3.36	-2.20	0.01	-1.91	-0.01
	2_22	0.80	-1.53	-1.53	-3.42	-3.44	-2.34	0.00	-1.89	-0.01
	2_23	0.64	-1.62	-1.63	-3.50	-3.52	-2.26	-0.02	-1.87	-0.01
	2_24	0.45	-1.71	-1.74	-3.58	-3.60	-2.16	-0.03	-1.84	-0.02
	2_25	0.27	-1.79	-1.84	-3.66	-3.68	-2.06	-0.04	-1.82	-0.02
	2_26	0.13	-1.88	-1.94	-3.74	-3.75	-2.01	-0.06	-1.80	-0.02
	2_27	0.00	-1.97	-2.04	-3.82	-3.83	-1.97	-0.07	-1.78	-0.02
3	3_1	0.04	-1.93	-2.00	-3.80	-3.81	-1.97	-0.07	-1.79	-0.02
	3_2	0.16	-1.79	-1.91	-3.64	-3.66	-1.95	-0.12	-1.74	-0.02
	3_3	0.32	-1.67	-1.83	-3.49	-3.51	-1.99	-0.15	-1.66	-0.02
	3_4	0.54	-1.49	-1.75	-3.34	-3.36	-2.03	-0.26	-1.59	-0.02

	3_5	0.77	-1.33	-1.67	-3.19	-3.21	-2.10	-0.34	-1.52	-0.02
	3_6	0.78	-1.43	-1.61	-3.04	-3.06	-2.21	-0.18	-1.43	-0.02
	3_7	0.72	-1.35	-1.61	-2.88	-2.90	-2.07	-0.27	-1.27	-0.02
	3_8	0.47	-1.34	-1.62	-2.73	-2.75	-1.81	-0.28	-1.11	-0.02
	3_9	0.04	-1.31	-1.63	-2.58	-2.60	-1.35	-0.32	-0.95	-0.02
	3_10	-0.43	-1.04	-1.63	-2.43	-2.45	-0.62	-0.59	-0.79	-0.02
	3_11	-0.99	-1.39	-1.64	-2.27	-2.30	-0.40	-0.25	-0.63	-0.02
	3_12	-1.62	-1.90	-1.65	-2.14	-2.15	-0.27	0.25	-0.50	0.00
	3_13	-1.89	-1.95	-1.53	-2.07	-2.05	-0.06	0.42	-0.54	0.01
	3_14	-1.78	-1.78	-1.38	-1.99	-2.00	0.00	0.40	-0.61	-0.01
	3_15	-1.59	-1.55	-1.18	-1.99	-1.95	0.04	0.37	-0.80	0.03
	3_16	-1.45	-1.15	-0.81	-2.06	-2.04	0.30	0.33	-1.25	0.02
	3_17	-1.30	-0.81	-0.45	-2.13	-2.14	0.49	0.36	-1.69	0.00
	3_18	-1.20	-1.02	-0.08	-2.21	-2.18	0.17	0.95	-2.13	0.03
	3_19	-1.10	-0.80	0.25	-2.14	-2.13	0.30	1.05	-2.38	0.01
	3_20	-0.92	-0.62	0.48	-1.95	-1.95	0.30	1.10	-2.43	0.00
	3_21	-0.74	-0.44	0.71	-1.68	-1.68	0.30	1.15	-2.39	0.00
	3_22	-0.37	-0.17	0.95	-1.33	-1.33	0.20	1.11	-2.28	0.00
	3_23	0.00	0.23	1.18	-0.94	-0.94	0.23	0.95	-2.12	0.00
4	4_1	-0.03	0.20	1.05	-0.90	-0.90	0.23	0.85	-1.95	0.00
	4_2	-0.05	0.22	0.87	-0.93	-0.93	0.27	0.66	-1.81	0.00

	4_3	0.03	0.23	0.70	-0.96	-0.96	0.20	0.47	-1.67	0.00
	4_4	0.12	0.21	0.53	-1.00	-1.00	0.09	0.32	-1.53	0.00
	4_5	0.20	0.19	0.36	-0.95	-0.95	-0.02	0.17	-1.31	0.00
	4_6	0.25	0.16	0.28	-0.82	-0.82	-0.09	0.11	-1.10	0.00
	4_7	0.22	0.14	0.26	-0.69	-0.69	-0.08	0.12	-0.95	0.00
	4_8	0.21	0.12	0.24	-0.56	-0.56	-0.09	0.13	-0.81	0.00
	4_9	0.29	0.05	0.23	-0.43	-0.43	-0.24	0.18	-0.66	0.00
	4_10	0.37	0.01	0.21	-0.30	-0.30	-0.36	0.20	-0.51	0.00
	4_11	0.40	0.02	0.20	-0.17	-0.17	-0.39	0.18	-0.37	0.00
	4_12	0.34	0.05	0.18	-0.08	-0.08	-0.29	0.13	-0.26	0.00
	4_13	0.28	0.16	0.16	-0.08	-0.08	-0.12	0.01	-0.25	0.00
	4_14	0.20	0.15	0.15	-0.08	-0.08	-0.05	0.00	-0.23	0.00
	4_15	0.12	0.16	0.13	-0.09	-0.09	0.04	-0.03	-0.22	0.00
	4_16	-0.03	0.11	0.12	-0.09	-0.09	0.15	0.00	-0.20	0.00
	4_17	-0.21	0.22	0.08	-0.09	-0.09	0.43	-0.14	-0.17	0.00
	4_18	-0.34	0.15	0.03	-0.09	-0.09	0.49	-0.12	-0.12	0.00
	4_19	-0.45	0.07	-0.02	-0.09	-0.09	0.53	-0.10	-0.07	0.00
	4_20	-0.57	-0.04	-0.07	-0.09	-0.09	0.53	-0.03	-0.02	0.00
	4_21	-0.57	-0.18	-0.13	-0.09	-0.09	0.39	0.05	0.04	0.00
	4_22	-0.47	-0.14	-0.18	-0.09	-0.09	0.33	-0.04	0.09	0.00
	4_23	-0.39	-0.15	-0.23	-0.09	-0.09	0.24	-0.08	0.14	0.00

	4_24	-0.36	-0.14	-0.28	-0.09	-0.09	0.22	-0.14	0.19	0.00
	4_25	-0.27	-0.04	-0.33	-0.19	-0.19	0.23	-0.30	0.14	0.00
	4_27	-0.11	-0.06	-0.39	-0.30	-0.30	0.05	-0.33	0.08	0.00
	4_28	0.03	-0.18	-0.44	-0.41	-0.41	-0.21	-0.26	0.03	0.00
	4_29	0.13	-0.33	-0.49	-0.52	-0.52	-0.46	-0.16	-0.03	0.00
	4_30	0.19	-0.32	-0.54	-0.63	-0.63	-0.51	-0.22	-0.08	0.00
	4_31	0.06	-0.30	-0.59	-0.73	-0.73	-0.36	-0.29	-0.14	0.00
	4_32	0.00	-0.31	-0.64	-0.91	-0.91	-0.31	-0.33	-0.27	0.00
	5_1	0.07	-0.31	-0.59	-0.89	-0.89	-0.38	-0.28	-0.30	0.00
	5_2	0.23	-0.30	-0.44	-0.91	-0.91	-0.53	-0.14	-0.47	0.00
	5_3	0.26	-0.30	-0.32	-0.93	-0.93	-0.56	-0.02	-0.61	0.00
	5_4	0.30	-0.28	-0.29	-0.94	-0.94	-0.58	0.00	-0.66	0.00
	5_5	0.38	0.02	-0.26	-0.91	-0.91	-0.36	-0.27	-0.65	0.00
	5_6	0.42	0.29	-0.23	-0.80	-0.80	-0.14	-0.52	-0.57	0.00
5	5_7	0.36	0.08	-0.20	-0.69	-0.69	-0.27	-0.28	-0.49	0.00
	5_8	0.33	-0.06	-0.17	-0.58	-0.58	-0.38	-0.11	-0.41	0.00
	5_9	0.34	-0.09	-0.14	-0.46	-0.46	-0.43	-0.05	-0.33	0.00
	5_10	0.23	-0.06	-0.11	-0.35	-0.35	-0.29	-0.05	-0.25	0.00
	5_11	-0.21	0.00	-0.08	-0.24	-0.24	0.21	-0.07	-0.17	0.00
	5_12	-0.52	0.07	-0.05	-0.22	-0.22	0.59	-0.11	-0.17	0.00
	5_13	0.07	0.00	0.16	-0.25	-0.25	-0.07	0.16	-0.41	0.00

	5_14	0.09	-0.07	0.29	-0.28	-0.28	-0.16	0.36	-0.58	0.00
	5_15	-0.15	-0.05	0.43	-0.32	-0.32	0.11	0.48	-0.74	0.00
	5_16	-0.32	0.10	0.56	-0.35	-0.35	0.42	0.47	-0.91	0.00
	5_17	-0.42	0.33	0.70	-0.38	-0.38	0.76	0.36	-1.08	0.00
	5_18	-0.44	0.23	0.83	-0.39	-0.39	0.66	0.61	-1.23	0.00
	5_19	-0.37	0.34	0.91	-0.37	-0.37	0.71	0.57	-1.29	0.00
	5_20	-0.34	0.29	0.96	-0.35	-0.35	0.62	0.68	-1.32	0.00
	5_21	-0.51	-0.18	1.02	-0.33	-0.33	0.33	1.20	-1.35	0.00
	5_22	-0.45	-0.34	1.07	-0.31	-0.31	0.10	1.41	-1.38	0.00
	5_23	-0.04	-0.25	1.12	-0.29	-0.29	-0.21	1.37	-1.42	0.00
	5_24	0.37	-0.20	1.18	-0.28	-0.28	-0.57	1.38	-1.45	0.00
	5_25	0.36	0.02	1.22	-0.36	-0.36	-0.34	1.20	-1.58	0.00
	5_26	0.01	0.48	0.01	-0.44	-0.44	0.47	-0.47	-0.45	0.00
6	6_1	0.13	0.58	1.39	-0.35	-0.35	0.45	0.81	-1.74	0.00
	6_2	0.76	0.74	1.59	-0.14	-0.14	-0.01	0.85	-1.73	0.00
	6_3	1.32	0.69	1.79	0.07	0.07	-0.63	1.10	-1.72	0.00
	6_4	1.52	0.34	1.99	0.28	0.28	-1.19	1.65	-1.70	0.00
	6_5	1.46	0.18	2.12	0.49	0.49	-1.28	1.93	-1.62	0.00
	6_6	1.40	0.24	2.14	0.70	0.70	-1.16	1.90	-1.44	0.00
	6_7	1.39	0.31	2.16	0.91	0.91	-1.08	1.85	-1.25	0.00
	6_8	1.52	-0.02	2.19	1.13	1.13	-1.53	2.20	-1.06	0.00

	6_9	1.45	-0.42	2.21	1.34	1.34	-1.87	2.63	-0.87	0.00
	6_10	1.32	-0.07	2.23	1.49	1.49	-1.39	2.30	-0.74	0.00
	6_11	0.95	0.11	2.19	1.61	1.61	-0.84	2.08	-0.58	0.00
	6_12	0.59	0.25	2.13	1.72	1.72	-0.34	1.88	-0.40	0.00
	6_13	0.34	0.43	2.06	1.75	1.75	0.09	1.64	-0.31	0.00
	6_14	0.26	0.66	2.00	1.78	1.78	0.40	1.34	-0.22	0.00
	6_15	0.23	0.47	1.86	1.72	1.72	0.24	1.39	-0.14	0.00
	6_16	0.20	-0.02	1.66	1.62	1.62	-0.22	1.68	-0.04	0.00
	6_17	0.24	-0.49	1.46	1.48	1.48	-0.72	1.94	0.02	0.00
	6_18	0.30	-0.67	1.25	1.25	1.25	-0.97	1.93	-0.01	0.00
	6_19	0.35	-0.70	1.03	1.00	1.00	-1.05	1.73	-0.03	0.00
	6_20	0.38	-1.17	0.68	0.66	0.66	-1.55	1.85	-0.03	0.00
	6_21	0.24	-1.22	0.34	0.31	0.31	-1.46	1.55	-0.03	0.00
	6_22	0.00	-1.31	-0.01	-0.03	-0.03	-1.31	1.30	-0.02	0.00
	7_1	0.02	-1.33	0.02	0.01	0.01	-1.35	1.35	-0.01	0.00
	7_2	0.15	-0.99	0.18	0.08	0.08	-1.14	1.17	-0.10	0.00
	7_3	0.33	-0.70	0.25	0.16	0.16	-1.03	0.95	-0.09	0.00
7	7_4	0.57	-0.39	0.32	0.25	0.25	-0.96	0.72	-0.08	0.00
	7_5	0.61	0.11	0.40	0.33	0.33	-0.50	0.28	-0.06	0.00
	7_6	0.43	0.45	0.47	0.41	0.41	0.02	0.02	-0.05	0.00
	7_7	0.25	0.30	0.54	0.50	0.50	0.05	0.25	-0.04	0.00

	7_8	0.15	0.16	0.62	0.58	0.58	0.00	0.46	-0.04	0.00
	7_9	0.44	0.27	0.77	0.67	0.67	-0.17	0.50	-0.09	0.00
	7_10	0.82	0.44	0.92	0.83	0.83	-0.39	0.48	-0.09	0.00
	7_11	1.35	0.67	1.07	0.98	0.98	-0.69	0.40	-0.09	0.00
	7_12	1.93	0.94	1.22	1.13	1.13	-0.99	0.27	-0.09	0.00
	7_13	2.48	1.32	1.37	1.28	1.28	-1.16	0.05	-0.09	0.00
	7_14	2.61	1.78	1.52	1.43	1.43	-0.83	-0.26	-0.09	0.00
	7_15	2.73	2.23	1.64	1.56	1.56	-0.50	-0.59	-0.08	0.00
	7_16	2.71	2.68	1.63	1.55	1.55	-0.03	-1.05	-0.08	0.00
	7_17	2.69	2.58	1.61	1.54	1.54	-0.12	-0.96	-0.07	0.00
	7_18	2.28	2.36	1.60	1.48	1.48	0.09	-0.76	-0.12	0.00
	7_19	1.53	2.14	1.45	1.29	1.29	0.61	-0.69	-0.16	0.00
	7_20	0.77	1.99	1.27	1.10	1.10	1.22	-0.72	-0.17	0.00
	7_21	0.00	1.99	0.98	0.86	0.86	1.99	-1.01	-0.11	0.00
8	8_1	0.04	2.26	1.03	0.91	0.91	2.22	-1.23	-0.12	0.00
	8_2	0.02	2.71	1.40	1.28	1.28	2.69	-1.32	-0.12	0.00
	8_3	0.02	3.21	1.72	1.69	1.69	3.19	-1.49	-0.03	0.00
	8_4	0.11	3.62	2.04	2.10	2.10	3.50	-1.58	0.06	0.00
	8_5	0.25	3.85	2.36	2.51	2.51	3.60	-1.49	0.15	0.00
	8_6	0.38	4.11	2.68	2.92	2.92	3.73	-1.43	0.24	0.00
	8_7	0.51	4.30	3.00	3.33	3.33	3.79	-1.29	0.33	0.00

	8_8	0.99	4.27	3.32	3.73	3.73	3.28	-0.95	0.41	0.00
	8_9	1.52	4.15	3.65	4.12	4.12	2.62	-0.50	0.47	0.00
	8_10	2.06	4.01	3.97	4.50	4.50	1.95	-0.04	0.54	0.00
	8_11	3.24	4.20	4.29	4.89	4.89	0.96	0.09	0.60	0.00
	8_12	4.27	4.64	4.52	5.24	5.24	0.38	-0.12	0.71	0.00
	8_13	4.74	5.10	4.71	5.44	5.44	0.36	-0.38	0.73	0.00
	8_14	5.21	5.55	4.91	5.65	5.65	0.34	-0.64	0.73	0.00
	8_15	5.12	5.98	4.86	5.70	5.70	0.86	-1.12	0.83	0.00
	8_16	5.00	6.40	4.80	5.67	5.67	1.39	-1.59	0.86	0.00
	8_17	4.89	6.29	4.61	5.53	5.53	1.40	-1.68	0.91	0.00
	8_18	4.62	6.10	4.36	5.27	5.27	1.48	-1.74	0.91	0.00
	8_19	4.33	5.71	4.11	4.94	4.94	1.39	-1.60	0.83	0.00
	8_20	4.03	5.22	3.71	4.41	4.41	1.19	-1.51	0.70	0.00
	8_21	3.56	4.67	3.30	3.88	3.88	1.10	-1.37	0.58	0.00
	8_22	2.88	3.74	2.89	3.35	3.35	0.86	-0.85	0.46	0.00
	8_23	2.19	2.82	2.48	2.83	2.83	0.62	-0.34	0.34	0.00
	8_24	1.52	1.89	2.07	2.30	2.30	0.37	0.18	0.22	0.00
	8_25	0.86	1.22	1.66	1.77	1.77	0.35	0.45	0.10	0.00
	8_26	0.41	0.62	1.25	1.24	1.24	0.21	0.64	-0.02	0.00
	8_27	0.39	0.21	0.90	0.81	0.81	-0.19	0.69	-0.09	0.00
	8_28	0.33	0.90	0.55	0.46	0.46	0.57	-0.35	-0.09	0.00

	8_29	0.10	1.46	0.19	0.12	0.12	1.37	-1.27	-0.08	0.00
	8_30	-0.16	0.61	-0.16	-0.23	-0.23	0.78	-0.77	-0.07	0.00
	8_31	-0.55	-0.44	-0.51	-0.57	-0.57	0.11	-0.07	-0.07	0.00
	8_32	-0.93	-0.69	-0.86	-0.92	-0.92	0.25	-0.17	-0.06	0.00
	8_33	-1.32	-1.13	-1.21	-1.26	-1.26	0.19	-0.08	-0.05	0.00
	8_34	-1.62	-1.74	-1.56	-1.61	-1.61	-0.12	0.18	-0.05	0.00
	8_35	-1.68	-1.88	-1.92	-1.96	-1.96	-0.19	-0.04	-0.04	0.00
	8_36	-1.75	-1.94	-2.27	-2.30	-2.30	-0.19	-0.33	-0.03	0.00
	8_37	-1.88	-2.01	-2.66	-2.65	-2.65	-0.12	-0.65	0.01	0.00
	8_38	-2.14	-2.21	-2.90	-2.69	-2.69	-0.07	-0.70	0.21	0.00
	8_39	-2.01	-2.09	-2.77	-2.52	-2.52	-0.08	-0.68	0.25	0.00
	8_40	-0.98	-0.97	-1.63	-1.55	-1.55	0.01	-0.65	0.07	0.00
	8_41	0.00	-0.12	-0.81	-0.74	-0.74	-0.12	-0.69	0.07	0.00
	8_42	0.01	-0.30	-0.37	-0.31	-0.31	-0.31	-0.07	0.06	0.00
9	9_1	-0.36	-0.62	-0.31	-0.09	-0.06	-0.27	0.31	0.23	0.03
	9_2	-1.55	-1.88	-1.88	-0.22	-0.27	-0.32	0.00	1.66	-0.05
	9_3	-2.28	-2.55	-2.54	-0.08	-0.14	-0.28	0.01	2.47	-0.06
	9_4	(-)2.62 (L), 1.77 (R)	(-)2.96 (L), 2.01 (R)	-2.97	0.16	0.14	(-)0.34(L), 0.24(R)	-0.02	3.12	-0.02

	9_5	(-)2.64 (L), 1.76 (R)	(-)2.7 (L), 1.66 (R)	-2.85	0.76	0.76	(-)0.06(L), 0.10(R)	-0.15	3.61	0.00
	9_6	1.83	(-)1.55 (L), 1.54 (R)	(-)1.70 (L), 2.16 (R)	1.81	1.81	-0.29	(-)0.15(L), 0.62(R)	-0.35	0.00
	9_7	2.02	1.74	2.34	2.68	2.90	-0.29	0.60	0.34	0.22
	9_8	2.51	2.01	2.44	2.91	2.93	-0.49	0.42	0.47	0.02
	9_9	3.16	3.15	2.90	2.89	2.89	-0.02	-0.25	-0.01	0.00
	9_10	3.63	3.84	3.47	2.78	2.78	0.21	-0.37	-0.69	0.00
	9_11	3.98	4.20	3.50	2.57	2.57	0.22	-0.71	-0.92	0.00
	9_12	3.65	3.84	2.95	2.29	2.29	0.19	-0.89	-0.66	0.00
	9_13	3.31	2.84	1.31	2.00	2.00	-0.47	-1.53	0.69	0.00
	9_14	2.68	2.16	0.63	1.71	1.71	-0.52	-1.53	1.08	0.00
	9_15	2.06	1.84	0.48	1.53	1.48	-0.22	-1.36	1.05	-0.05
	9_16	1.68	1.76	0.70	1.77	1.73	0.08	-1.06	1.07	-0.05
	9_17	1.38	1.06	0.69	2.30	2.30	-0.31	-0.38	1.62	0.00
	9_18	1.02	0.58	0.38	2.45	2.45	-0.44	-0.20	2.07	0.00
	9_19	0.73	0.57	0.19	2.17	2.17	-0.15	-0.38	1.97	0.00
	9_20	0.55	0.56	0.08	1.88	1.88	0.01	-0.49	1.80	0.00
	9_21	0.48	0.56	0.25	1.90	1.90	0.08	-0.30	1.64	0.00

	9_22	0.49	0.55	0.43	2.02	2.02	0.06	-0.12	1.59	0.00
	9_23	0.64	0.56	0.64	1.80	1.80	-0.08	0.08	1.16	0.00
	9_24	1.23	0.78	0.89	1.57	1.57	-0.44	0.10	0.68	0.00
	9_25	1.85	1.18	1.24	1.63	1.63	-0.67	0.06	0.39	0.00
	9_26	2.59	2.20	1.86	1.97	1.97	-0.39	-0.33	0.11	0.00
	9_27	2.65	3.16	2.75	3.20	3.18	0.51	-0.41	0.45	-0.02
	9_28	2.45	3.00	3.22	3.50	3.43	0.55	0.22	0.28	-0.07
	9_29	2.19	2.68	3.42	3.75	3.66	0.49	0.75	0.32	-0.09
	9_30	2.11	2.25	3.51	3.67	3.67	0.15	1.25	0.17	0.00
	9_31	2.61	2.42	3.42	3.52	3.52	-0.19	1.00	0.10	0.00
	9_32	3.11	2.87	3.23	3.40	3.40	-0.25	0.37	0.17	0.00
	9_33	3.93	3.15	3.21	3.28	3.28	-0.78	0.06	0.07	0.00
	9_34	4.16	3.05	3.13	3.13	3.13	-1.12	0.08	0.01	0.00
	9_35	3.94	2.43	2.59	2.76	2.76	-1.52	0.16	0.17	0.00
	9_36	1.36	0.65	1.74	2.12	2.12	-0.71	1.09	0.38	0.00
	9_37	0.51	0.16	0.95	1.13	1.12	-0.34	0.78	0.18	-0.01
	9_38	-0.04	-0.15	0.16	-0.21	-0.21	-0.11	0.31	-0.36	0.00
	9_39	-0.48	-0.28	-0.30	-0.95	-0.95	0.21	-0.02	-0.65	0.00
	9_40	-0.42	-0.32	-0.44	-0.98	-0.98	0.11	-0.13	-0.53	0.00
	9_41	0.00	-0.36	-0.46	-1.08	-1.07	-0.36	-0.10	-0.62	0.01
10	10_1	0.08	-0.33	-0.45	-1.12	-1.12	-0.41	-0.12	-0.68	0.01

	10_2	0.45	0.07	-0.27	-1.50	-1.51	-0.39	-0.34	-1.23	-0.01
	10_3	0.44	0.37	-0.05	-0.48	-0.48	-0.06	-0.42	-0.43	0.00
	10_4	-0.13	-0.11	0.20	0.93	0.93	0.03	0.31	0.73	0.01
	10_5	-0.76	-0.70	0.53	0.88	0.88	0.06	1.23	0.34	0.00
	10_6	-1.35	-1.36	0.85	0.76	0.76	-0.01	2.21	-0.10	0.00
	10_7	-1.91	-1.59	0.84	0.57	0.56	0.31	2.44	-0.28	0.00
	10_8	-2.02	-1.70	-0.14	0.27	0.28	0.32	1.56	0.42	0.01
	10_9	-1.53	-1.03	-0.63	-0.17	-0.17	0.50	0.40	0.46	0.00
	10_10	0.02	-0.20	-0.03	-0.23	-0.20	-0.21	0.16	-0.19	0.03
	10_11	0.68	0.69	0.60	0.28	0.18	0.01	-0.09	-0.32	-0.10
	10_12	1.13	1.29	1.16	0.69	0.57	0.15	-0.13	-0.47	-0.11
	10_13	1.11	1.77	1.49	0.00	0.00	0.66	-0.28	-1.49	0.00
	10_14	0.62	1.99	1.60	0.00	0.00	1.37	-0.39	-1.60	0.00
	10_15	0.27	0.00	1.71	0.00	0.00	-0.27	1.71	-1.71	0.00
	10_16	-0.25	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00
	10_17	-0.33	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00
	10_18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

11.7 Kosi-Bagmati Confluence

The confluence points for 1975 and 1990 are labelled as point 1 (86.60 E, 25.57 N) and 2, respectively (86.36 E, 25.73 N). Bagmati is merged with one of the reaches of the Kosi river near Jagmohra village at Point 2, which is 16.7 km along the river reach (13.5 km displacement) northwest from point 1 (Near Chharapati town in Khagaria district). The confluence point shifted to point 3 for the year 2000, situated 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 11-24 to 11-28. The 16.7 km movement of Kosi-Bagmati 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-Bagmati confluence has been governed by the channel dynamics of Bagmati 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 142 m 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 130 m 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 68 m in 2010, whereas the width of combined flow from Kosi-Bagmati measures 130 m in 2000 and 145 m 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 68 m in 2010 to 90 m in 2016, whereas the width of combined flow from Kosi-Bagmati measures 145 m in 2010 and 155 m 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.

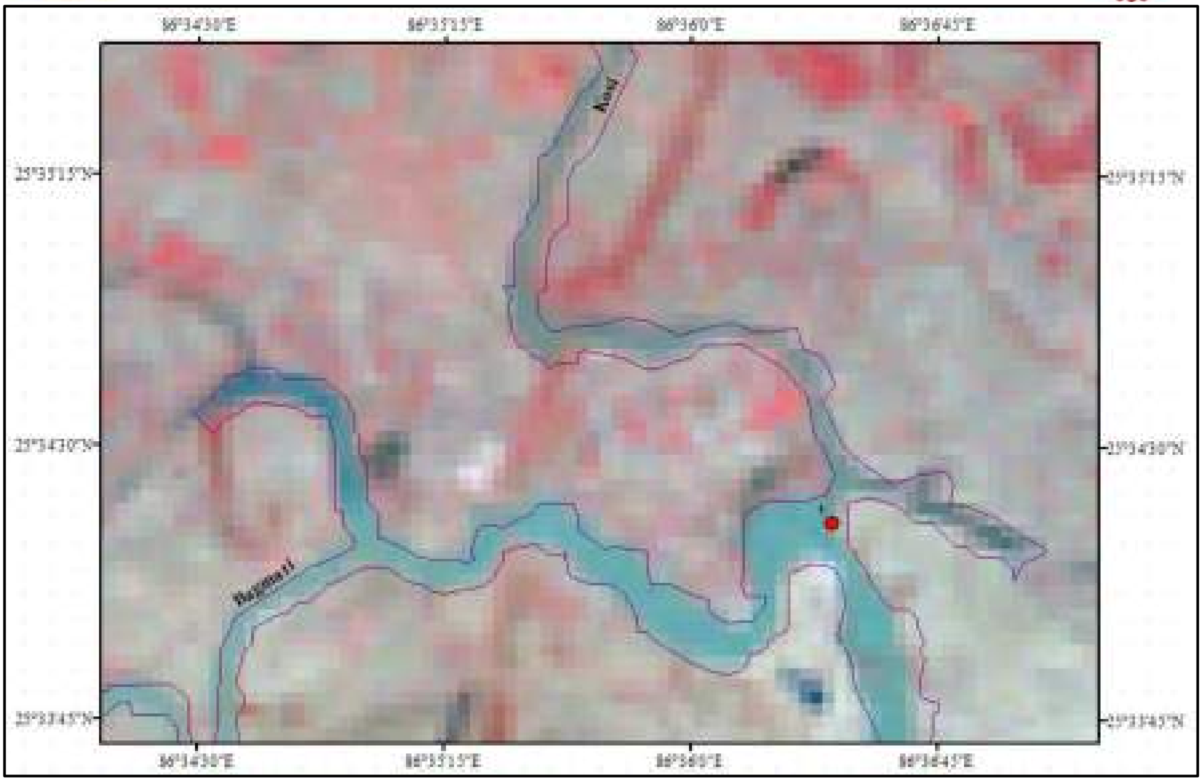


Figure 11-24: Confluence of Kosi-Bagmati in 1975

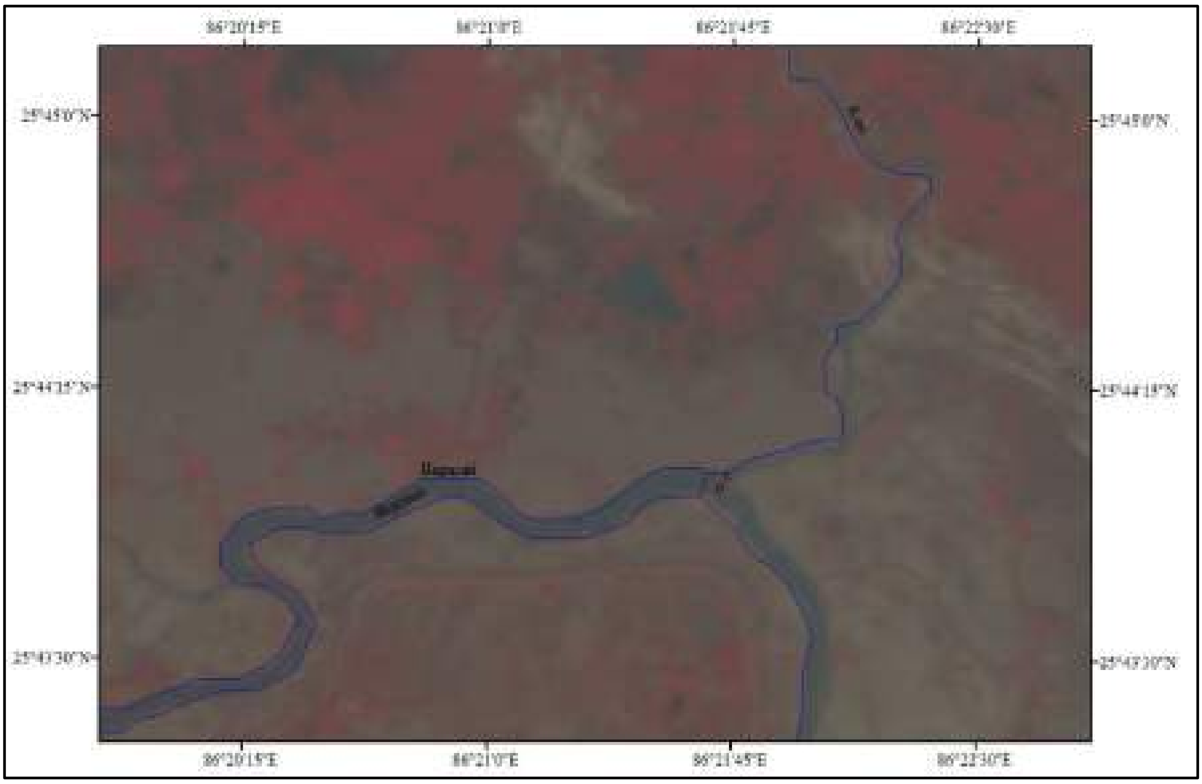


Figure 11-25: Confluence of Kosi-Bagmati in 1990

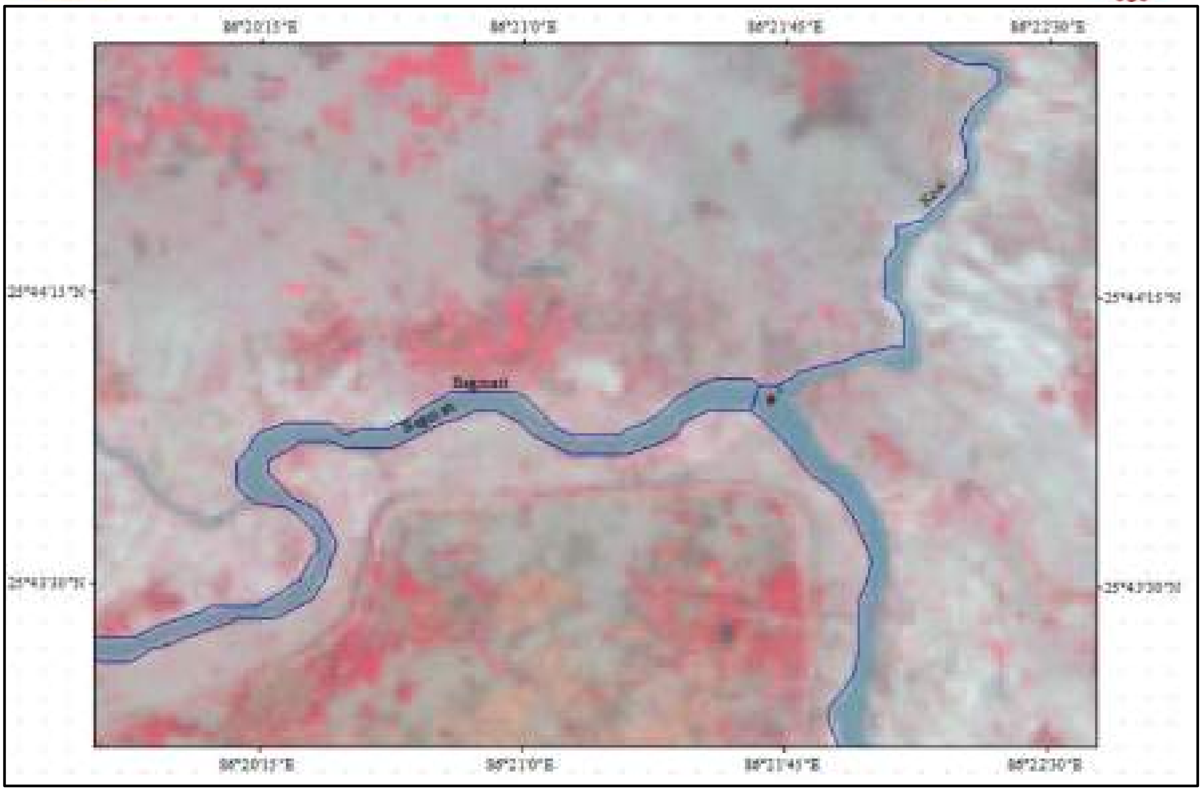


Figure 11-26: Confluence of Kosi-Bagmati in 2000

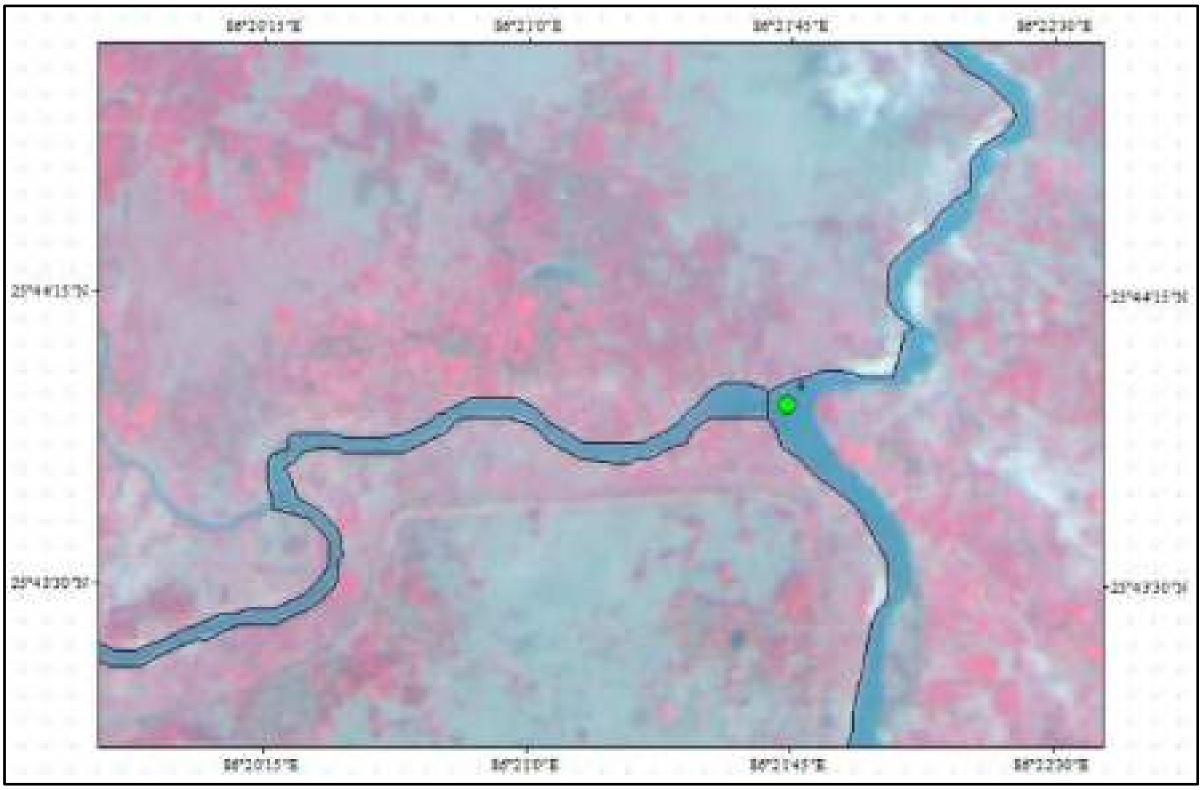


Figure 11-27: Confluence of Kosi-Bagmati in 2010

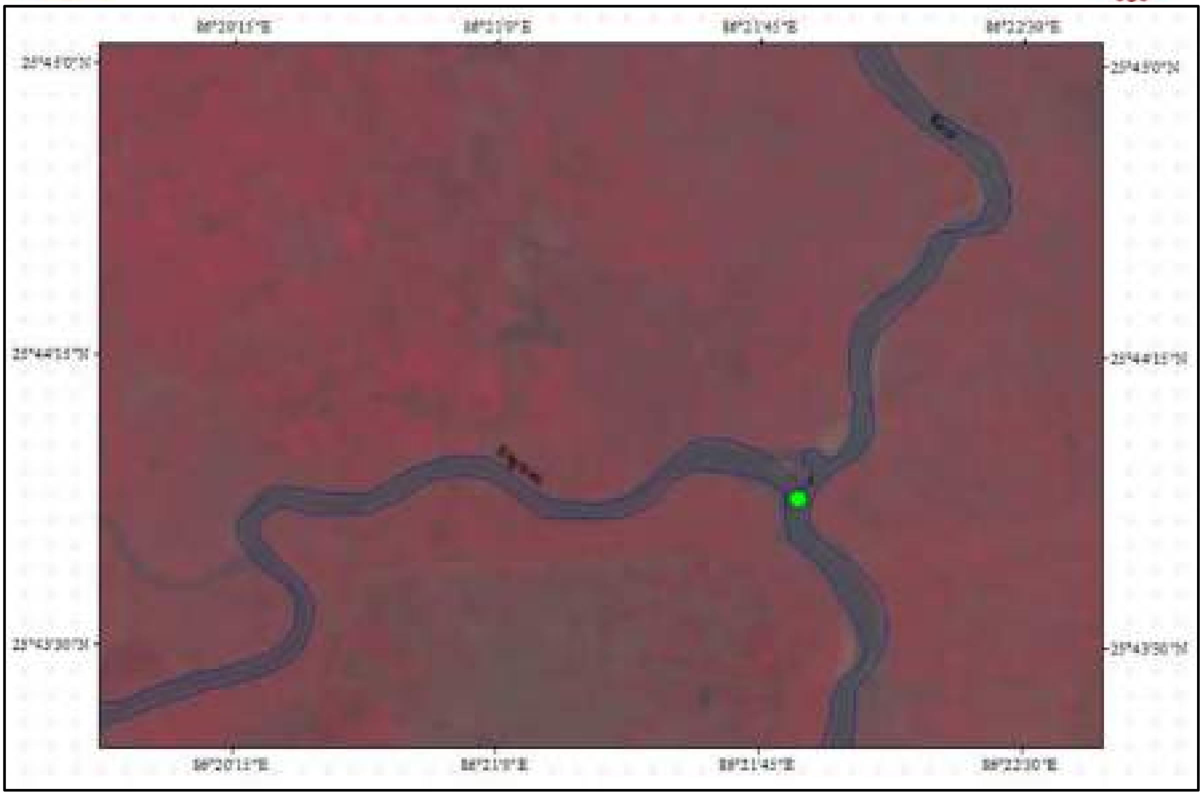


Figure 11-28: Confluence of Kosi-Bagmati in 2016

11.8 Kosi-Ganga Confluence

Historically, the Kosi-Ganga confluence has exhibited extensive migration, covering a considerable distance of approximately 40 Kms from Manihari to Katihar, primarily attributed to the migration of the Kosi channel. It has been determined that since the Kosi River overpowered the Gogri River and followed its course, the confluence has become relatively stable. This discussion is specifically focused on the Kosi-Ganga confluence for the duration from 1977 to 2016. Both the Kosi and Ganga rivers are characterized as large and dynamic, considering factors such as water and sediment flow, channel size, and planform changes. The Kosi River displays dynamic characteristics, featuring a meander belt spanning from 1 kilometer to 3.5 Kms, with an available river corridor of nearly 2.5 Kms in its lower reach (Parmar, 2022). The outfall of the Kosi River into the Ganga River is influenced by an anthropogenic control, specifically a railway bridge that acts as a pivot for the river. In contrast, the Ganga River, as the parent river, adopts a braided pattern in this stretch, with the braid plain width varying from 3.5 Kms to 12 Kms. The river corridor of the Ganga expands from 3.5 Kms to 8 Kms upstream of the confluence, widening to over 10 Kms just downstream. The confluence is situated in the lower reach of the Ganga River, which is highly dynamic in this zone, experiencing continuous erosion on its left bank. Consequently, this erosion has resulted in an overall migration of 4.4 Kms Westwards over the specified period. In summary, while both the Kosi and Ganga rivers exhibit high levels of dynamism, changes in the Kosi-Ganga confluence position predominantly arise from the planform dynamics of the Ganga River in its floodplain. Future speculation suggests the possibility of additional lateral migration of the confluence, considering the Ganga channel's curved right banks, which are conducive to bank erosion. Nonetheless, the presence of anthropogenic control over the Kosi River limits the likelihood of significant variations.

11.9 Abandoned Channels and Oxbow Formations

Abandoned channels are geomorphologic evidence of channel movement. They are most likely the 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:

A. 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).
B. 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).
C. 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.

A former stream channel that was cut off from the rest of the river and characteristically lacks year long standing water, is known as abandoned meander channel. For Kosi river system, abandoned channel analysis has been done. The results are shown in Table 11-6.

Table 11-6: Abandoned Channels and Ox-Bow Formation in Kosi River in Different Years

S. No.	Grid	Nearby Village / Town	Position	1975-1990	1990-2000	2000-2010	2010-2016
1	8	Heyatpur	86.55 E, 25.61 N	One oxbow at the right side of the stream can be seen in 1990 imagery in grid number 8. The reach swung towards its left, and the oxbow lake becomes visible in the 1990-year imagery	Oxbow lake is visible in the year 2000 image.	Oxbow lake is visible in the year 2010 image. The reach along the lake gets disappeared between 2000-2010.	No significant change, though oxbow lake and it is visible in 2016 imagery.
2	8	Hardia	86.60 E, 25.59 N	Reach has moved to the right side and formation of one small oxbow lake have been observed on the left side of the river reach.	Reach swung towards its right. In the year 2000 image the size of lake is slightly reduced than the in the year 1990.	Oxbow lake is visible in the year 2010.	In the year 2016, the oxbow lake's footprint is visible.
3	9	Mohanpur	86.89 E, 25.45 N	One oxbow lake in the process at the right side of the river can be seen in 1977 image. Tonal variations seen in the satellite image of the year 1977 indicate that specified reaches were part of the main channel, and the oxbow	No significant change	Oxbow lake is visible in the year 2010 image.	No significant change, though oxbow lake and it is visible in 2016 imagery

				lake has formed between 1977-1990			
4	9	Kishunpur Banwari	86.95 E, 25.46 N	One oxbow lake can be seen in the year 1977 on the right side of the reach, during 1977-1990, the size of oxbow lake has been increased.	No significant change	Reach swings towards its right. In the year 2010 image and the size of oxbow lake slightly reduced as compare to year 2000.Hence the meander length reduces from 2000-2010.	River reach swings towards its right and lake gets eliminated between 2010-2016. It is not visible in 2016 imagery.
5	9	Kaharpur	86.97 E, 25.43 N	Formation of lake is not visible in year 1990 imagery.	Formation of lake is not visible in year 2000 imagery.	Reach has moved to the right side and formation of one small oxbow have been observed across the left side of the river reach. The oxbow lake is visible in year 2010 imagery.	No significant change in oxbow lake and it is visible in 2016 imagery.

11.10 Improvements Over Existing Plan Form Index

As defined earlier, PFI considers 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, have suggested the following alternatives as improvements to the existing PFI:

$$T/B$$

$$(T/B) + N$$

$$\{(T/B)/N\} + N$$

The variables used in the proposed indices are the similar to PFI defined by Sharma, 1995 where T indicates total flow top width and B indicates entire channel width and N represents the number of braids. The first alternative presents the ratio of flow top width (Sum of top width from all active channels) to total channel width. Though it misses out on the 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 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 is much more comprehensive and should be utilised for finding out PFI. 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 by 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 11-7). Reaches with the highest N values from all Grids are selected for the demonstration.

Table 11-7: Comparison of Improved PFI Indices (Parmar and Khosa, 2017) and PFI Defined by Sharma, 1995

Grid ID	Flow Top Width	Length	N	PFI	T/B	T/B/N	(T/B)+N	(T/B/N)+N
1	662	1191	4	14	0.56	0.14	4.56	4.14
10	1517	2005	3	25	0.76	0.25	3.76	3.25
2	1910	3797	7	7	0.50	0.07	7.50	7.07
3	2235	4113	8	7	0.54	0.07	8.54	8.07
4	2336	6365	8	5	0.37	0.05	8.37	8.05
5	2258	5841	9	4	0.39	0.04	9.39	9.04
6	1373	8735	10	2	0.16	0.02	10.16	10.02
7	741	10985	6	1	0.07	0.01	6.07	6.01
8	1551	14696	7	2	0.11	0.02	7.11	7.02

11.11 Conclusions

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

A. The sinuosity index does not show any significant trend. The average sinuosity for the entire stretch of Kosi River is 1.20 in 2016, whereas the estimated radius of curvature varied from 0.6 to 9.7 km and represented grid-wise average radius of curvature from 3.1 to 7 km However, the scale of digitization 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.

B. BI is computed on a grid scale, while PFI is computed at 1 km chainage scale. It has been observed that braiding is significant in Grid 2, 3, 4 and 5 between 1977 to 1990. However, from 2010 to 2016, the higher braiding is observed in Grid 3, 4 and 5 majorly situated near Birpur, Bhaptiahi, Dagmara and Khokhaha villages in Supaul district of Bihar.

C. BI and PFI capture braiding pattern in two different forms. The first one captures it at reach scale, whereas PFI captures it at cross-section scale. Though both represent braiding phenomenon, cross section-based index IS 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, BI 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, BI is slightly different from PFI.

D. Shifting analysis of Kosi River has been carried out at 1 km interval, and it has been seen that river has experienced changes in river course at many locations. There is no significant shifting is observed in the Kosi in the year 2016 compared to 2010. However, the maximum variation was noticed in 2010 compared to 2000. The probable reason behind this shifting is the construction of the railway bridge and Kosi bridge in 2003.

Chapter 12: Erosion and Deposition Analysis

12.1 Channel Evolution Analysis

The analysis of channel evolution involves the examination of river channel geometry, including its dimensions, patterns, and longitudinal profiles. It also encompasses the identification of distinct river segments such as those in the upper reach and flood plains, as well as aggradation and degradation zones, and bank erosion. Such a study primarily relies on field surveys. Chapter 10 has already discussed some aspects of channel form and pattern derived from observed cross-sections data. The current chapter focuses on the estimation of areal retreat of erosion and deposition on a decadal scale using satellite imagery.

12.2 Erosion and Deposition

The computation of Areal Retreat (measured in km2) for erosion and deposition involves digitizing features and considering differences in channel area, sandbars, and water bodies based on their tonal variations as seen in satellite images. The estimation of erosion and deposition for the entire stretch of the Kosi river is carried out on a grid basis, where the grids correspond to the main channel of the river. The map accompanying the analysis indicates the specific grid index used in the computation.

12.3 Results and Analysis

The retreat of channel banks due to erosion and deposition has been estimated on a grid-scale for four different time frames - 1977-1990, 1990-2000, 2000-2010, and 2010-2016, and the results are presented in Table 12-1. The data in the table is arranged in tabular format, and each map displays the grid-wise channel bank retreat of erosion and deposition computed for the respective time period indicated on the map. This chapter provides an analysis of the erosion and deposition behavior of the Kosi river based on these results.

Table 12-1: Computation of Areal Retreat of Erosion-Deposition on Grid Basis (in km^2)

Grid Name		1	2	3	4	5	6	7	8	9	10
River Length (Km)		6.4	24.7	24.4	30.4	26.3	23.8	20.6	45.4	50.1	16.2
1977 - 1990	Erosion (-)	-0.48	-54.82	-61.87	-9.41	-11.75	-28.72	-6.00	-53.00	-24.23	-14.31
	Deposition (+)	0.20	8.06	0.59	7.82	22.83	19.70	9.34	16.75	10.82	5.19
	Change in Sandbar	0.60	104.70	60.80	-30.10	11.60	37.50	-4.20	-184.00	-20.90	2.00
	Net	0.32	57.94	-0.49	-31.68	22.68	28.48	-0.85	-220.24	-34.32	-7.13
1990 - 2000	Erosion (-)	-0.02	-2.39	-4.73	-2.78	-58.24	-94.74	-10.33	-14.83	-17.65	-7.86
	Deposition (+)	0.30	11.08	16.47	10.08	3.04	1.42	0.72	19.36	36.96	11.59
	Change in Sandbar	-0.50	-57.30	-18.10	48.60	45.30	74.70	7.00	-8.00	-8.10	-0.20
	Net	-0.22	-48.62	-6.36	55.90	-9.90	-18.62	-2.61	-3.47	11.21	3.53
2000 - 2010	Erosion (-)	-0.19	-1.72	-12.29	-11.34	-9.84	-2.12	-3.49	-8.90	-32.69	-5.49
	Deposition (+)	0.66	103.05	60.25	17.95	45.23	33.20	1.53	20.58	19.42	13.03
	Change in Sandbar	-0.80	-23.70	-25.20	-12.10	-21.00	-17.10	-15.00	-9.60	22.00	-0.50
	Net	-0.33	77.63	22.76	-5.49	14.39	13.99	-16.96	2.08	8.73	7.04
2010 - 2016	Erosion (-)	-0.15	-3.20	-5.82	-1.27	-5.40	-9.50	-1.79	-11.19	-6.82	-6.55
	Deposition (+)	0.14	2.04	10.80	18.22	20.55	0.74	1.30	7.18	49.04	9.05
	Change in Sandbar	1.00	2.90	8.60	-48.20	-6.70	12.10	25.70	17.40	-28.10	-0.80
	Net	0.99	1.74	13.57	-31.25	8.44	3.34	25.21	13.39	14.12	1.70

12.4 Interpretation of Data

The following conclusions have been drawn from erosion and deposition analysis:

A. The area covered by grid numbers 1 and 2, spanning from 0 to 31 km on the reference line (which is based on the average of the 1977, 1990, 2000, 2010, and 2016 river centreline), suggests erosion occurred between 1990-2000 in Nepal, while deposition was observed during other periods. Overall, a net erosion of 49 sq. km and a deposition of 139 sq. km were estimated for all periods.

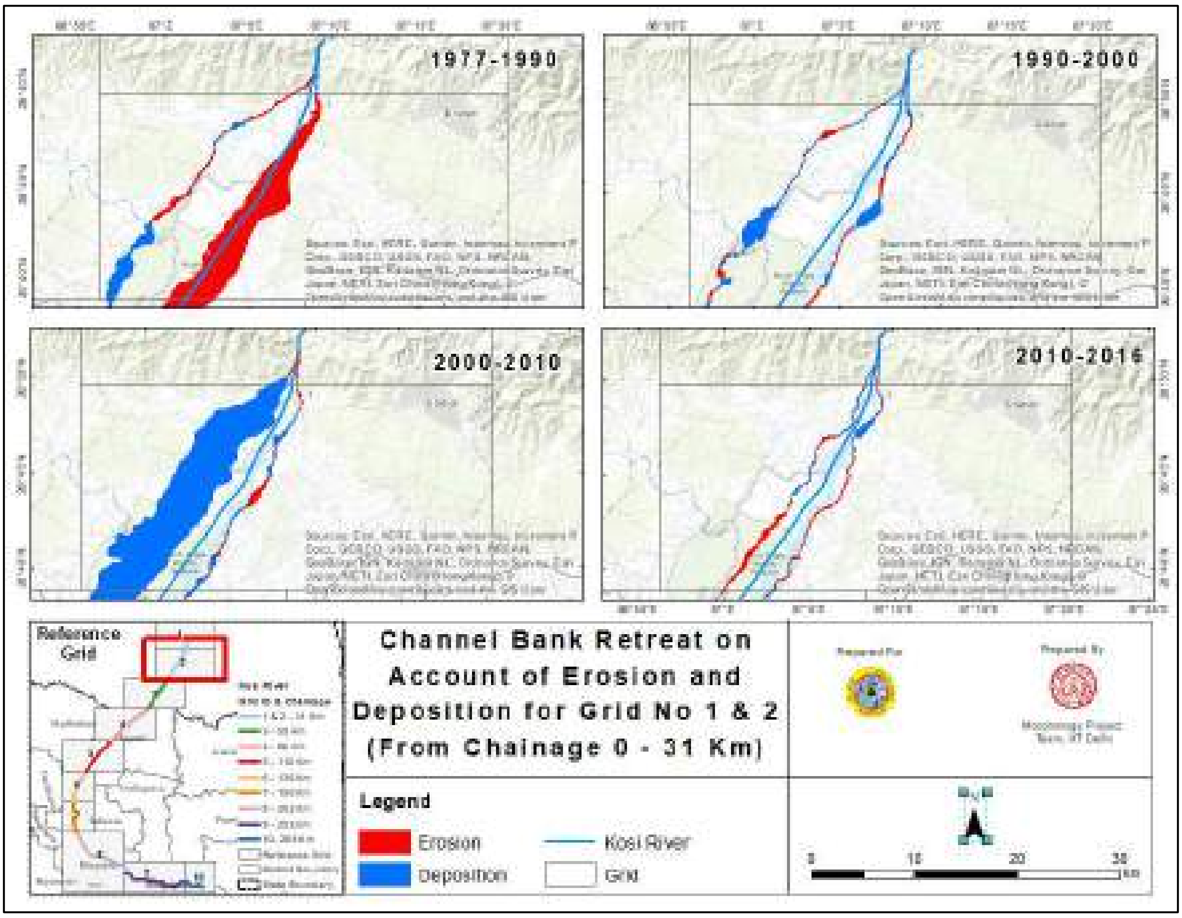


Figure 12-1: Channel Bank Retreat on Account of Erosion and Deposition for Grid 1 and 2

B. Grid number 3 covers the stretch of the Kosi River from 31 to 55 km. This grid is divided equally between Nepal and India and includes the Kosi Barrage, which is a dam constructed on the Kosi River near the India-Nepal border in 1959. The purpose of the dam is to regulate and control the flow of the Kosi River, which is prone to flooding during monsoon season.

During the periods of 1977-1990 and 1990-2000, this section of the river experienced erosion, while deposition was observed during 2000-2010 and 2010-2016. Overall, a net erosion of 7 sq. km and a deposition of 36 sq. km were estimated for all periods.

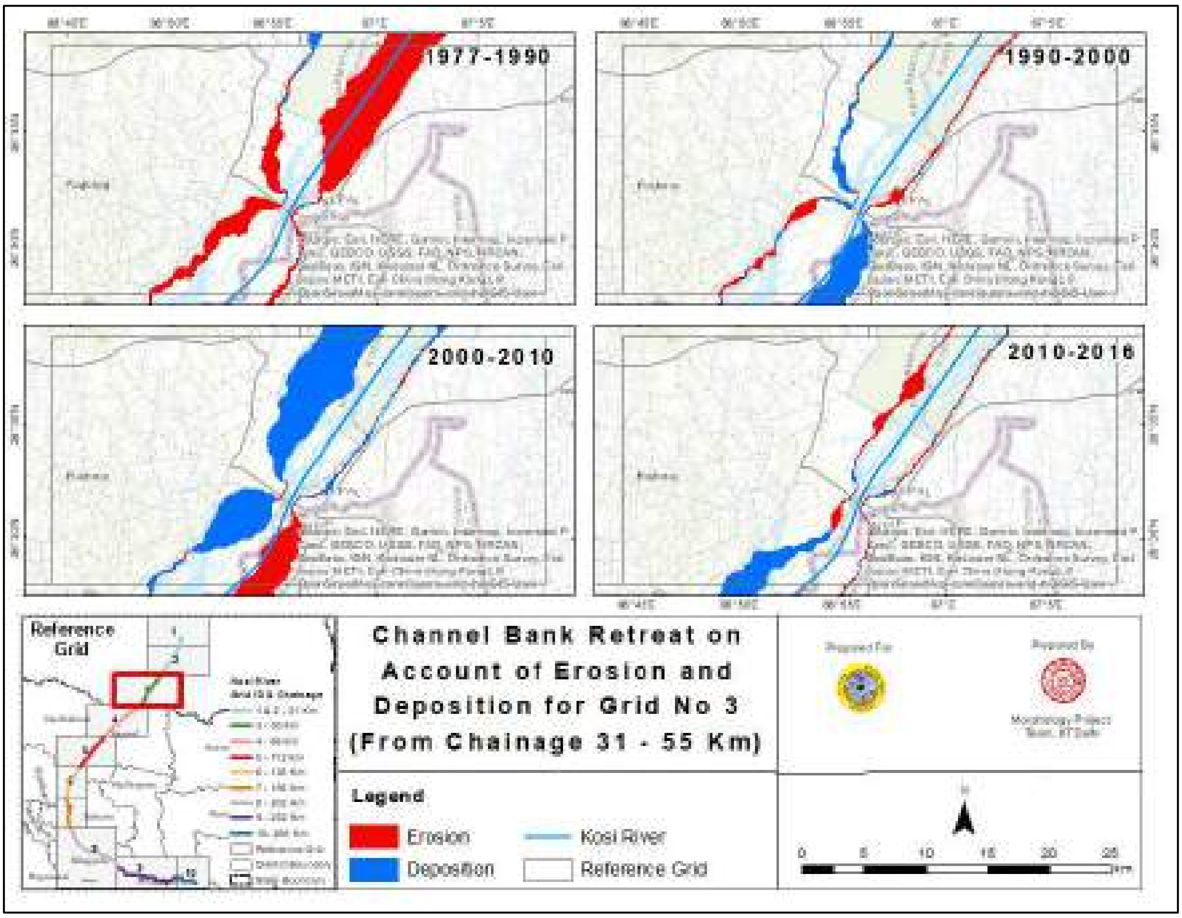


Figure 12-2: Channel Bank Retreat on Account of Erosion and Deposition for Grid 3

C. Grid number 4 encompasses a section of the Kosi River spanning 55 to 86 km, with the majority of the grid located in Bihar's Supaul district and the remaining portion in Madhubani district. Between 1977-1990, 2000-2010 and 2010-2016 this river segment encountered erosion, whereas deposition occurred during 1990-2000. Collectively, there was an estimated net erosion of 68 sq. km and a deposition of 56 sq. km over all time periods.

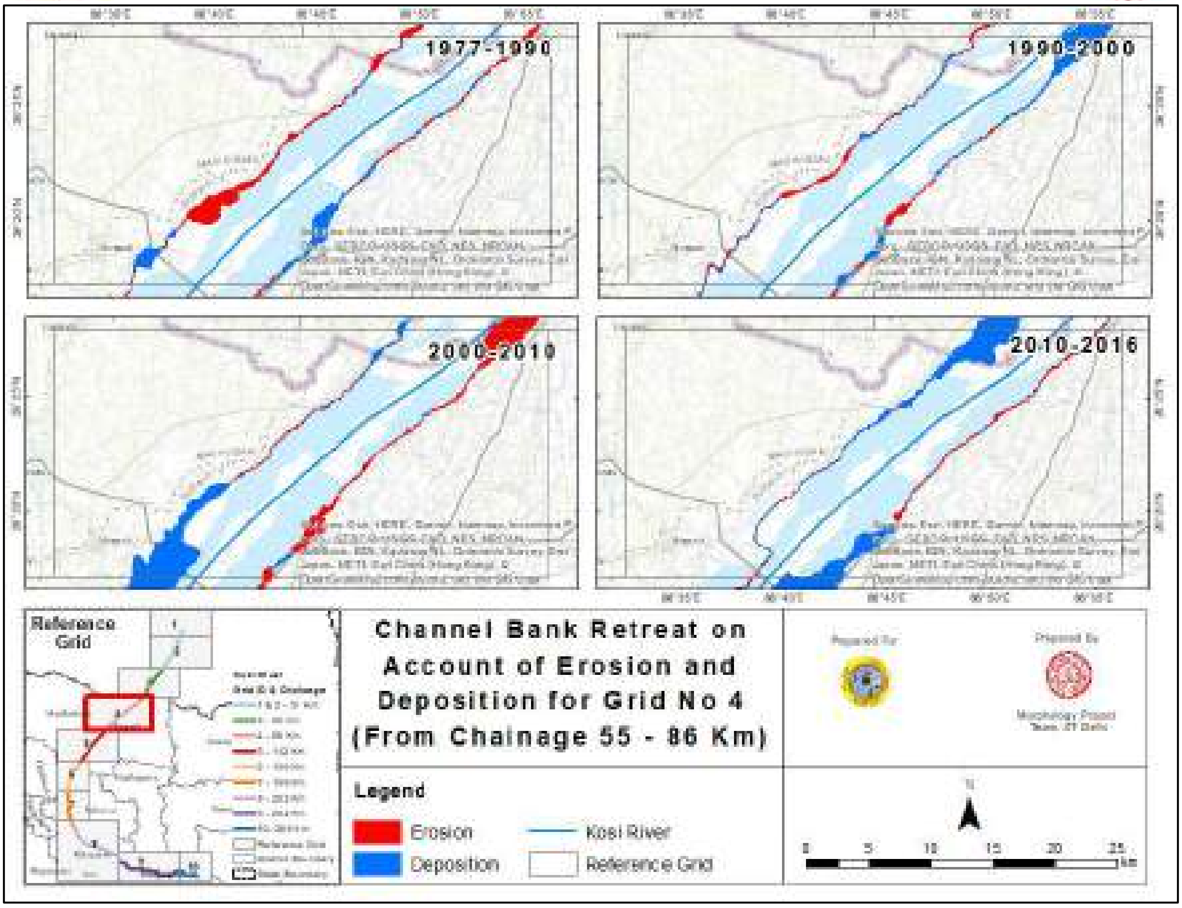


Figure 12-3: Channel Bank Retreat on Account of Erosion and Deposition for Grid 4

D. The area covered by grid number 5 comprises a stretch of the Kosi River ranging from 86 to 112 km. Most of this grid lies in Bihar's Supaul district, with the remainder located in Madhubani district. Erosion was only observed during the 1990-2000 period, while deposition occurred in all other time periods for this river segment. In total, there was an estimated net erosion of 10 sq. km and a deposition of 46 sq. km across all time frames.

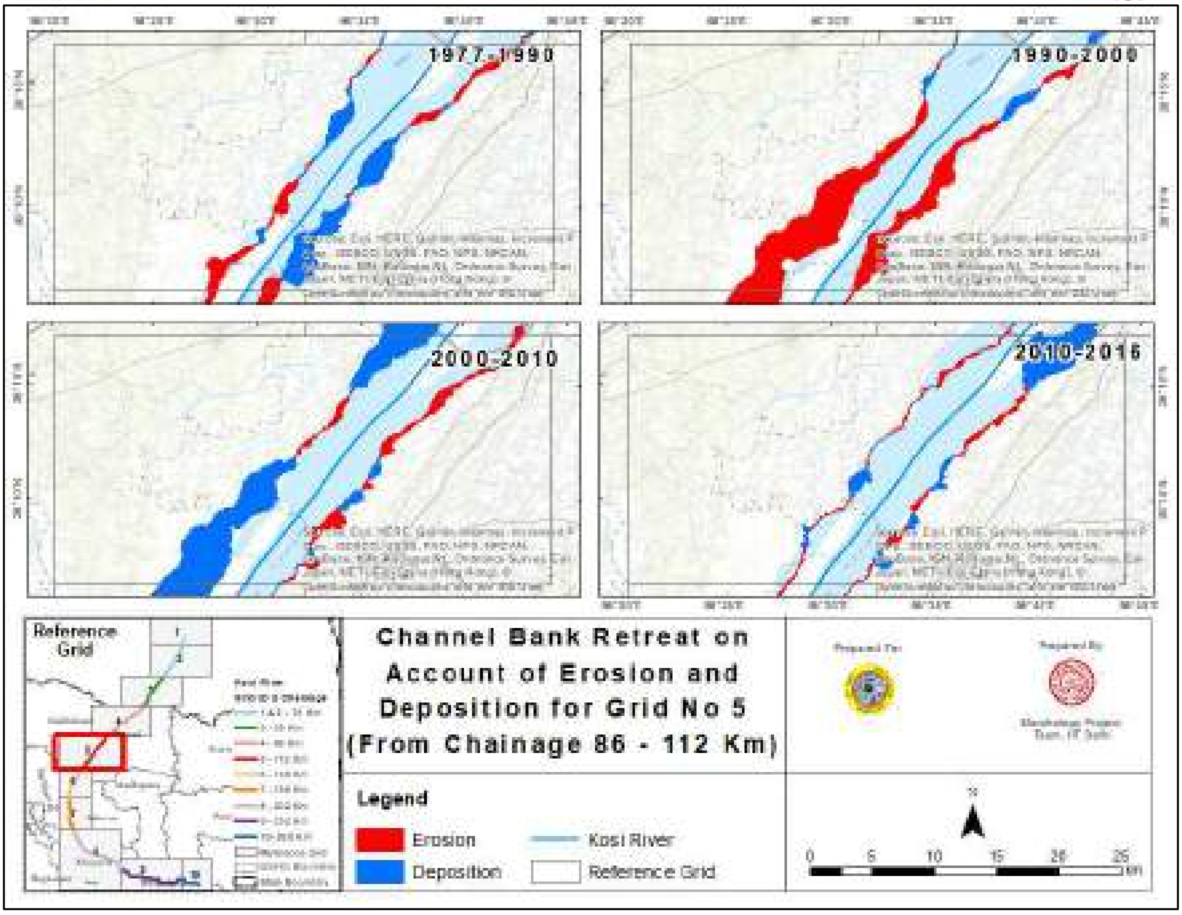


Figure 12-4: Channel Bank Retreat on Account of Erosion and Deposition for Grid 5

E. Grid number 6 covers a section of the Kosi River spanning from 112 to 136 km. The majority of this grid is located in Bihar's Saharsa district, with the remaining portion situated in Darbhanga, Madhubani, and Supaul districts. Erosion was only observed during the 1990-2000 period, while deposition occurred in all other time periods for this river segment. Overall, there was an estimated net erosion of 19 sq. km and a deposition of 28 sq. km across all time frames.

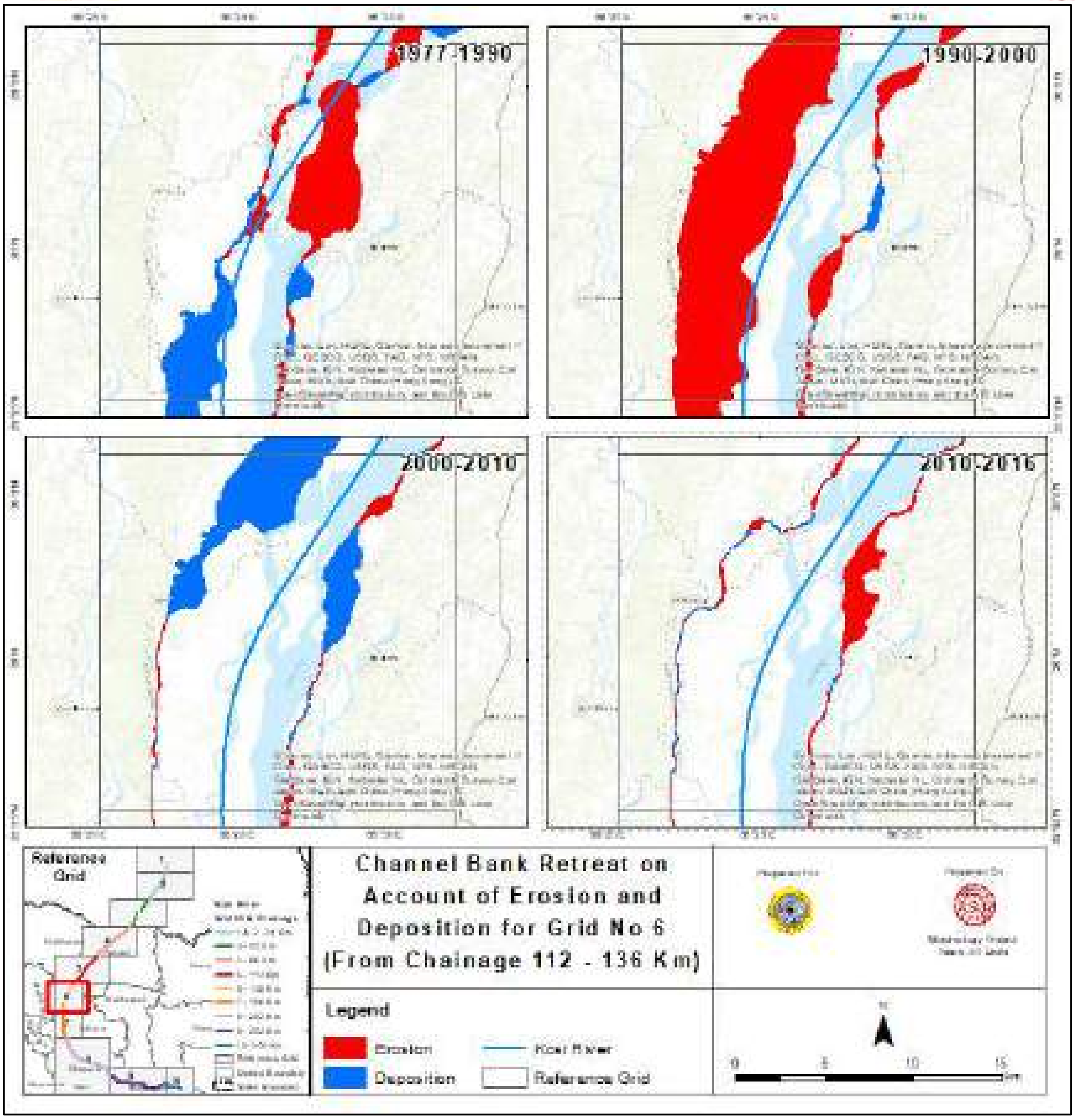


Figure 12-5: Channel Bank Retreat on Account of Erosion and Deposition for Grid 6

F. Grid number 7 covers a section of the Kosi River spanning from 136 to 156 km. The majority of this grid is located in Bihar's Saharsa district, with the remaining portion situated in Darbhanga district. Deposition was observed during 2010-2016 period, while erosion occurred in the period rest of the three periods, viz. 1977- 1990, 1990-2000 and 2000-2010 for this river segment. Overall, there was an estimated net erosion of 20 sq. km and a deposition of 25 sq. km across all time frames.

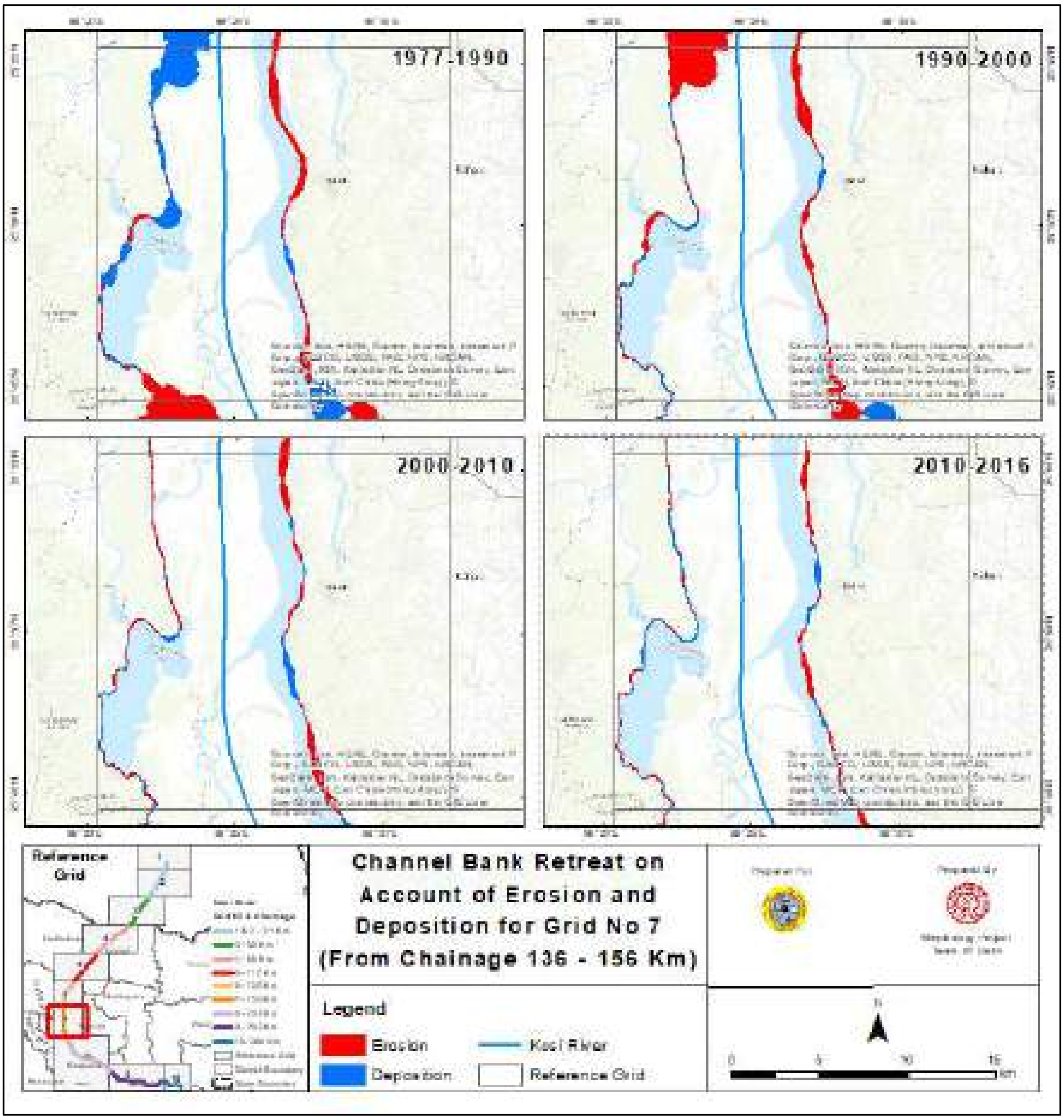


Figure 12-6: Channel Bank Retreat on Account of Erosion and Deposition for Grid 7

G. Grid number 8 encompasses a section of the Kosi River ranging from 156 to 202 km. The majority of this grid is situated in Bihar's Khagaria district, with the remaining portion located in Saharsa, Munger, and Begusarai districts. Erosion was observed during both the 1997-1990 and 1990-2000 periods, while deposition occurred during the 2000-2010 and 2010-2016-time frames for this river segment. Overall, there was an estimated net erosion of 224 sq. km and a deposition of 13 sq. km across all periods.

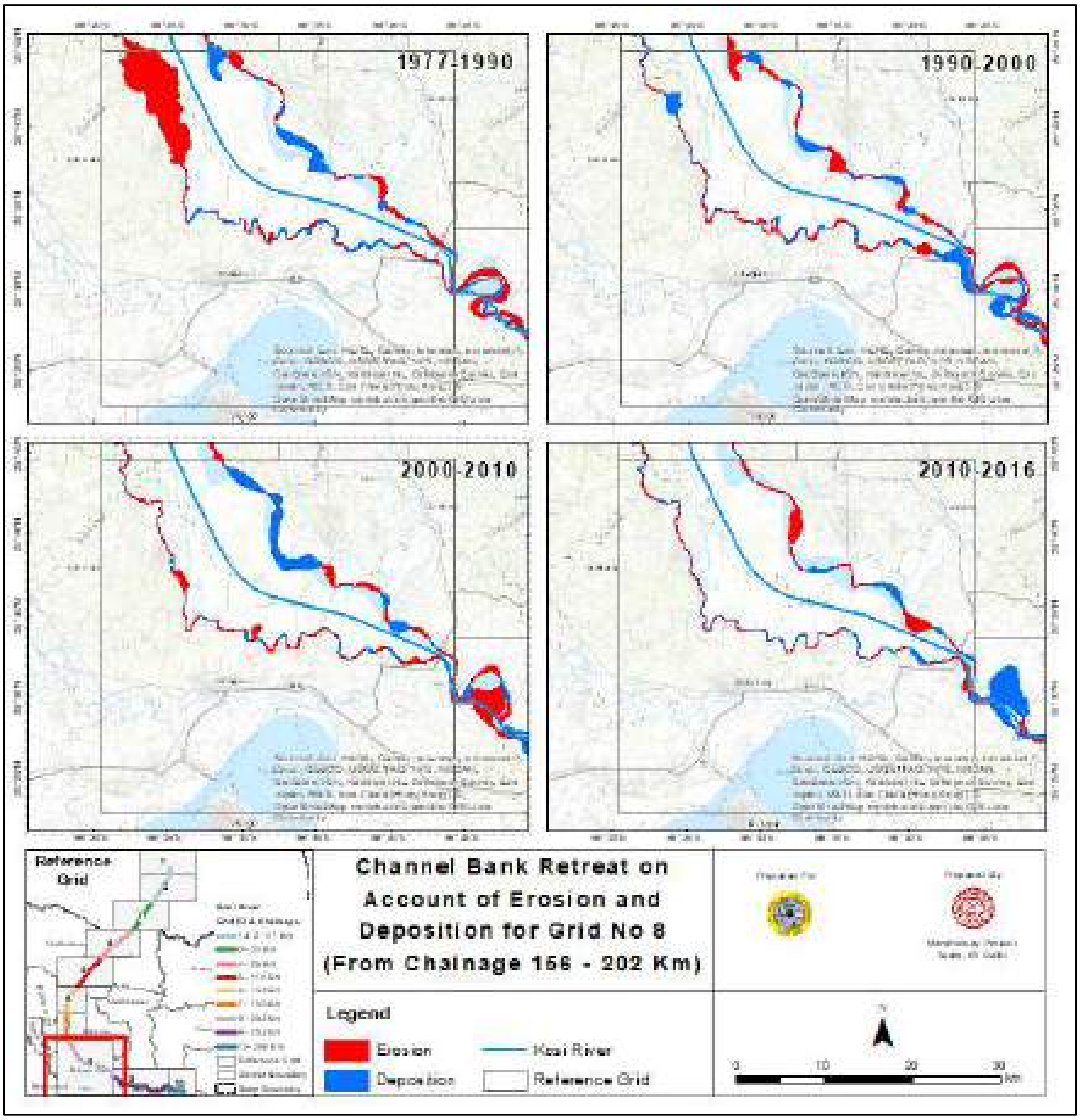


Figure 12-7: Channel Bank Retreat on Account of Erosion and Deposition for Grid 8

H. Grid number 9 includes a section of the Kosi River ranging from 202 to 252 km. The majority of this grid is situated in Bihar's Madhepua and Bhagalpur districts, with the remaining portion located in Khagaria and Purnia districts. Erosion was observed during both the 1977-1990, while deposition occurred during the other time frames for this river segment. Overall, there was an estimated net erosion of 34 sq. km and a deposition of 34 sq. km across all periods.

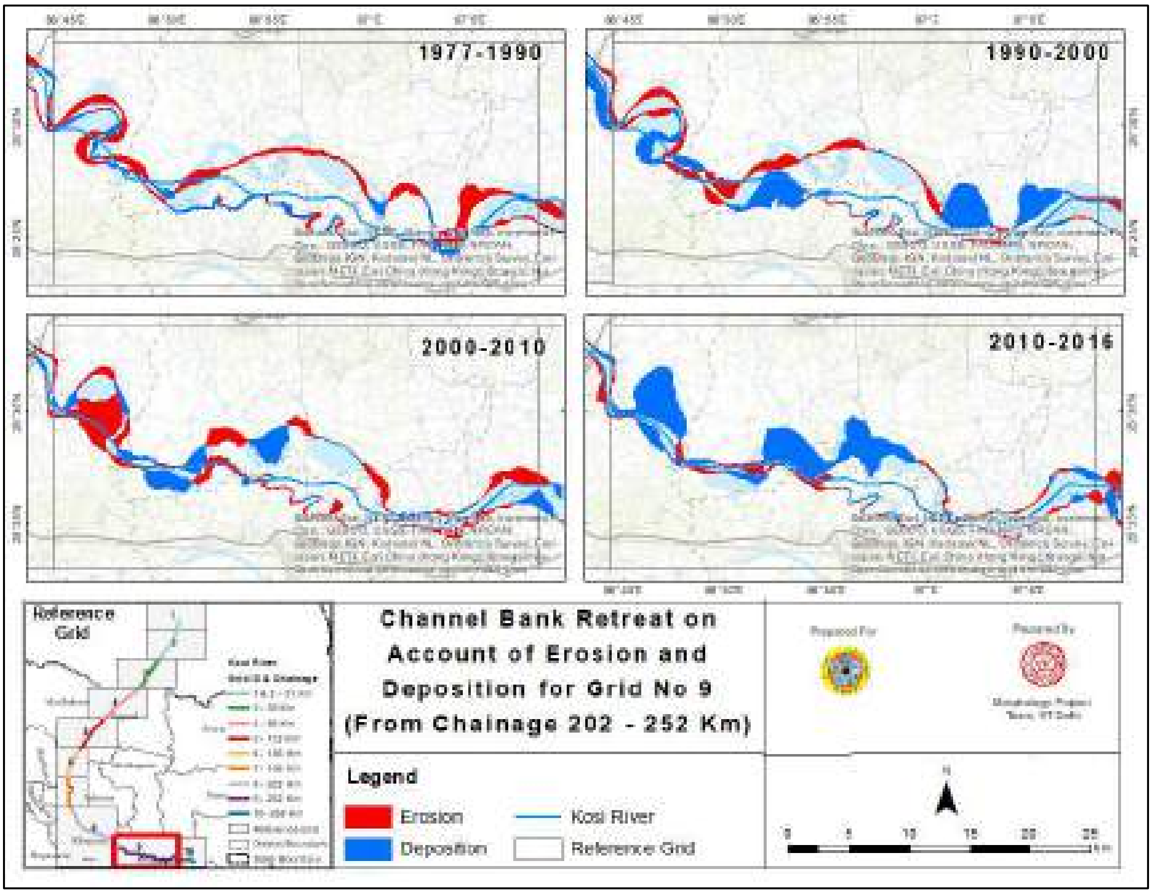


Figure 12-8: Channel Bank Retreat on Account of Erosion and Deposition for Grid 9

I. Grid number 10 encompasses the final stretch of the Kosi River, spanning from 252 to 268 km. Most of this grid is situated in Bihar's Kaithar district, with the remainder located in Bhagalpur and Purnia districts. Erosion was only observed during the 1977-1990 period, while deposition occurred in all other time frames for this river section. Collectively, there was an estimated net erosion of 7 sq. km and a deposition of 12 sq. km across all time periods.

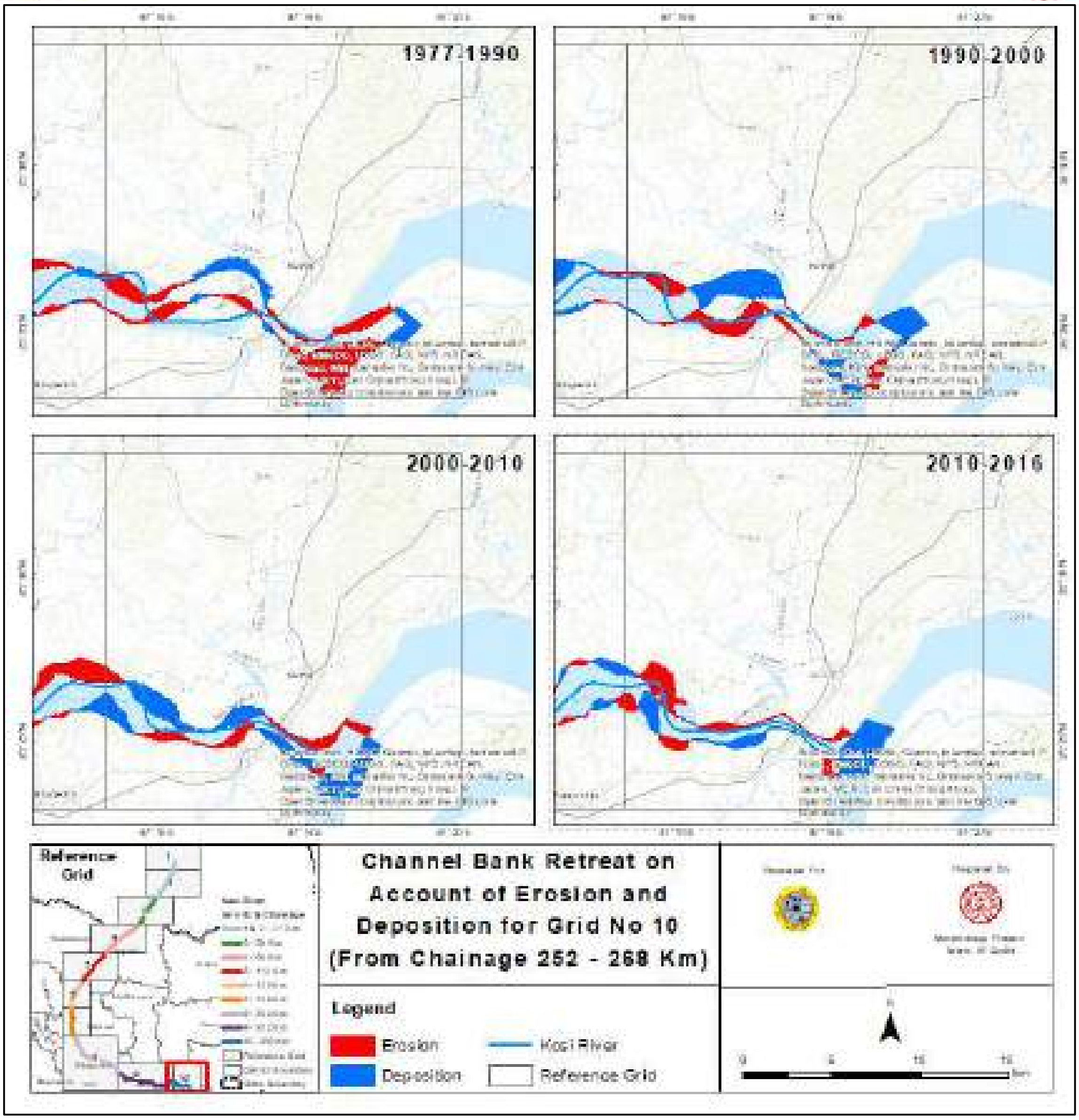


Figure 12-9: Channel Bank Retreat on Account of Erosion and Deposition for Grid 10

12.5 Aggradation and Degradation

To examine the aggradation and degradation of the river over a period of up to ten years, available cross-sections data from selected CWC sites (depicted in Figure 12.10) have been utilized. The Kosi River cross-sections are accessible at nine gauging stations, specifically Bhawanipur Village, Bishnupuria Village, Doudpur Village, Hariom Village, Jahangirpur, Kursela Bridge, Jai Rampur Village, Sohara Village, and Vijay Ghat, with the data availability presented in Table 12-2.

Unfortunately, the observational data set lacks seasonal specifics such as Pre and Post-monsoon or the survey month, thereby hindering any pre or post-monsoon comparisons.

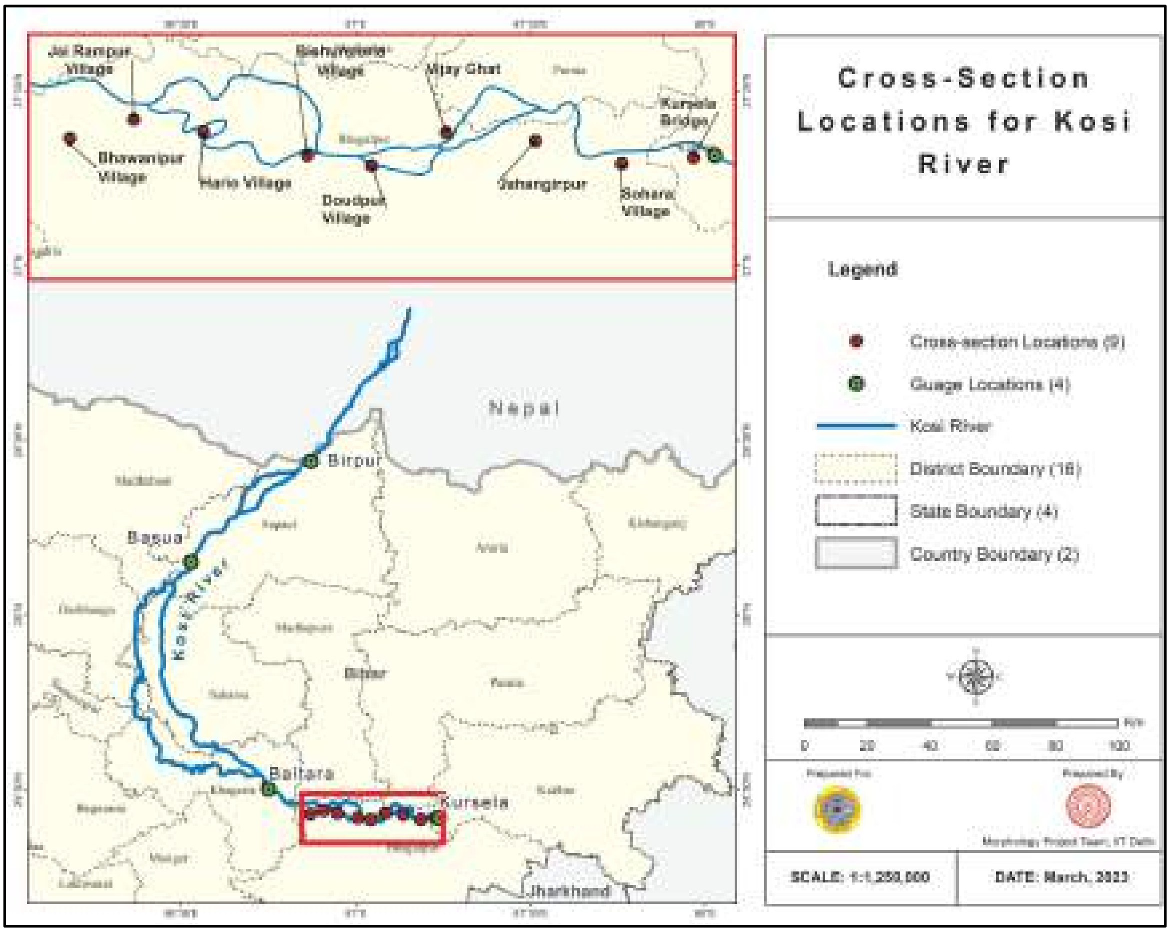


Figure 12-10: Hydrological Observation Sites for Kosi River

The cross-sections at the mentioned sites (Table 12-2) are illustrated in Figures 12-11 to 12-19, with yearly data depicted on the graph to facilitate a clear comprehension of the riverbed. The analysis of these cross-sections aids in comprehending the erosion and siltation trends along the Kosi River. The plotted cross-sections at various stations provide the following observations.

Table 12-2: Cross-section Data Availability at CWC Sites

S. No.	Station Name	Year
1	Kursela Bridge	2007-2012

Chapter 13: Major Structures and Their Impact on River Morphology

13.1 Identification of Structures

Various Structures built across the mainstream of Kosi river 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 Kosi 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 Kosi is shown in Figure 13-1.

Table 13-1. Road Bridges Across Kosi River

S. No.	Name	Average Width of Channel (Km)	Road Name	Year of Commencement
1	Kosi Barrage Bridge / Birpur-Kaushala Bridge	1.32	Mahendra Rajmarg / East-West Highway	1962
2	Kosi Bridge (Kosi Mahasetu)	6.16	NH 27 / E-W Corridor	2004
3	Baluha Ghat Kosi Bridge	7.33	Naluha Gandaul Hanti Road	2013
4	B P Mandal Bridge	1.17	Mahesh Khunt Saharsa Punia Road	1990

5	Katria Kursela Highway Bridge	0.61	Barauni Purnia Highway	Before 2005
6	Dhamara Ghat Bridge	6.05	Dahmara Road	Before 2005
7	Old MG Road Bridge	5.34	Old MG Road	
8	Vijay Ghat Bridge/ Babu Vishu Raut Setu	1.29	Mohanpur Bihari Ganj Road	

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

13.3 Railway Bridges on Kosi River

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

Table 13-2. Railway Bridges Across Kosi River

S. No.	Name	Average Width of Channel (Km)	Length of Bridge (Km)
1	Old MG Rail Bridge	5.23	0.316
2	Kosi Railway Bridge	0.54	1.88
3	Badla Ghat Bridge	6.13	1.58
4	Kosi Bridge at kursela	6.16	0.965

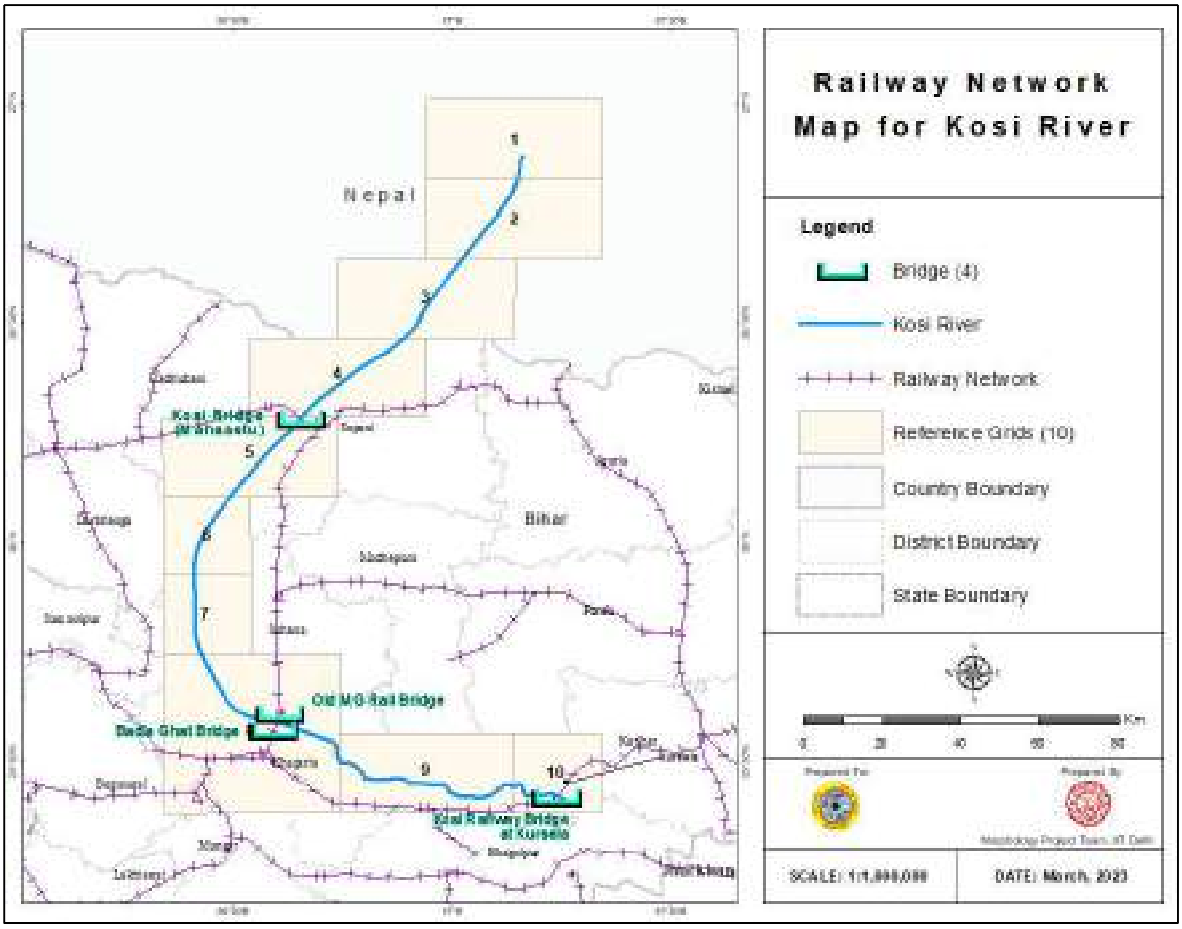


Figure 13-2: Railway Bridges and Network on Kosi River

The Birpur-Kushaha Bridge, also known as the Kosi Barrage Bridge, was built to enhance transportation and trade between India's Birpur in Bihar and Nepal's Kushaha in the Sunsari district. Its construction took place in 1994, while the Kosi Barrage was completed in 1963. Therefore, there were no significant changes observed in the years 1990, 2000, 2010, and 2016 due to the bridge, as shown in Figure 13-3.

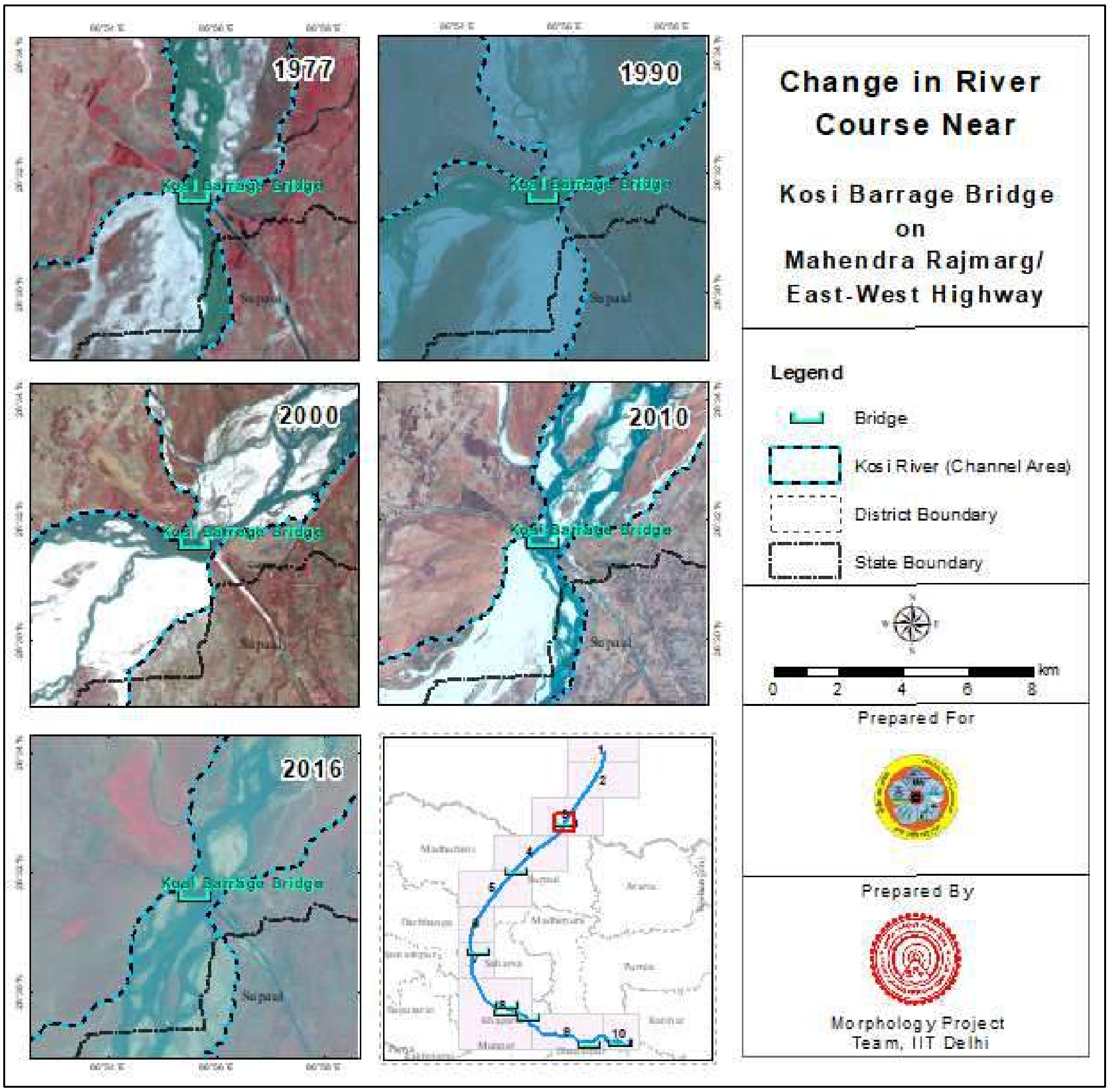


Figure 13-3: Change in River Course Near Kosi Bridge on East-West Highway

The Kosi road-cum-railway Bridge on NH27 cannot be seen in the imagery from 1977, 1990, and 2000, as illustrated in Figure 13-4. However, it becomes visible in imagery from 2000 onwards. A closer examination of the imagery reveals that the width of the river channel began to decrease from 2000 onwards as bridge piers and abutments can act as obstructions to the flow of water, causing the velocity of water to increase and leading to erosion of the riverbed downstream. This erosion can result in a narrower river channel. Nevertheless, the imagery from 2016 shows that the river downstream of the bridge has widened, potentially due to an increase in the river velocity beneath the bridge.

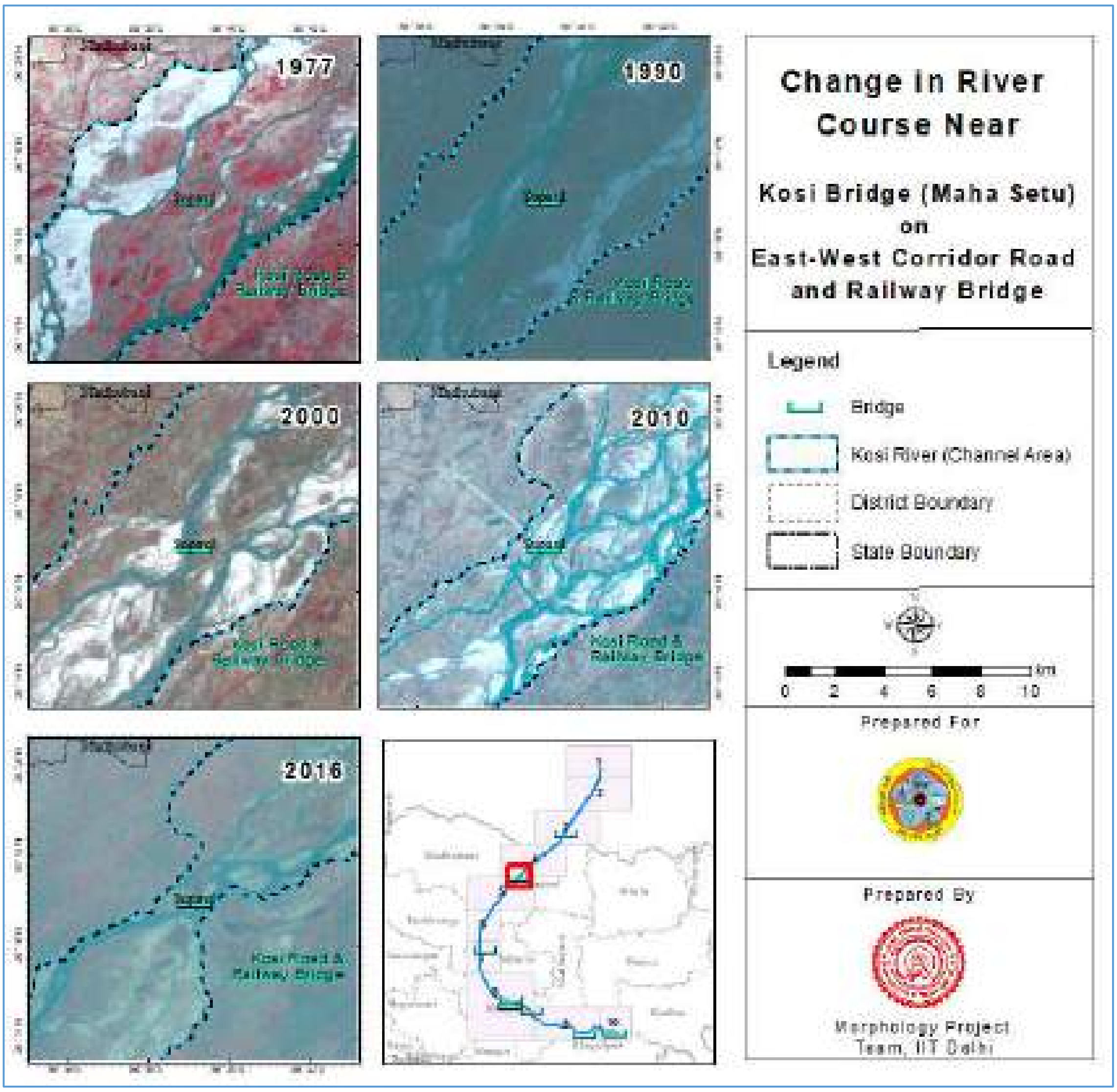


Figure 13-4: Change in River Course Near Kosi Bridge on East-West Highway

As can be seen from the Figures 13-5 not much change in river course is seen in Baluha Ghat Kosi Bridge before 2010. The river channel width have increased in width in 2016 as compared to as the bridge became operational in the year 2013, which may have caused the river channel width to increase.

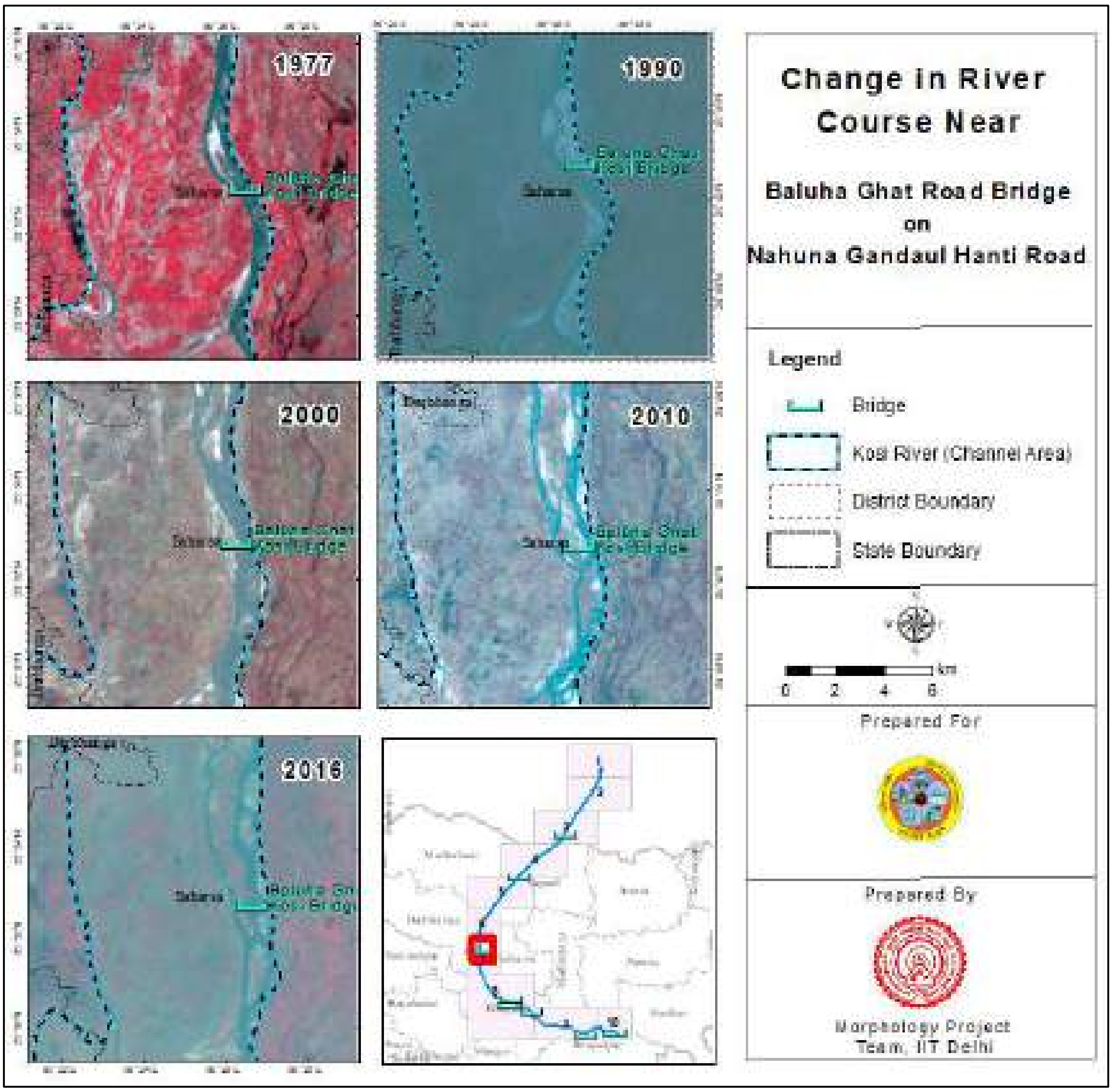


Figure 13-5: Change in River Course Near Badla Ghat Kosi Bridge on Naluha Gandaul Hanti Road

The Old MG Rail Road & Rail bridge shown in Figure 13-6 and Dhamara Ghat Bridge is shown in Figure 13-7, both the bridges are older than 1977 hence not much change in river course is observed.

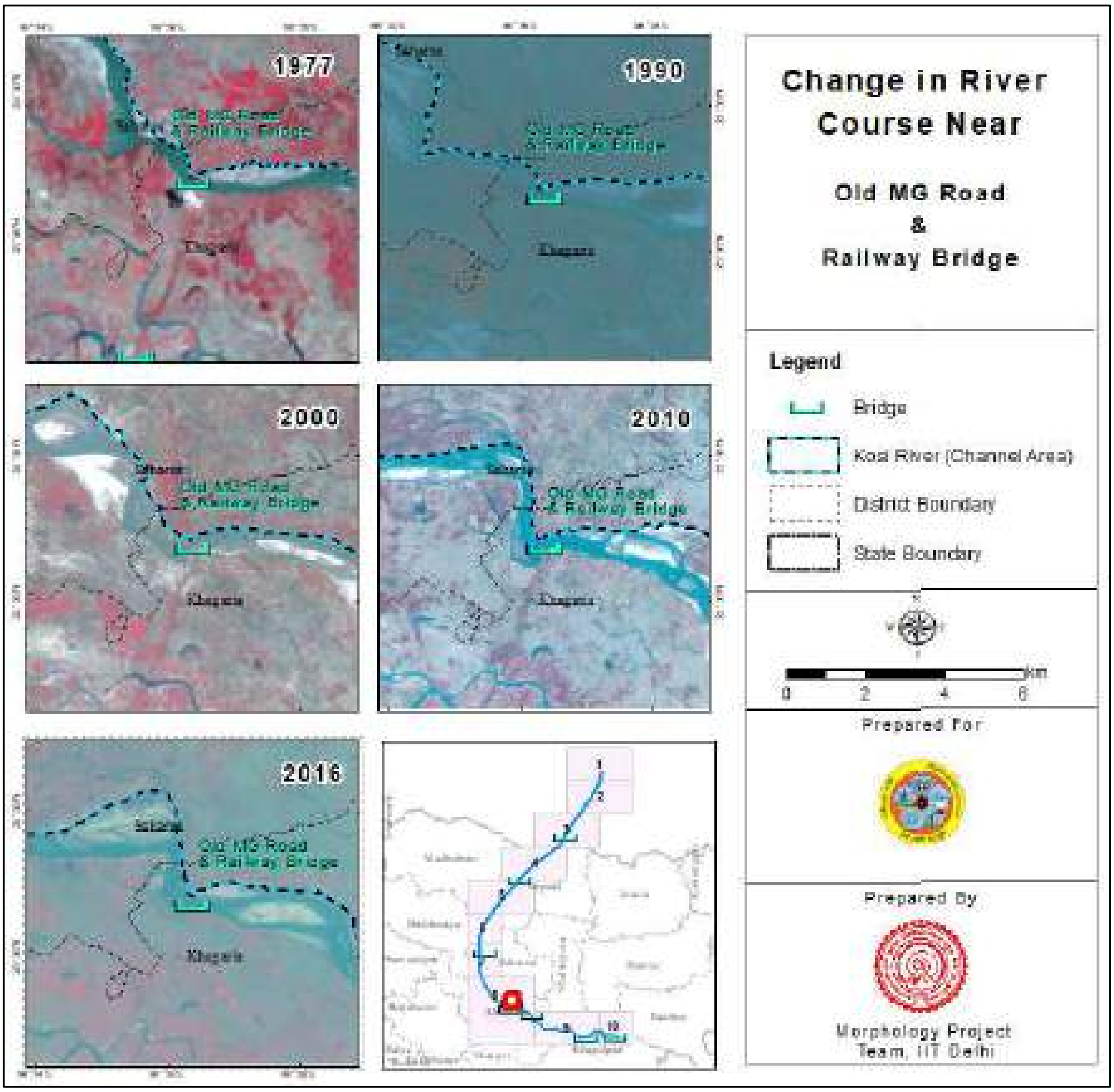


Figure 13-6: Change in River Course Near Old MG Rail Road Bridge

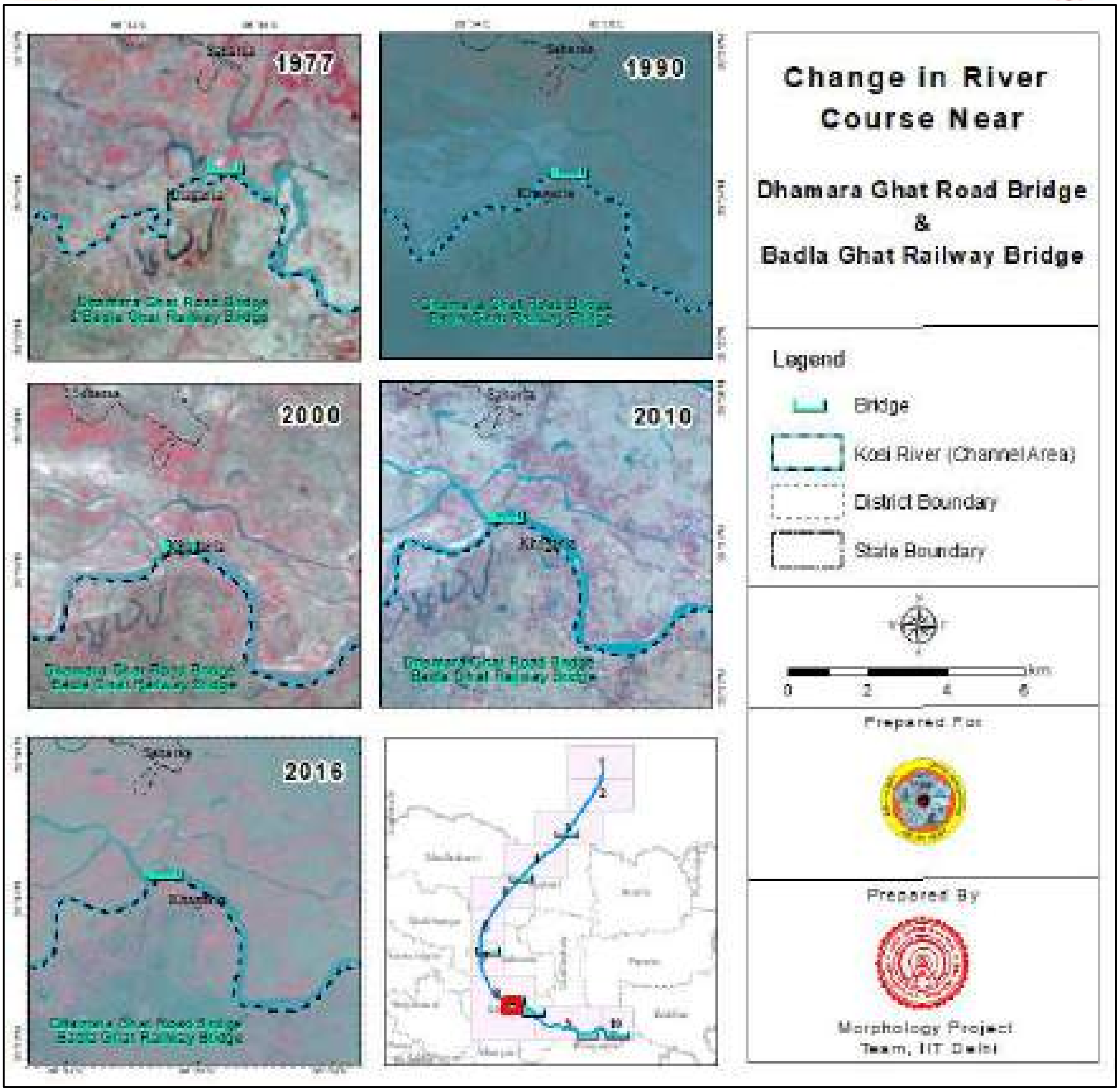


Figure 13-7: Change in River Course Near Dhamara Ghat Bridge on Dhamara Ghat Road

Figure 13-8 shows the location of BP Mandal Bridge Based on imagery from 1990 onwards, it appears that the BP Mandal Bridge was constructed after 1977. Additionally, there has been noticeable narrowing of the river channel downstream of the bridge. Bridge piers and abutments can act as obstructions to the flow of water, causing the velocity of water to increase and leading to erosion of the riverbed downstream. This erosion can result in a narrower river channel.

Also, the construction of a bridge can alters the flow of water in the river, leading to changes in the sediment deposition patterns. This can cause sediment to accumulate in the areas around the bridge piers and abutments, leading to narrowing of the river channel.

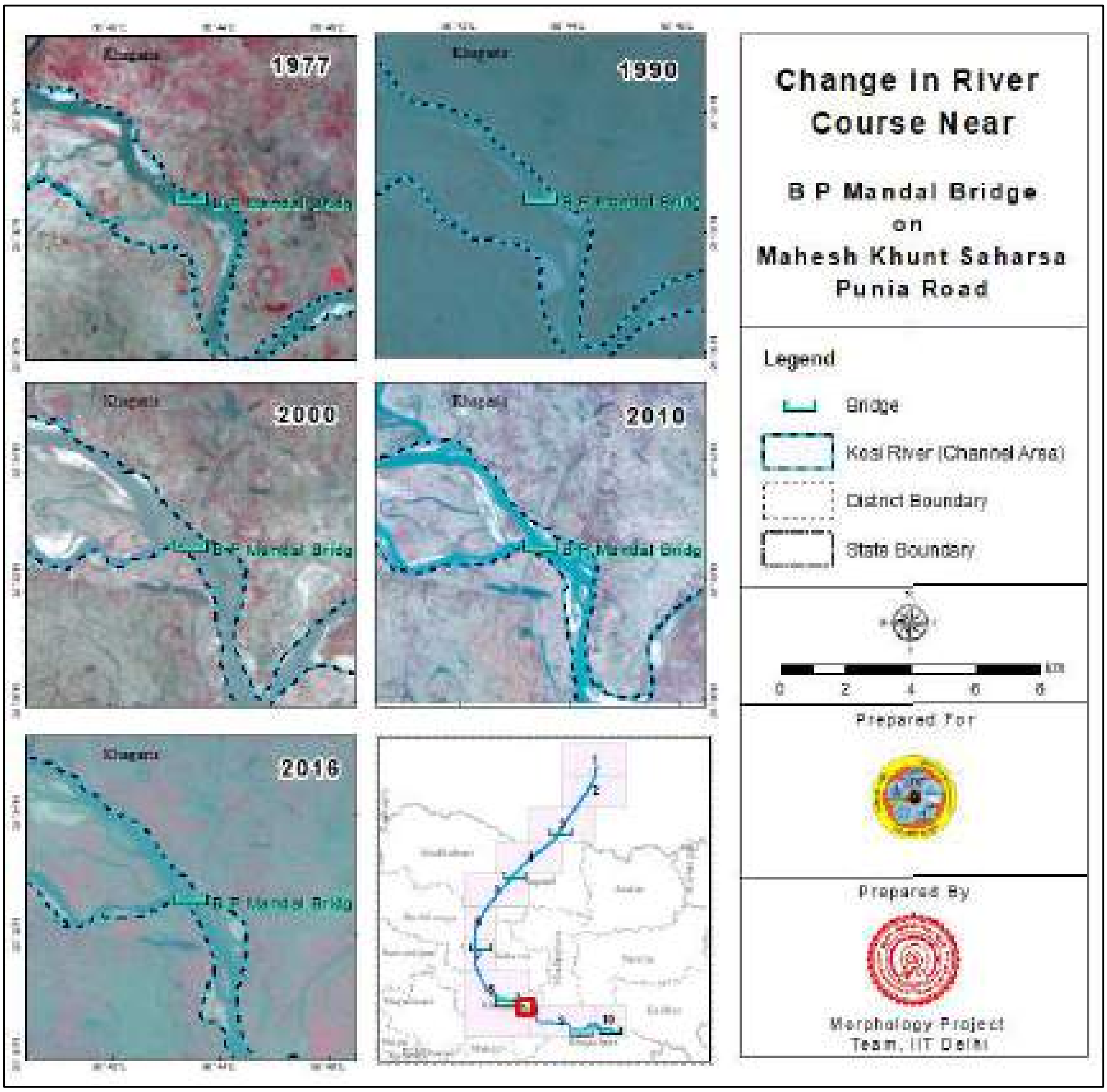


Figure 13-8: Change in River Course Near BP Mandal Bridge on Mahesh Khunt Saharsa Punia Road

The Babu Vishvaraut Setu bridge can be observed in satellite images from the year 2000 onwards. Figure 13-9 depicts that after the construction of the bridge, the river has split into two channels.

The bifurcation of the river into two parts after the construction of the Babu Vishvaraut Setu bridge could be due to several factors. One possible reason is that the construction of the bridge may have led to changes in the river's flow and direction, resulting in the river splitting into two channels. It is also possible that natural causes such as erosion, sediment deposition, or changes in water levels could have contributed to the river's bifurcation.

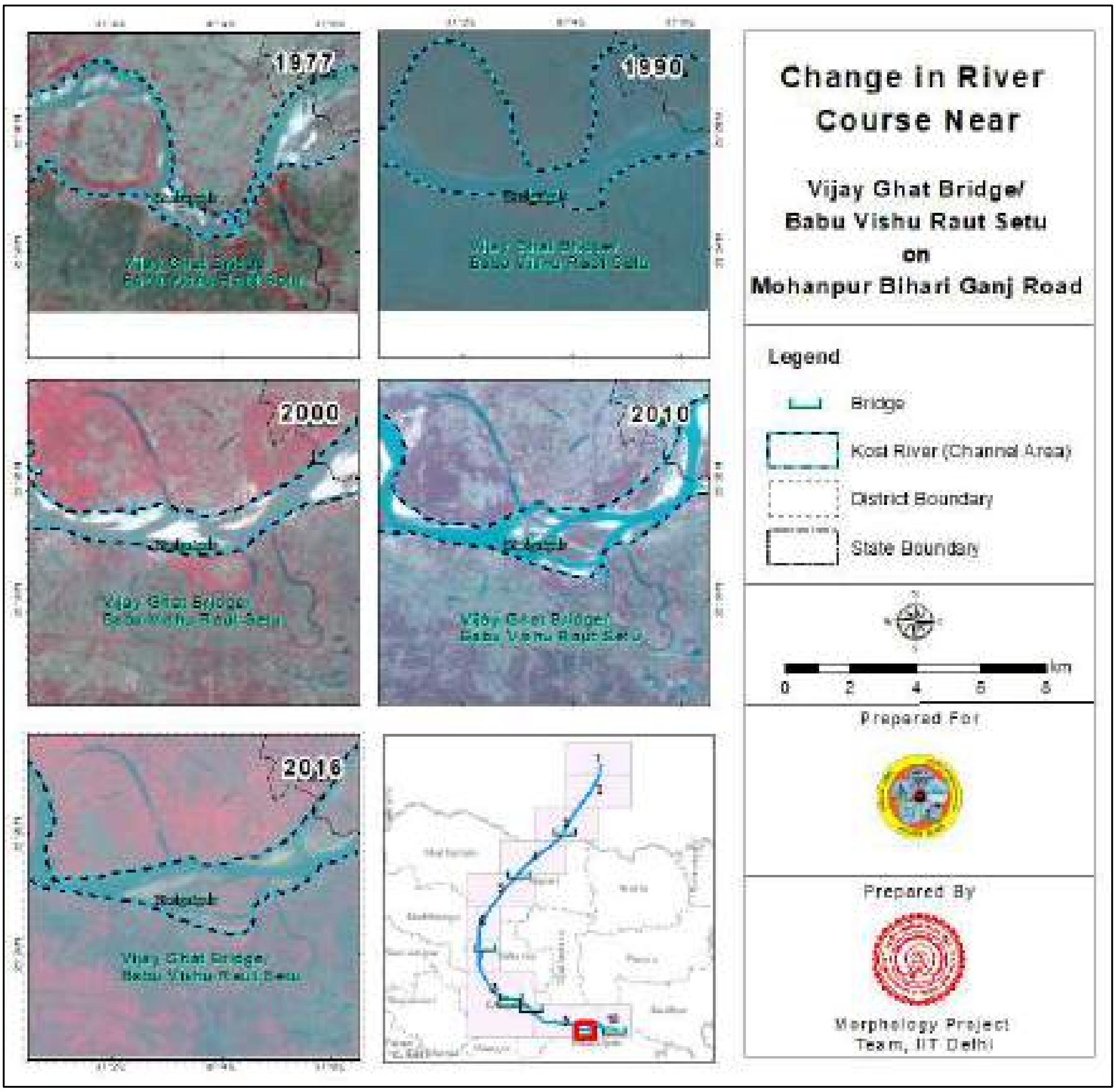


Figure 13-9: Change in River Course Near Babu Vishvaraut Setu Bridge on Mohanpur Bihariganj Road

After 1977, two bridges were constructed on the Kosi river, one for road and another for railway as shown in Figure 13-10 based on satellite imagery. The river has undergone multiple changes in its course since the construction of these bridges, which is apparent from the imagery.

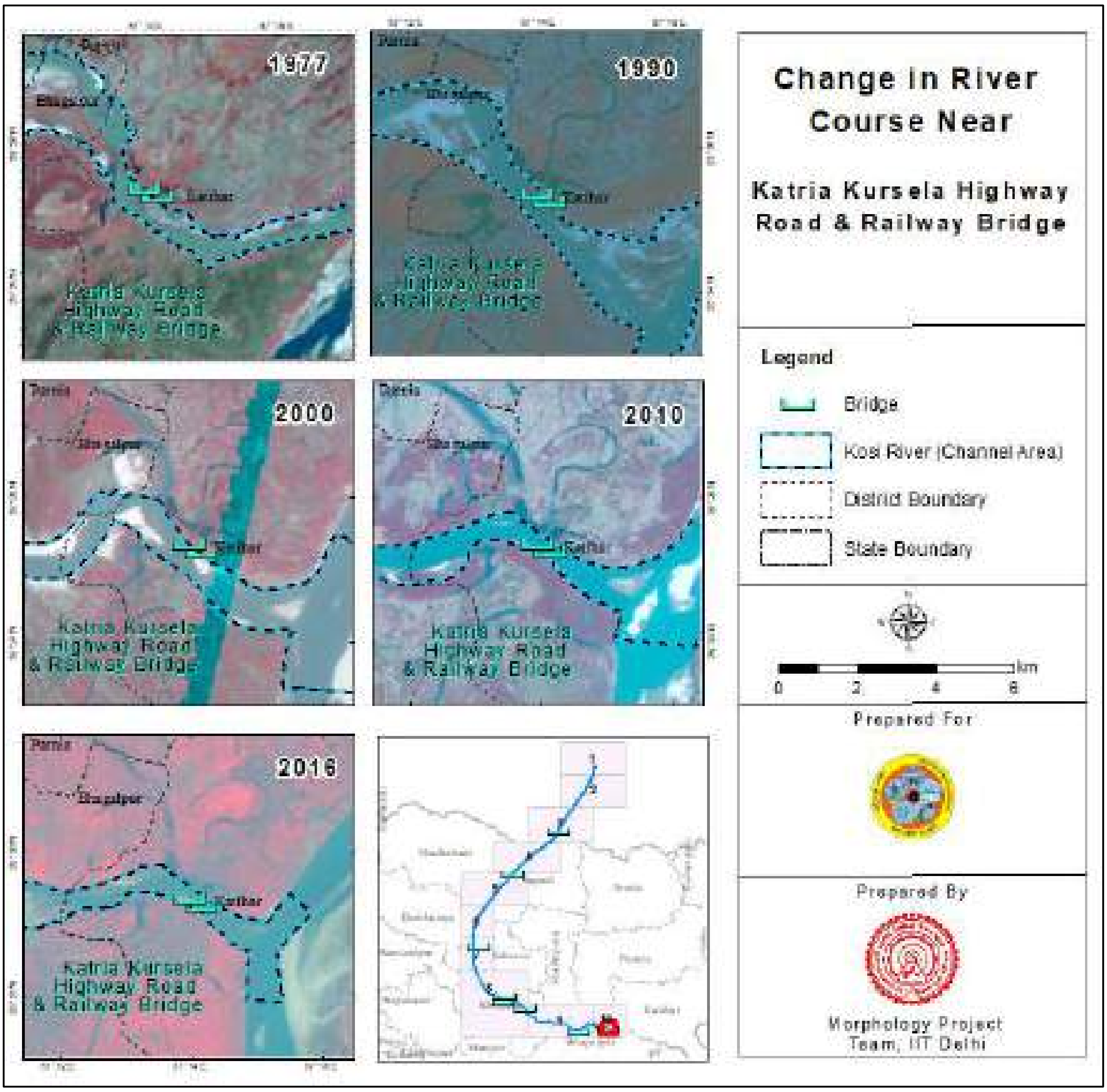


Figure 13-10: Change in River Course Near Katria Kursela Highway Bridge on Barauni Purnia Highway

The Kosi River is now spreading out its course after the construction of the Kataria Kursela Highway Bridge, causing it to change its confluence location with the Ganga River. This phenomenon could be occurring due to natural causes such as erosion and sediment deposition, or it could be a result of human activities such as construction of the bridge altering the flow and direction of the river. Further investigation is needed to determine the exact reason for this change.

13.4 Impact of Embankments

The main tributaries of Kosi river include the Sun Kosi, Arun, Tamur, Dudh Kosi, Indravati, Bhote Kosi, and Tamba Kosi Rivers. India's Flood Control Policy in 1954 and an earlier committee constituted in 1928 recommended the intensive construction of embankments throughout Indian rivers. Within two decades, the construction of dams and barrages further aggravated the erratic modifications to river flooding, in tandem with embankment effects.

The Kosi embankments were built in the mid-1950s by the Government of Bihar, India, to protect agricultural land and human settlements from the frequent flooding and erosion caused by the Kosi River. The embankments were constructed with the aim of confining the river to a narrow channel and preventing it from changing its course. The embankments were built along a stretch of approximately 260 km, from the upstream of Hanuman Nagar in Nepal to the downstream of Bhimnagar barrage in Bihar, India.

The embankments had some initial success in reducing flooding and erosion, but they also had unintended consequences. The embankments prevented the river from accessing its natural floodplains, leading to the deposition of sediment and the rise of the river bed above the surrounding floodplain. This made the river more vulnerable to breaches and catastrophic flooding during monsoon seasons. In addition, the embankments caused the river to shift its course, leading to the erosion of the river banks and the loss of land and property. Currently, we have walled the entire river. This has heightened the risk related to embankment failures, which magnifies the effects of floods and also water stagnation in places where water is unable to drain into the river, leading to chaos every year.

The Kosi River has a high sediment load, and the sediment deposition within the embanked channel caused the river bed to rise by up to 8 meters in some places. This, in turn, increased the risk of catastrophic breaches, as the embankments were not designed to contain the higher water levels that resulted from the sediment build-up. The Birpur barrage on the Kosi at the India-Nepal border and irrigation canals along the western and eastern Kosi embankments, further controlled the river flow. In the dry-season, they have now made the Kosi a water-starved river by regulating its flow regime. The extremes between which river flows fluctuated in this river were further aggravated, adding to the vulnerability of people directly dependent on river-based livelihoods.

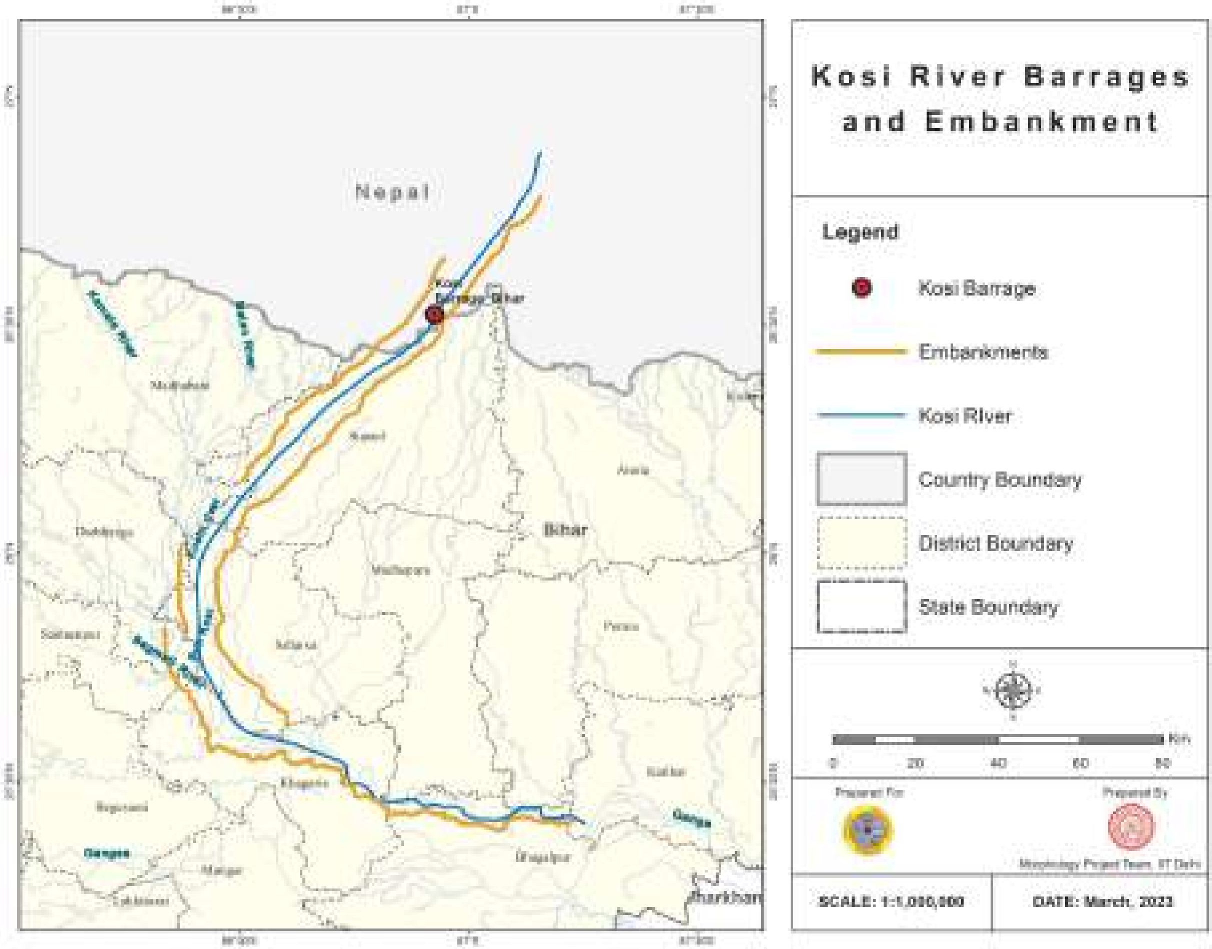


Figure 13-11: Kosi Barrage and Embankment on Kosi River

13.5 Conclusions

A. From the above observations it can be concluded that, the construction of bridges alters the natural flow of the river. The bridge acts as a barrier to the natural flow of the river, causing sedimentation upstream and erosion downstream.

B. The bridge can also increase the velocity of the water flowing under it, which can cause erosion of the river bed and banks. This can lead to increased flooding downstream and can also affect the safety of the bridge.

C. The construction of the bridge also causes maintenance issues due to the siltation and sedimentation that occurs as a result of the altered river flow. This results in the need for regular maintenance and dredging of the river bed and banks.

D. The impact of embankments on the Kosi River has been mixed, with both positive and negative impacts. While embankments can provide protection against flooding and erosion, they can also alter the natural flow of the river and lead to catastrophic breaches during floods.

E. The construction of embankments barrages and bridges requires careful planning and management to minimize negative impacts on the river and its surrounding areas.

Chapter 14: Islands and Sandbars

14.1 Islands and Sandbars

The land feature which is formed in a water body (lake, river, ocean) and 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 centreline 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, as shown in Figure 14-1; 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 Terminology Used

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 categorized into two categories: Sandbars and Islands.

Islands: Islands in a river are landforms that are completely surrounded by the water of the river. They can be formed by various geological processes such as sediment deposition and erosion. Some river islands are permanent features, while others may appear and disappear seasonally due to changes in water levels. River islands can provide important habitats for wildlife and can also be used for agriculture or recreation.

Sandbars: These are sandbars or islands that are visible in satellite imagery but are 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 or simply sandbars.

14.4 Islands and Temporary Sandbars in Kosi River

The Kosi river is known for its unique geomorphology, including its many islands and sandbars, which have significant ecological and cultural significance. Sandbars in the Kosi River play an important role in maintaining the river's ecosystem. These areas serve as habitats for a variety of plants and animals, including several rare and endangered species. They also help to regulate the river's flow, providing natural barriers that reduce erosion and prevent flooding during the monsoon season.

In addition to their ecological importance, sandbars in the Kosi River have cultural significance for the local communities that live along its banks. Many of these communities have lived on the islands and sandbars for generations, and their traditional livelihoods, such as fishing and farming, are closely tied to the river. These areas also have cultural and religious significance, with many temples and shrines located on the islands and sandbars.

However, sandbars in the Kosi River are also vulnerable to environmental and human-induced changes. The construction of dams, deforestation, and climate change are all threats that can disrupt the river's ecology and affect the livelihoods of the local communities. Ensuring that any development or human activities within and surrounding the Kosi River consider the ecological and cultural importance of its sandbars and are conducted sustainably is crucial. When the area of sandbars in a river increases, it can cause the river to change its course or shift its channel. This can occur when the sandbars obstruct the flow of water, causing it to change direction and carve out a new channel. The deposition of sediment on the sandbars can also cause the river's water levels to rise, which can lead to flooding and erosion of the surrounding land.

On the other hand, a decrease in the area of sandbars can also have an impact on the river's morphology. When the sandbars are removed or eroded, it can cause the river's flow to become faster and more turbulent. This can increase erosion of the river banks and cause the river to deepen and narrow its channel. In some cases, a decrease in sandbars and islands can also lead to a loss of habitat for plant and animal species that depend on these areas.

Table 14-1: Grid wise Sandbar Area (sqkm) for Kosi River

Year/ Reference Grid	1	2	3	4	5	6	7	8	9	10
2016	1.2	42.4	38.7	69.0	98.0	137.1	167.0	316.6	44.4	2.1
2010	0.2	39.5	30.1	117.2	104.7	125.0	141.3	299.2	72.5	2.9
2000	1.0	63.2	55.3	129.3	125.7	142.1	156.3	308.8	50.5	3.4
1990	1.5	120.5	73.4	80.7	80.4	67.4	149.3	316.8	58.6	3.6
1977	0.9	15.8	12.6	110.8	68.8	29.9	153.5	500.8	79.5	1.6

By examining Figure 14-2 and Table 14-1, it is evident that the area of sandbars significantly rose for grids 5, and 6 between 1977-2000, but declined between 2000-2010. Moreover, for grid 8, there was a notable decrease in sandbar area during the period 1977-2016, dropping from 501 sqkm in 1977 to 317 sqkm in 2016. Grid 9 shows a gradual decrease in sandbar area from 1977 to 2016, the sandbar area has almost reduced to half during this period. Grid 2 shows a significand increase in the area in the year 1990 as compared to 1977 owing to an anabranch joining the main river due to erosion. This area reduced again in 2000 - 2016 due to deposition of sand and disconnection of anabranch. Grid 3 also shows a reduction in sandbar area from 73 sqkm to 39 sqkm during the year 1990 to 2016.

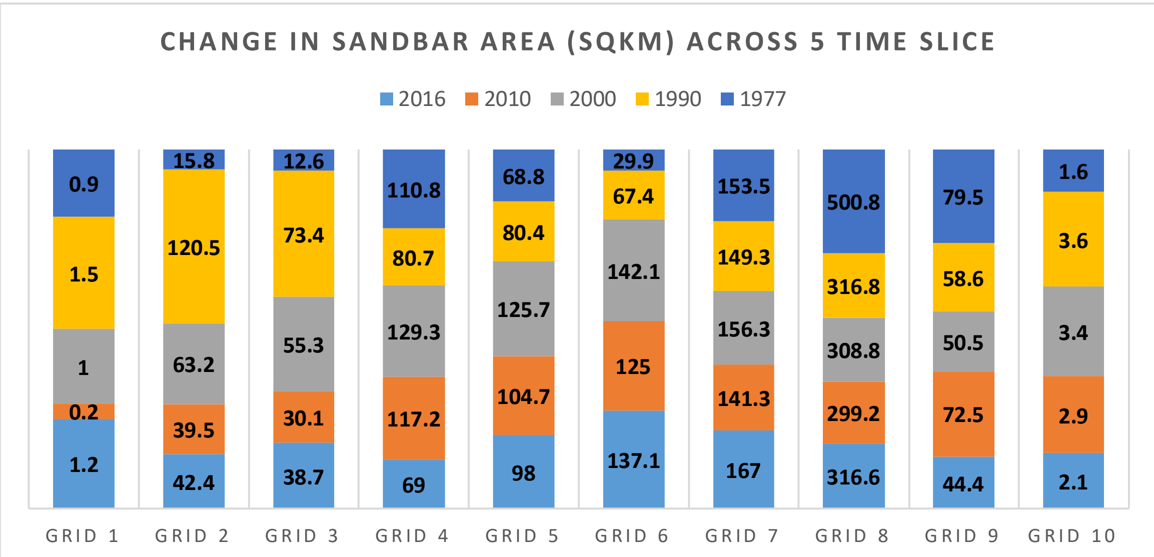


Figure 14-2: Grid wise Sandbars Area for Kosi River

Figures 14-3 to 14-11 show change in area of sandbars across the years 1977, 1990, 2000, 2010 and 2016.

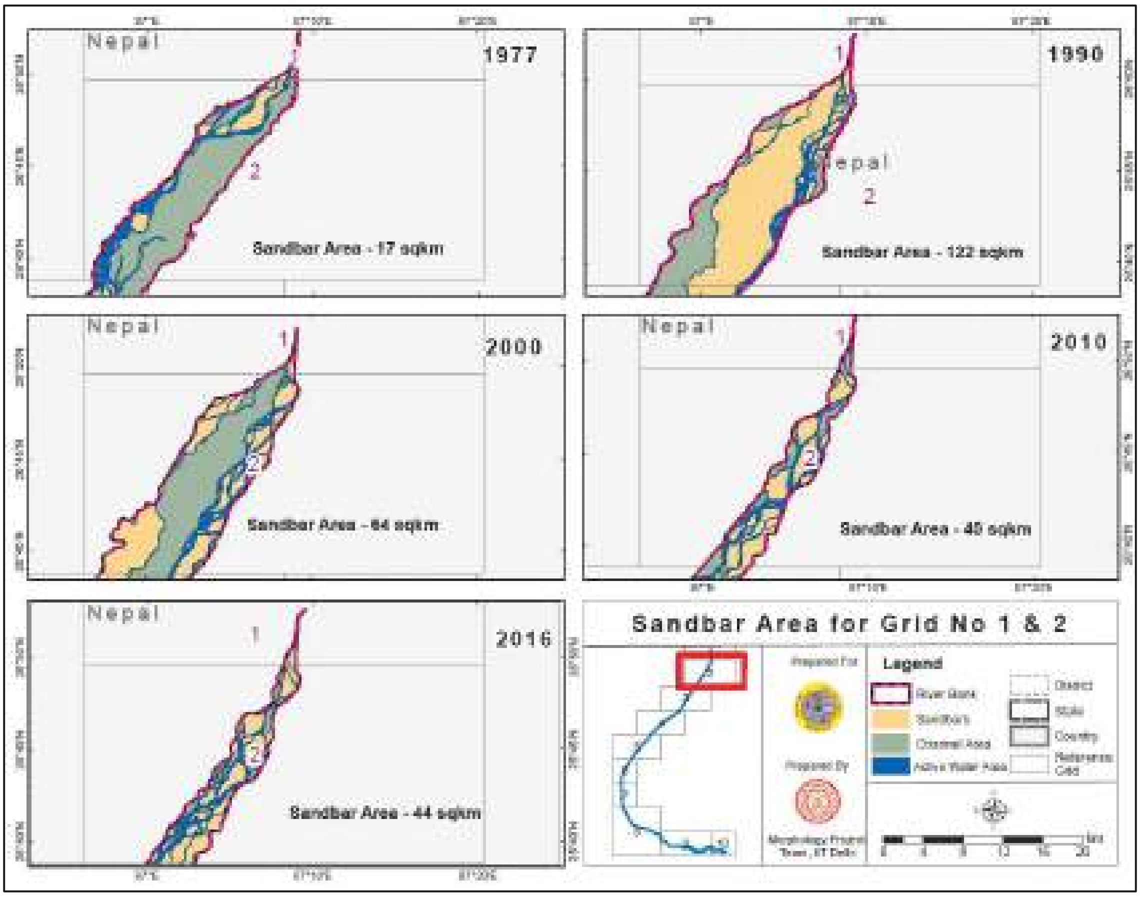


Figure 14-3: Change in Sandbar Area Across Years for Grid 1 and 2 of Kosi River

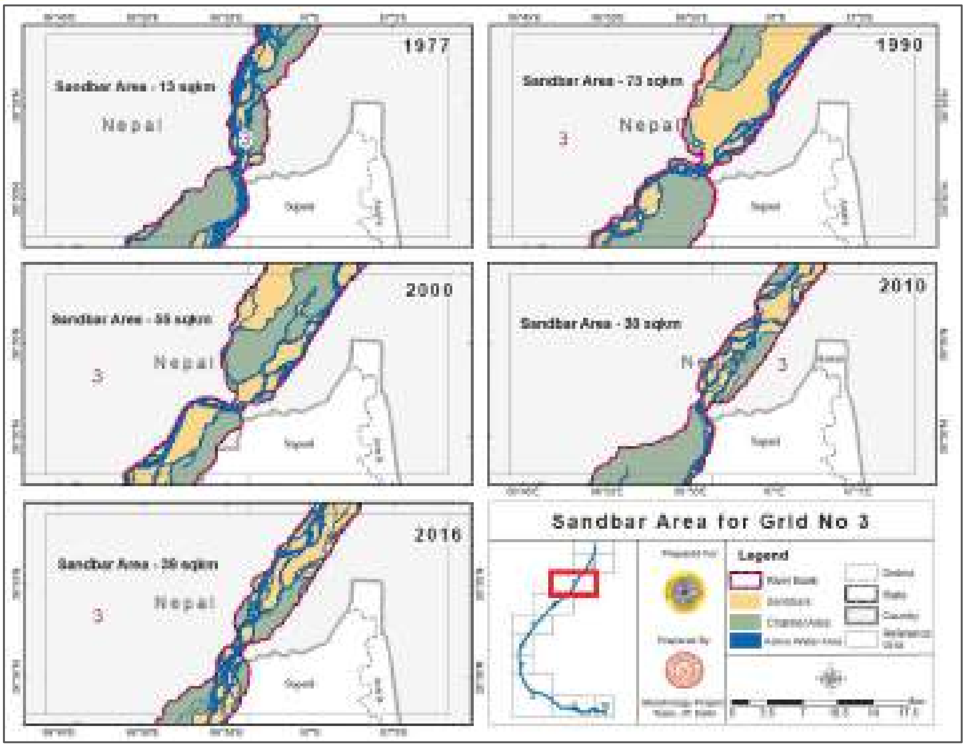


Figure 14-4: Change in Sandbars Area Across Years for Grid 3 of Kosi River

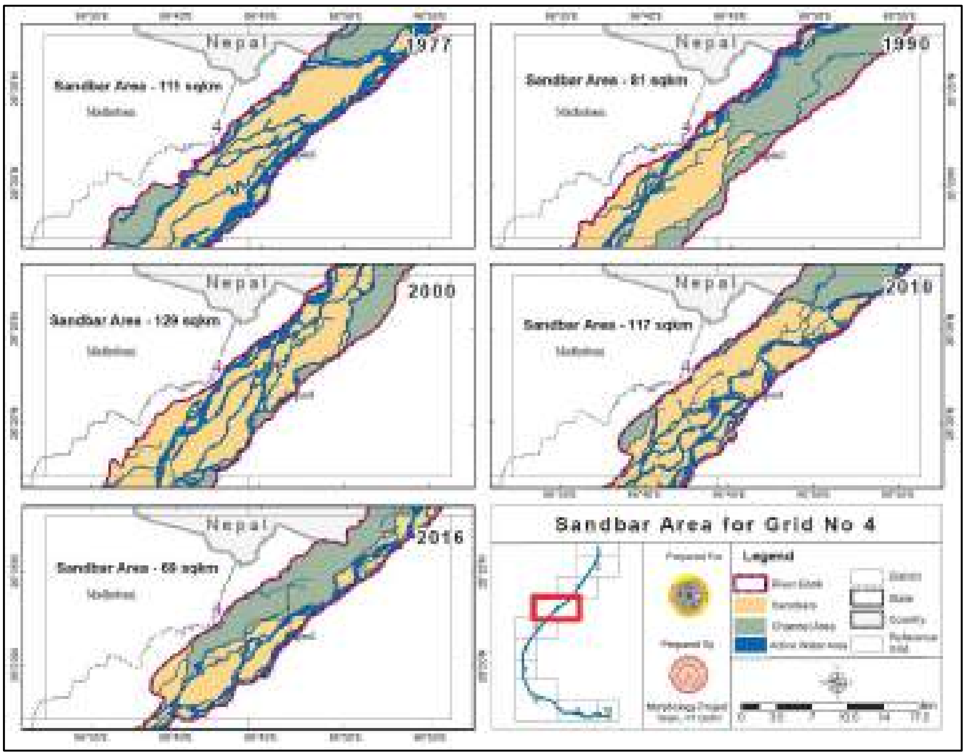


Figure 14-5: Change in Sandbars Area Across Years for Grid 4 of Kosi River

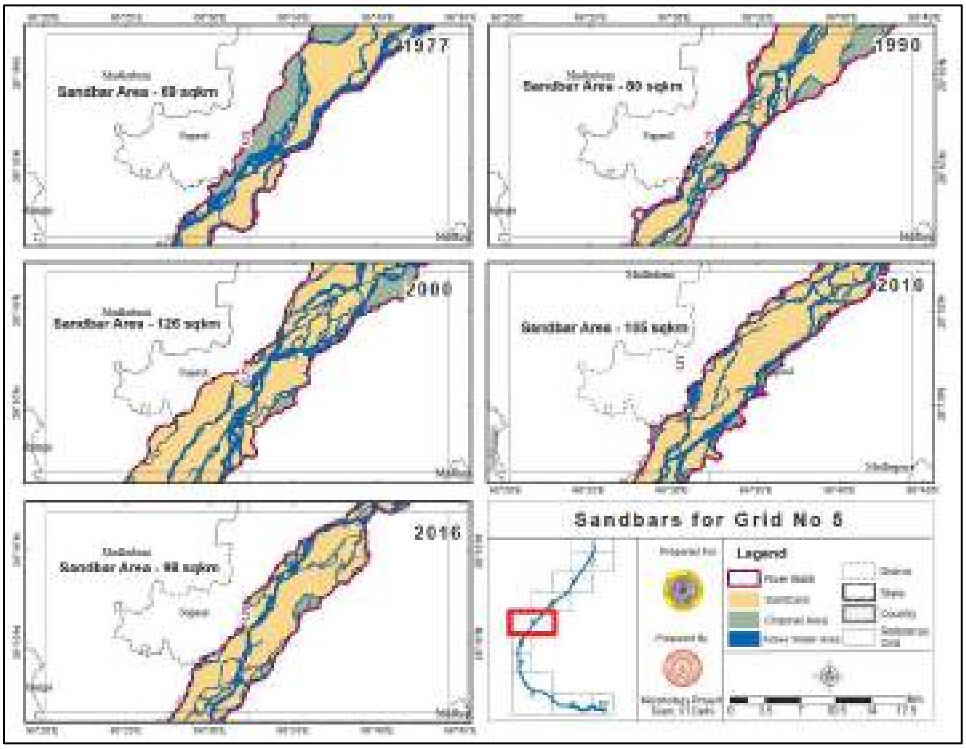


Figure 14-6: Change in Sandbars Area Across Years for Grid 5 of Kosi River

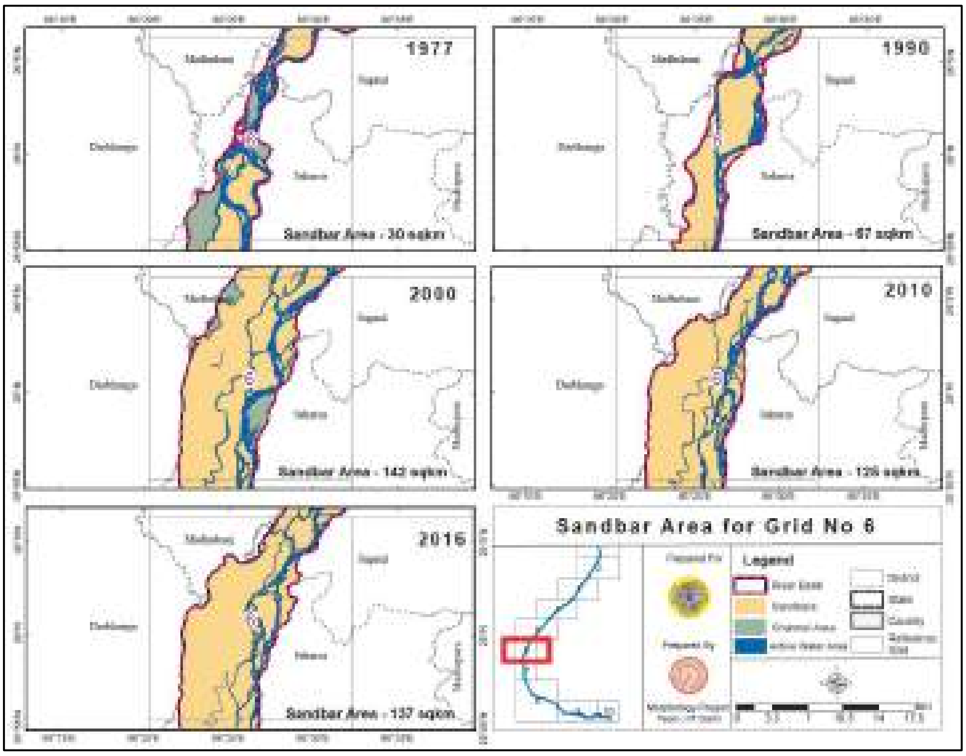


Figure 14-7: Change in Sandbars Area Across Years for Grid 6 of Kosi River

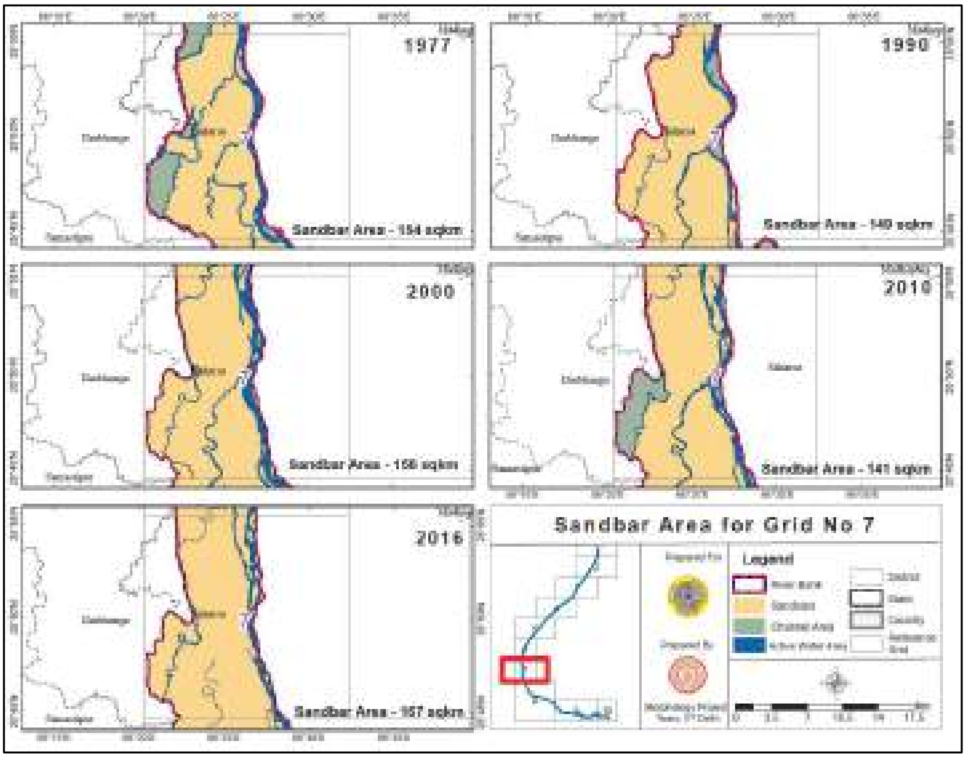


Figure 14-8: Change in Sandbars Area Across Years for Grid 7 of Kosi River

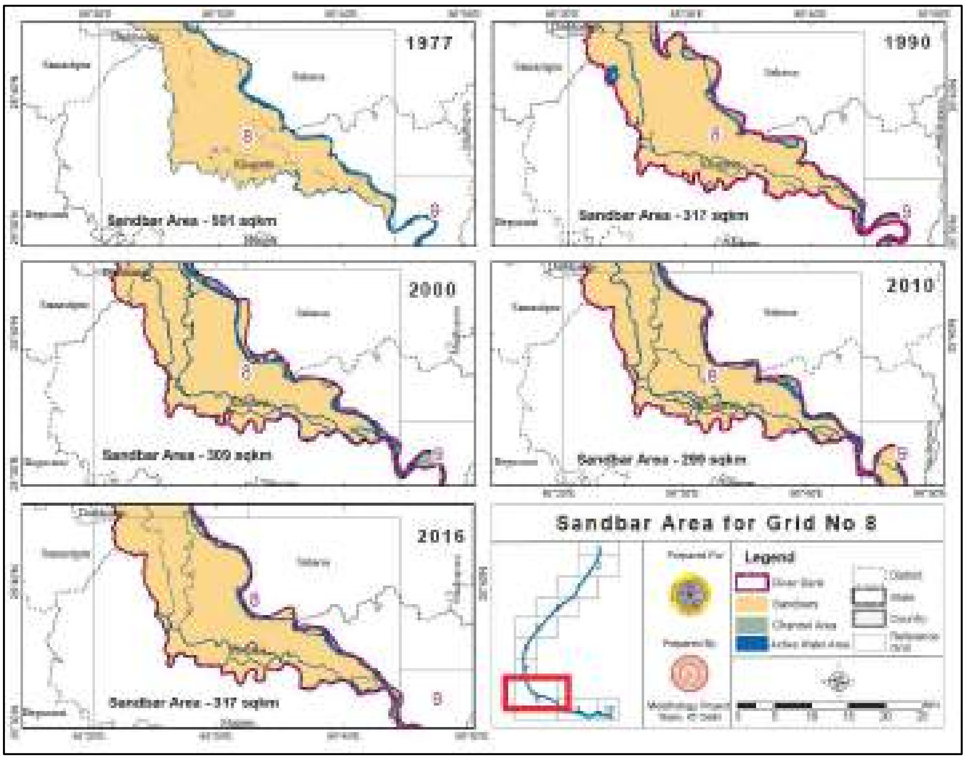


Figure 14-9: Change in Sandbars Area Across Years for Grid 8 of Kosi River

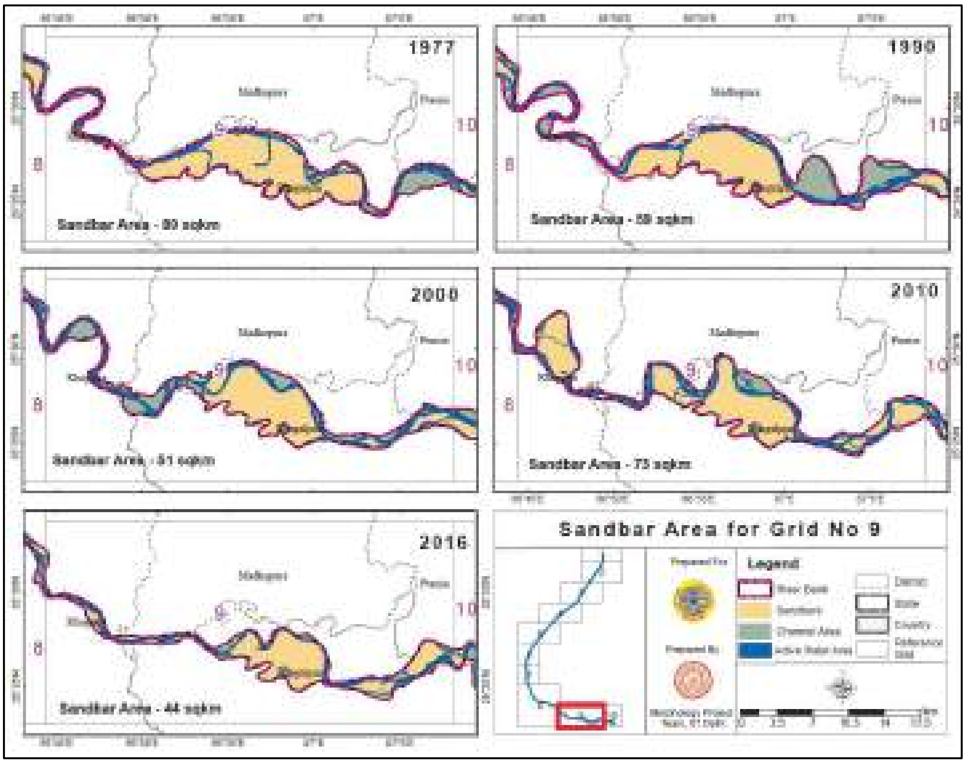


Figure 14-10: Change in Sandbars Area Across Years for Grid 9 of Kosi River

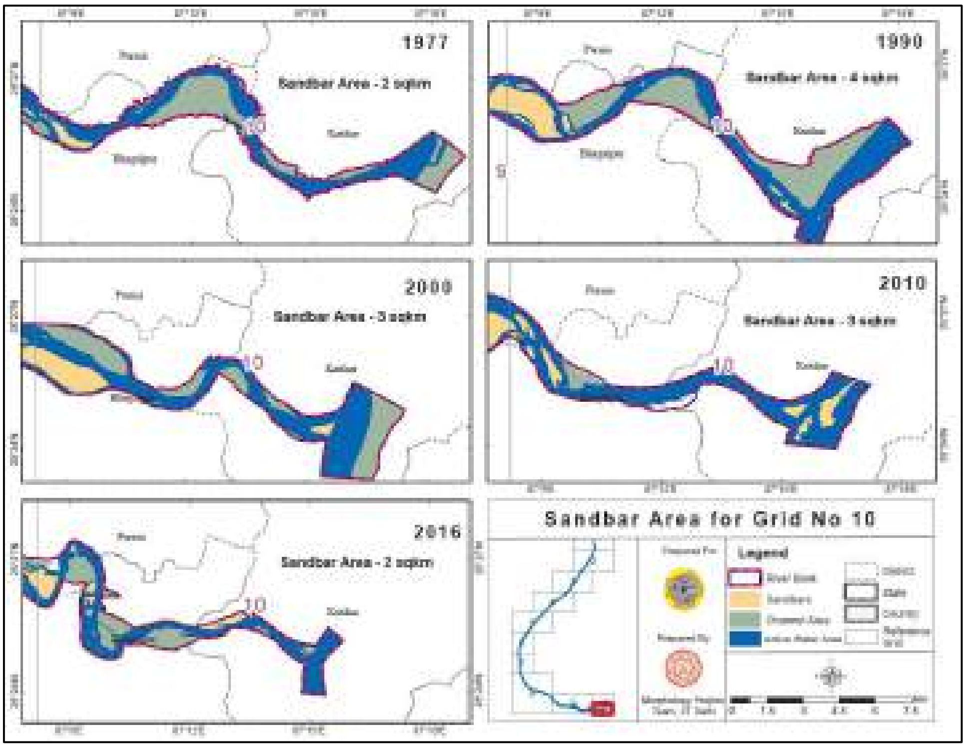


Figure 14-11: Change in Sandbars Area Across Years for Grid 10 of Kosi River

14.5 Conclusions

Based on the comprehensive analysis of sandbars and islands, the following key conclusions can be drawn:

i) Distinguishing between sandbars and islands solely based on remote sensing observations is not feasible. To establish definitive evidence, it is necessary to conduct laboratory-based analysis to determine the underlying geological foundation.

ii) In the specific context of morphological studies utilizing remote sensing techniques, sandbars or islands utilized for agricultural purposes, and legally owned by farmers, may be regarded as critical areas during certain flood events, particularly those with higher return periods.

iii) When assessing erosion and deposition, the examination of geometric properties and long-term changes in sandbar or island size over a span of several decades is employed to calculate the extent of areal retreat.

iv) Satellite imagery reveals the absence of any permanent sandbars or islands within the Bagmati system.

In summary, remote sensing alone cannot definitively differentiate between sandbars and islands. Laboratory-based analysis is crucial for establishing the geological foundation. Sandbars or islands utilized for agriculture, provided they are lawfully owned, may be significant during higher return period floods. Decadal changes in size are utilized to determine erosion and deposition, while satellite imagery confirms the absence of permanent sandbars or islands in the Kosi system.

Chapter 15: River Flood Affected Areas

15.1 General

The Kosi River is particularly prone to flooding in its lower reaches in the Indian state of Bihar. This is because the river channel in this region is highly unstable, and its banks are made up of loose sediment, making them susceptible to erosion during periods of heavy rainfall. The river's course is also highly meandering, and it frequently changes its course during floods as shown in Figure 15-1, leading to widespread inundation of the surrounding areas.

After flowing in higher gradients cutting through the Himalaya, the Kosi river exits and meets a flatter plains section with a very low gradient. This leads to millions of tonnes of silt being deposited in this section every year. The deposition has led to the formation of an alluvial deposit that is the largest of its kind in the world. When the river deposits silt in its course, the height of the river bed increases with respect to its neighboring land, and cause the river to change to a new course. This way, the Kosi river has shifted its course – or avulsed – numerous times. This has been easier in Bihar because of flatter plains and the high deposition rate.

The Kosi River is divided into three main stretches, namely the Upper Kosi, the Middle Kosi, and the Lower Kosi, based on its course and location. The Upper Kosi is located in the Nepal Himalayas, while the Middle and Lower Kosi stretches are in India. The Lower Kosi stretch, which is located in the Indian state of Bihar, is the most flood-prone section of the river. This is because the river channel in this region is highly unstable, and its banks are made up of loose sediment, making them susceptible to erosion during periods of heavy rainfall. The river's course is also highly meandering, and it frequently changes its course during floods, leading to widespread inundation of the surrounding areas. As silt causes the level of riverbed to rise, the straight course of the river is disturbed. Therefore, the river searches for a lateral path (left or right), changing its course and breaching embankments on the new path.

The Lower Kosi stretch of the river is about 200 km long and covers an area of about 9,000 sq km. The region is densely populated, and the floods that occur here affect millions of people every year, causing loss of life, displacement, and damage to property and infrastructure.

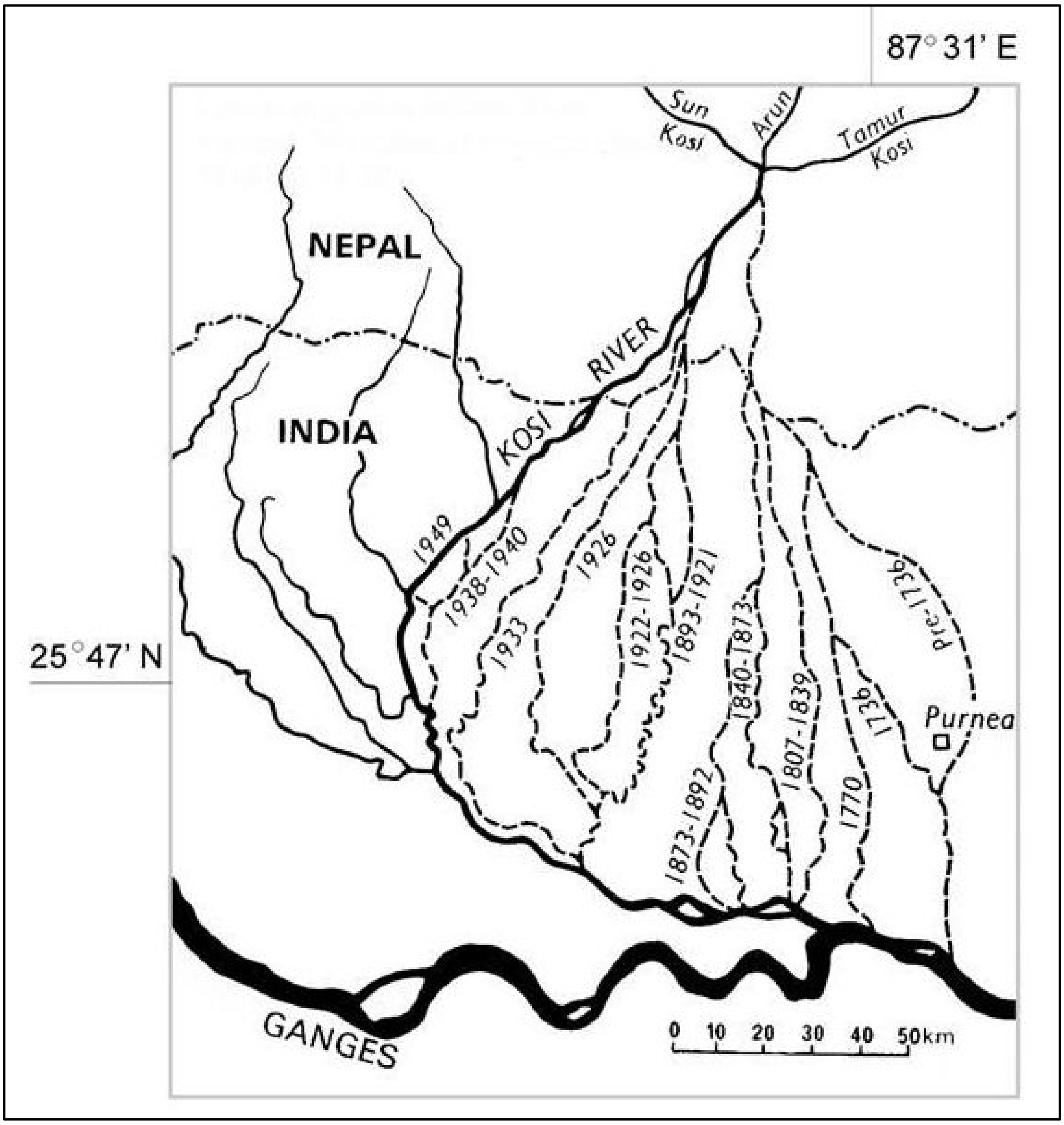


Figure 15-1: Kosi River Path Across the Years

(Source: https://doi.org/10.1007/978-3-319-70335-0_8)

The Middle Kosi stretch of the river, which is located in the Indian states of Uttar Pradesh and Bihar, is also prone to flooding, particularly in the areas near the border with Nepal. The floods in this region are mainly caused by the overflowing of the river's tributaries and the heavy rainfall in the catchment area. The Upper Kosi stretch of the river, which is located in the Himalayas in Nepal, is less prone to flooding compared to the lower stretches. However, landslides and glacial lake outburst floods (GLOFs) in the upper reaches can cause flash floods downstream, particularly in the Middle Kosi stretch of the river.

The river's flooding is also exacerbated by human activities such as deforestation, construction of embankments, and encroachment of floodplains, which reduce the river's capacity to carry water and increase the risk of flooding. Overall, the Kosi River floods primarily during the monsoon season, which lasts from June to September, due to heavy rainfall in its catchment area and its unstable channel.

15.2 Historic Flood Events (1975–2012)

From 1975 to 2010, North Bihar experienced several floods that caused damage to property and crops, as well as loss of life:

A. In August 1978, the Kosi River floods caused widespread devastation in Bihar and Nepal, affecting the Lower and Middle stretches of the river. More than 500 people were reported dead, and millions were displaced.

B. In July 1984, the Kosi River flooded again, affecting the Middle and Lower stretches of the river in Bihar and Nepal. Over 400 people were reported dead, and thousands were displaced.

C. In September 1987, the Kosi River flooded once again, affecting the Lower and Middle stretches of the river. More than 1,500 people were reported dead, and millions were displaced.

D. In 1998, excessive pressure on embankments caused damages along rivers such as Burhi Gandak, Bagmati, Adhwara and Kosi, resulting in 381 deaths and damage to public property worth 9,284 lacs rupees. Crop damage was estimated at 36,696.68 lacs rupees. Maximum discharge in the first week of July in most of the rivers in North Bihar caused excessive pressure on the embankment along the rivers resulting in damages at several places. Embankments of Burhi Gandak, Bagmati, Adhwara and Kosi were partially damaged. Three hundred and eighty one persons died and public property worth rupees 9,284 lacs was damaged. There was crop damage of about rupees 36,696.68 lacs.

E. In August 2004, the catchment area of North Bihar rivers received heavy rainfall in the first week of July, breaking the previous three years' flood records and surpassing the 1987 flood. The Kosi River flooded once again, affecting the Middle and Lower stretches of the river. More than 1,000 people were reported dead, and millions were displaced.

F. In August 2008, an unprecedented flood occurred due to a breach in the Eastern Kosi Afflux Embankment near Kussha village in Nepal. The breach caused miseries to lakhs of people in Sunsari and Saptari districts of Nepal and Supaul, Madhepura, Araria, Saharsa, Katihar and Purnea districts of Bihar. The Kosi river entirely changed its course and was eventually tamed back to its original course by the Water Resources Department after a tremendous effort.

G. September 2010: The Kosi River flooded again, affecting the Lower stretch of the river in Bihar. The floods were caused by heavy rainfall in the catchment area and breaches in the river embankments. More than 500 people were reported dead, and millions were displaced.

15.3 Flood Maps

Kosi river path across the districts is shown in Figure 15-2.

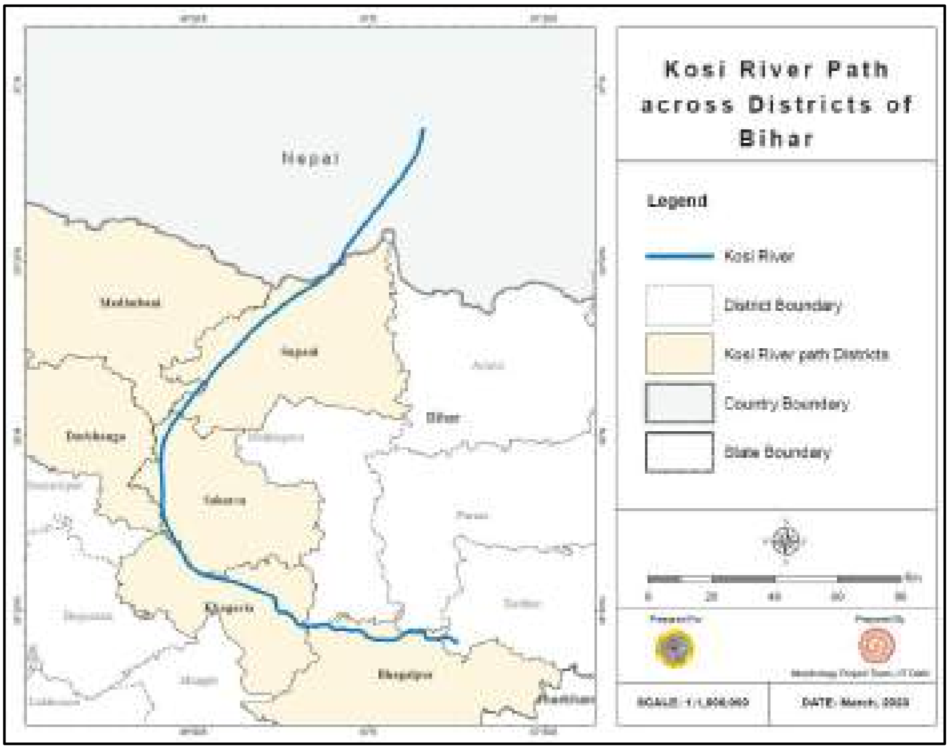


Figure 15-2: Kosi River Path Across Districts

The district wise flood inundation map and flood hazard map are shown below in Figures 15-3 to 15-8. The map is collected from the Bihar State Disaster Management Authority's online portal http://bsdma.org/Atlas.aspx).

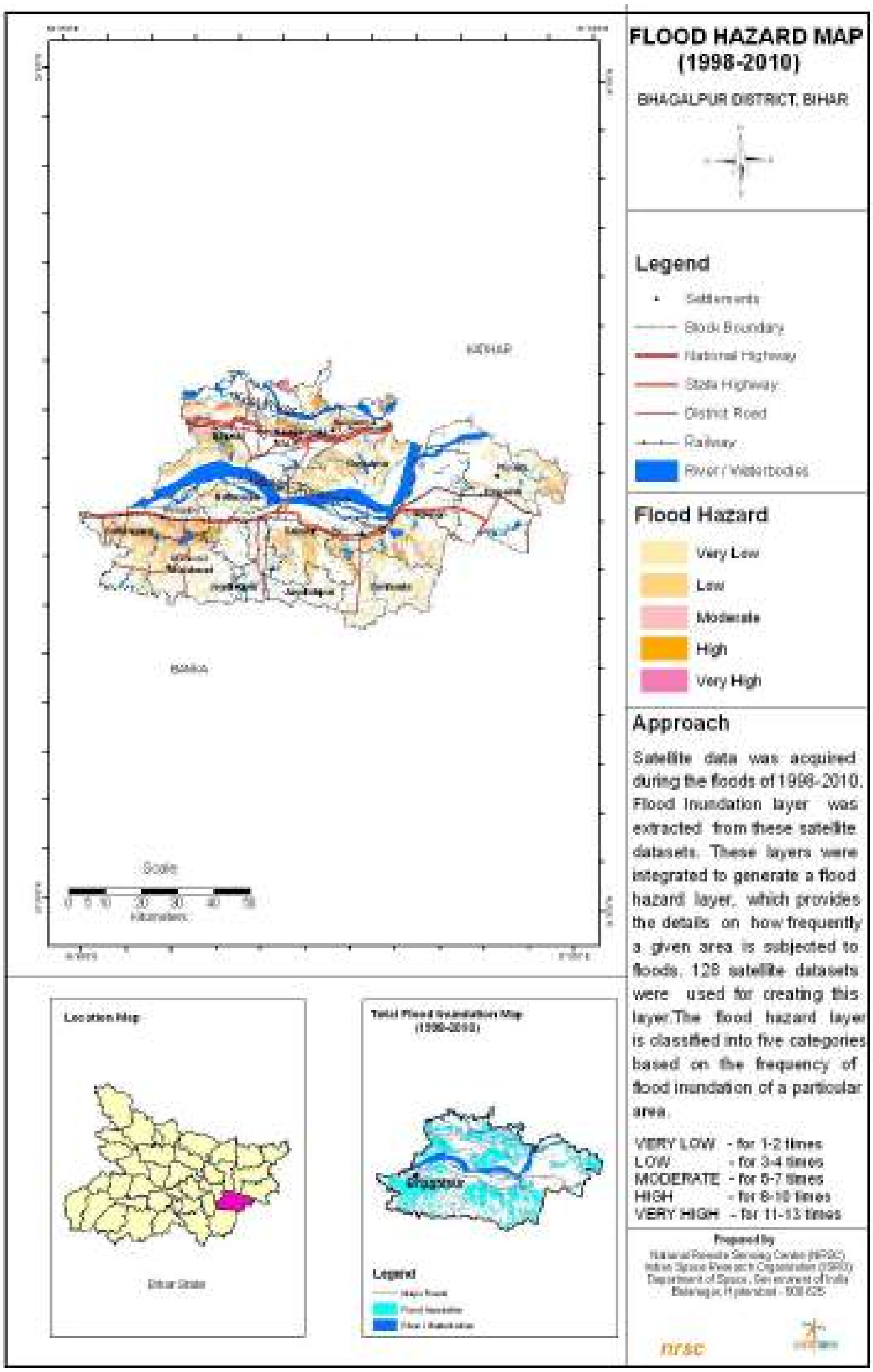


Figure 15-3: Kosi River Path Across Bhagalpur District

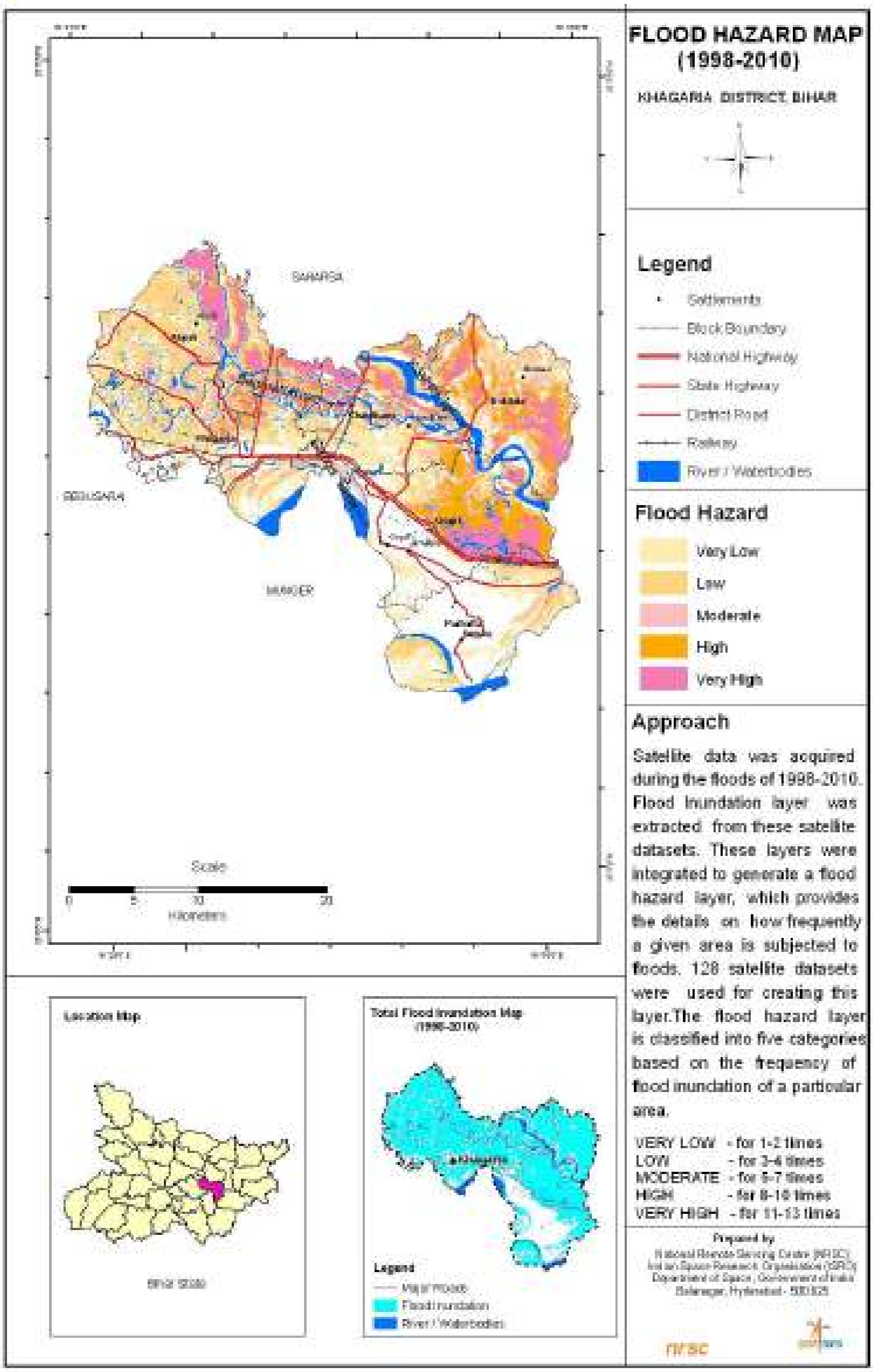


Figure 15-4: Kosi River Path Across Khagaria District

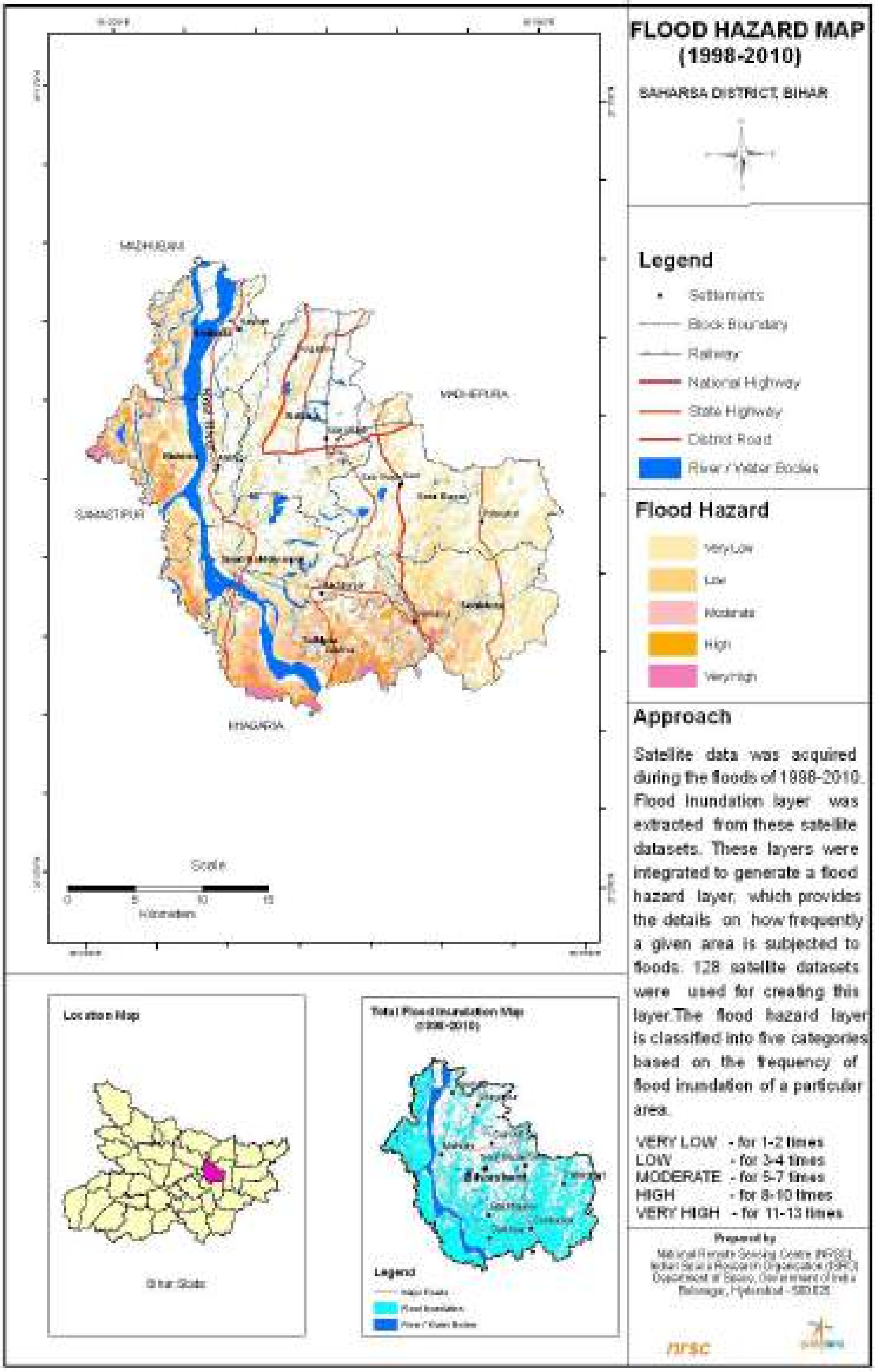


Figure 15-5: Kosi River Path Across Saharsa District

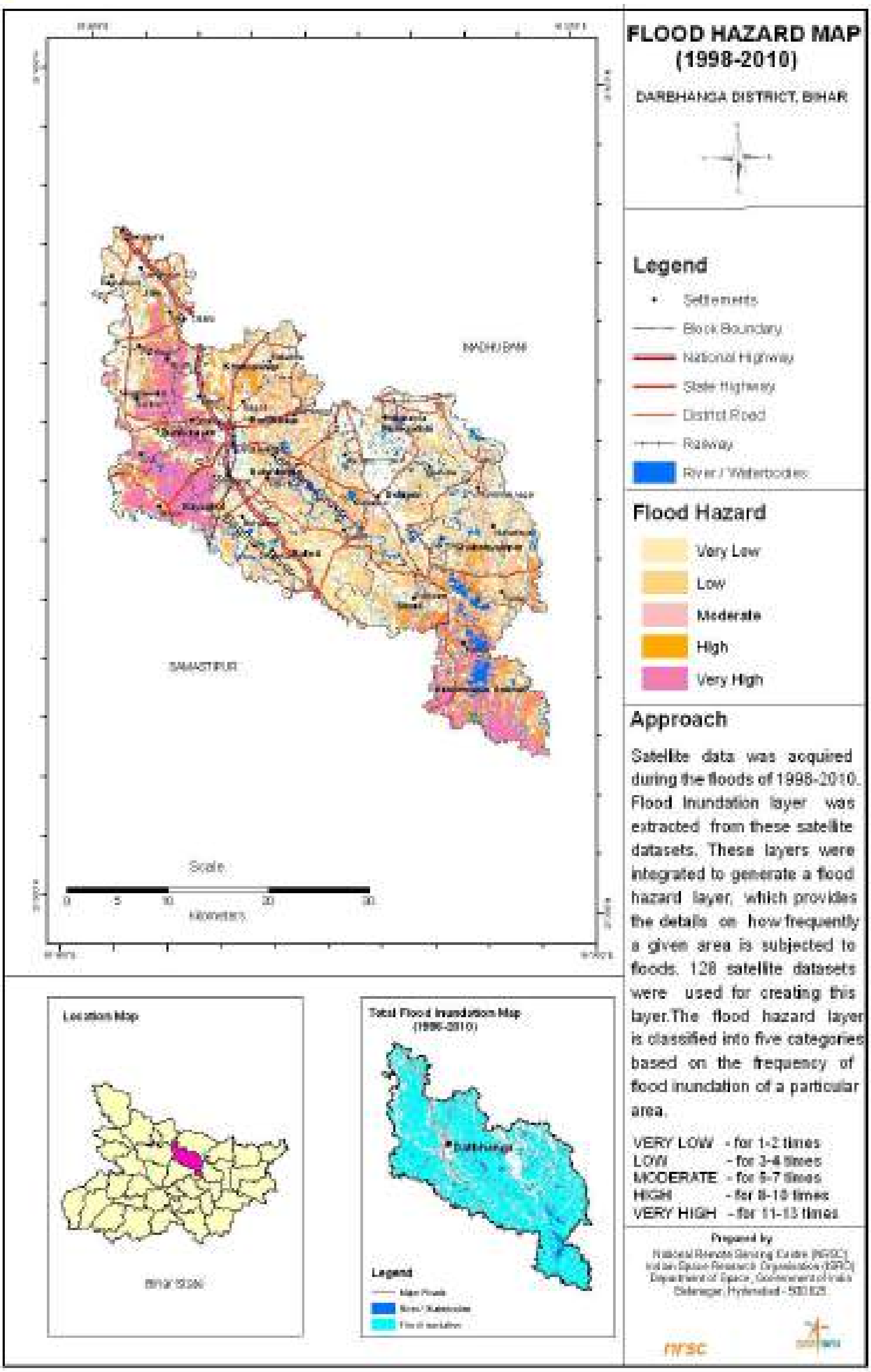


Figure 15-6: Kosi River Path Across Darbhanga District

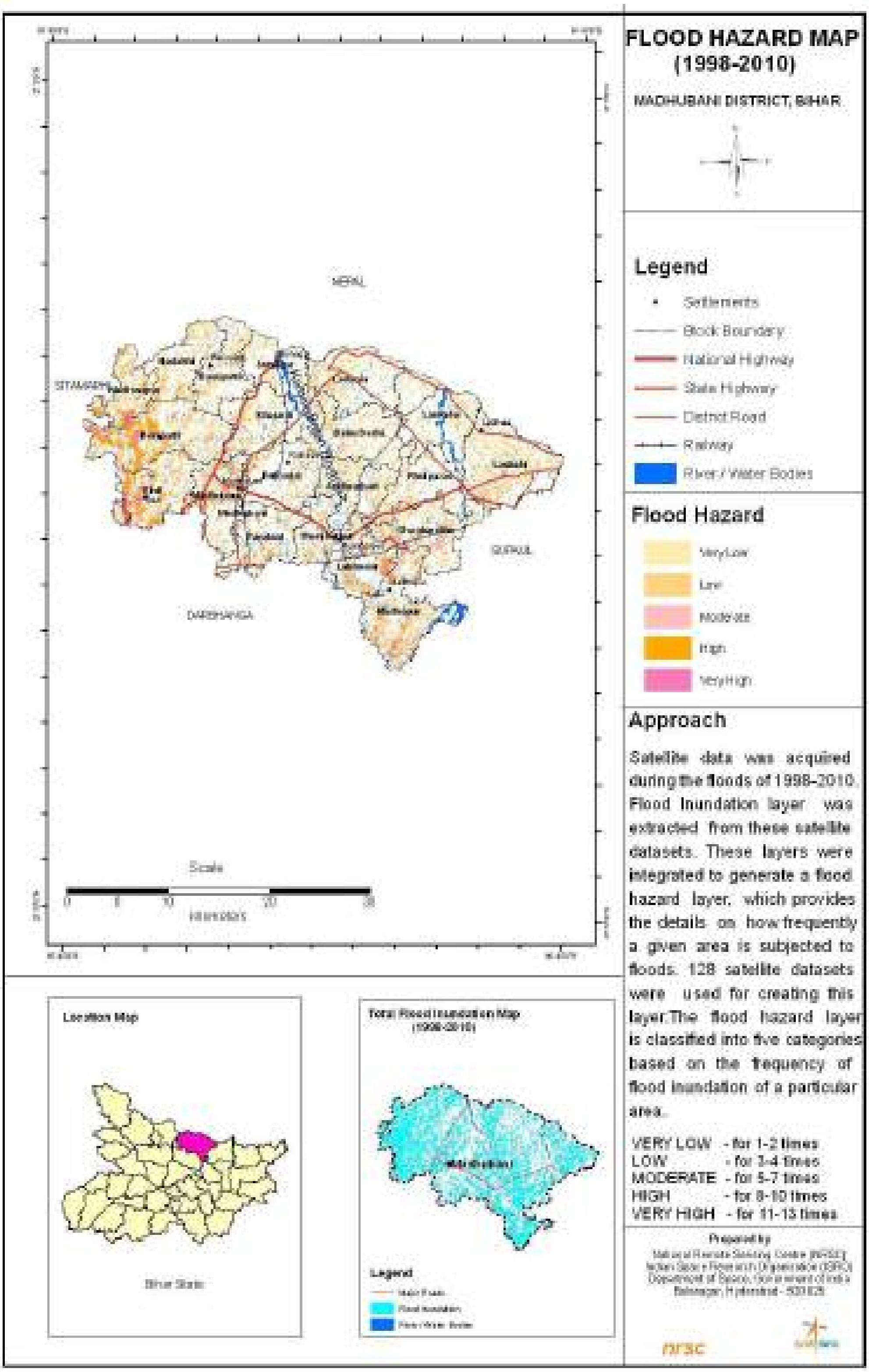


Figure 15-7: Kosi River Path Across Madhubani District

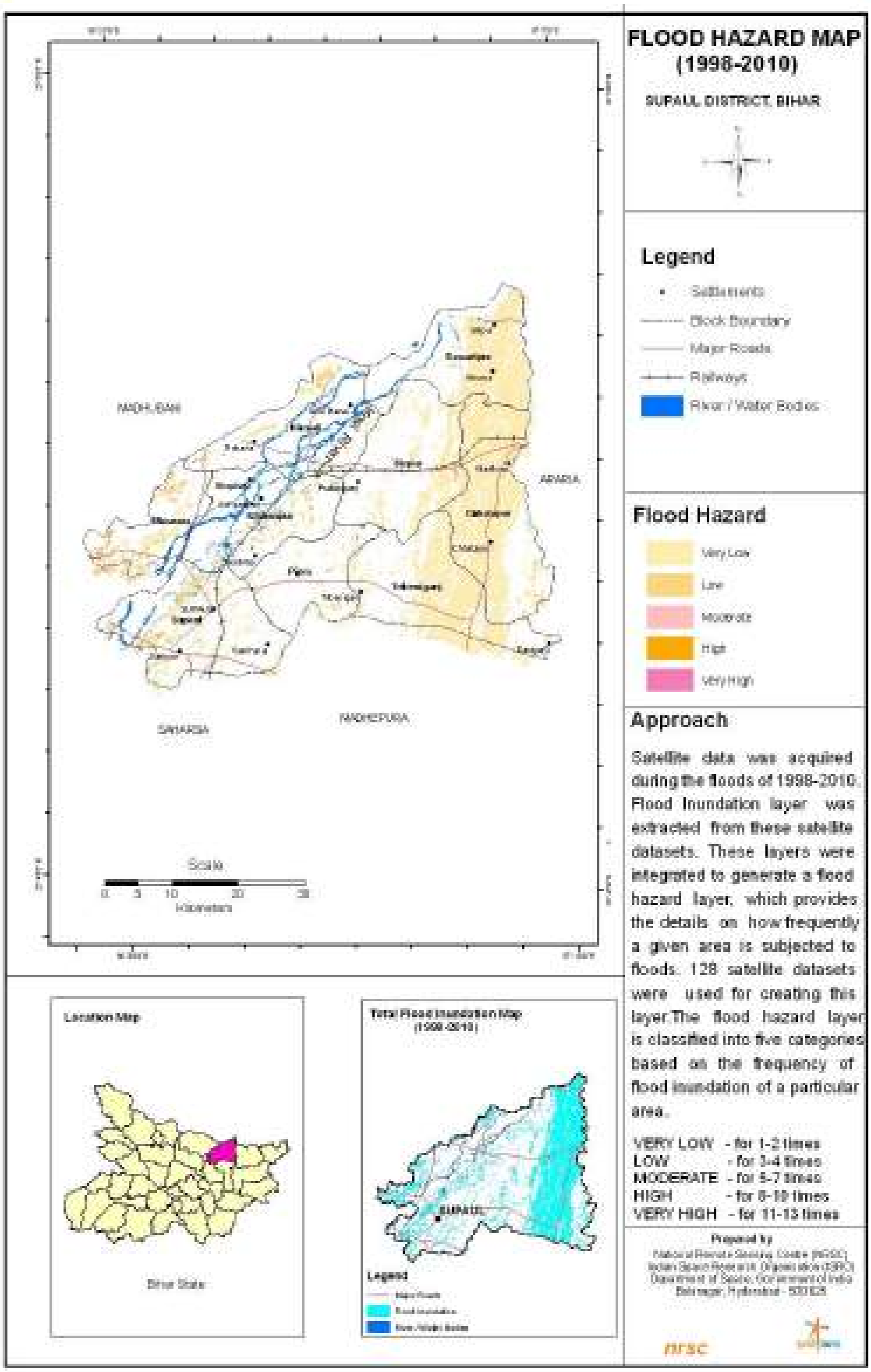


Figure 15-8: Kosi River Path Across Supaul District

15.3 Morphological Changes

The frequent flooding of the Kosi River has led to significant changes in its channel morphology, particularly in the Lower and Middle stretches of the river. The river channel has shifted significantly, and the river has formed new channels and abandoned old ones. The floods have also led to the formation of sandbars, islands, and braided channels. There is deposition of large amounts of sediment in the river channel and on its banks. The deposition of sediment has caused the river channel to become shallower and wider, and the banks have become steeper and more unstable.

The frequent flooding of the Kosi River has led to changes in the flow of water in the river. During floods, the river flow increases significantly, and the water moves at a much faster pace. This has led to erosion of the river banks, and the deposition of sediment in the river channel.

The frequent flooding of the Kosi River has also led to changes in the hydrology of the region. The floods have increased the groundwater recharge, and the river floods have provided a significant amount of water for irrigation.

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.

16.2.1 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.

16.2.2 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.

16.2.3 Modelling Scale

In space, typical modelling scales (Dooge, 1982) 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.

16.2.4 Scaling and Linkages Across Scales

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., 1986). 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.

A. **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.

B. **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 of Drainage Pattern of Kosi 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 and Sivapalan, 1995).

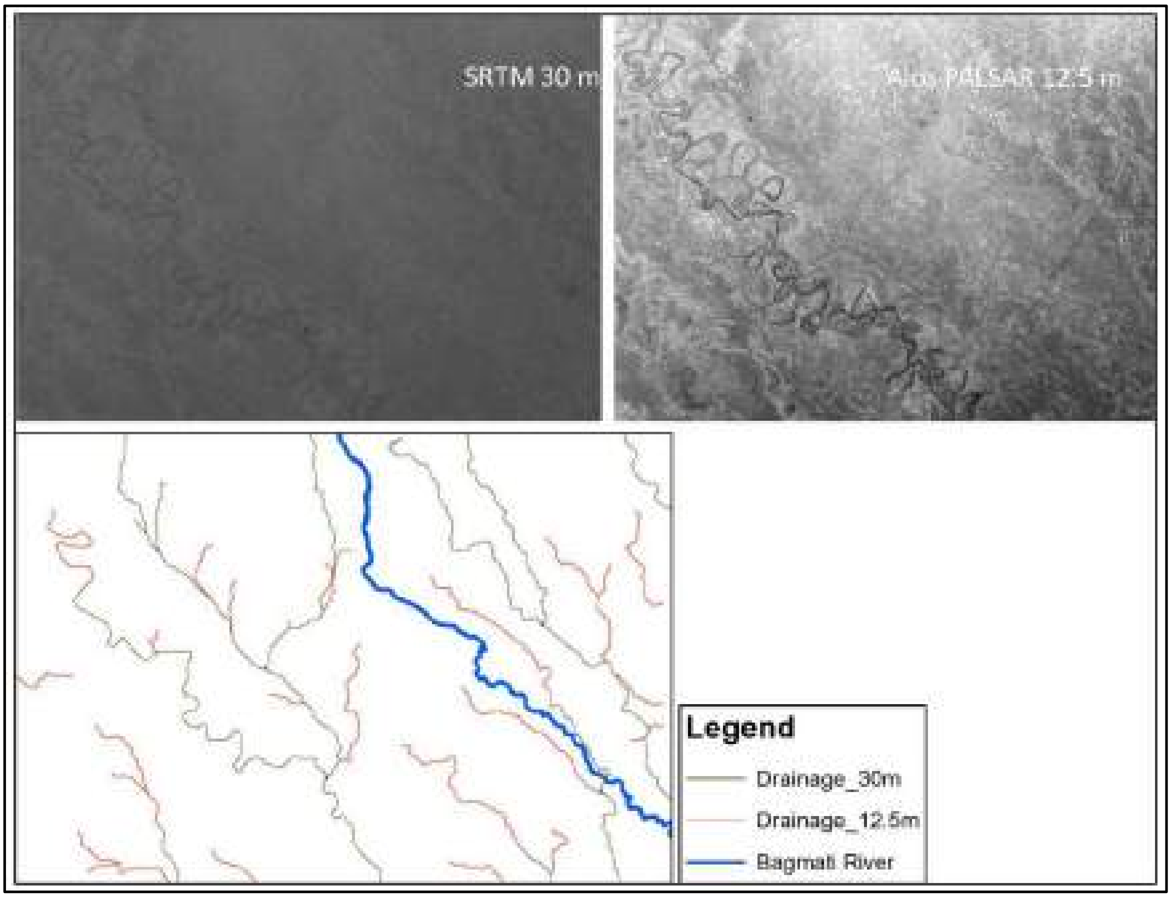


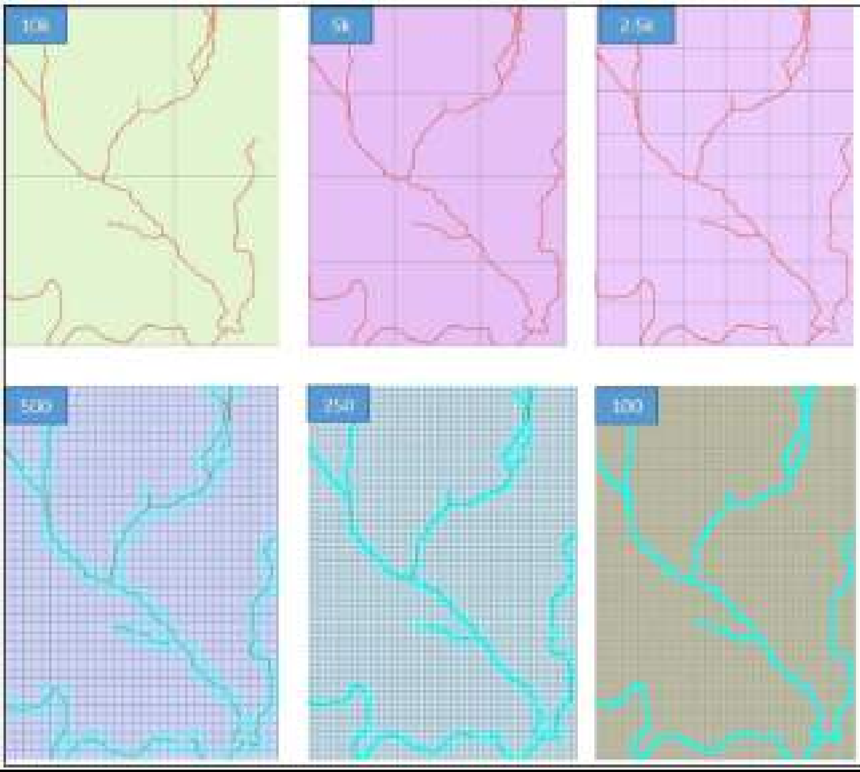
Figure 16-1: Effect of Grain Size on Drainage Pattern of Kosi River Stretch

16.3.1 Fractal Dimension of Kosi 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 162 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 boxcounting 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 the equation below.

$$DB = -\lim \left[\frac{\log N\varepsilon}{\log \varepsilon}\right]$$

This is read as "the negative limit of the ratio of the log of the number of boxes (N) at a certain scale (ε) over the log of that scale (ε)". The DB is the slope of the regression line for the log-log plot of box size (or scale) and count, which is 1.158 (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

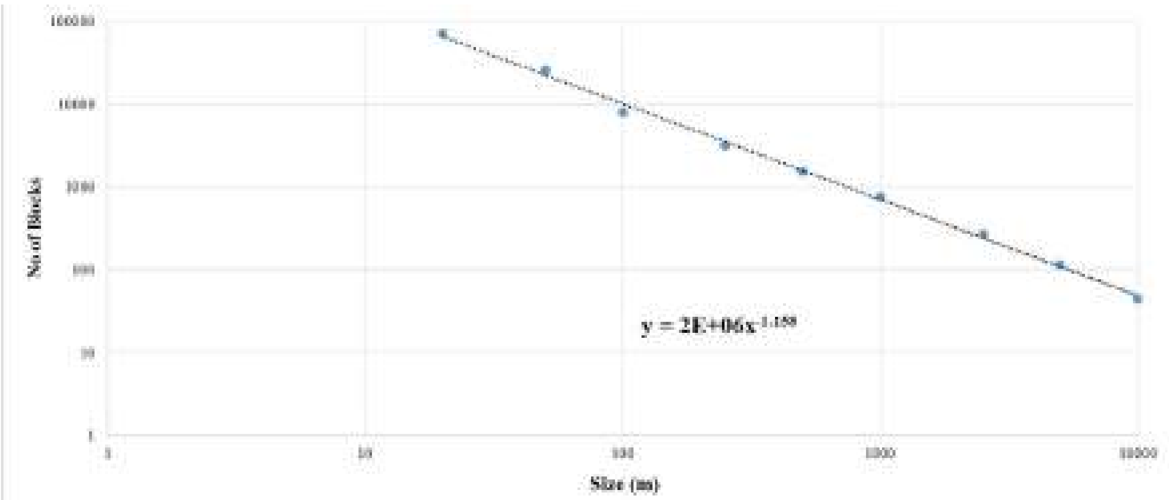


Figure 16-3: Fractal Dimension Calculation

The following conclusion can be drawn from the analysis:

A. The estimated properties of any feature are scale specific. Hence if the scale of the analysis changes, the outcome will also change.

B. 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.

16.4.2 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.

16.4.3 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.

16.4.4 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 Kosi 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 1977 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 1977 is considered as a reference condition. Various features as explained in Chapter 6 (Section 6.1) are marked on 1977 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 centreline 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 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 centrelines for different years obtained from remote sensing images.

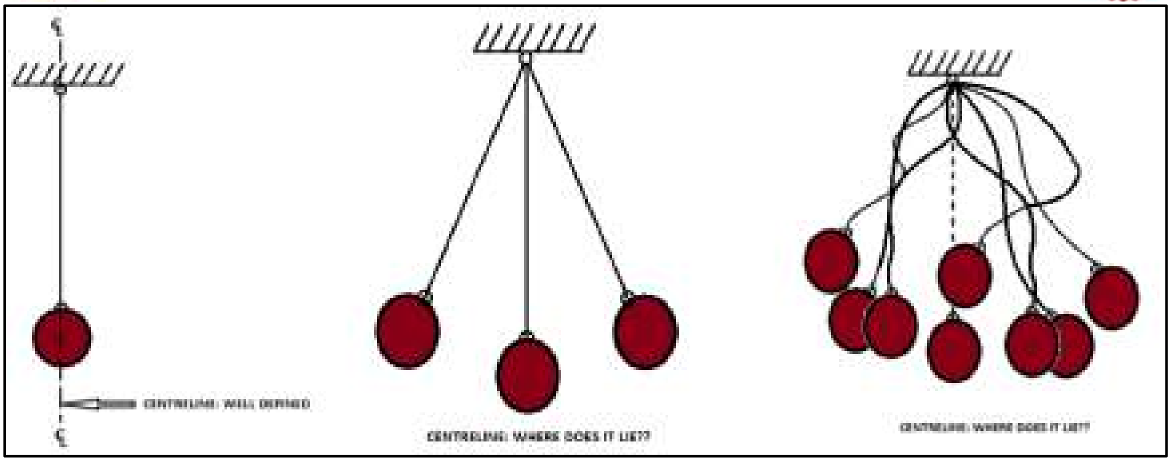


Figure 16-4: Movement of Simple Pendulum

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. Parmar and Khosa, 2017 may be referred to for a comprehensive discussion on the concept.

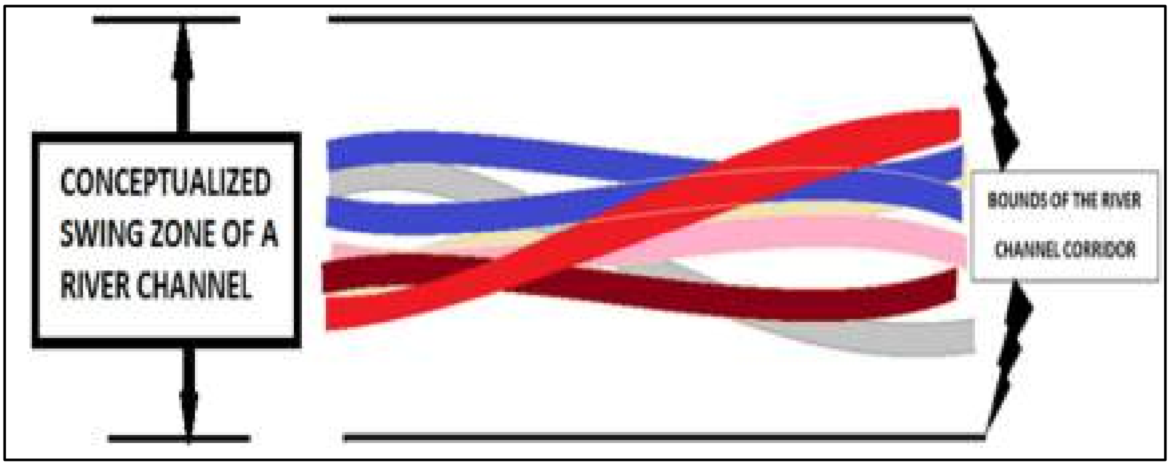


Figure 16-5: Swing Zone of River Channel and River Corridor

16.5.2 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.

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. Kosi river system 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 behavior becomes critically important prior to decision making. In comparison with Bagmati, River Kosi has changed significantly in the last century even though changes are smaller in a few stretches of River Kosi.

In this study, 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 180° 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 indicates that overall shifting of reaches of Kosi River in Grid 2, Grid 3, Grid 6, Grid 8, Grid 9 and Grid 10 are observed as the active. The Kosi River reaches in Grid 1. Grid 4, Grid 5 and Grid 7 have also shown relatively less shifting compared to the remaining reaches. However, it is difficult to isolate the reason for the same. Though the physiography of the basin seems to be the fundamental reason, the role of the altered flow regime should not be neglected. Both natural and anthropogenic activities have a significant bearing on channel morphology. Significance alteration in topography, valley, and the geology of the basin promoted the shifting of the channel. On the other side, anthropogenic activities such as encroachment, channelization of river courses at some locations, river training works and altered flow regimes mostly result in the stabilization of river courses. Flood control lines are not suitable for defining the river boundary in the case of the Kosi River and, therefore, cannot be considered as a criterion. Since, none of the rivers reaches has moved from one grid to another grid and angle between centerlines is well within the equilibrium limits. Therefore, none of the reaches is considered as unstable/ critical based on the above criteria. However, certain stretches exhibited significant swinging, particularly in grid 3 and grid 6, which could potentially contribute to instability.

16.5.3 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 2 km and channel width of 600 m may be considered as unstable based on above criteria, however, if section is meandering and ox-bow formation, neck cutoff in the section may be the primary cause for centreline fluctuation and thus reflect the characteristic behavior 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.

16.5.4 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.

16.5.5 Expert judgement and historical data:

Over the past 200 years, the Kosi river system has undergone a substantial shift in its course, spanning over 133 kilometers from east to west. As a result, defining the boundaries of the river corridor has become an impossible task. This shift is likely influenced by various factors such as changes in the geologic foundation, tectonic plate movements, alterations in the overall physiography of the region, or a combination of these elements. Efforts have been made in the past to construct embankments and implement river training works in an attempt to control the river's course and mitigate the impacts of flooding. However, these attempts have proven insufficient in addressing the larger issue. Therefore, it is crucial to have a comprehensive understanding of the behavior of the river system before making any decisions.

Considering these factors, along with expert judgments and insights derived from a literature review, can aid in defining whether a particular reach of the river is active or stable. It is imperative to consider all these aspects to make informed decisions regarding the management of the Kosi river system.

16.5.6 Unstable and Stable Reaches

Based on the above approaches discussed in 16.5.2, 16.5.3 and 16.5.4, the Kosi river have been analyzed from Grid 3 to Grid 10 (Kosi in the Indian territory) by comparing the transition in river channel area from 1977 to 2016. However, to call them as critical or not is something related to perspective as mentioned earlier. Based on the criteria of centerline swinging and variation in river course, the majority of the River Kosi's course can be considered stable. However, some stretches in the specific sections, such as grid 3 and grid 6, have shown significant swinging that have the potential to contribute to instability. These findings are derived solely from remote sensing analysis, and for definitive conclusions, historicalfield investigations are necessary.

Grid 3 (Near Kosi barrage)

The channel areas expanded significantly in the year 2000 compared to 1977. Upstream (u/s) of the Kosi barrage, the channel area was expanded up to 4.8 Km in the East direction, and the channel was shifted 2.8 Km westwards downstream (d/s) of the Kosi barrage. By 2016, the Kosi River remained limited to its corridor at u/s of Kosi Barrage, depicting a reduction in the thickness of the channel area by 4 km. However, at the d/s of the barrage, the channel area shifted up to 3 km in the East direction for the stretch upto 10 km till Madhora (Supaul, Bihar), as shown in Figure 16-6.

Grid 4 (Near Bhaptiahi village in Supaul district)

The Kosi River channel experienced minimal variation in 2000 compared to 1977. A slight westward shift of 0.3 km to 2.7 km was observed near Bhaptiahi village (Supaul) along a 7.5 km stretch of the river by 2000. However, the significant anthropogenic impact of the Kosi railway and Kosi bridges, which were under construction starting from June 2003, became evident on the channel area by 2016. The channel area near Nirmali (Supaul district) narrowed down to 1.9 km, reducing approximately 3.2 km on each side, indicating no significant shifting beyond the river corridor.

Grid 5 (Near Khokhaha village in Supaul)

In comparison to the year 1977, notable changes occurred in the Kosi channel area. The channel expanded westwards by approximately 6 km due to the generation of distributaries between Khokhaha (Supaul) and Garaul (Saharsa), covering an area of approximately 6500 hectares in southern Madhubani by 2000. However, by 2016, the expanded channel area underwent a narrowing process, reducing its width by up to 4.2 km in the westward direction for the above-mentioned stretch. This reduction can be attributed to the anthropogenic impact caused by the construction of the Kosi bridge along its downstream river course.

Grid 6 (Near Bhaptiahi village in Supaul district)

As previously mentioned, (Grid 5), the Kosi channel area underwent significant expansion in 2000. It extended westward by approximately 5 km due to the generation of distributaries originating from Pachgachhia (Supaul). Additionally, an eastward expansion of up to 3 km from Baspiti (Supaul) to Mohanpur was observed along the river course. However, no further expansion of the channel occurred by 2016. Instead, there was a narrowing of the channel from the west direction, ranging from 0.5 km to 4 km along the river course from the Kosi bridge to Bakunia village (Saharsa). Notably, grid 6 exhibited no significant variation in the river channel between 1977 and 2016.

Grid 7 (Near Bhaptiahi village in Supaul district)

In this grid, no significant variation was observed in Kosi channel areas between year 1977 to 2016.

Grid 8 (Near Kamla village in Khagaria district)

The Kosi channel area experienced a substantial westward expansion, extending up to 5.8 km from the southern end of Darbhanga district to Ambaicharua (Khagaria) in 2000, in comparison to the conditions observed in 1977. This expanded channel area eventually meets the Bagmati river near Jagmohra (Samastipur). Notably, between year 2000 to 2016, no significant variation was observed in the Kosi river channel area, indicating relative stability over that period.

Grid 9 (Near shared boundary of Khagaria and Bhagalpur districts)

The meander in the vicinity of Dharhi village (Khagaria) underwent significant deformation between 1977 and 2000, indicating a substantial increment in the meander neck from 2.3 km to 4 km. The expansion extended the outer bend boundary to encompass areas such as Dharhi, Balaitha, Chorhli, and Barun (all in Khagaria district). However, by 2016, the meander form had dissolved entirely due to alterations in the river course. Furthermore, the river channel experienced a minor change in the course, with a northward convexity for a short stretch near Muraut (Madhepura) in

2000, compared to 1977. However, this convexity gradually transformed into a relatively straight river course by 2016. The channel's maximum width decreased by up to 3.5 km, predominantly in the 10 km stretch near Dhodhia (Bhagalpur).

Grid 10 (Near Kosidhar village in Purnia district)

Within this specific grid, the Kosi river enters the Katihar district after flowing through the Bhagalpur district. An interesting observation is the alteration in the river channel course. In 1977, the channel exhibited a northward convexity, but by 2000, it underwent a transformation to a southward convexity between the Kosidhar (Purnia) and Katareah (Katihar) regions. The changes continued, and by 2016, the channel further evolved, expanding to reach Bhauwa Parbal village in Purnia to the north and Madrauni Pachhiarital village in Bhagalpur to the south. This expansion amounted to approximately 1.2 km on each side, demonstrating a distinctive bend in the river channel compared to its configuration in 2000. The Kosi-Ganga confluence is an integral part of this grid, represents the merging point of the Ganga and Kosi River. During the period from 1977 to 2016, the Kosi-Ganga confluence exhibited relative stability, with minor fluctuations in its position. The confluence maintained a consistent location, indicating a relatively balanced sediment deposition and channel dynamics. The confluence discussed here, known as the Kosi-Ganga confluence, has historical significance as the Bagmati-Ganga confluence. For visual reference, please see the Figure 16-6.

Figure 16-6: Unidirectional Shifting of the Kosi River Corridor

When we explore the historical confluence of the Bagmati and Kosi rivers with the Ganga over a 200-year timeframe, it becomes apparent that the present-day Kosi-Ganga confluence can be identified as the Bagmati-Ganga confluence. This observation reinforces the notion that the merging of the Bagmati river with the Ganga has exhibited stability over the past two centuries.

16.6 Conclusions

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 Kosi shows distinct patterns of channel bank retreat and river course dynamics. According to these distinct patterns, River Kosi has been discussed into four different grids as below:

Grid 3:

This course mainly covers the segment where river Kosi enters in India from Nepal, downstream of the Kosi barrage. The channel width expands from 1.5 km to 5 km in 8 km of downstream of Kosi barrage. The braiding index is relatively low in this reach. The highest average shifting of river centreline is observed as 1.5 km in the period of 2000-2010 near Madhora, Supaul district. The channel patter was found straight.

Grid 4:

This course mainly covers the reach of Kosi upstream of Kosi bridge near Nirmali in Supaul district where the river course was narrowed to 1.9 km. The braiding index is relatively higher in this reach. The highest average shifting in this grid is observed as 0.5 km in the period of 2000-2010 and no shifting outside the river corridor was noticed. The channel patter was found straight.

Grid 5:

This course mainly covers the reach of Kosi upstream of Kosi bridge near Narhi in Supaul district. The highest average shifting of centreline in this grid is observed as 0.85 km in the period of 2000-2010; however, the expansion of river channel is noticed up to 6 km. Negligible shifting is observed after 2010 till 2016. The braiding index is very high in this reach. The channel patter was found straight.

Grid 9:

This course mainly covers 52 km of the Kosi reach, 20 km upstream of Kosi-Ganga confluence. In this area, the meander near Dharhi village (Khagaria) existed in 1997 and deformed in 2000 is dissolved by 2016 due to change of river course. The highest average shifting of centreline in this grid is observed as 0.61 km in the period of 2000-2010. The braiding index is relatively low in this reach. The channel pattern is mostly sinuous.

Based on the analysis conducted, it can be concluded that none of the river reaches have shifted from one grid to another, and the angles between the centerlines remain within the equilibrium limits. As a result, none of the reaches are considered unstable or critical based on the aforementioned criteria. Overall, the majority of the course of the River Kosi can be regarded as stable in the considered study duration. However, it is worth noting that specific sections, specifically grid 3 and grid 6, have exhibited significant fluctuations that could potentially lead to instability.

Chapter 17: Conclusions

The following conclusions can be drawn from the present study:

A. Land-use changes in the Kosi River Basin have been estimated using remote sensing imageries from different years. It has been found from 2010 land use that a major part of the basin is covered with agriculture (36.19 %), followed by barren/fallow land (31.5 %), forest (24.38 %), snow/glaciers (3.68 %), water bodies (2.6 %) and built-up land (0.34%). The built-up area has increased by 62.8 %, whereas forest area has reduced by 1.12 %. As discussed in Chapter 16, due to overlapping of scales, the impact of this land-use change on river morphology cannot be explicitly assessed. However, one may indirectly predict the pattern of erosion and deposition based on land use changes observed. Accordingly, it can be said that the decrease in forest and increase in the urban area, might have resulted in increased erosion in the Kosi basin.

B. Though frequency analysis of the observed streamflow of Kosi has been attempted, it may not represent the actual reality of the system the streamflow is highly regulated in the present condition. Therefore, the results of this frequency analysis may be used in the limited context of the current morphological study and might not be suitable for other applications such as design flood estimation.

C. The average sinuosity for the entire stretch of the Kosi River is 1.3, whereas the radius of curvature varied between 3.1 to 7 km. Based on Braiding Index, it can be said that braiding is higher in selected reaches of Kosi, mainly in Grid 3 to 5.

D. The confluence of Kosi-Ganga has proven to be significantly more stable over the past four decades compared to the confluence of Bagmati-Kosi. Between 1977 and 2016 (study period), the maximum shifting of the Kosi-Bagmati confluence took place primarily between 1977 and 1990, after which it relatively stabilized till 2016, showing total shift of 13.5 km toward North-West direction. In contrast, the Kosi-Ganga confluence experienced a westward shift of 4.4 kilometers when observed in 2016, in comparison to its location in 1977.

E. From 1977 to 1990, erosion (264.6 sq. km) exceeded deposition (101.3 sq. km) in the Kosi River. Between 1990 and 2000, erosion was 102.6 sq. km greater than deposition. However, deposition exceeded erosion by 226.8 sq. km from 2000 to 2010. For the period of 2000 to 2016, deposition was higher than erosion by 67.4 sq. km. In summary, significant erosion occurred from 1977-2000, while significant deposition occurred from 2000-2016. Aggradation and degradation patterns analyzed from Kosi River cross-sections are in line with satellite-based erosion deposition maps.

F. A few locations have been identified in Grid 8 (Heyatpur and Hardia) and Grid 9 (Mohanpur, Kishunpur Banwari and Kaharpur) of Kosi River that may experience neck cut off/ ox-bow formation/ abandonment of reach.

G. River course dynamics of Kosi analyzed from 1977 to 2016 in the form of channel centerline movement at 1 km interval, showed that the river has changed its course at a few locations. The analysis revealed that the significant shifts occurred in Grid 8 (3.8 km, 1977-1990) at the connecting boundary of Khagaria and Saharsa districts near Belahi town and, in Grid 6 (2.6 km, 1990-2000) near Nauhata town in Saharsa district. From 2010 to 2016, there was negligible shift in the river.

After carefully examining the aforementioned results, a comprehensive overhaul of conventional remote sensing-based techniques was conducted to establish a cohesive framework to better understand the multiscale morphodynamical attributes of river Kosi. The specific morphodynamical attributes that were examined in the study include Shifting, Braiding, Anabranching, Meandering and Areal retreat by erosion and deposition.

The findings of the study indicate that the upper reaches of the Kosi River exhibit a high degree of dynamism, characterized by a braided pattern. This implies that the river frequently shifts its course and forms multiple interconnected channels, resulting in a complex network. In the middle reaches of the river, anabranching is observed, indicating the presence of multiple channels that diverge and reunite within the river's floodplain. This intermediate section of the river displays a considerable degree of variability. In contrast, the lower meandering reach of the Kosi River exhibits a relatively stable pattern. In this section, the river maintains a consistent path and displays the absence of significant shifts or channel diversions which suggests a more stable hydraulic regime.

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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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MEMORANDUM

A FRAMEWORK FOR

STUDY OF RIVER MORPHOLOGY, MORPHODYNAMICS AND MORPHOMETRICS

A REVISED CONCEPTUAL FRAMEWORK FOR CENTRELINE, SHIFTING AND SOME BRAIDING PLANFORM INDICES

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MEMORANDUM – I

To: Morphology Group, Water Resources Section

From: Rakesh Khosa and Vilakshna Parmar

Topic: Centerline Shifting and Refined Braiding Planform Indices

INTRODUCTION:

Most rivers are historical artefacts that are in an unceasing state of dynamic evolution but without an unequivocal terminal state. It is also clear that there are a mix of stimuli at work that have been shaping, and indeed continue to shape these latter drainage features. Most notably, these triggers, natural and otherwise, not only operate at a range of temporal and spatial scales but, interestingly, may also have significant intersecting overlaps over a range of the latter scales.

Typically, therefore, the morphological behaviour and/or morphological responses of the latter drainage relics do not, in general, exhibit a consistent morphological signature across all spatial and temporal scales but instead, any particular reach of a given river may bear the combined and complex mix of various latter signature patterns. Importantly, these may only rarely lend themselves to individual, scale specific descriptive characterization even if the sought characterization is limited squarely to the scale over which the reach is abstracted. More often, disaggregation or extraction of these patterns, and other related features individually, may not be possible given the reality of the aforementioned overlapping temporal and spatial scales at which the underlying morphological dynamics is impinged upon by the diverse range of observable as well as non-observable causal triggers.

QUASI-STATISM OF A RIVER COURSE

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 presence and alignment of local/regional geological fault lineaments**. 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 the following Figures 1 and 2 (Ref: web resources):

Figure 1: Channel formation by incision

Figure 2: Channel formation by incision

Notwithstanding the latter, it is imperative to acknowledge that in general, for a vast majority of major river systems, these geological fault lines act as robust, but sometimes delicate cradles that, over time, acquire the configuration of a **dedicated stable corridor** within which, over time, individual drainage paths are carved out by the concentration of water streams. These paths that develop ultimately acquire the configuration of river channels.

The concomitant erosional and depositional processes together with regional scale geo-dynamics induced by subsurface tectonic activities, amongst others, would be expected to influence and shape changes in the latter channels over time. The reality of these auto-cyclic as well as allocyclic processes has indeed been recorded to be incessant and observed to occur over time scales ranging from geological to the relatively more rapid and these river channels respond to the latter diverse range of natural triggers in an autonomous and spontaneous manner.

The proposed hypothesis attributes an important role to the aforementioned dedicated river corridor which, as averred in this study, demarcates a **swing-width**, to so put it, within which the stream of concentrating river flow can rightfully assume any pathway depending upon a diverse set of factors that include:

(i) Topography and relief topology.
(ii) River bed morphology
(iii) Hydro-meteorological characteristics.
(iv) Fluvial transportation and depositional characteristics
(v) Topology of the conjunctive Hydrodynamic and Morphodynamical Potential field.
(vi) Geo-dynamic tendencies of the underlying sub-surface geological field.
(vii) Lateral connectivity.
(viii) Exchange with subsurface flow pathways.
(ix) Hydrodynamic compulsions.

The hypothesis of a 'dedicated river corridor' as a hydro-morphologically demarcated 'swing zone' is presented as an averment that emphasizes the point that the aforementioned factors trigger seemingly recalcitrant but, by no means arbitrary, responses of the river stream within it. For example, it is hypothesized that a river channel's course has an innate potential to swing between alternate flow paths - albeit restricted to within the overall corridor of the aforementioned dedicated passageway – and within the aforementioned passageway, a channel course may swing between alternative flow paths as illustrated in the following Figure 3.

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

THE RIVER CENTRELINE AND ITS INNATE ETHEREAL NATURE

In this part of the treatise, an effort has been made to present a more rational perspective on the widely used, albeit imaginary and often perception based, concept of a river '**<u>centreline</u>**', and which is routinely estimated from satellite imageries.

A related, and no less profound, missing link in our understanding of the overall concept of the 'River Centreline' 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, hydrodynamic and morphological attributes of the river. In other words, the question that arises is whether the notion of a river's imaginary centreline is just a representation of the current position of the wet channel or it holds a deeper philosophical and hydro-morphological relevance. More fundamentally, the following question encapsulates the nebulous nature of the latter concept of the River Centreline:

Is a 'River Centreline' universally and uniquely definable in terms of a consistent rule that makes it amenable to an objective identification?

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

(i) Does the centerline coincide with the thalweg line?
(ii) Does the centerline bifurcate the volumetric flow rate into two equal halves?

(iii) 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) Does the centerline divide the bankfull width of the river into two equal halves between the connected bank lines?

(v) Does the centerline bisect the wetted top width between the two water lines along the river banks?

(vi) Where does the centreline lie in a braided reach with a highly skewed channelization plan form?

A difficulty presented by the aforementioned posers is that river cross sections are rarely, if ever, symmetric between banks as illustrated in Figure 4.

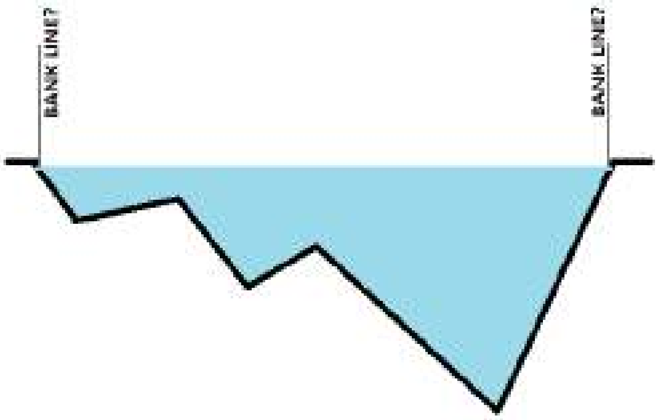


Figure 4: Asymmetry in river cross section profiles

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 5 and 6. The latter figure shows a reach of river Yamuna upstream of Hathnikund barrage. As a further complication of the latter issue, water may occupy different channels within the overall **dedicated river corridor** in different years, essentially prescribed by the underlying fluvial considerations and along with the overlapping influence of the autocyclic and allocyclic forces and as depicted above in Figure 3.

Figure 5: Skewed wet channel of a river during season of low flows

Figure 6: Skewed wet channel of Yamuna upstream of Hathnikund barrage

Realistically, 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 7, 8 and 9 respectively for river Yamuna.

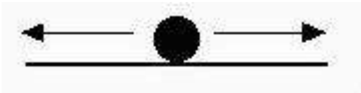
Figure 7: Multiple wet channels of river Yamuna

Figure 8: No wet channel seen in river Yamuna downstream of Tajewala

Figure 9: Disjointed network resulting perhaps from disjointed interception and capture of subsurface flows

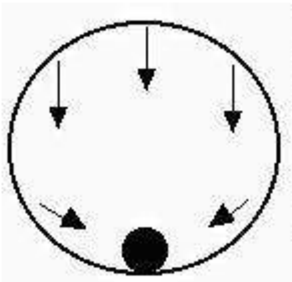
Looking at it from a different perspective, it is now possible to theorize that for a river channel course, in the absence of allocyclic and other avulsive triggers, three broad categories of states, all stable within their respectively restricted context, may be defined. These may be depicted as shown below as Figure 10a, 10b, 10c, 10d and 10e:

(i) Neutrally stable state (Figure 10a):



(ii) Locally stable state (Figure 10b):

(iii) Globally stable state (Figure 10c):



And, of course in the context of the hypothesized dedicated river corridor, globally stable state may be depicted as Figure 10d:

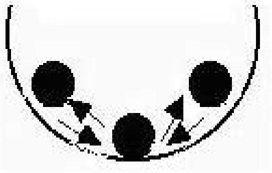


Figure 10d: Globally stable state for a river corridor

Alternatively, and more realistically, a globally stable state for a river course may be depicted as shown in Figure 10e with alternate possible individual stream paths although constrained to exist within the overall available swing zone of its dedicated corrido. The figure further highlights that there are alternative channel courses which are not just possible, but indeed, such a scenario is more realistic and plausible.

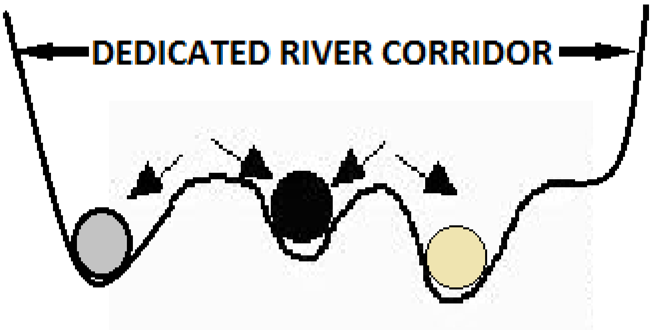


Figure 10e: Alternative representation of globally stable state for a river corridor

Figures 10 (a, b, c, d, e): Contexts of stability of river channel courses

As presented in the aforementioned depiction, an acknowledgement of the latter realism is indeed essential in order to better understand and appreciate the underlying significance of otherwise esoteric concepts of (i) **river centreline**; (ii) **river course shifting;** (iii) **critical river reach**; and (iv) **river planforms**.

To foster a better understanding of the concept of a River Centreline, the following illustration examines a parallel analogy with reference to a simple pendulum having the following attributes and circumstances:

Attributes:

(i) The tether connecting the pendulum bob to the anchor is not rigid.

(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.

Three alternate 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 erratic 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 accompanying each depiction is a corresponding poser about the concept of the ‘centreline’.

Circumstance (i):

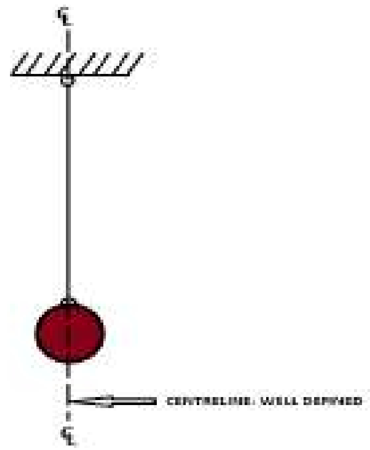


Figure 11: Centreline when Pendulum is at rest and in a tranquil/quiescent environment

Circmstance (ii)

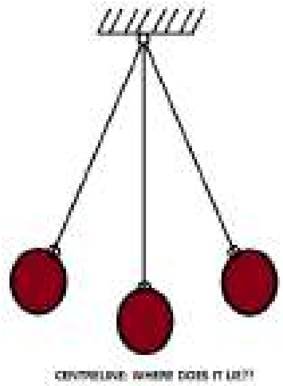


Figure 12: Pendulum is swinging in a frictionless and tranquil/quiescent environment (undamped oscillations)

Circumstance (iii):

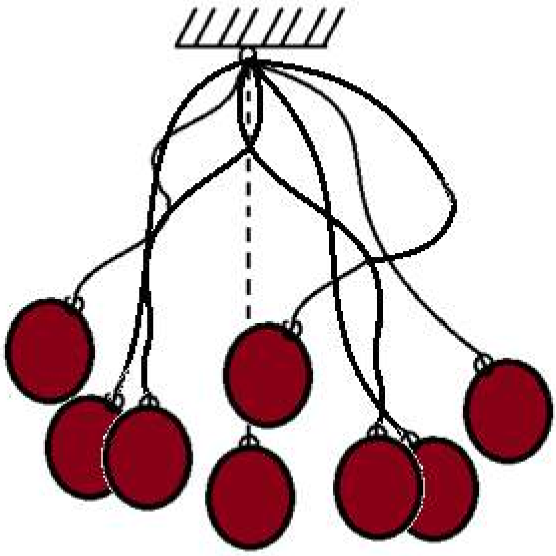


Figure 13: Pendulum is placed in a zone with strong and randomly turbulent air movements

The above illustration highlights the immutable reality that the concept of 'river centreline' is rooted in the interplay of multi-scale dynamics within the integrated domain of hydro-morphodynamics and the **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 channels is illustrated.

Accordingly, any attempt to demarcate the centreline of such dynamic 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 further reference to Figure 15, where the river details have been masked for effect, the planform of the centreline is dictated essentially by the coarser scale orientation of the floodplain valley.

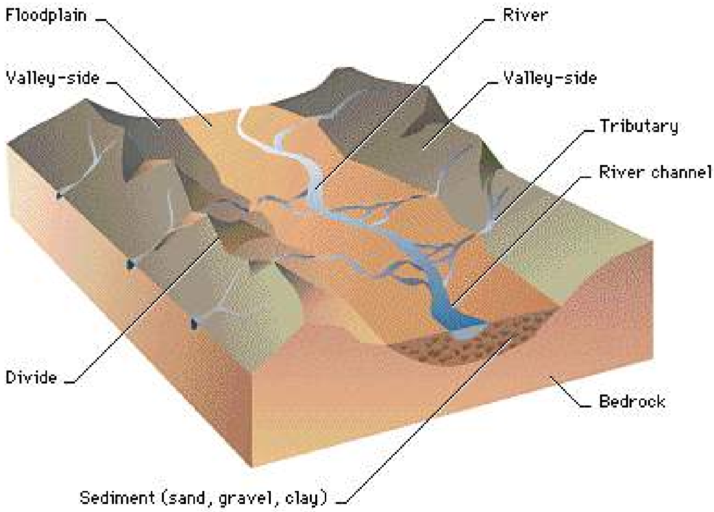


Figure 14: Schematic of a long & narrow floodplain valley along with its principal drainage feature (in blue)

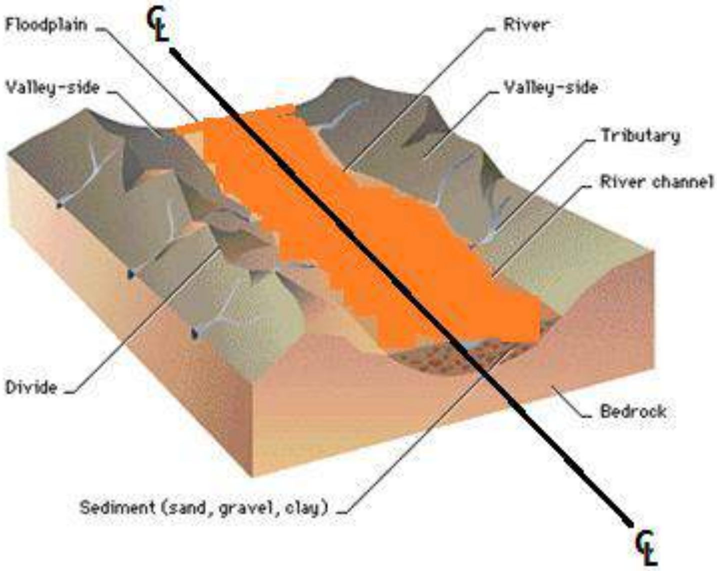


Figure 15: Schematic of a long & narrow floodplain valley with its principal drainage feature masked

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

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.

FLOW DIRECTION UNDER NORMAL AND DRY WEATHER CONDITIONS

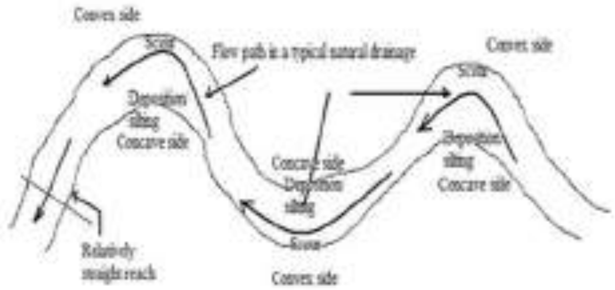


Figure 16

FLOOD FLOW PROPAGATION UNDER MODERATE TO EXTREME CONDITIONS

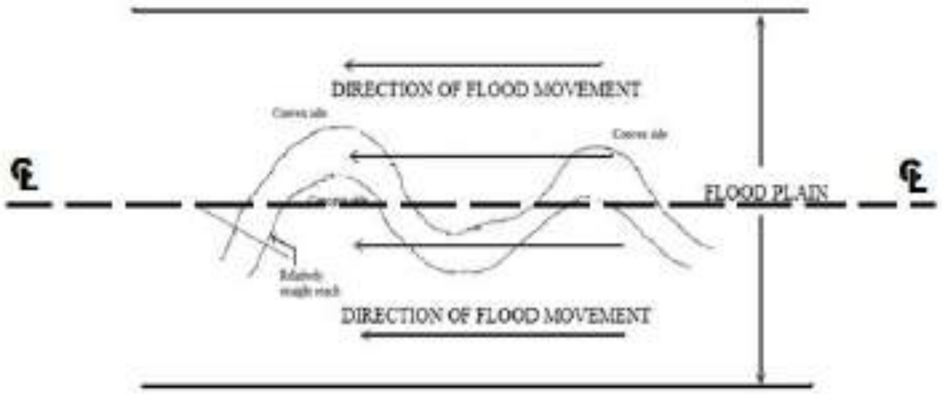


Figure 17

During seasons when the flow rate is limited to 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 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 relatively steeper energy gradient along the shorter flood plain flow paths, the rising flood flow velocities there may also be sharper as compared to that of the flows 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 and as also reiterated above in the foregoing discussion, the centreline will be straighter and along the general orientation of the encompassing flood plain valley when the latter feature is captured based solely on the wet season flood flow condition. Clearly, the sensitivity of the centreline planform configuration to 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 subjective and, therefore, leading to inconsistent inferences!!

Figures 18 and 19 show a reach of river Gangless in Leh and highlights the constraining influence exercised by 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 a further 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 contained within its 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 return period magnitude of flow rates as, for example, were observed during the aforementioned 50 year event, and indeed further 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 with specific 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*)

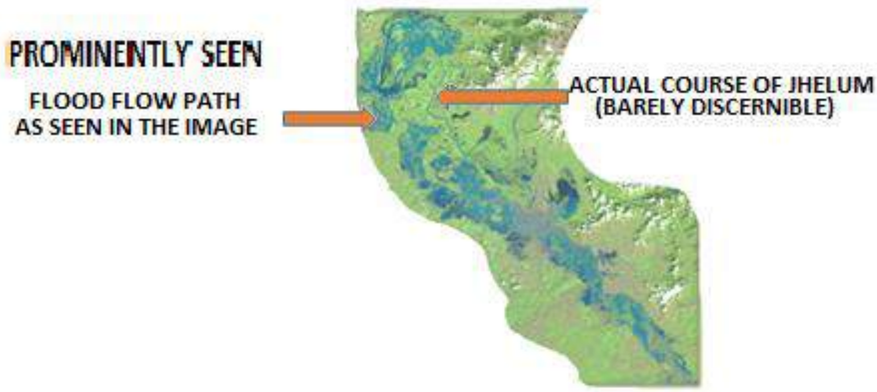


Figure 22: Flood mapping of September, 2014 event

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. Further, in Figure 23 also, the course of Jhelum is clearly discernible but shows only disjointed and scattered elements the September, 2014 flooding event pockets along its course. In contrast, however, the adjoining engineered 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, the task of centreline delineation based solely 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 also be seen in Figure 24.

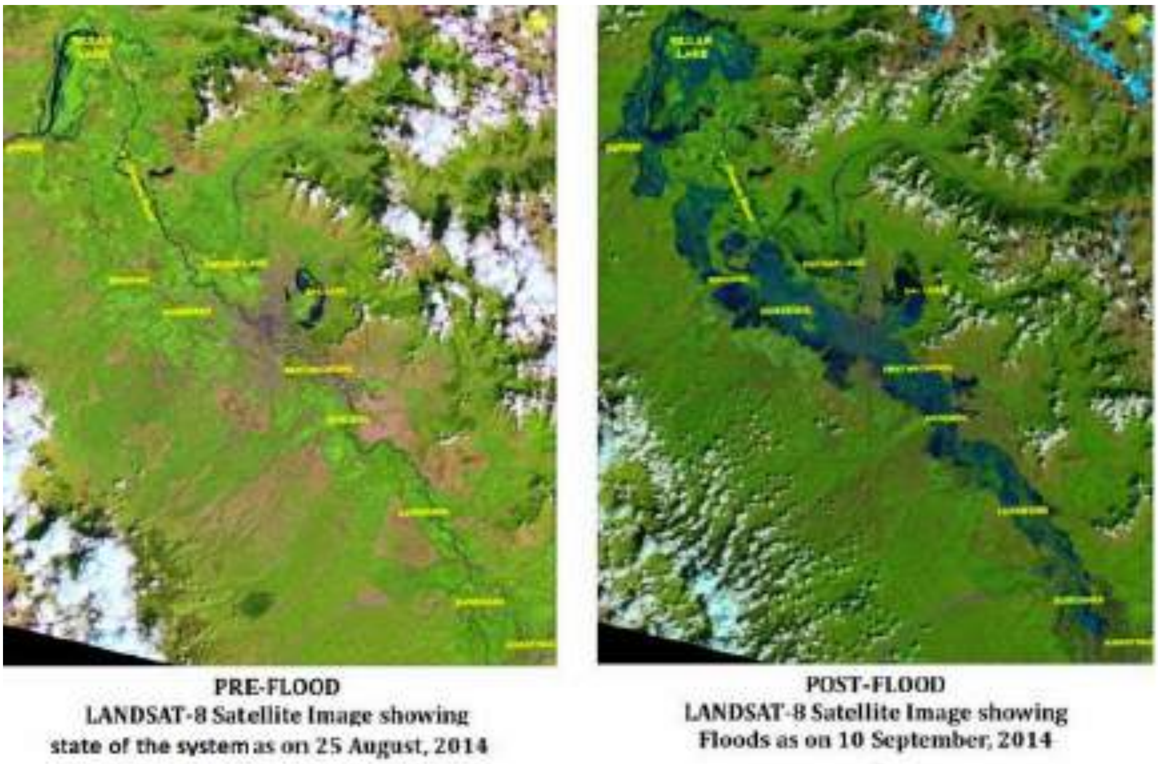


Figure 24: Comparison of river corridor between pre and post September floods

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 in terms of its 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 imagery was 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 Agency of Natural Resources Report, May 2009) 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 and its connected attribute of the '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. This suggests that as an alternative, the latter index does indeed offer the potential to be a benchmark index 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 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 with 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 a result of diverse range 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

THE WAY FORWARD: IMPORTANT CONSIDERATIONS FOR RIVER CENTRELINE

In consideration of the foregoing discussion, the hydro-morphological multi-scale non-stationarity in the latter systems emerges as a dominant theme and suggests that the **river centreline specification must only be contextual**. As a possible way forward, therefore, the river centreline may be estimated (or marked) on the basis of various, but context specific, physical processes as explained in the following discussion.

Centreline for dry beds

As an opening remark, the discussion may best be initiated with a question: What constitutes a consistent centreline 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: Braided dry river bed sensed on the basis of reflectance of white sands deposits

A river reach may run dry for reasons of upstream abstraction or the river is seasonally ephemeral i.e. non-perennial. These rivers face many challenges that directly affect its morphometric prognosis. For example, activities such as (i) unauthorized sand mining; and (ii) 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 the resulting unnatural morphometric changes that result in the affected river's bed and banks which translates into altered fluvial processes of hydrodynamic and sediment transport characteristics. Figures 29, 30(a) and 30(b) present a vivid illustration of the latter concerns. Similarly, the affected reaches may trigger formation of newer braids within the river and while newer ones are getting carved, some of the existing ones may experience abandonment!

Figure 29: Satellite imagery of patterns created by sand hauling from Yamuna sand bed

Figure 30(a): Altered Yamuna bed and bank profile as a result of mining of white sands deposits

Figure 30(b): Altered Yamuna bed and bank profile as a result of mining of white sands deposits

Centrelines with Hydrological Basis:

The water will occupy the steepest Hydro-Morpho-Dynamic 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 accuracy in obtaining single or multiple 'deepest channel' points may also be constrained 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) non-homogeneous bed deposits across the cross section leading to inconsistent reflectance, (iv) particulate matter being transported in suspension and along the river bed, (v) location of confluences with tributaries, and (vi) 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 and gorges. 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 with orientation of flow paths changing with flood levels. As a result, the latter also lends a measure of dynamism to the orientation of the illusive centerline and, as a further consequence, divesting the feature of its integrity as well its meaning. This phenomenon is commonly observed in river reaches that are in relatively mildly sloping flood plains and also in distributary (branching) 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. In view of a direct association with the concept of the bankfull, it is theorized that morphology of river channel's cross-section likewise evolves under the persistent action of the bankfull flow condition. It is noteworthy therefore, that centerlines that are mapped based on the simulated 'bankfull' appears to be reasonable and consistent approach and the latter 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 from Remote Sensing Images:

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 <u>**abandoned**</u> or <u>**recently vacated,**</u> channel course but understandably, <u>**usually temporarily**</u>.

(vii) Often it has been known in India that migrating populations and indeed recent non-native foreign settlers, in the absence of formally designated resettlement zones, begin to occupy easily available channel flood plain areas. Interestingly, the observed pattern of these settlements suggests that the encroachment 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 tonal 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 indisputably a source of abundant geophysical data pertaining to various surface and near-surface aspects of hydro-geomorphological 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 reason, plausibility, patience, cautious judgement and prudence when seeking to attribute any physical meaning to the features extracted from these imageries.

Remote Sensing Based Current Practices:

The current practice is to digitize the centreline based on the wet stream (water area) captured of the river. This centreline is just a snapshot position of the stream. Since these images are acquired at different times of the year, the centreline can be assumed to be representation of the river course, as it existed on the date of image acquisition.

<u>Approach 1:</u> If the image is acquired for the period of bankfull discharge, the stream can represent the average flow direction in the river and centreline can be marked from the stream. Issues: Apart from the challenge of estimation of bankfull discharge, the level of difficulty also rises here due to the need for hydro-metrological data. Hydro-metrological observations are required to ensure concurrence of image capture date with that of the occurrence of bankfull discharge. The relevant imageries (if available) will usually be of monsoon months and presence of cloud cover will pose a serious challenge when extracting the morphometric features.

<u>Approach 2:</u> An alternate way of delineating the centreline using remote sensing technique is using non monsoon month image. An important feature extracted from the latter image would be the channel area . This is the region of sand area, where reflectance is very high, and water area. In hope that the region of visible sand area, attributed as channel, represents the bankfull channel width, the centreline of this will represent the bankfull discharge orientation.

Issues: In India, the channel areas are occupied for the agricultural and habitation purposes (Living with Floods). This brings the channel area under vegetative cover, which reduces the reflectance of sand and the estimated channel deviates from the actual channel. And so does the orientation of centreline approximated from the channel.

Though, remote sensing products provides us with abundance of data of various geophysical features on earth. It is important to understand that satellite captures the snapshot of the geomorphic system, it does not explain the dynamics of the system. And, one has to be cautious while attributing any physical meaning to the features extracted from the imageries.

SPECIAL FEATURES

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 31) 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 31) 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.

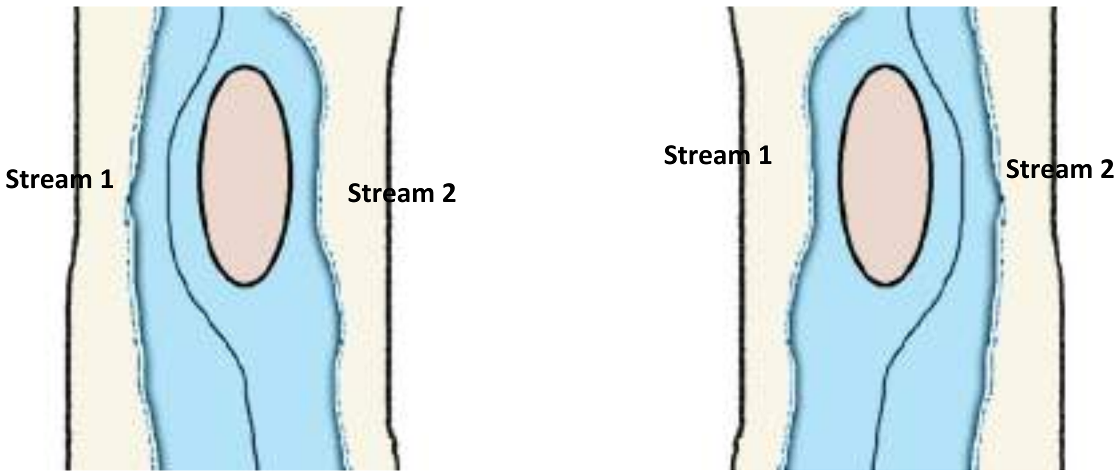


Figure 31: Braided rivers

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,

<u>all the occupied threads with corresponding multiple centerlines that pass through each occupied thread</u>. 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 **<u>anastomosing or anabranching</u>** systems.

Bankline vs Centreline: Applications in the study of junctions and confluence points

Delineation of the morphological feature of river banklines seeks to establish the latter as it has numerous important applications especially when investigating morphodynamic aspects of confluence points or confluence zones between a river and its tributaries. While the intersection point between centrelines of the dominant river and its tributary stream has an intuitive appeal as it is amenable, at least in theory, to a precise determination. However, the latter concept is largely imaginary and intangible for reasons discussed in detail in the aforementioned sections and therefore may not yield objectively formulated inferences especially when the latter determination of confluence points constitutes a critical input in morphological and related investigations. Clearly, confluences defined on the basis of intersection of centrelines are liable to be poorly specified on account of the level of subjectivity that abounds in this approach.

Another challenge in approach based on the concept of centrelines arises on account of the fuzziness when defining orientation of the two approaching centrelines as these depend on the planforms of the main river and the approaching tributary. In addition to scale dominating the accuracy with which these approaching centrelines can be captured, it is also expected that the two courses would each carry a measure of tortuosity in planforms along their respective courses and the projected tributary centreline may intersect with the main river centreline some distance, generally downstream, off the confluence zone.

On the other hand, however, banklines are indeed amenable to a tangible and consistent identification, albeit subject to unambiguously specified adopted benchmark references. It is strongly averred that in the study of confluence points and their intrinsic dynamic nature, intersection of banklines presents a more credible and consistent basis. Such confluences can be easily captured - being intersection points of tangible morphological entities – as coordinates where the first bankline of the tributary (oriented with respect to the main river as the upstream intersection among the two intersecting points) meets the bankline of the main river course. As a better illustration, it may be noted that there are two alternative approaches namely:

(1) Tributary may approach the main river along the left bank:

In this case, the confluence point would be defined by the intersection point between the left bankline of the main river and the right bankline of the tributary.

(2) Tributary may approach the main river along the right bank:

In this case, the confluence point would be defined by the intersection point between the right bankline of the main river and the left bankline of the tributary.

CASE ILLUSTRATION: 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, on account of prescribed and regulated water abstractions, the river rarely carries more than a fraction of its bankfull discharge and the braid like features that are observable are likely due to channel occupation by the meagre residual releases of the available flow into the river (Figure 32). In the latter Figure 32, the channel area occupation is also evident in the form of discernible agricultural landholdings.

Figure 32: Yamuna River d/s of Hathinikund barrage.

With the aforementioned impairment of the natural hydrological regime and the accompanying changes in flow pattern, the river responds with corresponding changes in the wet channel area. For example, an increase in the water area is clearly evident from a comparison between Figures 33 (segment shown as reach 1 is also shown in Figure 6) and 34. Clearly, it follows from the comparison, 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 33: Yamuna River u/s of Paonta Sahib.

Figure 34: 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 hydro-morphological 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 template comprising of a system of meridional and latitudinal lines that enclose a square/rectangular grid of pre-specified scale. The relationship of the particular morphological planform with the geographical coordinate system comprising of the aforementioned meridional and latitudinal lines is proposed to be used as shown below in alternate forms as depicted in Figures 35 and 36. The addition of the river channel along with accompanying details are shown for illustration purposes in Figures 37 and 38. It is expected that this geographical grid based reference template will be better amenable to the capture of river planforms together with spatio-temporal changes that may be observed in these latter forms from one timeline to the next available capture.

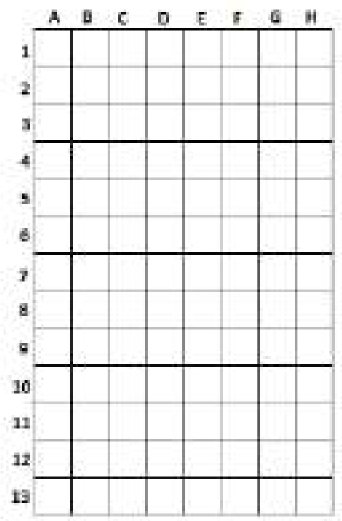


Figure 35: Reference Template (1)

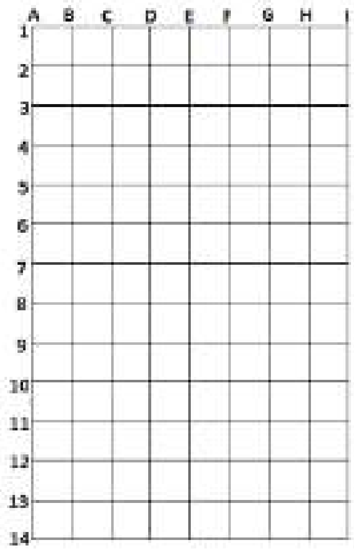


Figure 36: Reference Template (2)

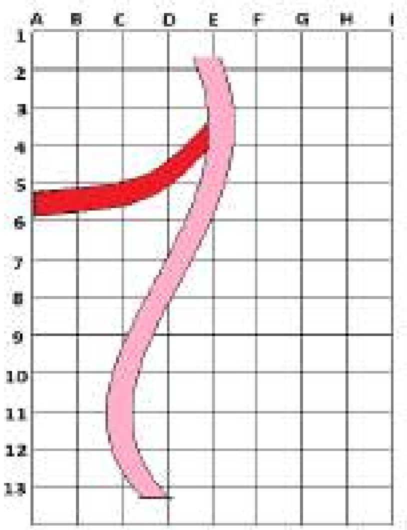


Figure 37: Reference Template

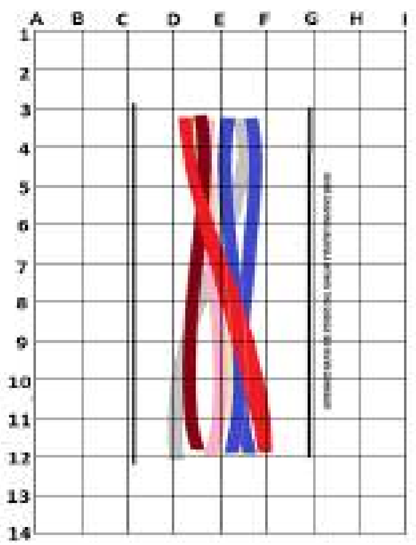


Figure 38: Reference Template

With the adopted numbered grid based system, the referencing of the morphological feature is now a straightforward process in which the position of any morphological artifact may be recorded in terms of two offsets from latitudinal line and similarly two offsets off the meridional lines for a total of four offsets with the orientation being recorded as **N, S, E** or **W** as the case may be.

NOW, 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, river systems are anything but intransigent entities, and over a limited span observational window, the position of a river's observed course is just a fleeting reality. As for the current practice, the centreline is digitized based on the active stream (or active water area) in that time window in the manner of a snapshot position of the stream. Since these images may be acquired at different times of the year and beyond, the centreline can be assumed to be a representation of the flow channel and the flow direction in the river on the date of image acquisition.

The relentlessness of underlying influence of the all-pervasive auto-cyclic and, to some extent, allocyclic triggers is a common and acknowledged reality facing all river systems. However, there indeed are differences when the system is observed across time scales or morphometric epochs. These individual systems are observed to alternate between different morphological states - for example, observing a river channel's course between successive 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 affected and hence deemed to be vulnerable, and also (iv) time span over which transit in (or over) a given state is observed prior to its abandonment and/or occupation.

Notably, in addition to the strength of the underlying allocyclic and auto-cyclic processes, the duration of these latter transits are also controlled by the dynamics and scale & statism of river basin's morphological restraints as dictated by factors that include:

(i) Anthropogenic interventions in all its diversity
(ii) Bed morphology and nature of bed constituents
(iii) Fluvial transport of particulate matter along the bed and in suspension
(iv) Surface topography including presence of deep valleys & gorges
(v) Scale of relief and undulations in surface topography
(vi) Movement of glaciers and ice caps
(vii) Relatively rapid scale of changes in landforms as a result of avalanches and landslides

The way forward

A. A consistent and appropriately calibrated reference system shown as Figure 35 or Figure 36 is proposed as the basic template on which geo-referenced morphological entities can be mapped to scale and labelled with specified important attributes of interest and corresponding chronology.

B. With regards to the task of river centreline delineation, the latter feature should be captured in terms of its **entire set** of possible morphological facets. For example, the following facets may be appropriate:

- **(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 may be mapped for all discernible and 'plausible' channel trails. Within channel sand deposits have observed reflectance values that is in sharp contrast with off piste regions that lie 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 snapshot in time. These will further facilitate in the following:

- **(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 capture the timeline of evolution of the mapped channels together with the corresponding rates.

SHIFTING, AVULSION AND AUTO-CYCLIC EVOLUTION OF RIVERS

In the preceding discussion, it has been emphasized that a complex interplay of multi-scale processes such as weather and long-term climatic variability is responsible for the formation and subsequent evolution of rivers. Other important factors, and which carry influence at a range of spatial and temporal scales, include the (i) basin physiography and basin relief, (ii) nature of basin regolith and pedosphere, (iii) land use, (iv) hydrologic & morpho-hydrodynamic setting of the basin, (v) upland erosion potential, (vi) sediment transport characteristics, (vii) channel erosion-depositional processes and channel bank retreat, (viii) seismo-tectonic setting of the basin and importantly, (ix) anthropogenic and other externalities.

Shifting of River:

Rivers generally flow along the fault lines or lineaments and the channel morphology understandably bears their characteristic influence. Changes in these latter subsurface features may manifest on the surface as uplifting, subsidence, development of rifts and these have the potential to alter the evolutionary trajectories of the contained water bodies among others.

Depending upon the magnitude of these subsurface and surface readjustments, transitions in the geo-coordinates of surficial features such as rivers may be observed at a range of time scales ranging from very slow and gradual to very rapid as when river avulsions are observed. There is need for a distinction to be made between the aforementioned transitions when observed in the river course within its rightfully designated 'dedicated river corridor' against transitions that may be observed of its 'dedicated river corridor' itself accompanied by a lateral translation or indeed a **'shift'** of the swing zone of the river channel.

The need for a clear distinction between the latter transitions i.e. transitions of the river channel within the swing zone as defined by its dedicated river corridor and the transitions that may be observed of the dedicated river corridor is indeed imperative for a proper understanding of the river morphology and its innate dynamism. For emphasis, it may be noted that these transitions are due on account of processes that occur at scales ranging respectively from mainly autocyclic for the former case to mainly allocyclic for the latter transitions wherein the transit that is observed of the swing zone itself - as demarcated by the width of the dedicated river corridor - is indeed an inevitable consequence, albeit of relatively rare occurrence in nature, of the underlying seismotectonic dynamism.

The aforementioned distinction now provides a basis for the definition of the 'S**hifting' feature in rivers which needs to be revised to mean a gradual and unidirectional preferential movement of the river course on account of displacement of the river corridor itself - usually in response to allocyclic seismotectonic readjustments that may occur within the basin.** As an example, Kosi River in Bihar is known to have **shuffle shifted**, in incremental steps from a pre-dominantly NE orientation when it is presumed to have been a tributary of the NS flowing River Mahananda circa 1730 to a NS orientation, as a tributary of River Ganga circa 1770 and then to its current position as a tributary of River Bhagmati. Interestingly, the orientation of the current course of River Kosi is NW till its approach to Bhagmati and thereafter makes a dramatic turnaround in an arcuate manner to flow along a NE course above its outfall into Bhagmati and thereafter adopting the latter river's WE orientation. At its most westerly point, River Kosi is over 115 km west of the course it followed over 200 years prior.

In line with the proposed hypothesis presented earlier in the foregoing discussion, geological fault lineaments act as cradles for the river channels that form in response to the hydrological concentration of storm runoff. Further, the dedicated river corridor is a riverine morphological feature that straddles across the latter geological fault lineaments and within the latter corridor, the river course had the potential to swing between alternate paths and, notably, the river's duration of residence in each state within its dedicated corridor - alternatively also referred to in the foregoing discussion as it's swing zone - is by no means **ad infinitum**.

As depicted in Figures 39 and 40, the shifting of the river's dedicated corridor is remarkably observed in the region between River Mahananda and the current course of River Kosi but bounded on it's southern flank by River Bhagmati prior to Bhagmati's confluence with River Ganga.

With reference to Figures 39 and 40, River Kosi, prior to 1700s, is seen to follow the course that appears to be aligned with the Malda Fault-Purnea Graben. Further to the west is observed the Bhawanipur Fault. In the preriod 1870s to 1890s, River Kosi is recorded to have followed a course running along the Bhawanipur Fault with it's characteristic NS bearing. Finally, in the current period, River Kosi is aligned along the Begusarai Fault and, after confluence with River

Bhagmati, follows a course from West to East and being delimited by River Ganga and Bhagalpur Fault in the South. Interestingly, further to the West of Begusarai Fault, the East Patna Fault may be the next stop for River Kosi if further '**<u>horsting</u>**' were to occur to the east of Kosi.

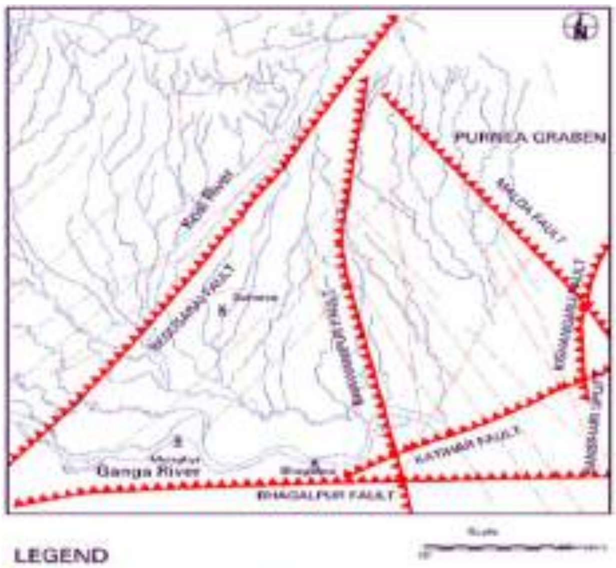


Figure 39: T ... da Fault-Purnea Graben in t ... the West and Bhagalpur-Katihar Faults and River Ganga in the South (Agrawal and Bhoj, 1992)

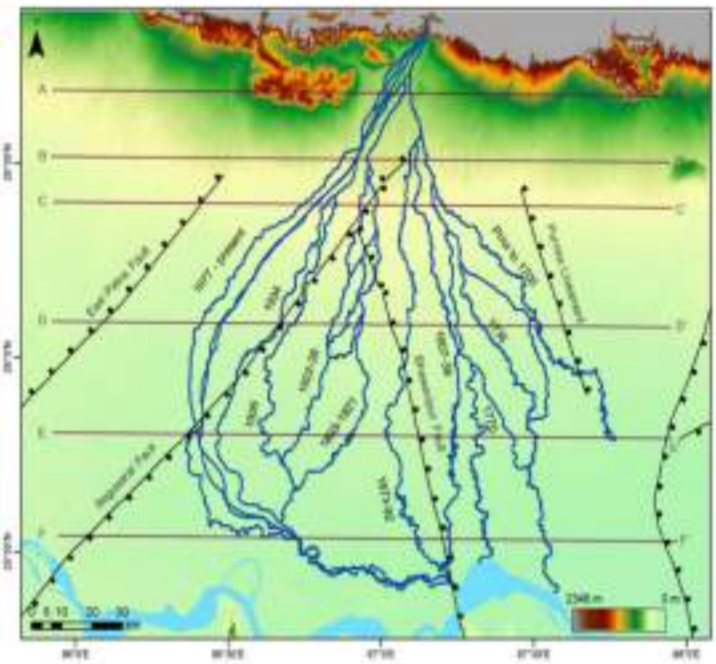


Figure 40: Course shifting history of River Kosi beginning circa 1700 (Srivastava, 2012)

In contrast with the shifting theory, on the other hand, **avulsion is a sudden change - reversible and, in some cases, irreversible - of a river's course.** **A**vulsions can be triggered as much by the proverbial tectonic upheavals as also by landslides, engineering failures and also by sluggish autocyclic processes leading to an accumulation of strain energy over time till the morphological entity tips towards an alternate and viable state of maximally dissipated state of hydro-morphodynamic potential. One can infer from the meaning itself the level of destruction that may accompany an avulsion. River Kosi – a tributary of Ramganga in Uttarakhand and the ancient Saraswati are often cited as classic examples.

Autocyclic Evolution of the Rivers:

Rivers are non-stationary dynamic hydro-morphological features and bear a strong signature of (i) range of hydrological flow regimes observed across time, (ii) hydrodynamic variability in flow, and (iii) history of erosion, deposition and transport of sediment down its course. The formation of oxbows by meandering rivers, movement of a river within its swing zone, intermittent and alternate abandonment and reoccupation of braids by water streams in braided rivers, observed alternate paths of the wet channels, and shifting of the river corridor itself cannot therefore be attributed to or even be characterized as shifting or as avulsive phenomena.

Figures 41 and 42 below are two scenes that capture a reach of river Brahamputra in the years 2014 and 1990 respectively. It is observed that in the more recent scene of 2014, the principal wet stream skirts along the right bank while in the year of 1990, the wet stream is seen to be confined to the left side of the river. These stream movements have also been labelled as local avulsions by some researchers/investigators which is indeed an untenable characterization.

To further drive the point, it is observed that while the wet streams appear to be having a distinctly wandering character and are also seen to be evolve rather rapidly in this markedly braided river reach, they, however, also seem to be confined within the latter river's swing zone or indeed its river corridor. It is argued that in the absence of any catastrophic geodynamic event, the river will remain within this channel corridor and it is within this band that the channel planform is seen to evolve and hence, reference may be made to this corridor also as the river's 'Planform Evolution Band' within which its 'Channel Planform Evolution', over the relevant morphological time scales, is seen to be constrained.

Figure 41: Brahmaputra in 2014

Figure 42: Brahmaputra in 1990

Importantly, delineation of the dedicated swing zone/channel corridor/channel evolution band is a connected challenge. In this regard, an approximate delineation of active floodplain may indeed be based on a return period of around 10 years and further, in case river terraces are of interest, these may be delineated based on hydrodynamic water spread corresponding to a flood event with return period ranging from 25 to 50 years.

BRAIDING PLANFORM – SHARMA (1995) AND FRIEND & SINHA (1993) INDICES REVISITED

Introduction

River braiding, as a morphological feature, is an attribute of a river reach more than being just a cross sectional signature. The intertwining of wetted pathways within the confining bounds of the river banks is indeed the single most recognisable feature of a braided river reach. Obviously, this alludes to the presence of multiple wetted channels along the reach and additionally, an equal number of discernible intersections across the cross sectional transect.

For a braiding reach, a morphometric basis for an otherwise purely qualitative and descriptive detail of river-braid planform may be obtained from a combination of, among others, the following:

(i) Cumulative length of all wetted braids along the reach,
(ii) Reach length,
(iii) Total wetted width as a fraction of the overall width of the cross section,
(iv) Density of nodes or junctions of braid confluence and braid branching.
(v) Overall interconnectedness amongst the multiple wetted channels

The aforementioned recognises that any attempt to describe a river braids planform is essentially a loosely perceived and judgment-based articulation of the river's planform presentation. Clearly, such a fuzzy characterization is in recognition that there are a diverse set of plausible and similarly credible descriptions of braid planform morphology.

From the above, it now emerges that a rigorous analytical formulation for an 'Index' based measure of a river's planform is indeed a far-fetched aspiration. The formulation is also likely to face challenges on account of the overlapping of scales of an innately diverse range of process and observation scales within which the operational spatio-temporal dynamism lends its diverse set of signature characteristics to such a natural system. A further complexity arises from the now widely acknowledged fractal nature of the braided river's planform topology.

An alternative way forward to achieve an 'objective' river braid planform characterization, having shunned the idea of a rigorous analytical formulation based approach, seems to point towards an intuitive construct as a basis for the elusive 'planform index' and, further, also suggests that there is a multiplicity of possible forms that such an index may have.

The benchmarks, as a guide towards the goal of arriving at those 'elusive' forms of planform indices, should include the following:

(i) Indices should be amenable to quantification without the need for complex arithmetic; and
(ii) Indices should be based on those river planform attributes that also lend themselves to routine measurements, albeit inevitably influenced by scale issues.
(iii) Indices should also have an intuitive appeal.
(iv) Indices should be amenable to a concordant visual judgement.

Accordingly, it is hypothesized that the braiding severity observed along a river reach may be captured in terms of the following:
(i) Ratio of cumulative length of all wetted braids to the reach length,
(ii) Number of wet braids across a cross section
(iii) Total wetted width as a fraction of the overall width of the cross section,
(iv) Junction density over the river reach

In the following discussion, modifications are suggested in the cross section based Braiding Index proposed by Sharma and the reach based indices proposed by Friend and Sinha (1993).

Sharma's Index {SI}:

Sharma's Braiding Index is a cross section based numeric and has the form given by the expression

SI = {(W/B)/N}

where N is the number of wet channels intersecting the indicated cross section profile, B denotes the maximum bank to bank width of the cross section and W is the cumulative total of widths of all individual wetted braids as seen across the cross section of interest. The following points are worthy of note:

(1) The ratio {W/B} has a value less than unity for a braided cross section and, when divided by the number of wet channels N, the index, SI, is rendered still smaller. Thus, it is seen that the severity of braiding is proportional to the **reciprocal** of the numerical value of SI in the expression mentioned above.

(2) N (i.e. the number of wet channels) acts as a scaling factor to remove any ambiguity that might result without it in case W approaches B for a highly braided system in which the overall bank to bank width, B is interspersed by a hypothetically large number of narrow width wet braids.
Mathematically, the latter case presents an anomalous situation and leads to inconsistent inferences as indicated below:

$$\lim_{N\to\infty}\left(\frac{W}{B}\right) \to\Rightarrow 1$$

(3) As indicated, SI is a planform index that is based on cross section features rather than being a reach-based index and, therefore, lacks an intuitive appeal.

(4) As mentioned in (1) above, a higher level of braiding severity is associated with a lower numerical value for SI although a larger value for N (number of wet channels) intuitively implies a higher braiding severity.

The consequent inconsistent inferences that are likely are illustrated with reference to the following Figure 43:

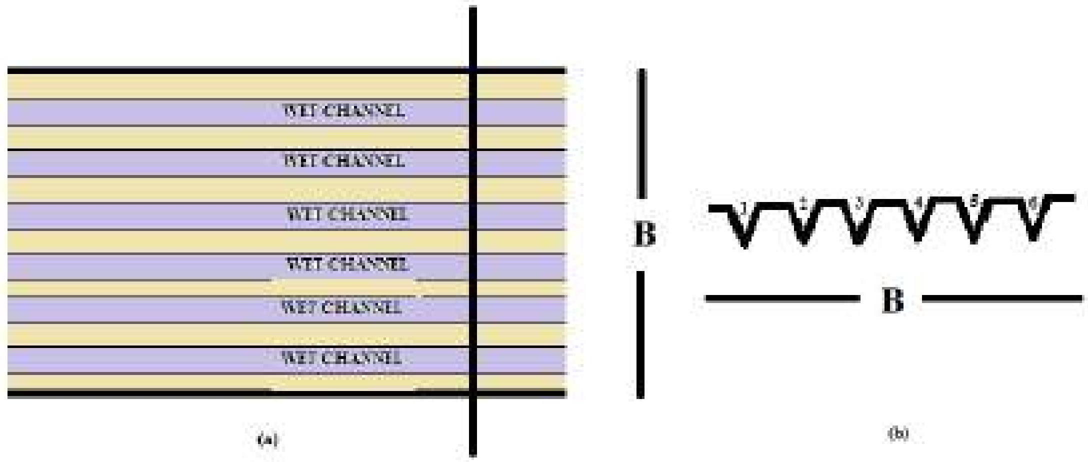


Figure 43 (a) and (b): Case of six parallel wet channels within the river width = B

For the configuration of Figure 43 (a) and (b), a value of SI << 1 is clearly indicated thus alluding to a highly braided planform. This inconsistency arises primarily on account of the earlier observation that SI is merely a capture of cross sectional features and not planform features namely braid junctions, which typically would require a two dimensional, (X,Y) based spatial context.

Misleading inferences are also likely as illustrated by the following example of two alternate channel cross section geometries in which one channel cross section is seen to have two wet braids while the other is seen with three wet braids.

With regards to the ratio (W/B), there are innumerable combinations possible in nature and it is realistically possible to obtain (W/B) ratio values of 0.5 and 0.9 respectively for the two cases as described above. Thus, we have the following interesting results for SI:

(1) Case of two wet channels: SI = 0.5/2 = 0.25
(2) Case of three wet channels: SI = 0.9/3 = 0.3

The interesting dilemma that now begs resolution depends on which channel cross section bears the signature of more braided planform? Is braiding implied to be more severe in the river whose cross section has two wet channels (SI=0.25) or is it the cross section with three wet channels (SI=0.3)?

Difficulties of specification also arise as these indices are severely dependent on the hydrodynamic attribute of the depth of the flow (wetted channels) as the two measures namely W as well as B are both dependent on the flow condition at the time of recording observations. For example, a braided reach may see a complete submergence of these features during even moderately high flows and thereby, leading to a comprehensively altered observer's perspective of the actual reality!!

As a cautionary note, it is strongly recommended that the reported value of SI should invariably be accompanied by a detailed note on date of channel planform observation and the prevailing hydrodynamic conditions. This additional accompanying information is expected to yield more informed inferences on channel planform characterization. Further clarity is also likely if the reported value of SI is accompanied by the following statistics:

(i) Range of braid widths
(ii) Standard deviation of braid widths
(iii) Coefficient of variation of braid widths.

Notwithstanding the foregoing difficulties, it would be highly desirable if the numerical value of SI, based as it is only on cross sectional features, also reflect the important, but hitherto missing, information regarding the number of wet braids/channels that are actually present along the cross sectional transect and which, together, has returned the particular numerical value for SI (value is less than unity) as has actually been obtained.

Towards this end, alternate variations of Sharma's braiding index are proposed as given below:

(1) [{(W/B)/N} + N]
(2) [(W/B) +N]
(3) (W/B)*100 %

An obvious advantage of index (1) being that the numerical value of the index will be as a number having both (i) a non-zero integer component, and (ii) a real part after the decimal point. While the real part will reflect the braiding severity and would be the same value as returned by SI, the integer part, interestingly, will capture the actual number of wet channels that were observed to cut across the cross sectional transect and whose attributes would have been used to obtain a numerical value for {W}.

Friend and Sinha (1993) Index:

Friend and Sinha's Braiding Index (henceforth referred to as FSI) is a **Reach based Index** and has the form given by the expression:

FSI = $\{L_T/L_M\}$

This Braiding Planform Index, being a reach-based capture of channel braiding morphometrics, therefore has a greater appeal as compared to the former index proposed by Sharma. In the expression for FSI, the terms L_T and L_M are as described below:

(1) Length of the Main (Principal Channel/Braid): L_M
(2) Total length of all channels/braids over the given reach: L_T

The following points are noteworthy with regard to FSI:

(1) FSI is a reach based index of river planform.
(2) In contrast with SI, the hydrodynamic status of the river does not have a serious impact on the estimation of FSI as the latter factor is opaque to the wetted channel widths.
(3) The hydrodynamic status is likely to influence the number of channels within the bank span of the river that are observed to be actively transporting water down the river reach.
(4) The hydrodynamic status is likely to influence the length of the observed wetted channels.

Notwithstanding the fact that FSI is a reach-based measure of braiding severity, the channelization shown in Figure 43 above is also likely to be adjudged as a case of a relatively high braiding severity by the latter index. Clearly, this index also fails to capture the depicted morphological realities of Figure 43 and, therefore, showing up to be as ineffective as the SI based measures, albeit to varying degrees! As in the aforementioned discussion, the most important element that these latter indices fail to capture is the role and significance of the number of braid junctions that are observed over the river reach.

Clearly a need emerges for alternate forms of indices that are sensitive to the latter morphological signatures and, therefore, as successful, if not more, at capturing the braided planform signatures of river reaches.

ALTERNATIVE BRAIDING INDICES

Define the following channel morphometric attributes:

(1)	Length of Reach:	$\mathbf{L_R}$
(2)	Length of the Main (Principal) Channel/Braid:	$\mathbf{L_M}$
(3)	Total length of all channels/braids over the given reach:	$\mathbf{L_T}$
(4)	Number of Junctions over the given reach:	$\mathbf{N_J}$
	Braiding Ratio (Reciprocal of FSI Braiding Index), R_B	$\mathbf{L_M / L_T}$
(5)	Average Bank Span Width of the river over the reach length:	$\mathbf{B_{AV}}$

Three categories of Braiding Indices are suggested namely (i) Inverse Measures, (ii) Proportionate Measures, (iii) Neutral Measures, and (iv) Other Measures. Within each category, the indicated forms of Braiding Indices – totalling fifteen (15) in all - are suggested based on their intuitive appeal:

(A) INVERSE MEASURES

(i) R_B / N_J
(ii) $(L_R/L_T) / N_J$
(iii) L_R / N_J
(iv) L_M/N_J

(B) PROPORTIONATE MEASURES

(i) N_J / R_B

(ii) $N_J /(L_R/L_T)$

(iii) N_J / L_R

(iv) N_J / L_M

(v) L_T / L_M (F-S Index)

(vi) L_T / L_R (Variant of F-S Index)

(vii) $N_J / (L_R*B_{AV})$ (Captures Junction Density within the designated rectangular domain)

(viii) $N_J*(L_T /L_R)$ (under the category of 'OTHER MEASURES')

(ix) $N_J*(L_T /L_M)$ (under the category of 'OTHER MEASURES')

(C) NEUTRAL MEASURES

(i) N_J / L_T

(ii) L_T / N_J

(D) OTHER MEASURES

Mentioned as (vii) and (viii) under 'PROPORTIONATE MEASURES'

These suggested indices are arranged in the following table (Table 1) as hereunder:

Table 1: Some intuitive choices for Braiding Indices

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

Procedure

The procedure recommended is based on a Delphi based approach. A collection of scenes of braided reaches will be presented to experts for opinion and assessment. Experts will rank the latter collection of braided scenes based on an individual judgement according to a formal protocol as explained below.

Step 1: Extract scenes of braided reaches (not necessarily of the same river; any number of rivers nationally/globally; assume 10 such scenes)

Step 2: Obtain a priori numerical measures of the various braiding indices for each scene and arrange them together in the form of the following table (Table 2)

Table 2:

	Values for Braiding Indices (i), (ii), (iii), …., (xv)									
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	…..	(xv)
Scene 1										
Scene 2										
Scene 3										
Scene 4										
Scene 5										
Scene 6										
Scene 7										
Scene 8										
Scene 9										
Scene 10										

Step 3: Obtain ranks of braiding severity from each individual expert member of the cohort group (assumed here to be 8 in all and labelled from (a) to (h)) without sharing information in Table 2. These ranks are obtained individually, in confidence, **and based on visual judgement only**. These ranks can similarly be tabulated as in Table 3 below and provides the information for Table 4 as well.

Table 3

	Number ranks (1 to 10) based on judgement of each individual (expert) cohort member (a), (b), … (h)							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Scene 1								
Scene 2								
Scene 3								
Scene 4								
Scene 5								
Scene 6								
Scene 7								
Scene 8								
Scene 9								
Scene 10								

Table 4

	Ranking Statistics					
	Min	Max	Median	Mean	Std Dev	CV
Scene 1						
Scene 2						
Scene 3						
Scene 4						
Scene 5						
Scene 6						
Scene 7						
Scene 8						
Scene 9						
Scene 10						

Note: Rank =1 implies most braided and rank =10 implies least braiding

Step 4: Shuffle and redistribute individual assessments among the experts anonymously. Each has his/her own original table and another table by someone not known. Comparison is made and each has the option to revise his/her original table. It is now possible to reconstruct Tables 3 and 4 again with refined ranks to obtain Table 5 and a table of important statistics as in Table 4 above.

Table 5

	Refined number ranks (1 to 10) based on judgement of individual researchers (a), (b), … (h)							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Scene 1								
Scene 2								
Scene 3								
Scene 4								
Scene 5								
Scene 6								
Scene 7								
Scene 8								
Scene 9								
Scene 10								

It is reasonable to expect that after this iteration, the column of std. dev. and CV in the table of statistics will have smaller numbers when compared with corresponding columns in Table 3

Step 5: Step 4 is repeated as many times as may be deemed necessary till no further changes are recorded. Two cases arise.

<u>Case 1</u>: **Special case**

All members of the cohort group converge to a common judgement and assign similar ranks from 1 to 10 to all the ten scenes. It is to be noted that for this latter special case, all Std. Dev. and CV values as per Table 4, will have reduced to zero for all scenes. Table 6 captures the scenario for this special case.

Table 6: Final (converged number ranks (1 to 10)

	Converged ranks
Scene 1	
Scene 2	
Scene 3	
Scene 4	
Scene 5	
Scene 6	
Scene 7	
Scene 8	
Scene 9	
Scene 10	

Finally, the information may be compiled and presented in the form of a final scores table as given below (Table 7).

Table 7

	Conv ranks	Score of each index based on absolute difference between ranks									
		(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	….	(xv)
Scene 1											
Scene 2											
Scene 3											
Scene 4											
Scene 5											
Scene 6											
Scene 7											
Scene 8											
Scene 9											
Scene 10											
Sum total of differences											

<u>Case 2</u>: General case

No convergence of ranks is observed after many iterations and there are divergent judgments on some or all of the various scenes presented to the cohort group for examination and ranking. The final compilation of ranks awarded by each member of the cohort group may be arranged in a 'table of discord' as shown below as Table 7.

Table 7

	Final (discordant) number ranks (1 to 10)							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Scene 1								
Scene 2								
Scene 3								
Scene 4								
Scene 5								
Scene 6								
Scene 7								
Scene 8								
Scene 9								
Scene 10								

Further, information on some common statistics may be put together along the lines of Table 3 above and presented as a summary of rank statistics as shown in Table 8.

Table 8

	Statistics of final ranking					
	Min	Max	Median	Mean	CV	(X) percentile value
Scene 1						
Scene 2						
Scene 3						
Scene 4						
Scene 5						
Scene 6						
Scene 7						
Scene 8						
Scene 9						
Scene 10						

Now all that remains to be done is to compare assigned ranking with the numerical values for each of the braiding indices to establish the relative strengths and weaknesses in each of the proposed braiding indices. How to do that??

Procedure:

A basic element of the process is also to rank the various braiding indices that have been proposed in terms of suitability. Towards this goal, a tangible measure of synergy with the 'average' perception of the cohort group constitutes a key benchmarking element. Accordingly, data in Table 2 (reproduced below together with Table 8 for a quick and easy reference) needs to be organized and readjusted in a manner that presents the proposed indices on a scale of desirability in an unambiguous manner.

Table 1:

	Values for Braiding Indices (i), (ii), …, (x)									
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)
Scene 1										
Scene 2										
Scene 3										
Scene 4										
Scene 5										
Scene 6										
Scene 7										
Scene 8										
Scene 9										
Scene 10										

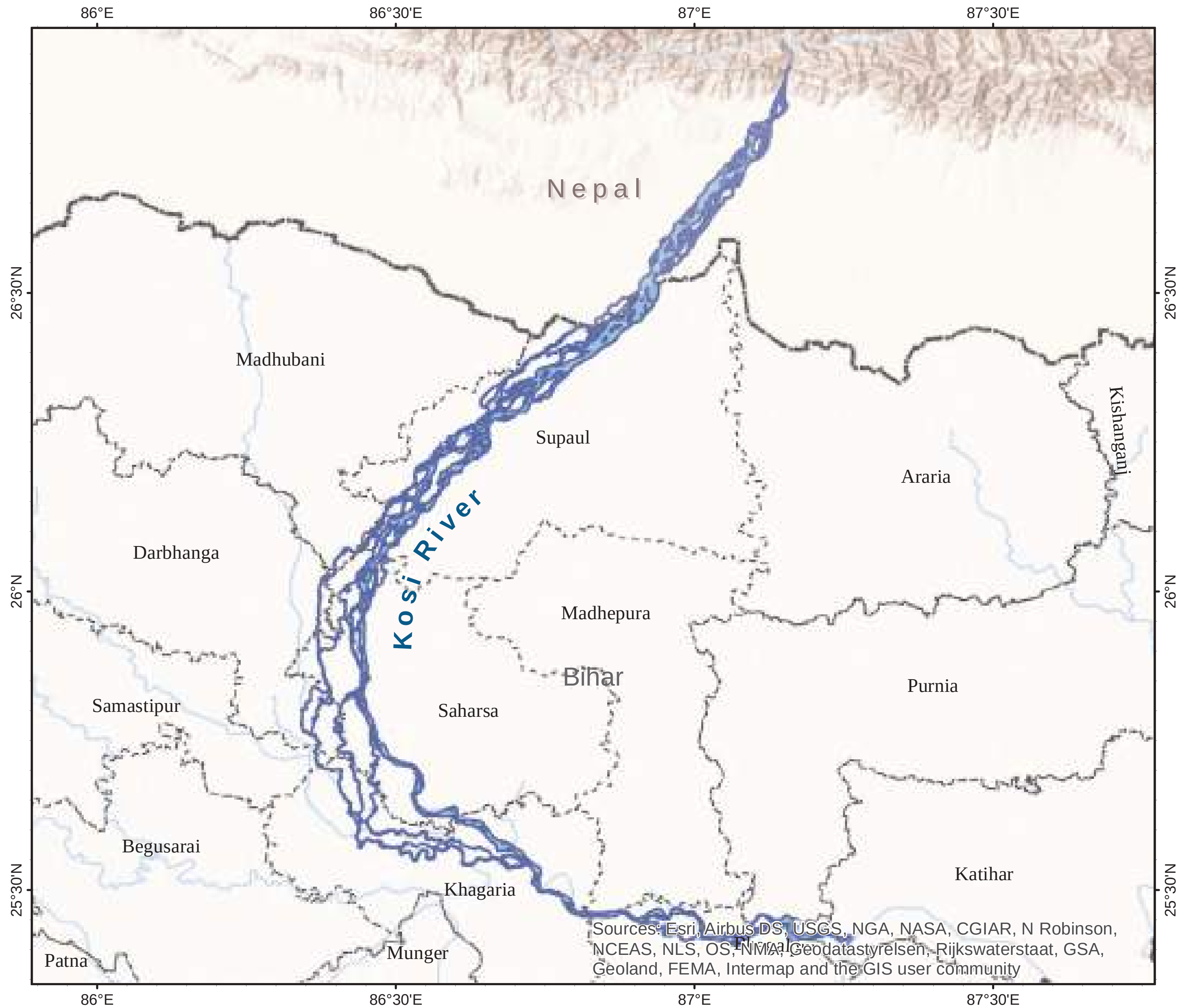
Table 7

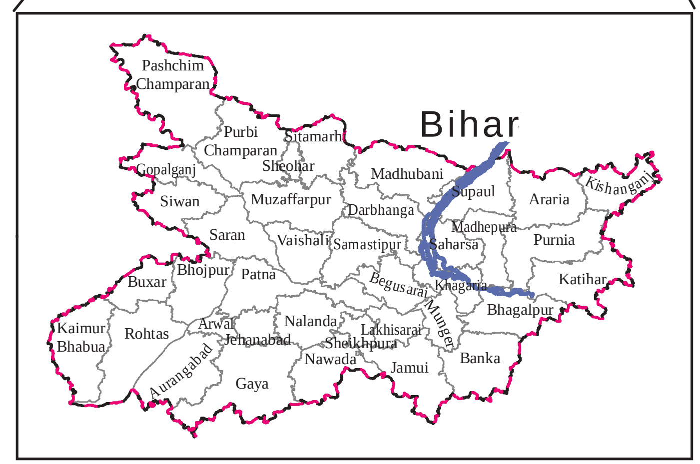
	Final (discordant) number ranks (1 to 10)							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Scene 1								
Scene 2								
Scene 3								
Scene 4								
Scene 5								
Scene 6								
Scene 7								
Scene 8								
Scene 9								
Scene 10								

Reconciliation of information in Tables 2 and 8 proceeds iteratively towards a resolved ranking of the suggested Braiding Indices.

ANNEXURE II

Map Book





Study Area for Kosi River
INDIA

Legend

- Kosi River
- District Boundary
- State Boundary
- Country Boundary

N W E S

0 20 40 60 80 100 Km

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,150,000

DATE: March, 2023

Available Toposheets for Kosi River

Legend

Available Toposheets (28)

72 J/2	72 K/1
72 J/3	72 K/5
72 J/4	72 K/6
72 J/6	72 K/10
72 J/7	72 K/13
72 J/8	72 K/14
72 J/10	72 K/15
72 J/11	72 O/1
72 J/12	72 O/2
72 J/14	72 O/3
72 J/15	72 O/5
72 J/16	72 O/6
72 N/2	72 O/7
72 N/3	
72 N/4	

Kosi RIver
Country Boundary
District Boundary
State Boundary

N
W E
S

0 20 40 60 80 Km

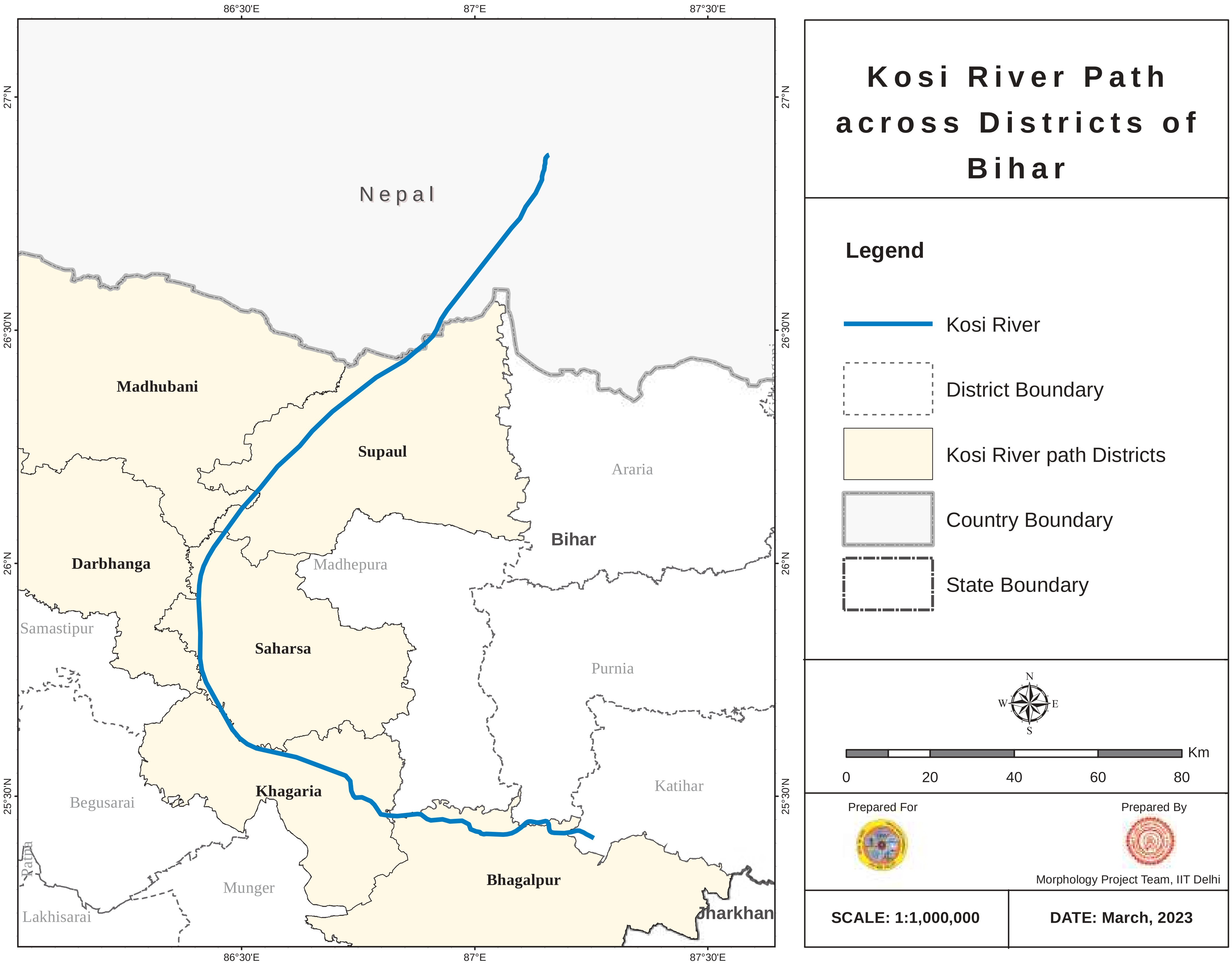
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,000,000

DATE: March, 2023



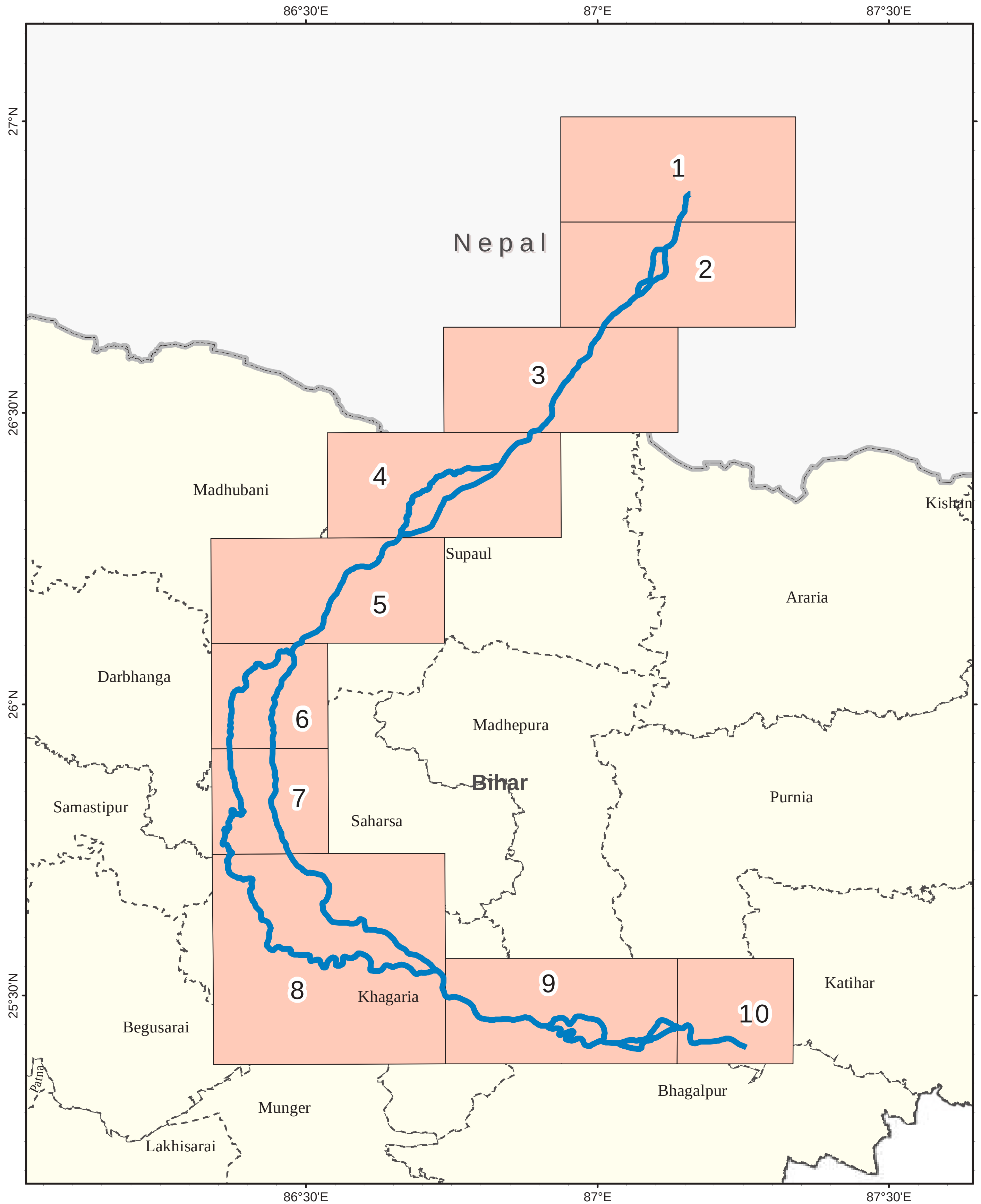
Kosi River Path across Districts of Bihar

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,000,000 | **DATE: March, 2023**



Grid Template for Analysis of Kosi River

Legend

- Kosi RIver
- Reference Grids (10)
- Country Boundary
- District Boundary
- State Boundary

N
W E
S

Km
0 20 40 60 80

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,000,000	DATE: March, 2023

Cities/Towns and Villages around Kosi River

Legend

- Villages# (717)
- Cities/Towns# (71)
- Kosi RIver
- Reference Grids (10)
- Country Boundary
- District Boundary
- State Boundary

Villages and Cities with buffer of 15 km around the Kosi river are displayed

N W E S

0 20 40 60 80 Km

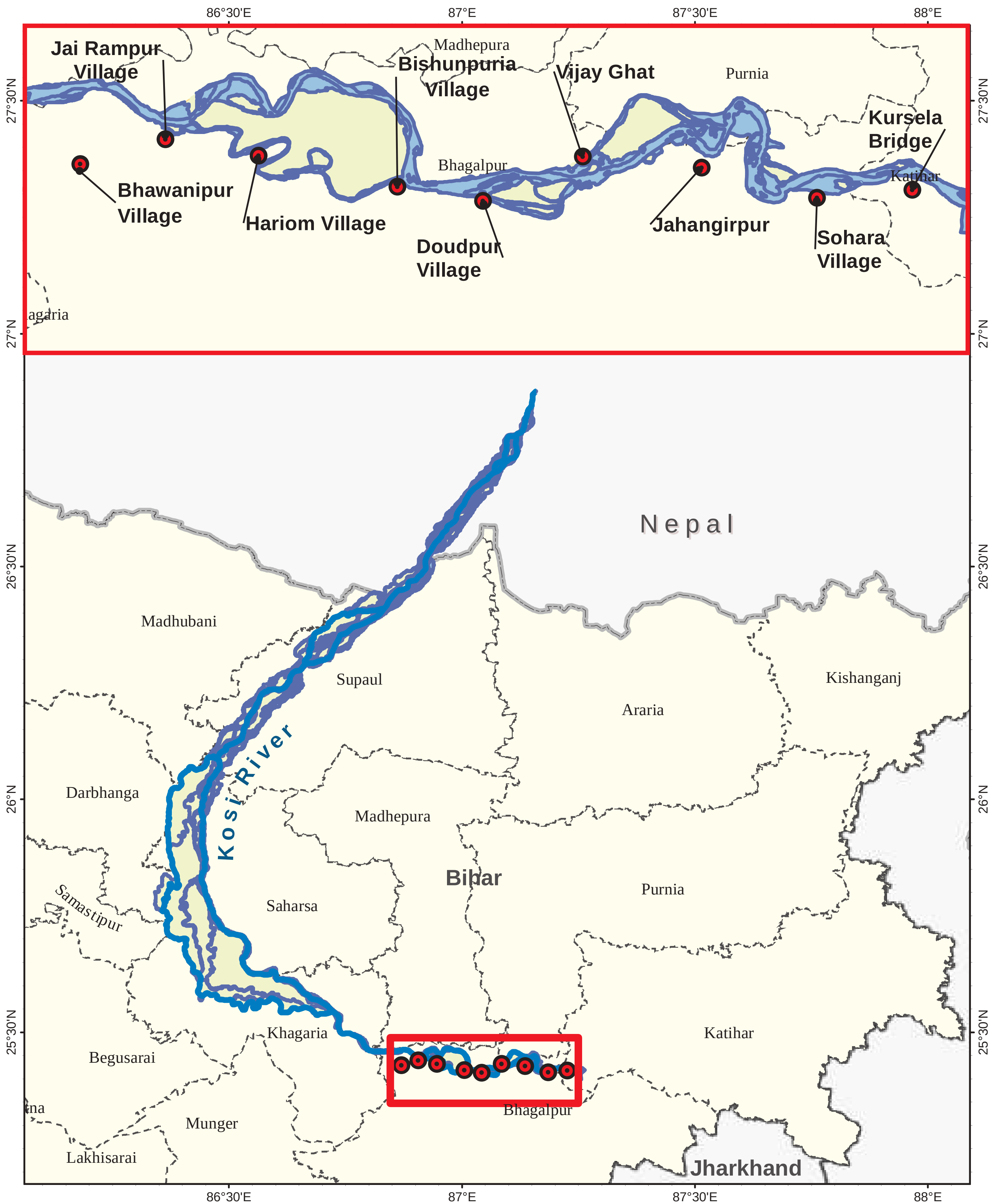
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,000,000

DATE: March, 2023



Cross-Section Locations for Kosi River

Legend

- Cross-section Locations (9)
- Kosi RIver
- District Boundary
- State Boundary
- Country Boundary

N W E S

0 20 40 60 80 100 Km

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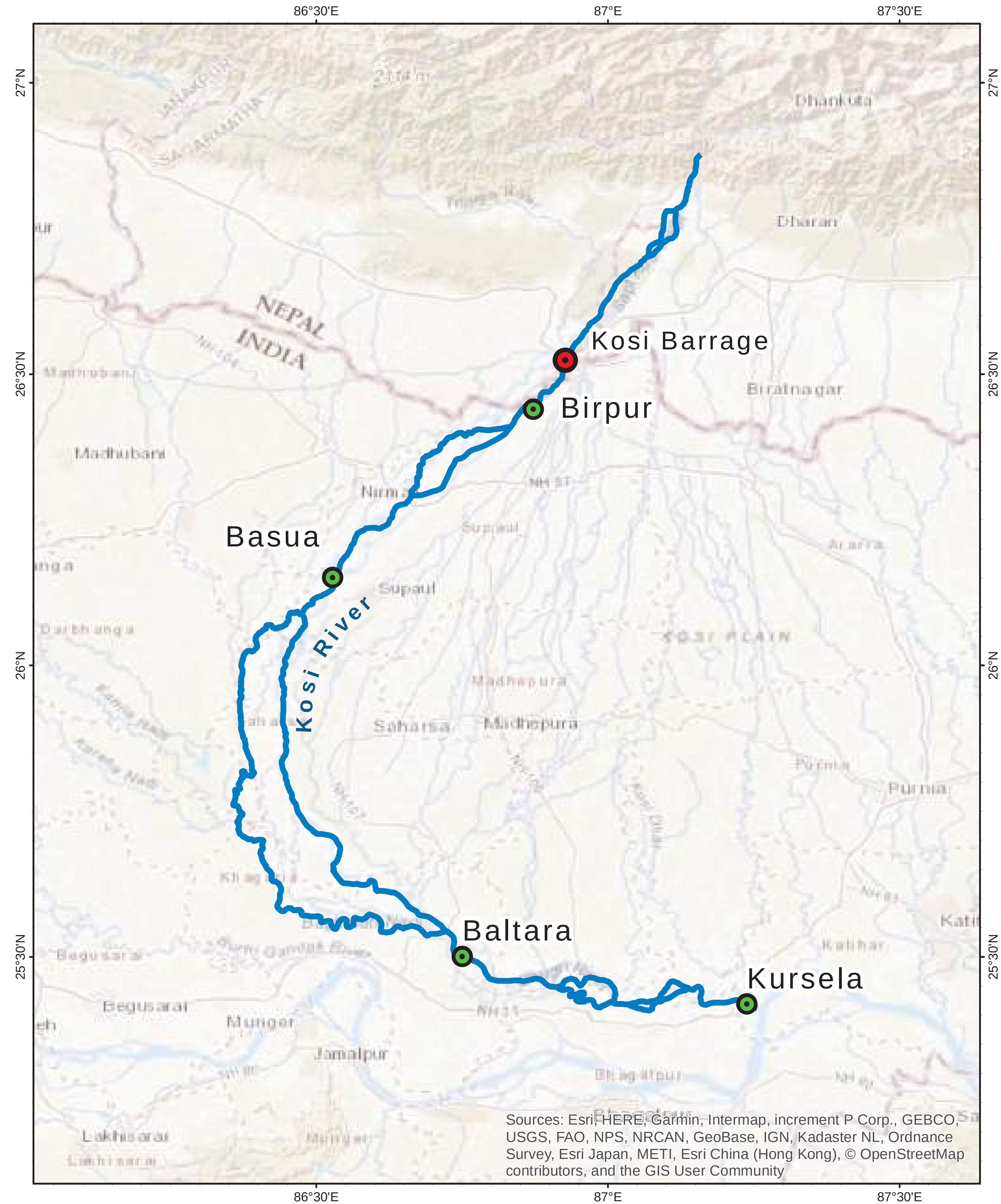
Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,250,000	**DATE: March, 2023**



Hydrological Observation Sites for Kosi River

Legend

- Kosi Barrage
- Guage Locations
- Kosi RIver

N W E S

0 20 40 60 80 Km

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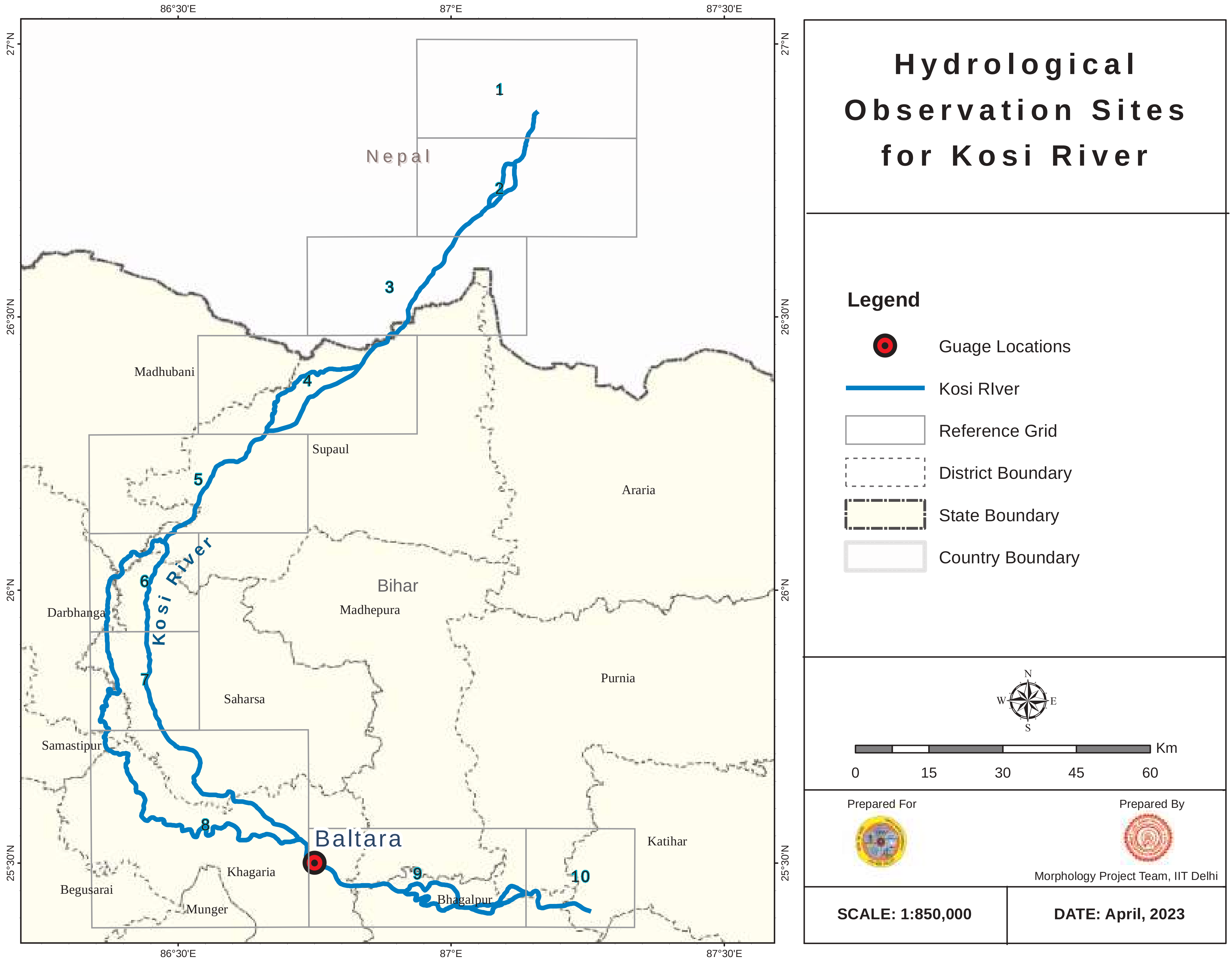
Prepared By

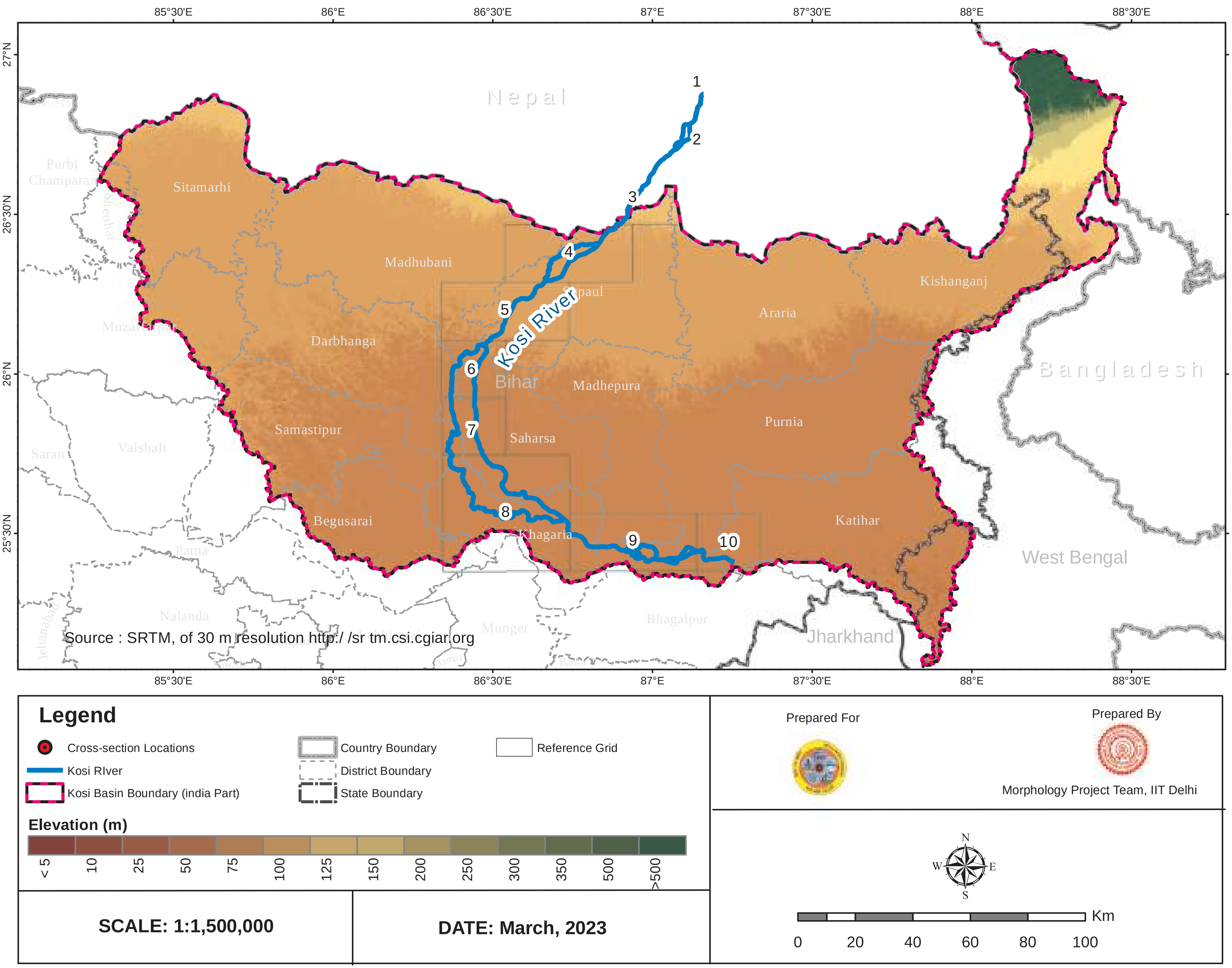
Morphology Project Team, IIT Delhi

SCALE: 1:1,150,000	**DATE: March, 2023**

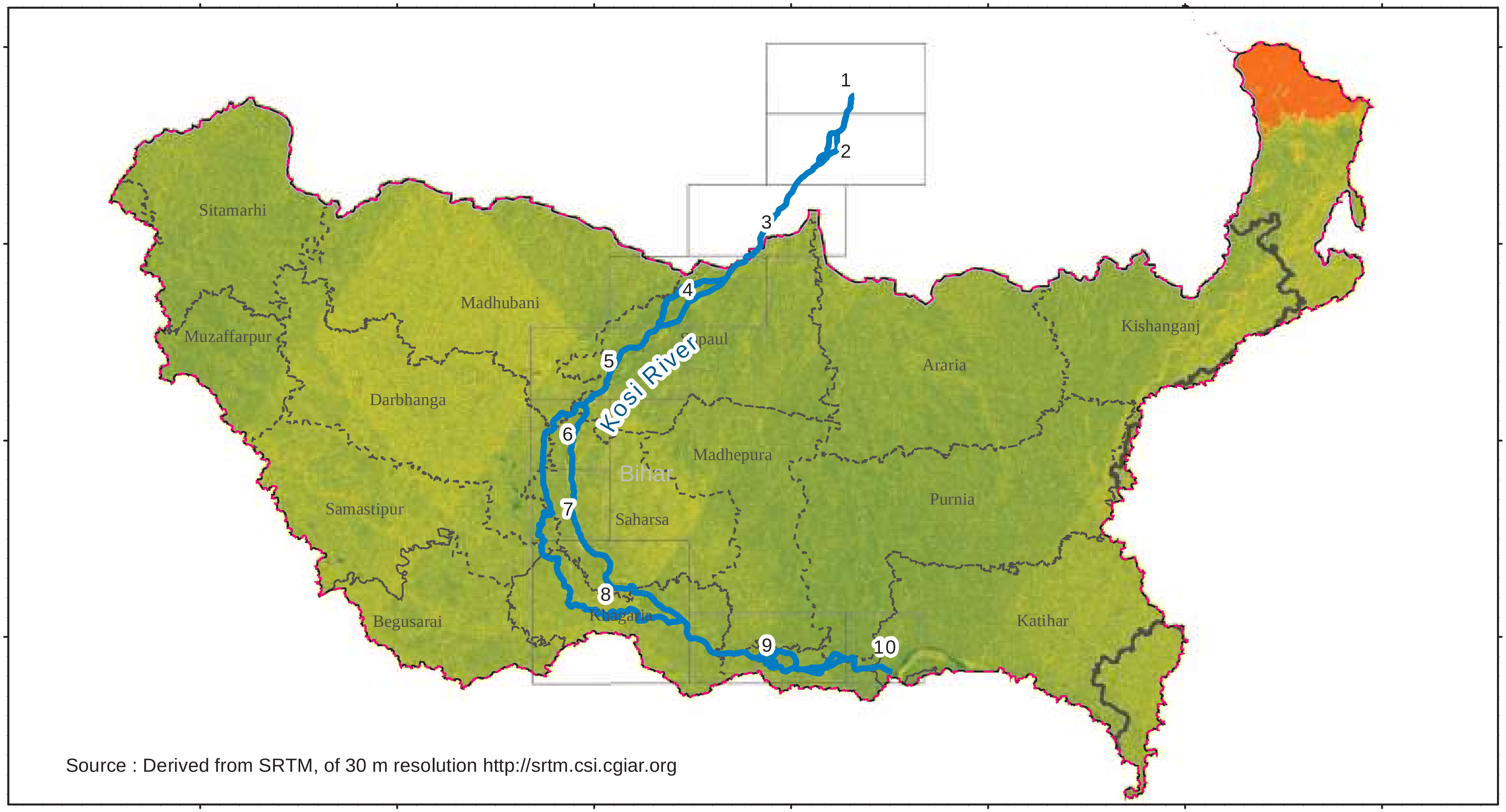


Hydrological Observation Sites for Kosi River
86°30'E
87°E
87°30'E
27°N
26°30'N
26°N
25°30'N
Nepal
1
2
3
4
5
6
7
8
9
10
Madhubani
Supaul
Araria
Kosi River
Bihar
Darbhanga
Madhepura
Saharsa
Purnia
Samastipur
Baltara
Katihar
Khagaria
Begusarai
Munger
Bhagalpur
Legend
Guage Locations
Kosi RIver
Reference Grid
District Boundary
State Boundary
Country Boundary
N
W
E
S
Km
0
15
30
45
60
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
SCALE: 1:850,000
DATE: April, 2023

Digital Elevation Model (DEM) for Kosi River



Slope Map for Kosi River



Legend

- Cross-section Locations
- Kosi RIver
- Kosi Basin Boundary (india Part)
- Country Boundary
- District Boundary
- State Boundary
- Reference Grid

Percent Slope

< 1 | 2.5 | 5 | 7.5 | 10 | 15 | 500 | >500

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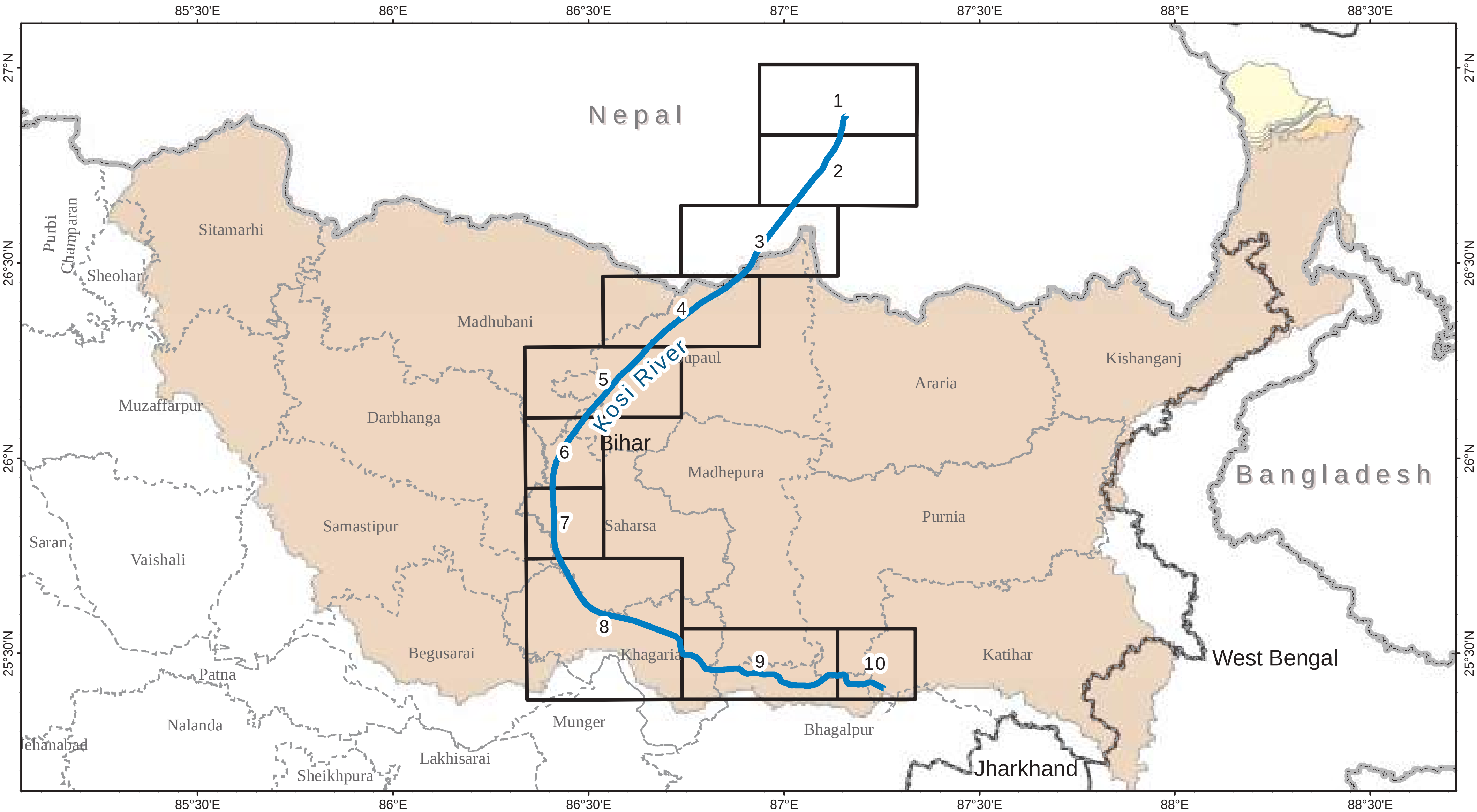
N S W E

0 20 40 60 80 100 Km

SCALE: 1:1,500,000

DATE: March, 2023

Geology Map for Kosi River



AGE	Legend	
Mesoproterozoic	Kosi RIver	
Permian	Reference Grid	
Ploicene-Pliestocene	Country Boundary	
Proterozoic	District Boundary	
Quaternary	State Boundary	

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N W E S

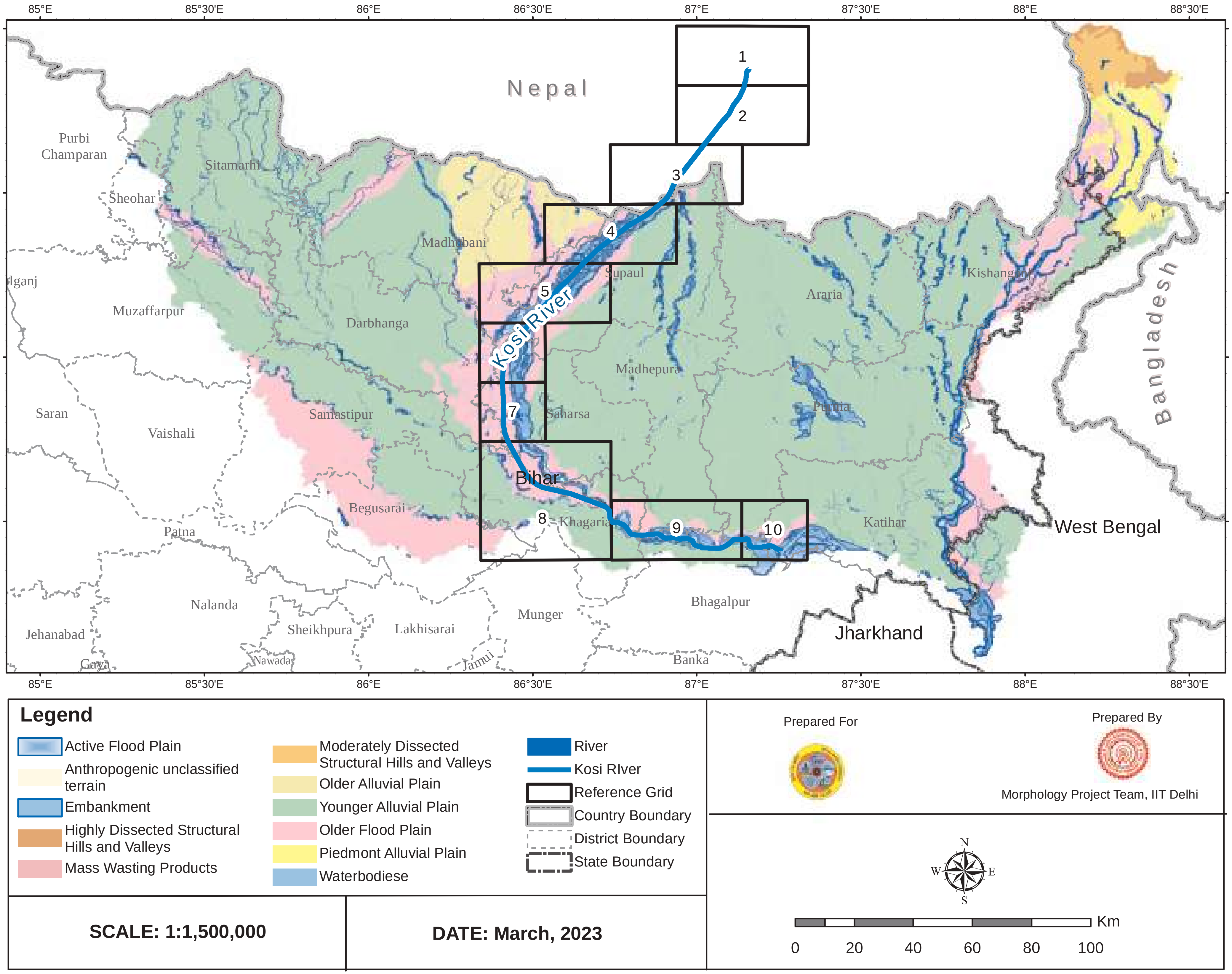
Km

0 20 40 60 80 100

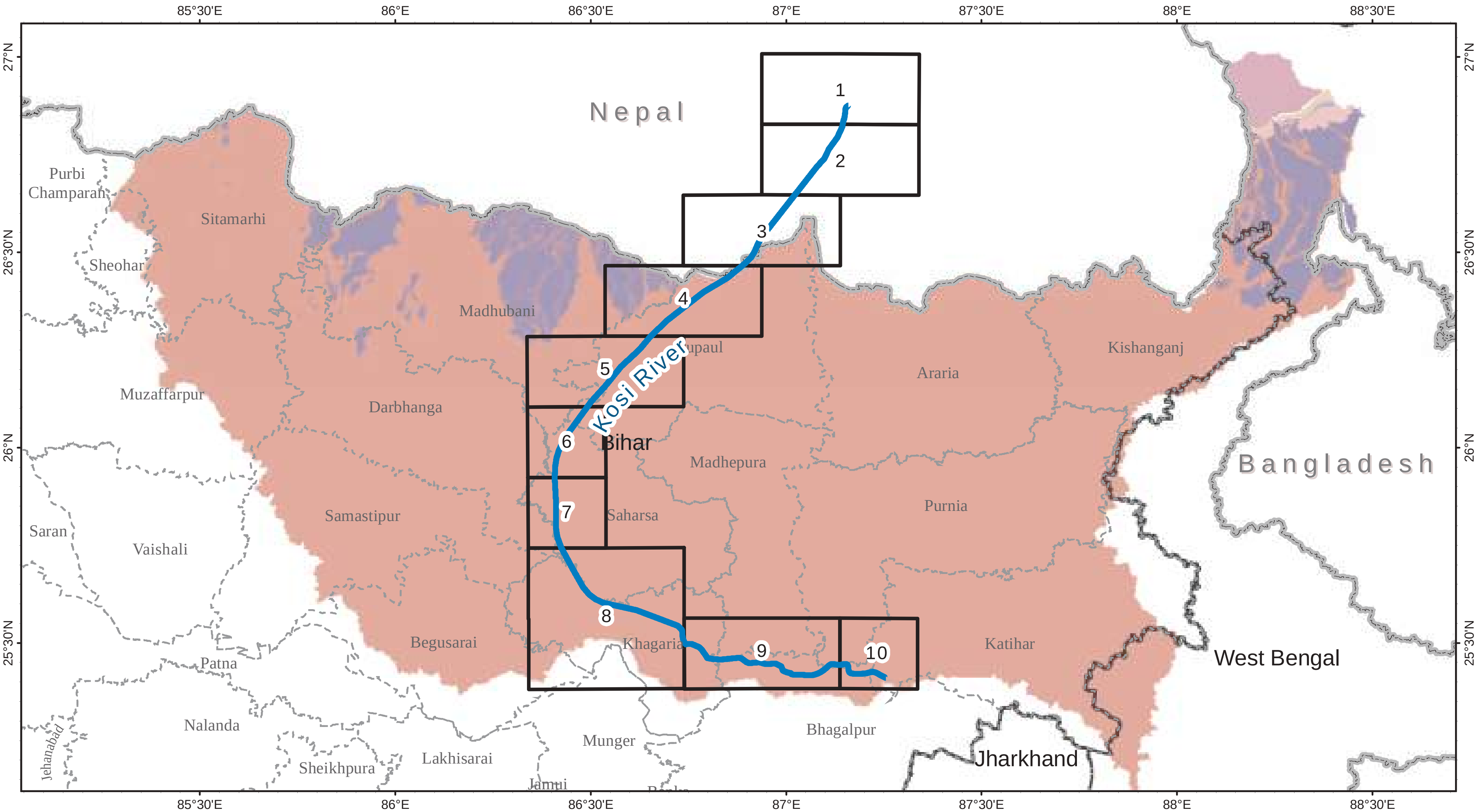
SCALE: 1:1,500,000

DATE: March, 2023

Geomorphology Map for Kosi River



Lithology Map for Kosi River



Legend

Group Name

- Central Crystalline Gneissic Complex
- Daling
- Lower Gondwana
- Newer Alluvium
- Older Alluvium
- Siwalik
- Kosi RIver
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

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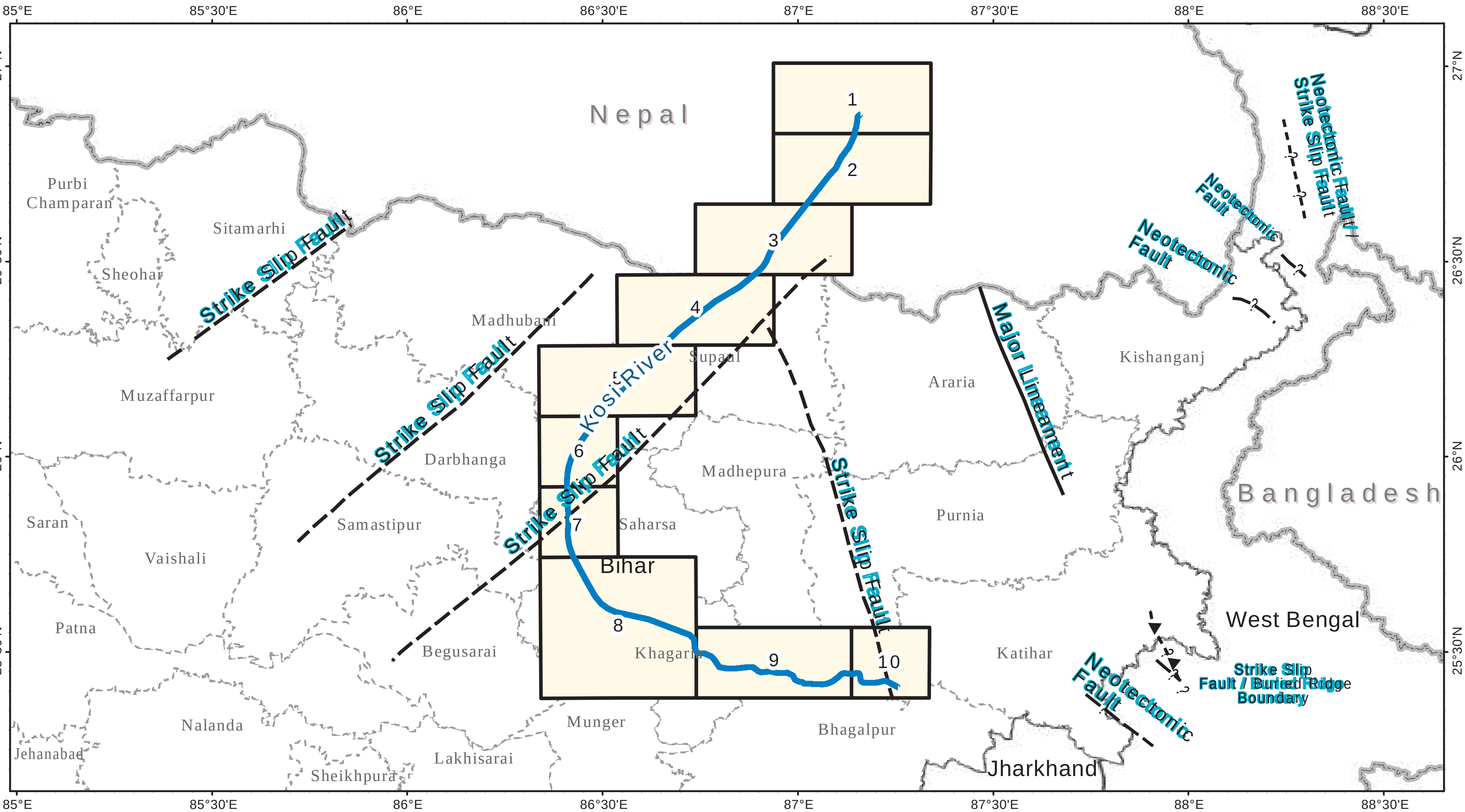
N W E S

0 20 40 60 80 100 Km

SCALE: 1:1,500,000

DATE: March, 2023

Fault Map for Kosi River



Legend

Fault line

- Major Lineament
- Neotectonic Fault
- Neotectonic Fault / Strike Slip Fault
- Strike Slip Fault
- Strike Slip Fault / Buried Ridge Boundary

- Kosi RIver
- Reference Grid
- Country Boundary
- District Boundary
- State Boundary

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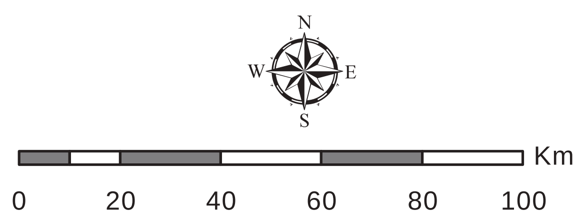
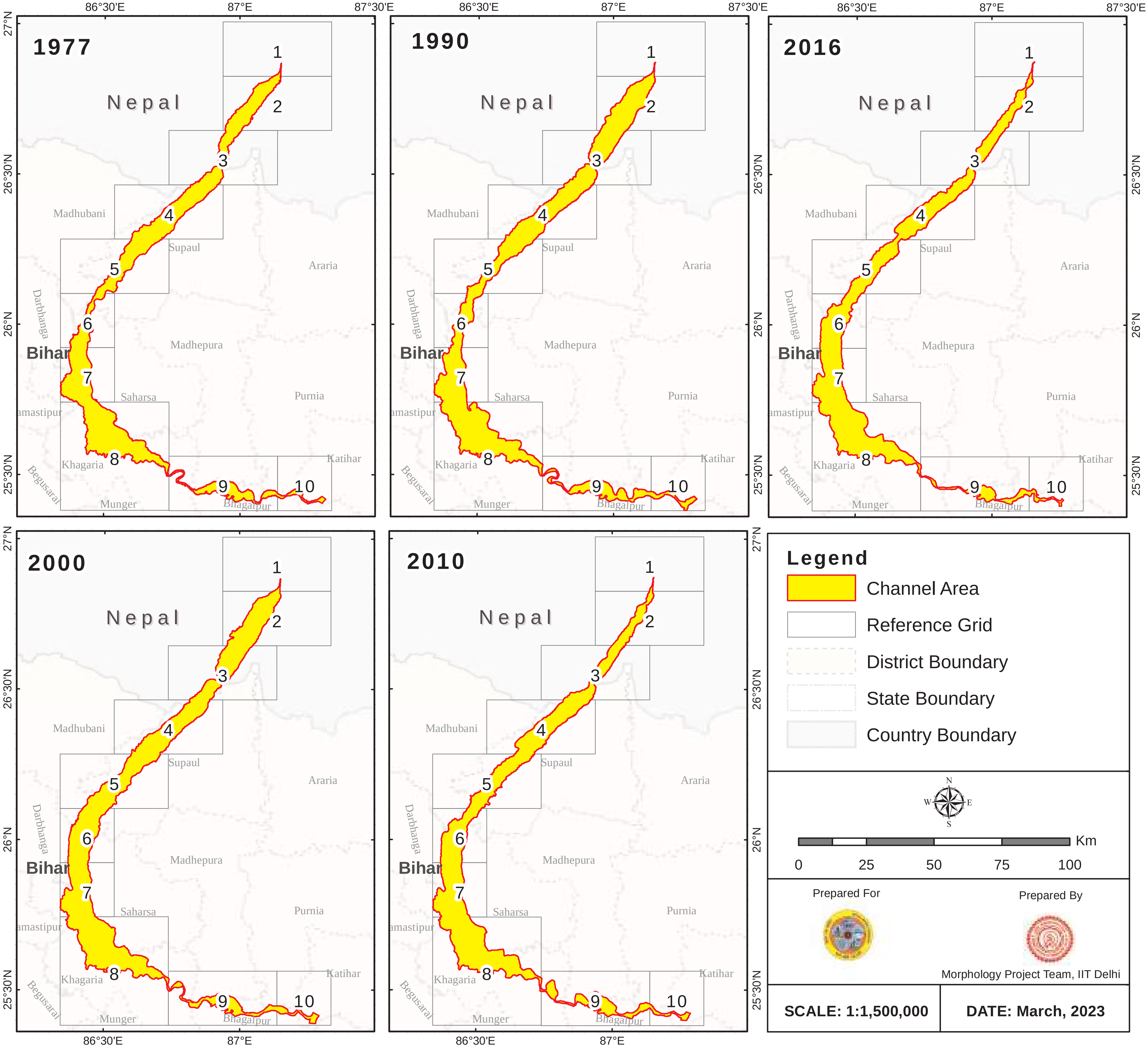
SCALE: 1:1,500,000

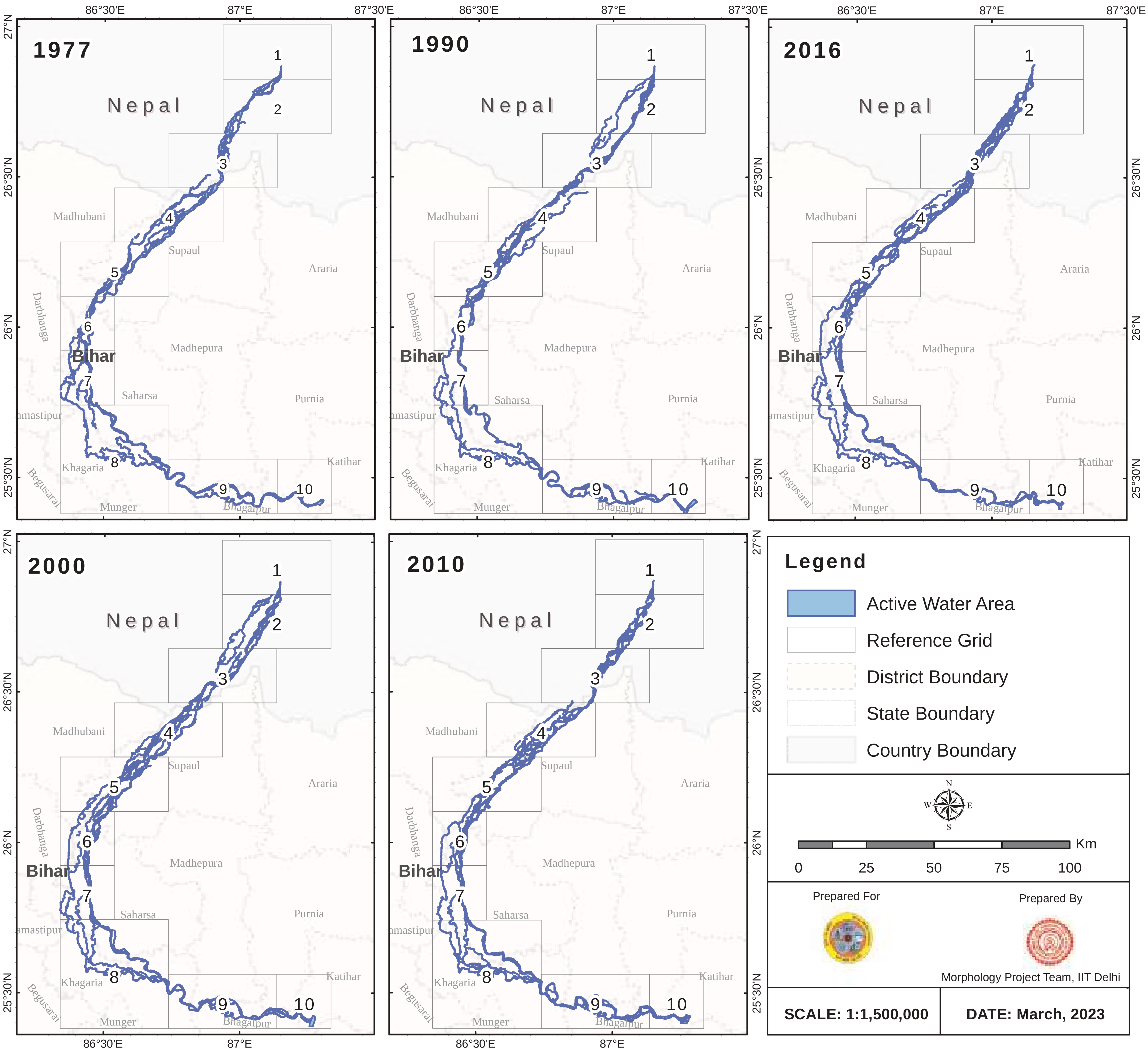
DATE: March, 2023



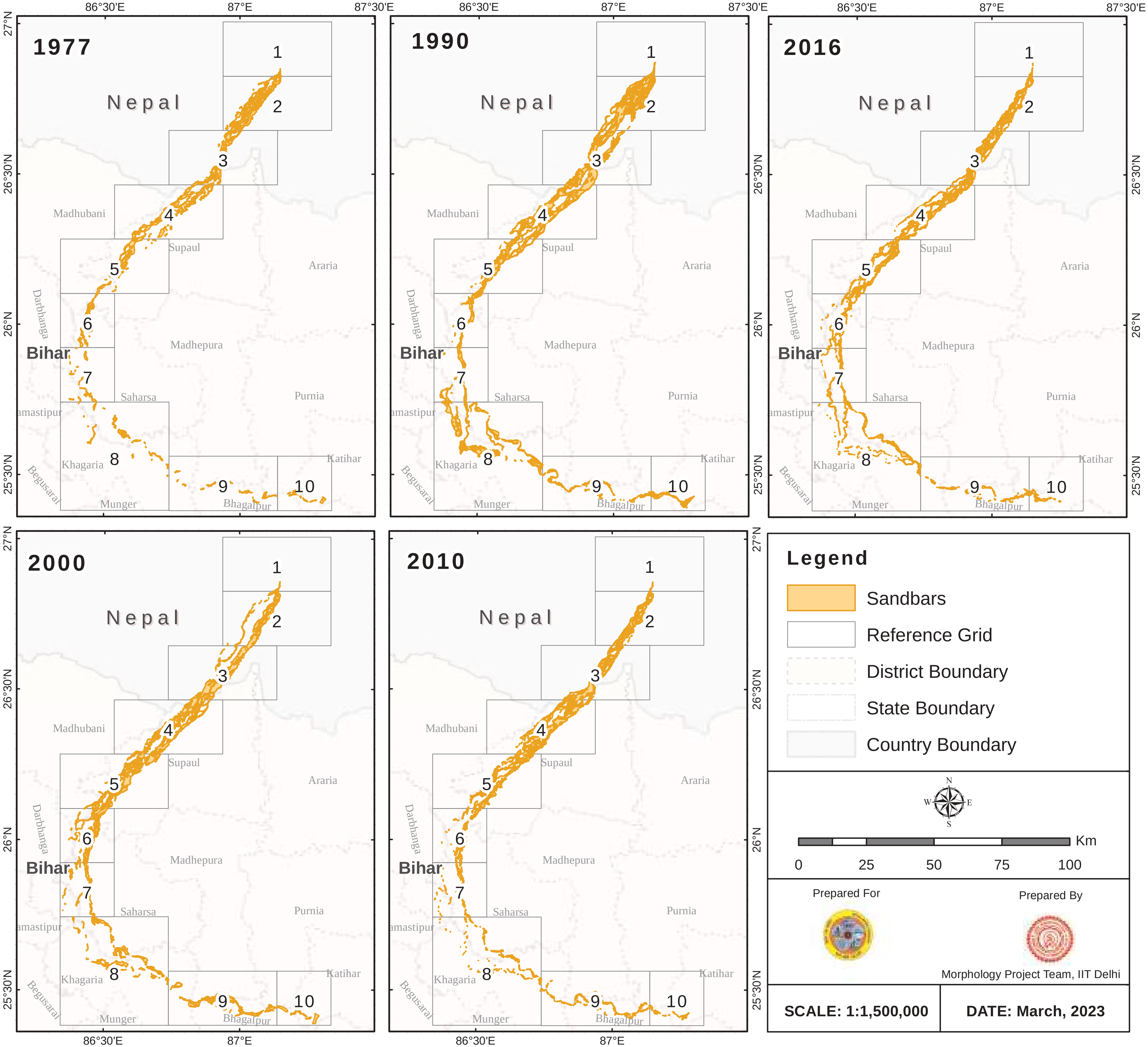
Channel Area for Kosi River



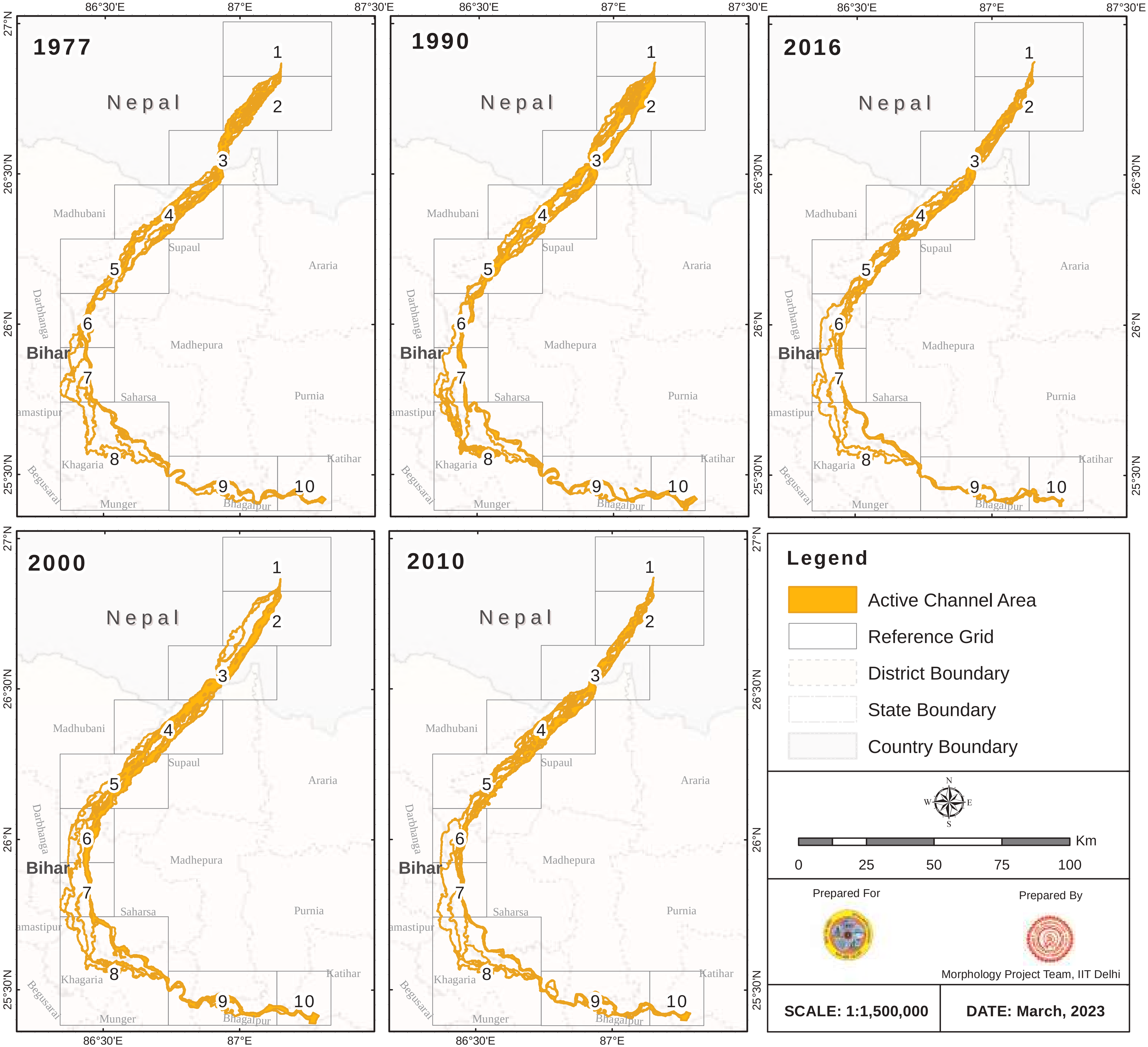
Active Water Area for Kosi River



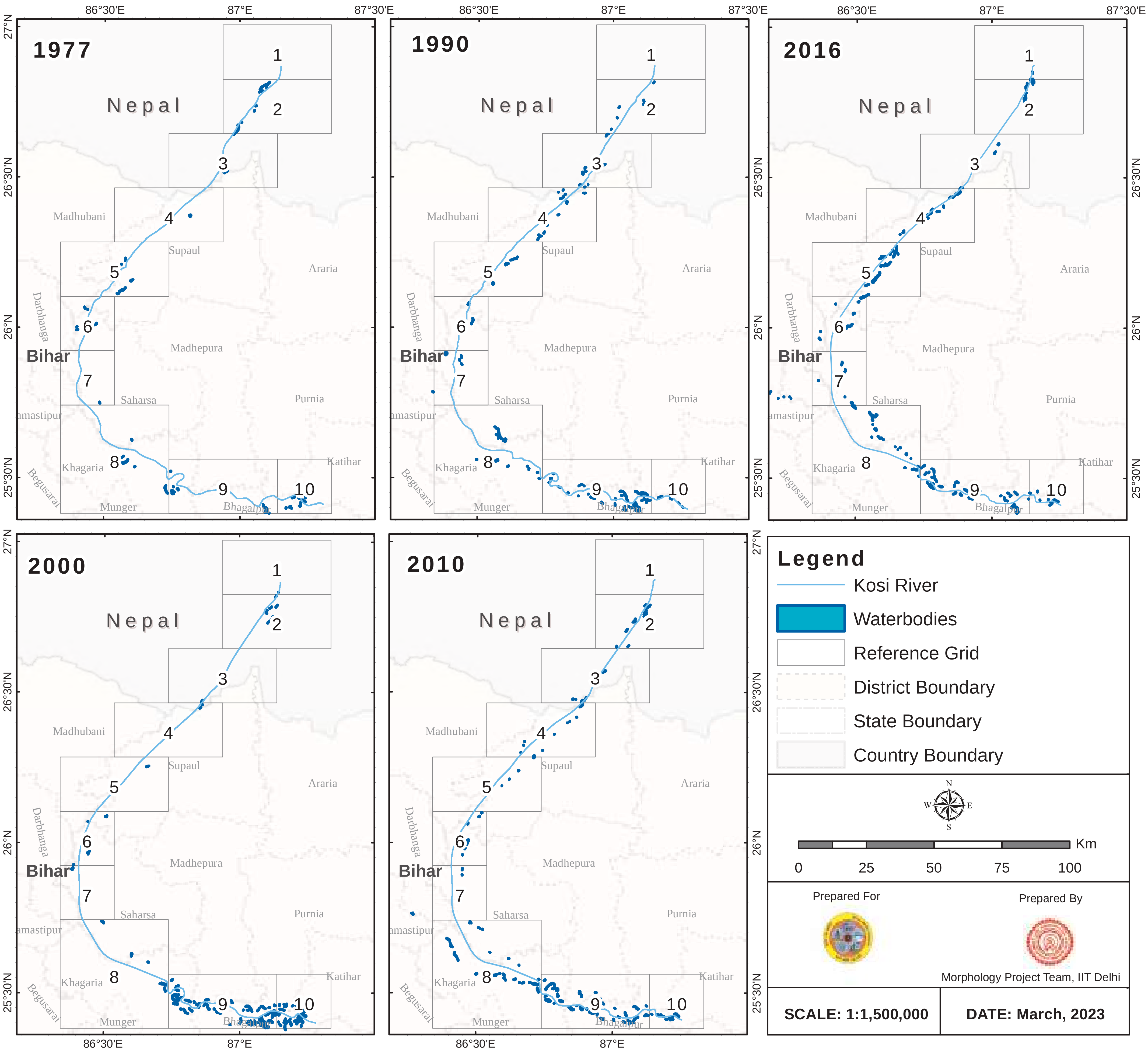
Sandbars for Kosi River

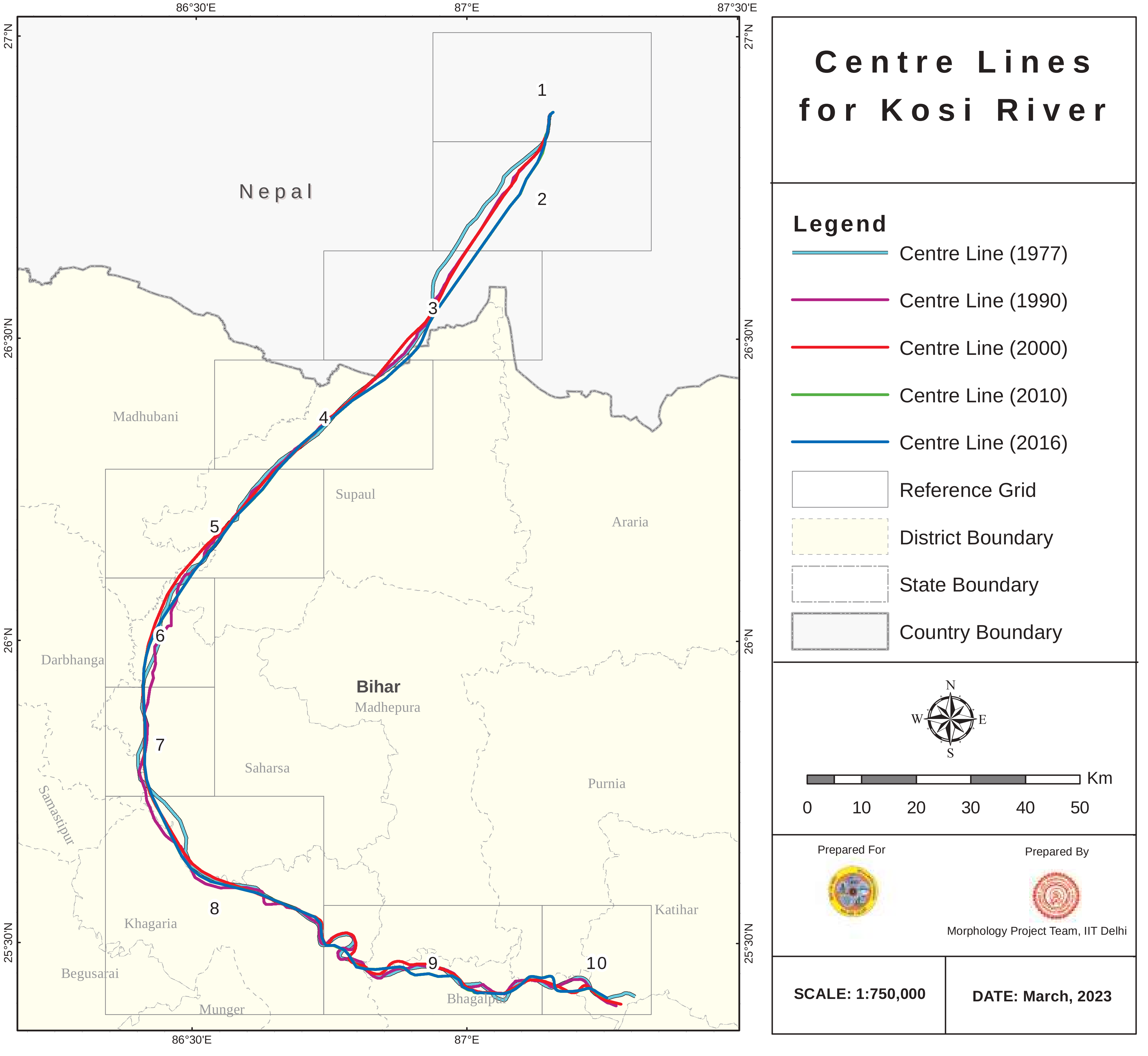


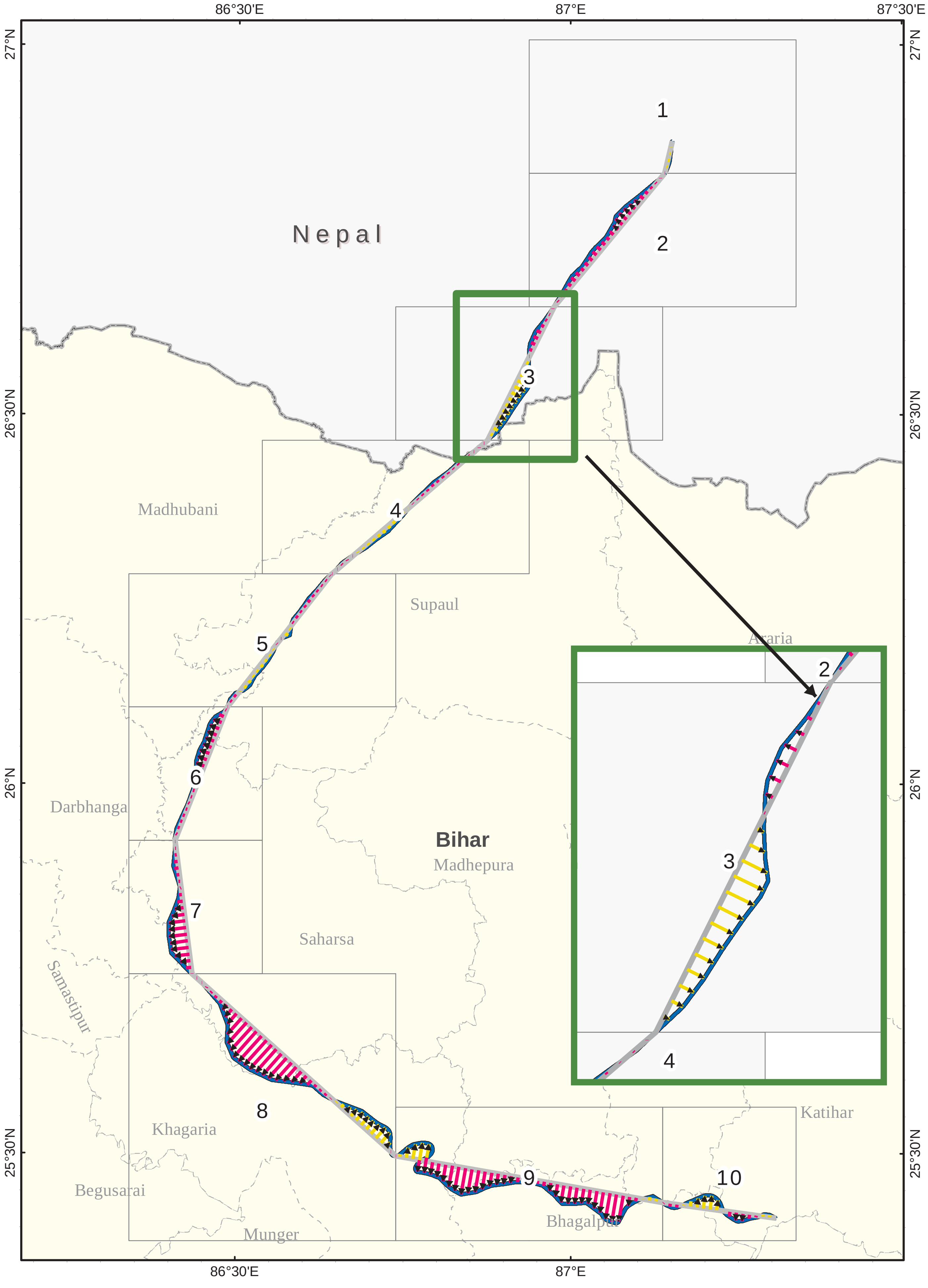
Active Channel Area for Kosi River



Waterbodies along Kosi River




Centre Lines for Kosi River
Legend
Centre Line (1977)
Centre Line (1990)
Centre Line (2000)
Centre Line (2010)
Centre Line (2016)
Reference Grid
District Boundary
State Boundary
Country Boundary
N
W
E
S
Km
0 10 20 30 40 50
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
SCALE: 1:750,000
DATE: March, 2023
86°30'E
87°E
87°30'E
27°N
26°30'N
26°N
25°30'N
Nepal
Bihar
Madhubani
Supaul
Araria
Darbhanga
Madhepura
Saharsa
Purnia
Samastipur
Khagaria
Katihar
Begusarai
Munger
Bhagalpur
1
2
3
4
5
6
7
8
9
10



Computation of Distance between Reference Line and Centerlines

(based on 1977 centre line)

Legend

Orientation

- Left
- Right
- Reference Line (1977)
- Centre Line (1977)
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N S E W

Km

0 10 20 30 40 50

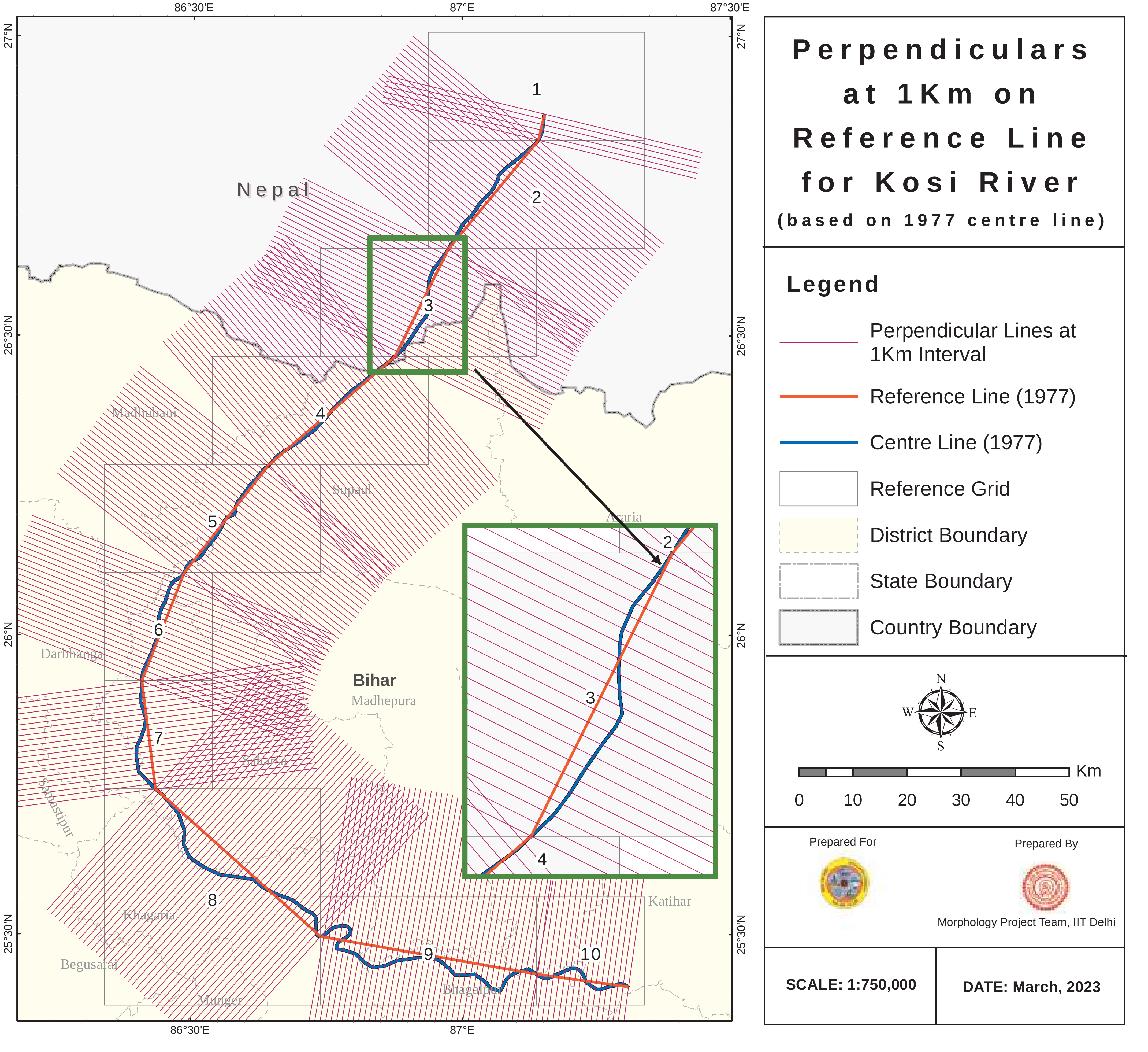
Prepared For

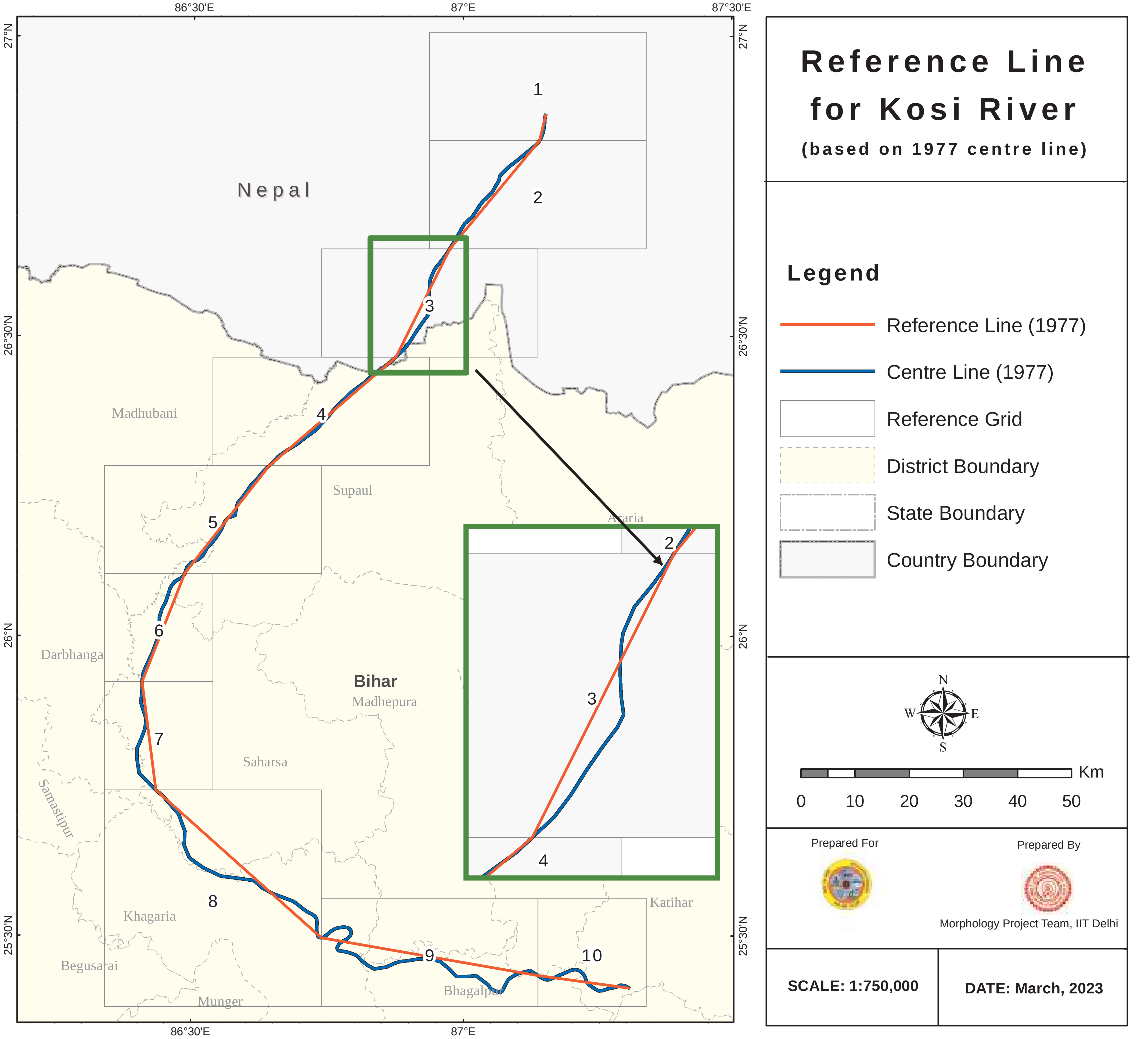
Prepared By

Morphology Project Team, IIT Delhi

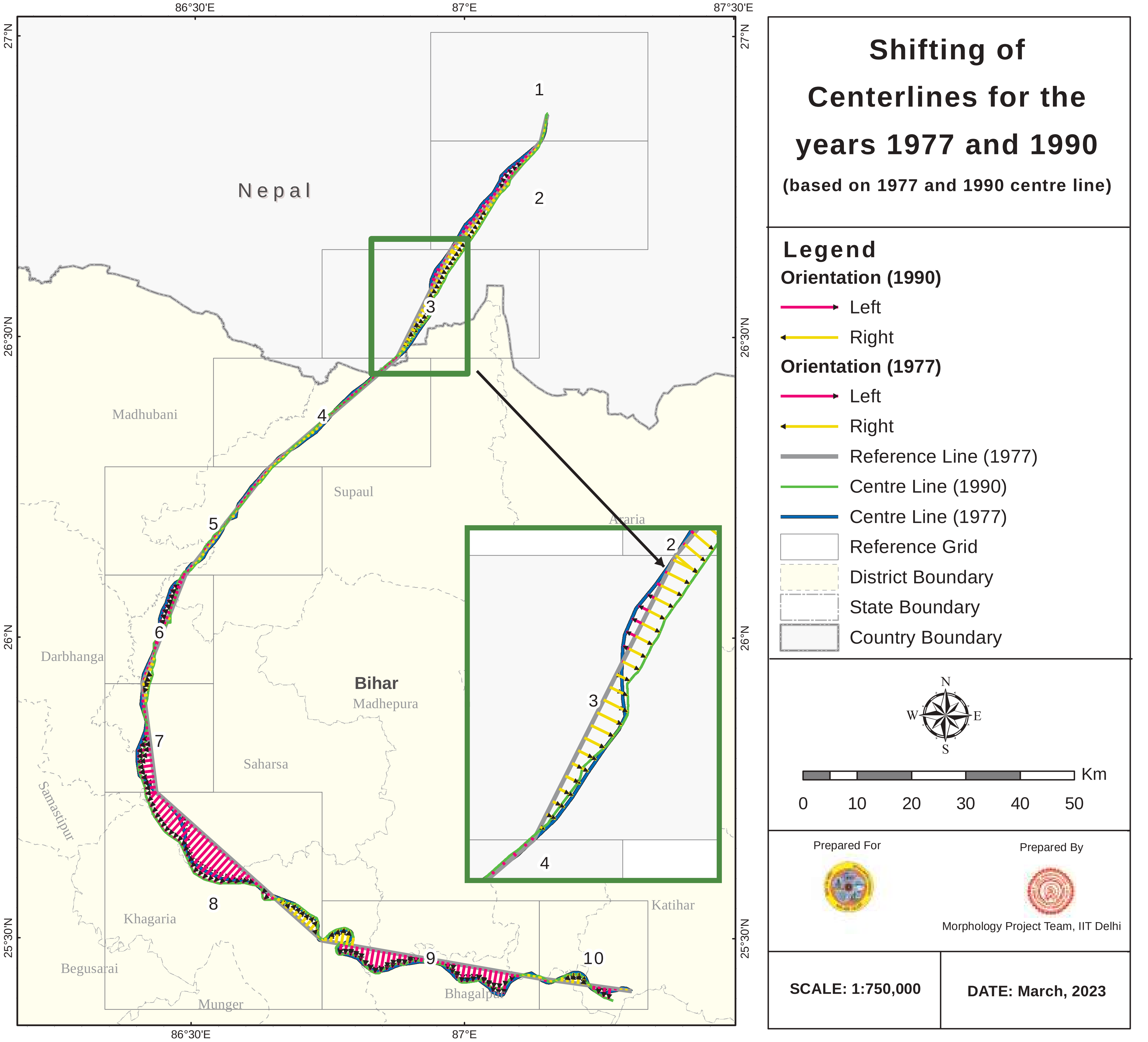
SCALE: 1:750,000

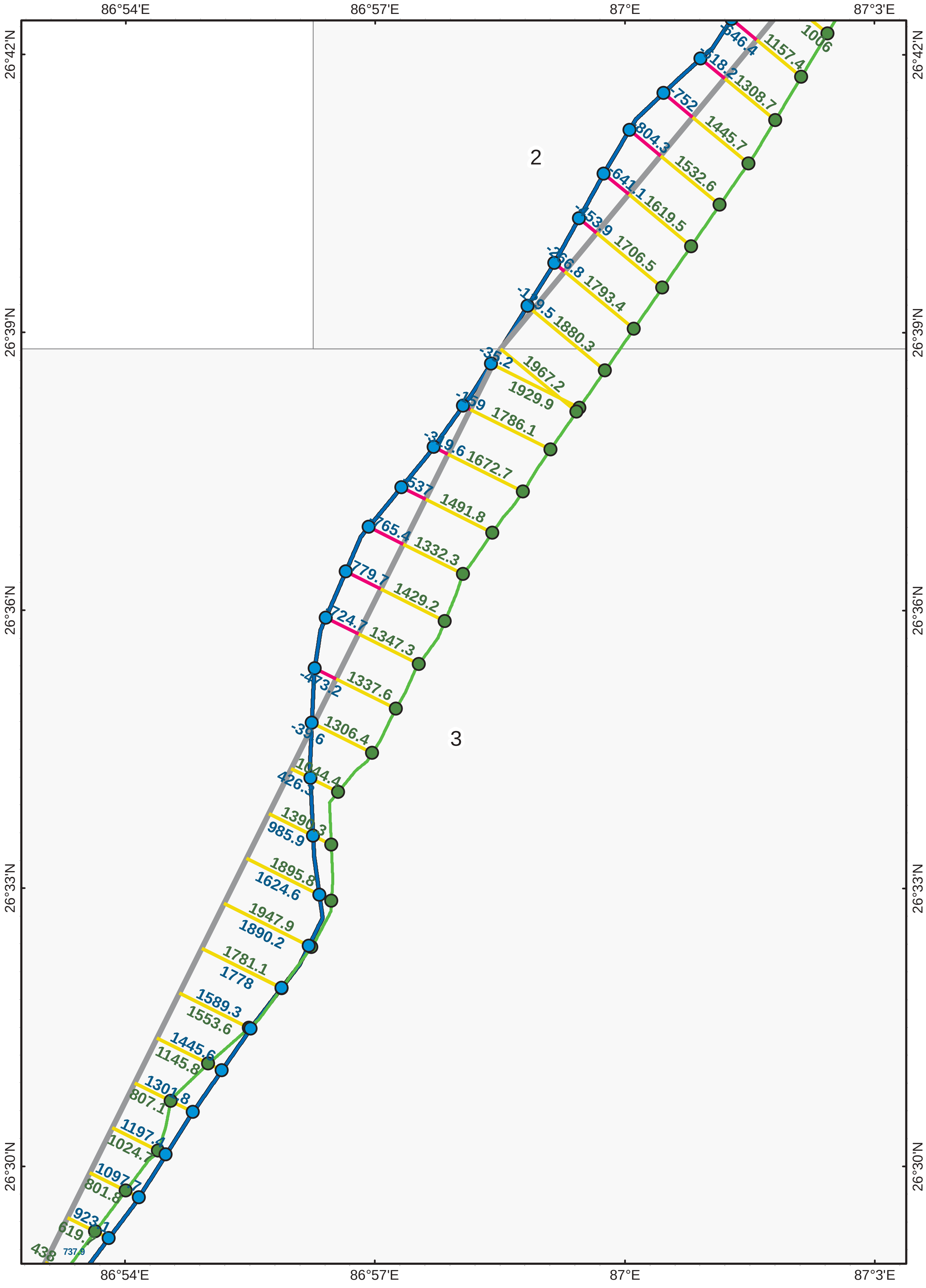
DATE: March, 2023


Perpendiculars at 1Km on Reference Line for Kosi River
(based on 1977 centre line)
Legend
Perpendicular Lines at 1Km Interval
Reference Line (1977)
Centre Line (1977)
Reference Grid
District Boundary
State Boundary
Country Boundary
N
S
E
W
Km
0
10
20
30
40
50
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
SCALE: 1:750,000
DATE: March, 2023
86°30'E
87°E
87°30'E
27°N
26°30'N
26°N
25°30'N
Nepal
Bihar
Madhubani
Supaul
Araria
Darbhanga
Madhepura
Saharsa
Samastipur
Khagaria
Begusarai
Munger
Bhagalpur
Katihar
1
2
3
4
5
6
7
8
9
10



Reference Line
for Kosi River
(based on 1977 centre line)
Legend
Reference Line (1977)
Centre Line (1977)
Reference Grid
District Boundary
State Boundary
Country Boundary
N
S
E
W
Km
0
10
20
30
40
50
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
SCALE: 1:750,000
DATE: March, 2023
86°30'E
87°E
87°30'E
27°N
26°30'N
26°N
25°30'N
Nepal
Bihar
Madhubani
Supaul
Araria
Darbhanga
Madhepura
Saharsa
Samastipur
Khagaria
Begusarai
Munger
Bhagalpur
Katihar
1
2
3
4
5
6
7
8
9
10


Shifting of Centerlines for the years 1977 and 1990
(based on 1977 and 1990 centre line)
Legend
Orientation (1990)
Left
Right
Orientation (1977)
Left
Right
Reference Line (1977)
Centre Line (1990)
Centre Line (1977)
Reference Grid
District Boundary
State Boundary
Country Boundary
N
S
E
W
Km
0
10
20
30
40
50
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
SCALE: 1:750,000
DATE: March, 2023
86°30'E
87°E
87°30'E
27°N
26°30'N
26°N
25°30'N
Nepal
Bihar
Madhubani
Supaul
Araria
Darbhanga
Madhepura
Saharsa
Samastipur
Khagaria
Begusarai
Munger
Bhagalpur
Katihar
1
2
3
4
5
6
7
8
9
10



Computation of Shifting of Centerlines for the years 1977 and 1990

(based on 1977 and 1990 centre line)

Legend

- Offsets 1990
- Offsets 1977

Orientation (1990)

- Left
- Right

Orientation (1977)

- Left
- Right
- Reference Line (1977)
- Centre Line (1990)
- Centre Line (1977)
- Reference Grid

N
W E
S

Km

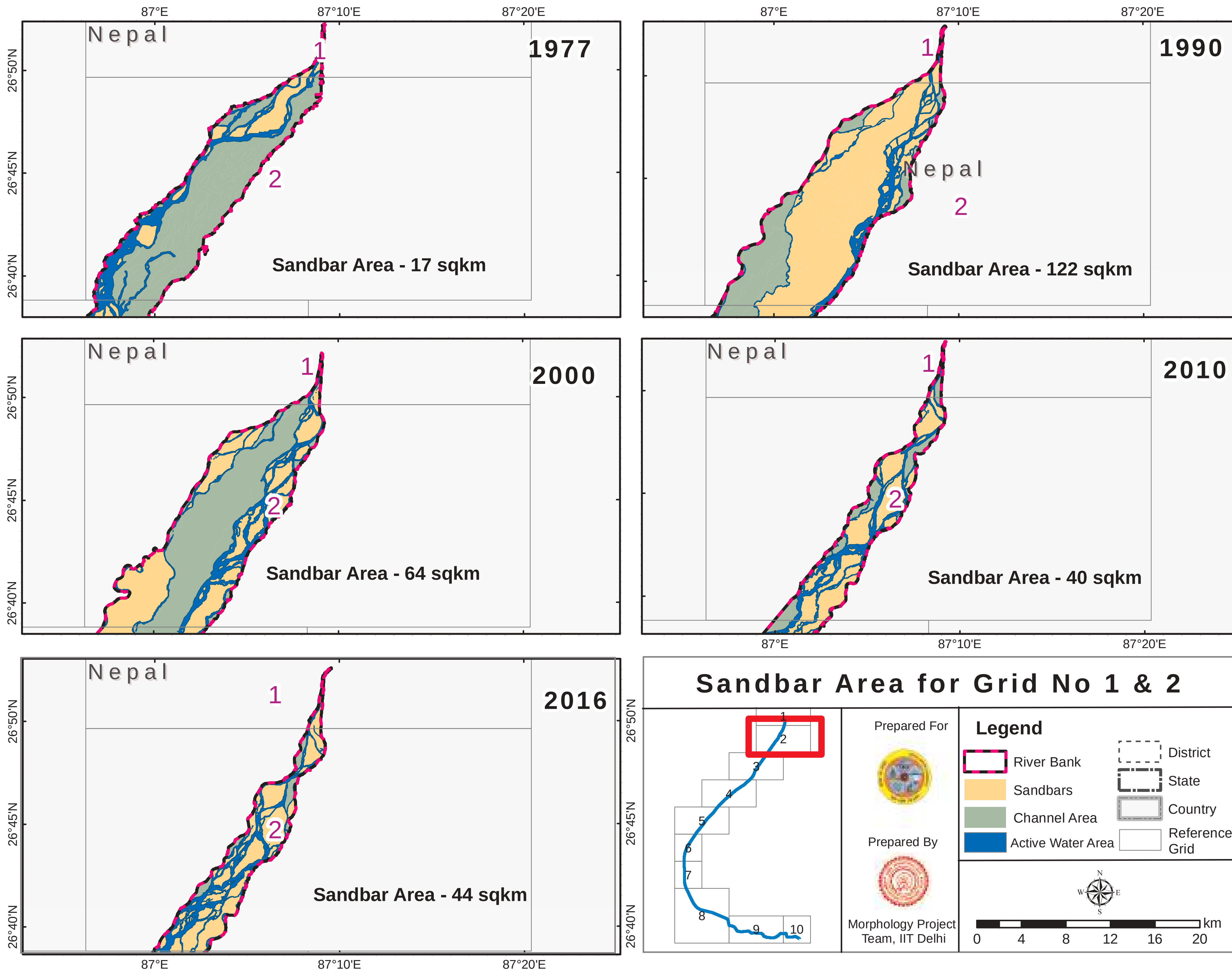
0 1 2 3 4 5 6 7

Prepared For

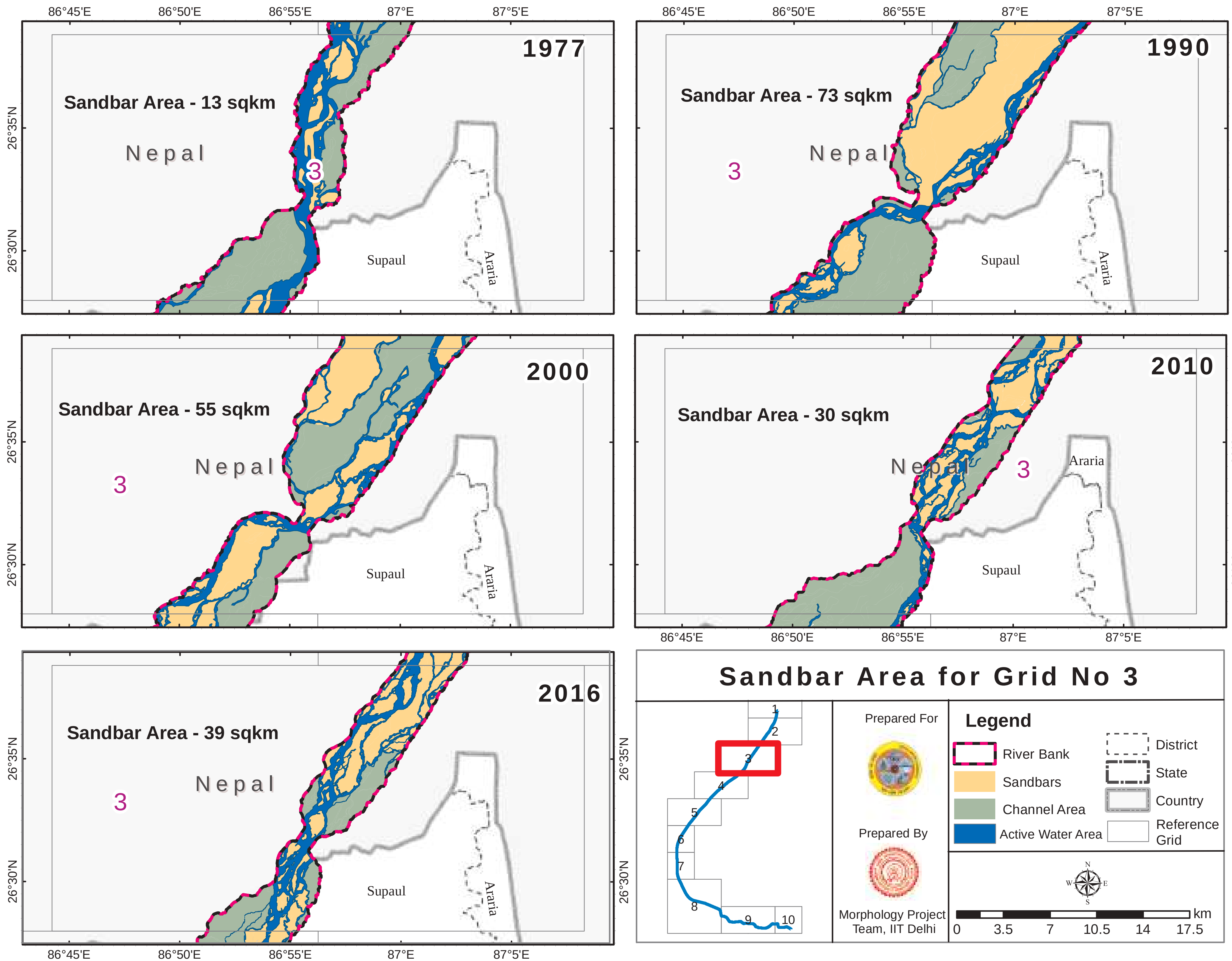
Prepared By

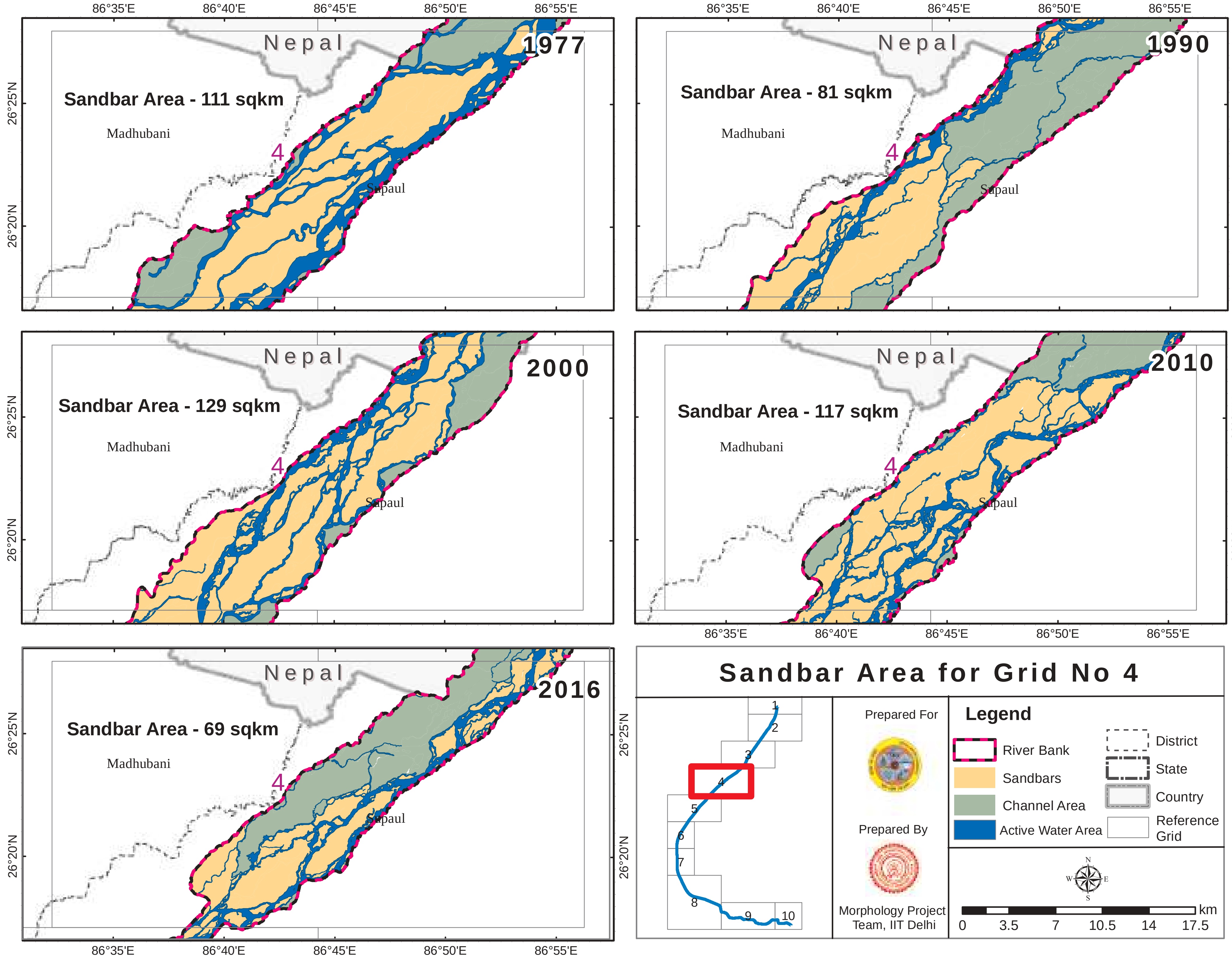
Morphology Project Team, IIT Delhi

SCALE: 1:100,000	DATE: March, 2023

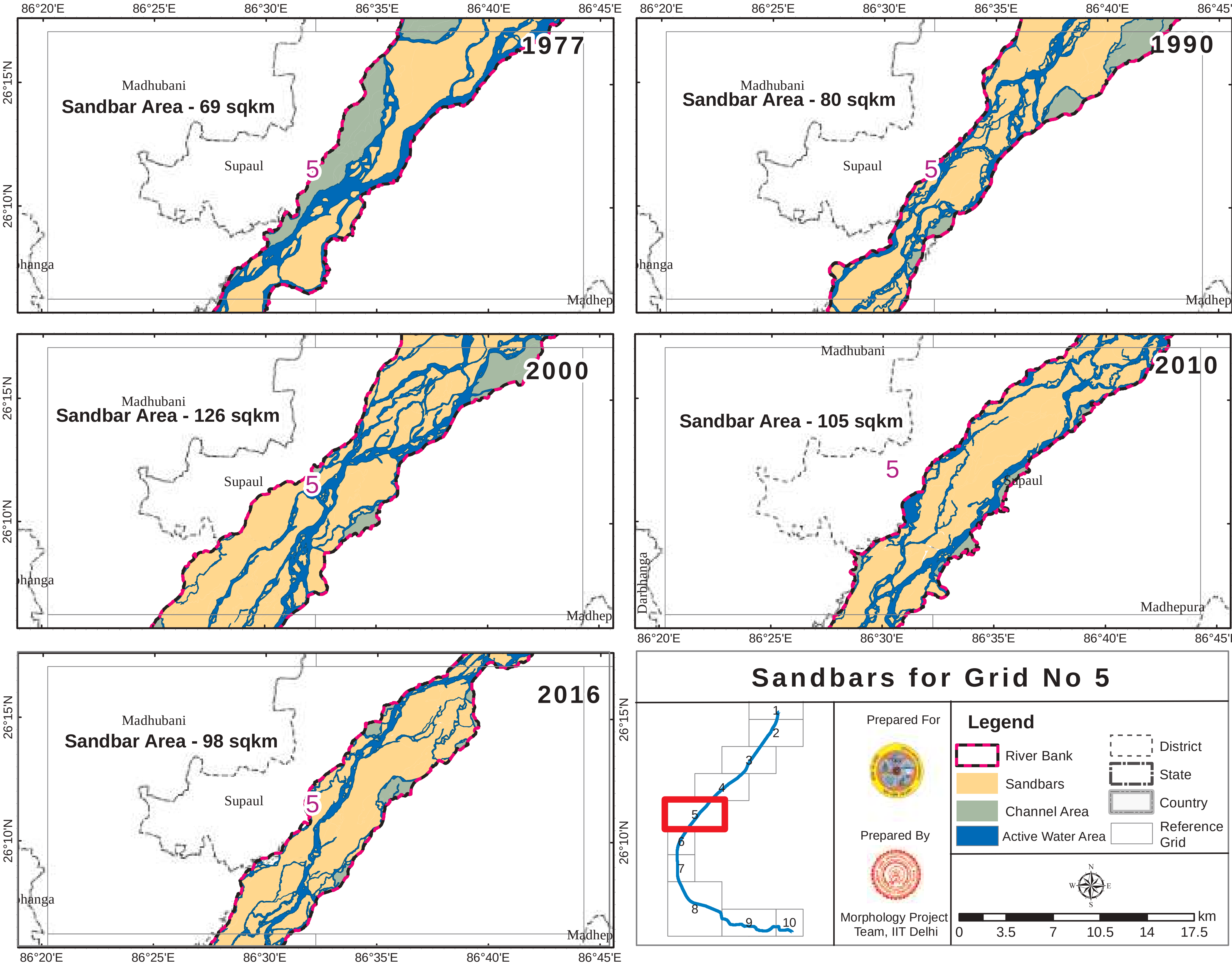


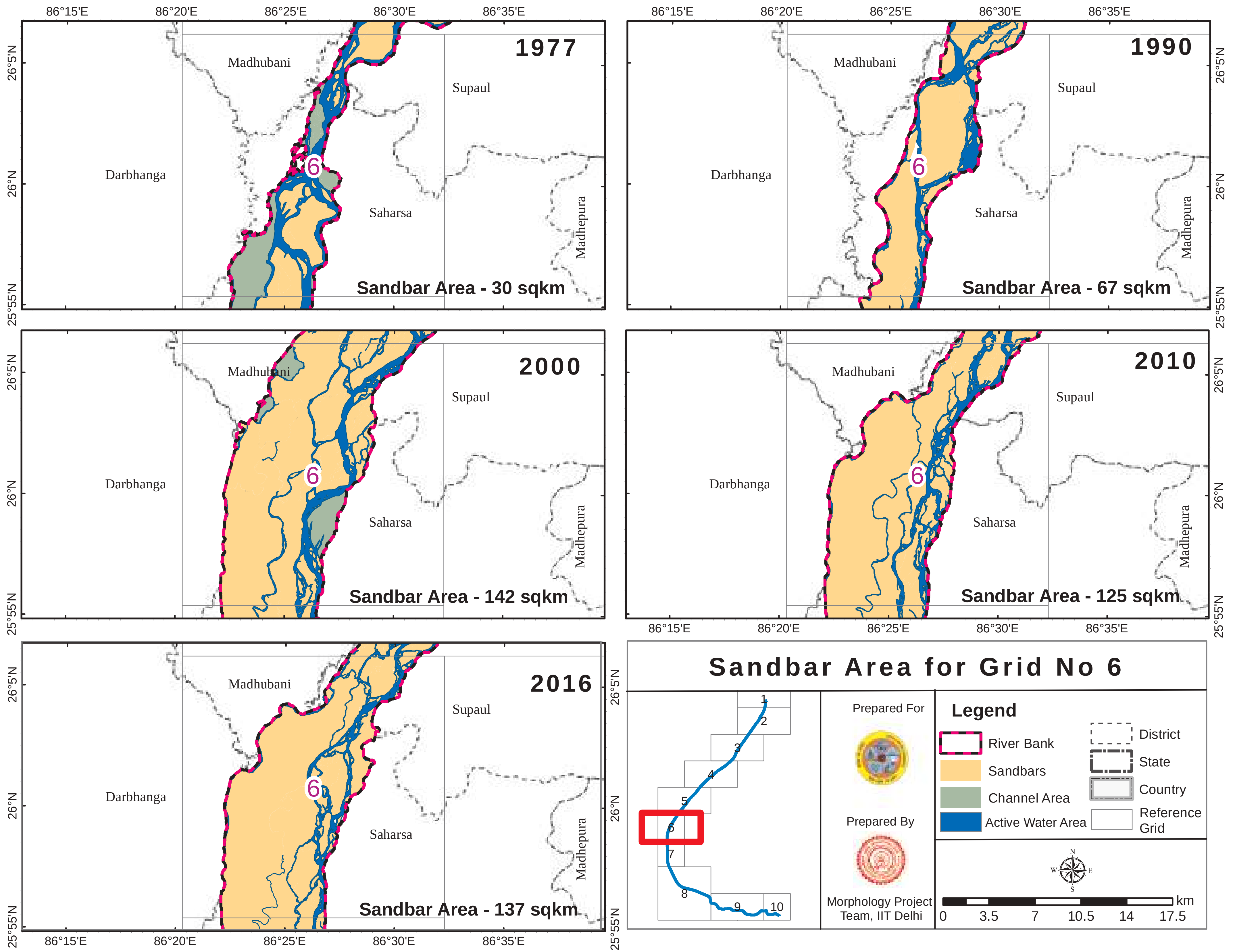
87°E
87°10'E
87°20'E
26°50'N
26°45'N
26°40'N
Nepal
1
2
1977
Sandbar Area - 17 sqkm
1990
Sandbar Area - 122 sqkm
2000
Sandbar Area - 64 sqkm
2010
Sandbar Area - 40 sqkm
2016
Sandbar Area - 44 sqkm
Sandbar Area for Grid No 1 & 2
1
2
3
4
5
6
7
8
9
10
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
N
S
E
W
km
0
4
8
12
16
20


1977
Sandbar Area - 13 sqkm
1990
Sandbar Area - 73 sqkm
2000
Sandbar Area - 55 sqkm
2010
Sandbar Area - 30 sqkm
2016
Sandbar Area - 39 sqkm
Nepal
Supaul
Araria
3
86°45'E
86°50'E
86°55'E
87°E
87°5'E
26°35'N
26°30'N
Sandbar Area for Grid No 3
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
N
S
E
W
0
3.5
7
10.5
14
17.5
km
1
2
3
4
5
6
7
8
9
10

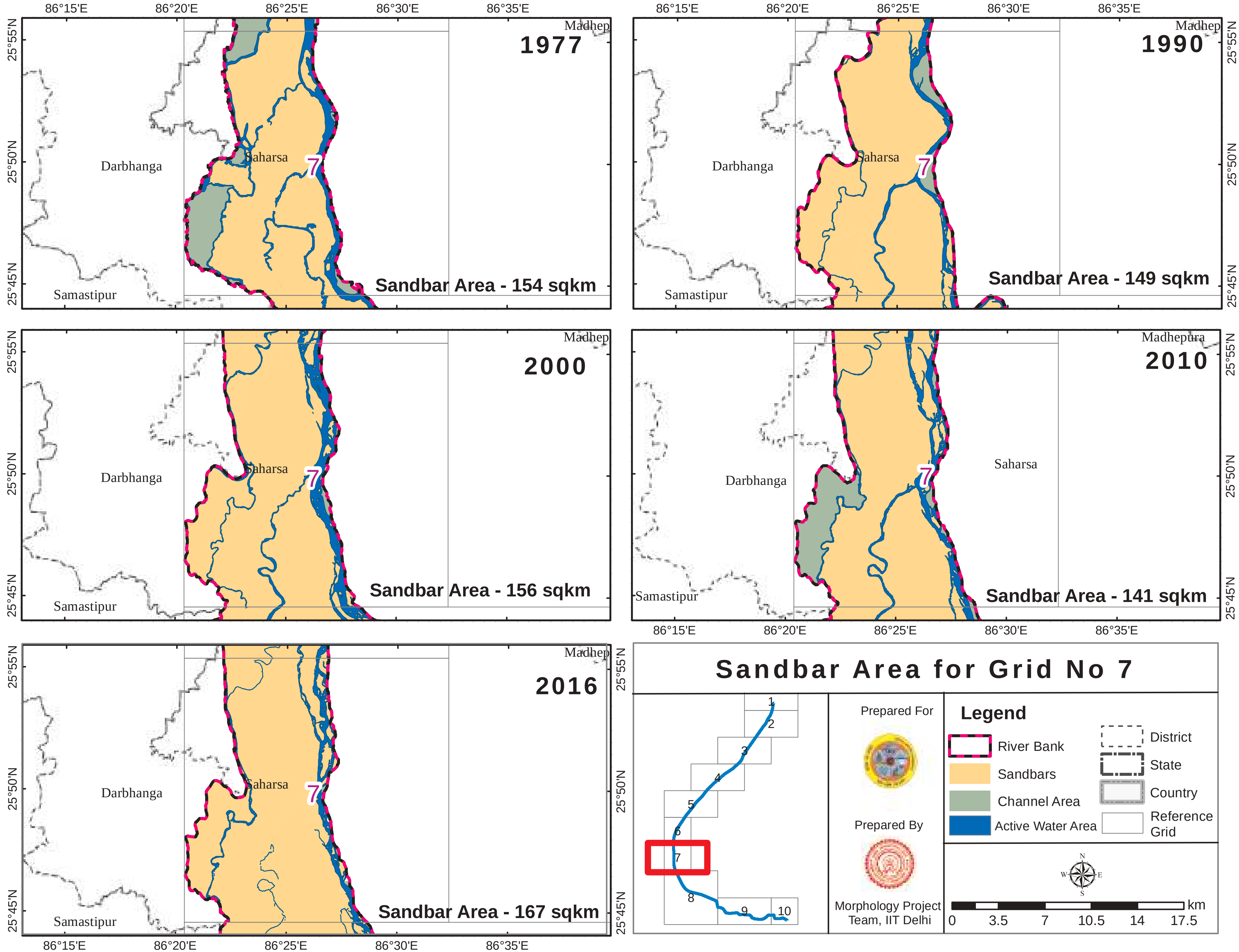


Sandbar Area for Grid No 4
1977
Sandbar Area - 111 sqkm
1990
Sandbar Area - 81 sqkm
2000
Sandbar Area - 129 sqkm
2010
Sandbar Area - 117 sqkm
2016
Sandbar Area - 69 sqkm
Nepal
Madhubani
Supaul
4
86°35'E
86°40'E
86°45'E
86°50'E
86°55'E
26°25'N
26°20'N
1
2
3
4
5
6
7
8
9
10
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
N
S
E
W
km
0
3.5
7
10.5
14
17.5

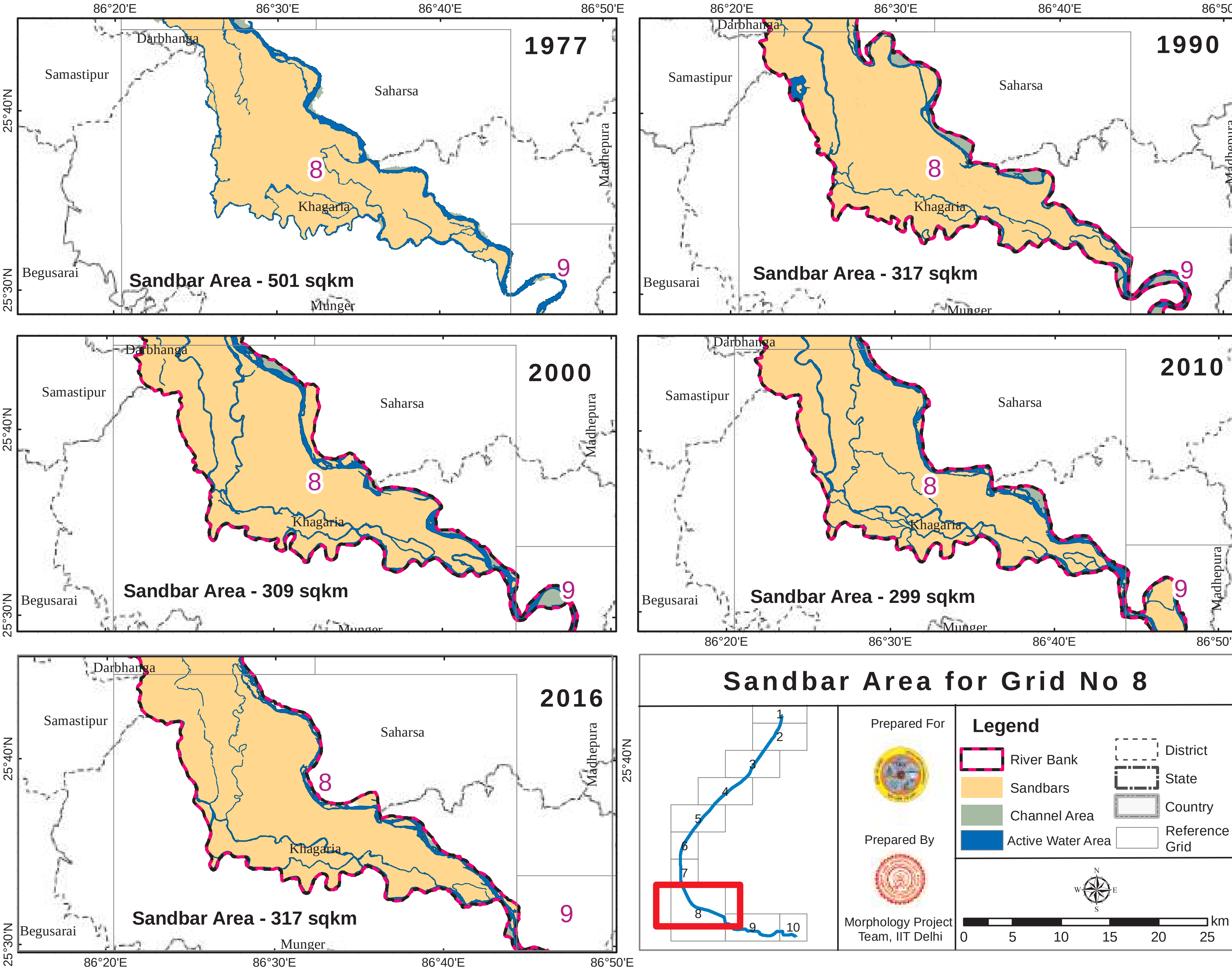

Sandbars for Grid No 5
1977
Sandbar Area - 69 sqkm
1990
Sandbar Area - 80 sqkm
2000
Sandbar Area - 126 sqkm
2010
Sandbar Area - 105 sqkm
2016
Sandbar Area - 98 sqkm
Madhubani
Supaul
Darbhanga
Madhepura
86°20'E
86°25'E
86°30'E
86°35'E
86°40'E
86°45'E
26°15'N
26°10'N
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
km
0
3.5
7
10.5
14
17.5



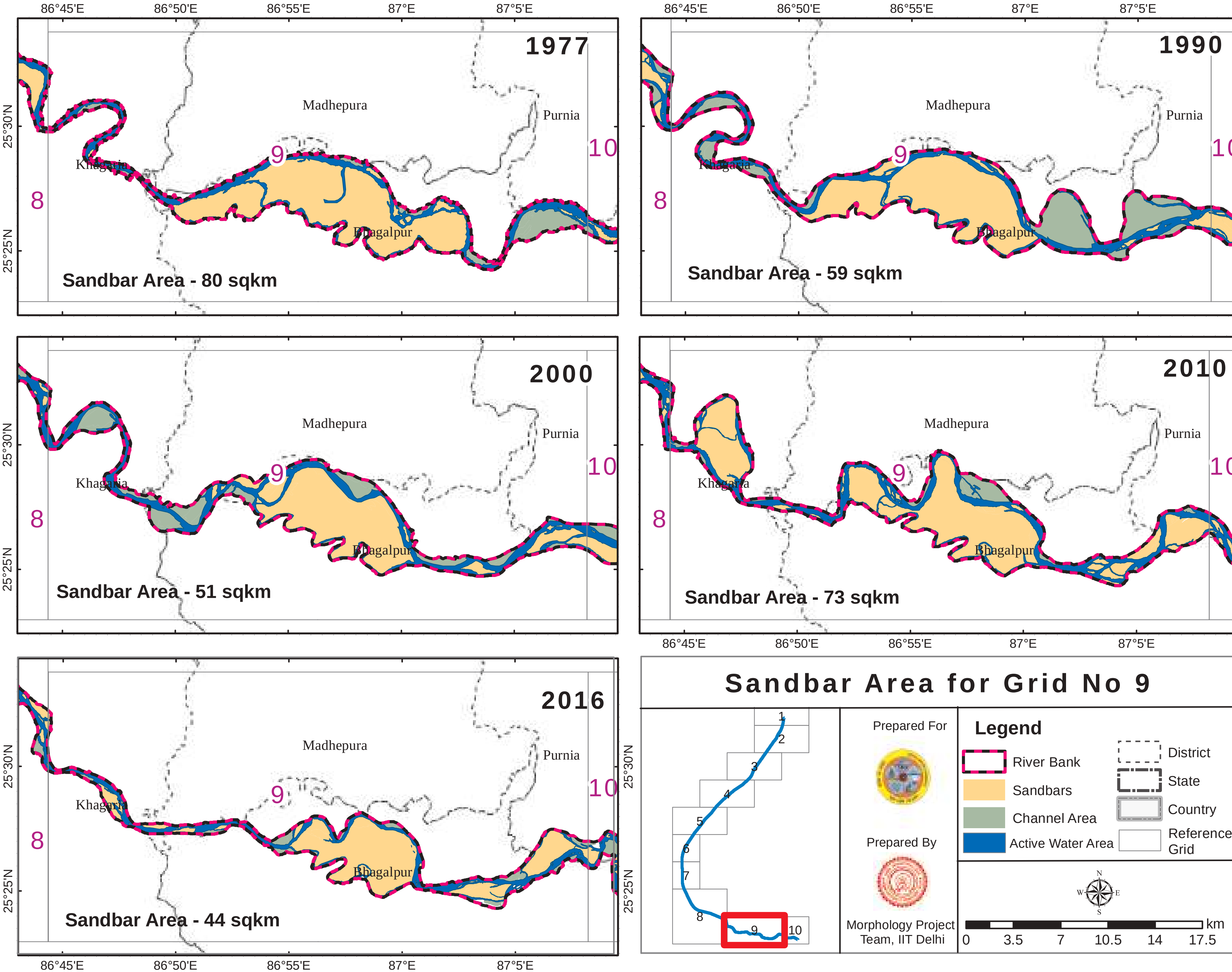
1977
Sandbar Area - 30 sqkm
1990
Sandbar Area - 67 sqkm
2000
Sandbar Area - 142 sqkm
2010
Sandbar Area - 125 sqkm
2016
Sandbar Area - 137 sqkm
Madhubani
Supaul
Darbhanga
Saharsa
Madhepura
6
86°15'E
86°20'E
86°25'E
86°30'E
86°35'E
26°5'N
26°N
25°55'N
Sandbar Area for Grid No 6
1
2
3
4
5
6
7
8
9
10
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
N
S
E
W
km
0
3.5
7
10.5
14
17.5



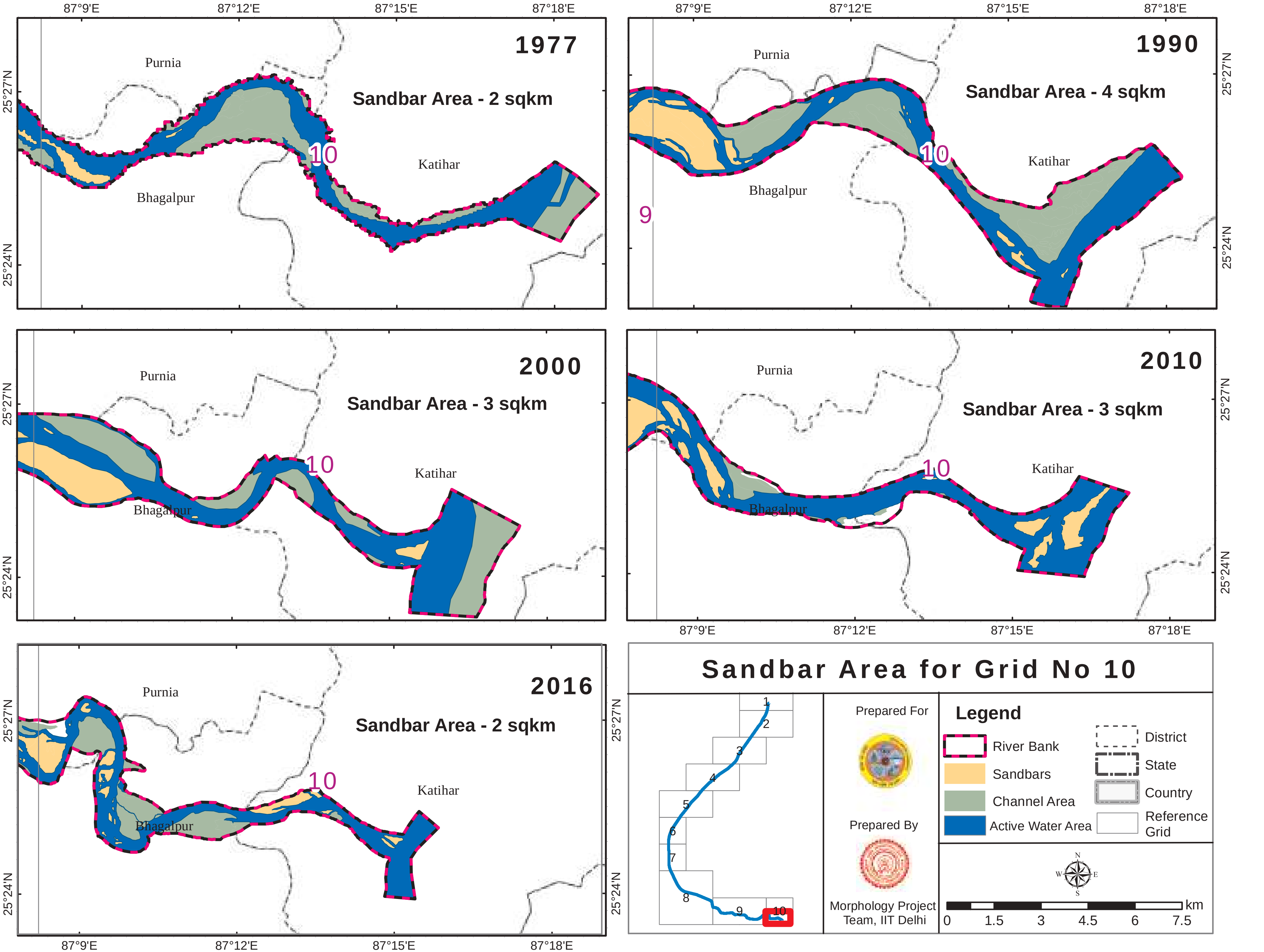
Sandbar Area for Grid No 7
1977
Sandbar Area - 154 sqkm
1990
Sandbar Area - 149 sqkm
2000
Sandbar Area - 156 sqkm
2010
Sandbar Area - 141 sqkm
2016
Sandbar Area - 167 sqkm
Darbhanga
Saharsa
Samastipur
Madhepura
7
86°15'E
86°20'E
86°25'E
86°30'E
86°35'E
25°45'N
25°50'N
25°55'N
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
km
0
3.5
7
10.5
14
17.5
1
2
3
4
5
6
7
8
9
10



1977
Sandbar Area - 501 sqkm
1990
Sandbar Area - 317 sqkm
2000
Sandbar Area - 309 sqkm
2010
Sandbar Area - 299 sqkm
2016
Sandbar Area - 317 sqkm
Darbhanga
Samastipur
Saharsa
Madhepura
Khagaria
Begusarai
Munger
8
9
86°20'E
86°30'E
86°40'E
86°50'E
25°30'N
25°40'N
Sandbar Area for Grid No 8
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
km
N
S
E
W

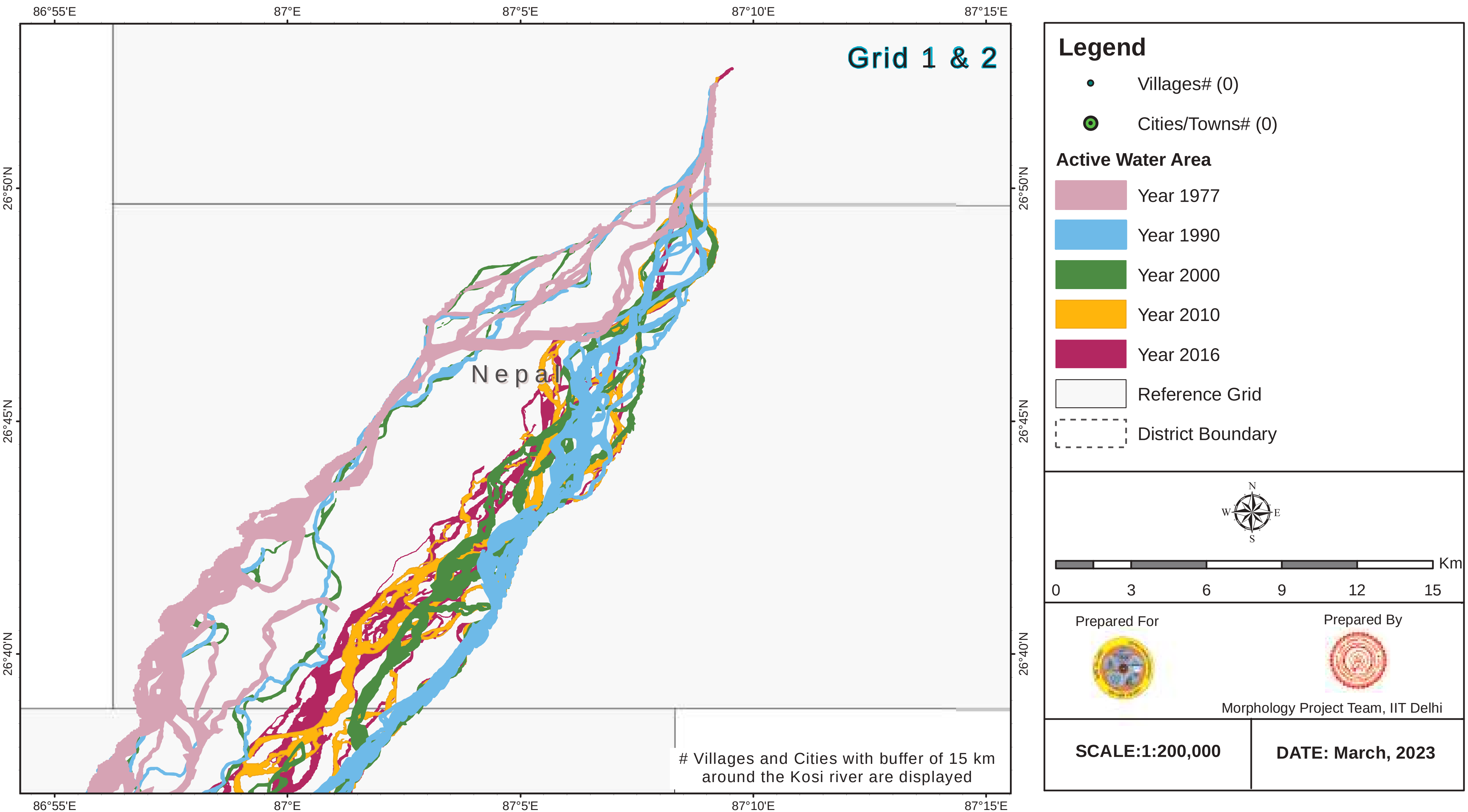


Sandbar Area for Grid No 9
1977
Sandbar Area - 80 sqkm
1990
Sandbar Area - 59 sqkm
2000
Sandbar Area - 51 sqkm
2010
Sandbar Area - 73 sqkm
2016
Sandbar Area - 44 sqkm
Madhepura
Purnia
Khagaria
Bhagalpur
8
9
10
86°45'E
86°50'E
86°55'E
87°E
87°5'E
25°30'N
25°25'N
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
km
0
3.5
7
10.5
14
17.5

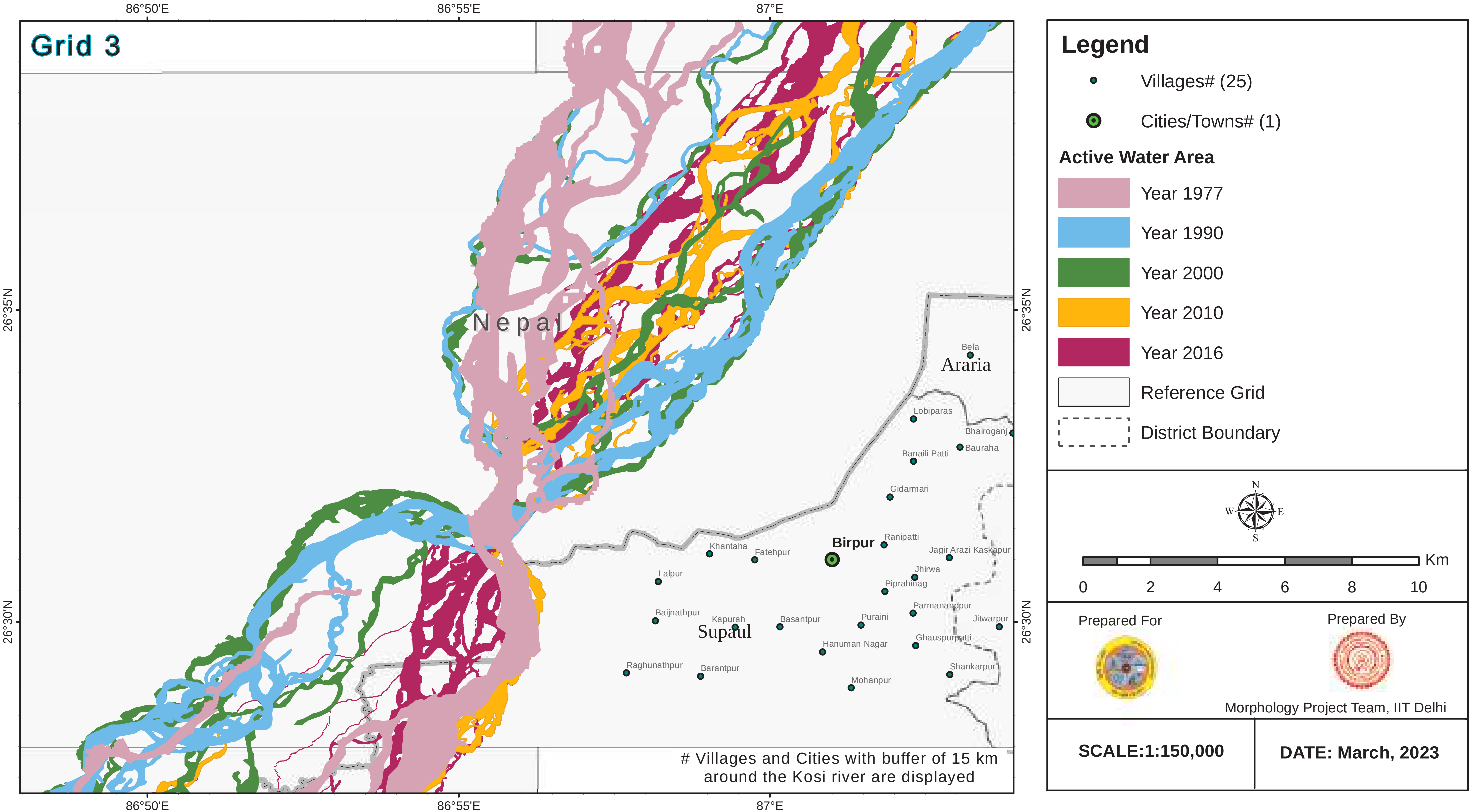


1977
Sandbar Area - 2 sqkm
1990
Sandbar Area - 4 sqkm
2000
Sandbar Area - 3 sqkm
2010
Sandbar Area - 3 sqkm
2016
Sandbar Area - 2 sqkm
Purnia
Katihar
Bhagalpur
87°9'E
87°12'E
87°15'E
87°18'E
25°27'N
25°24'N
Sandbar Area for Grid No 10
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Legend
River Bank
Sandbars
Channel Area
Active Water Area
District
State
Country
Reference Grid
0 1.5 3 4.5 6 7.5 km

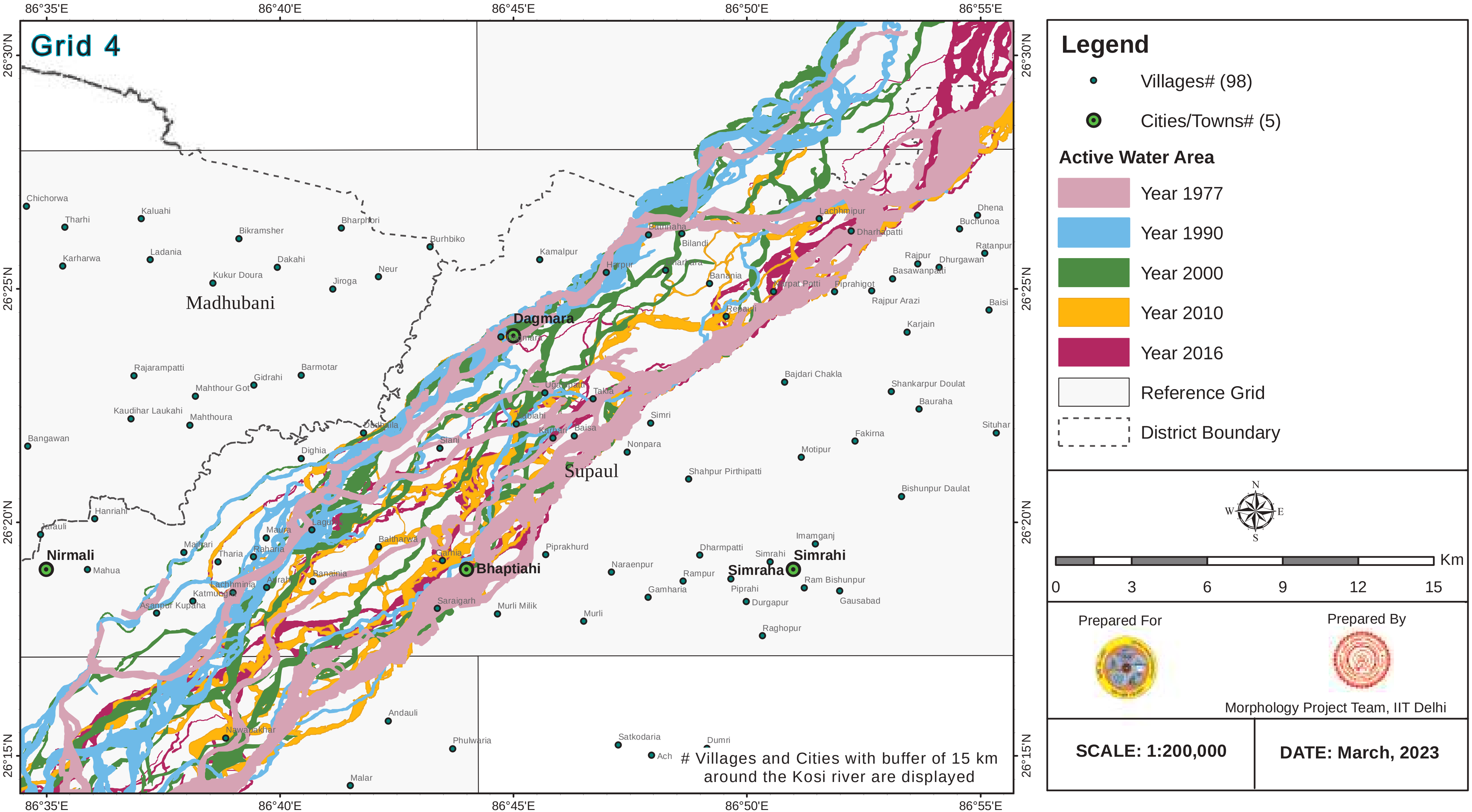
Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 1 & 2



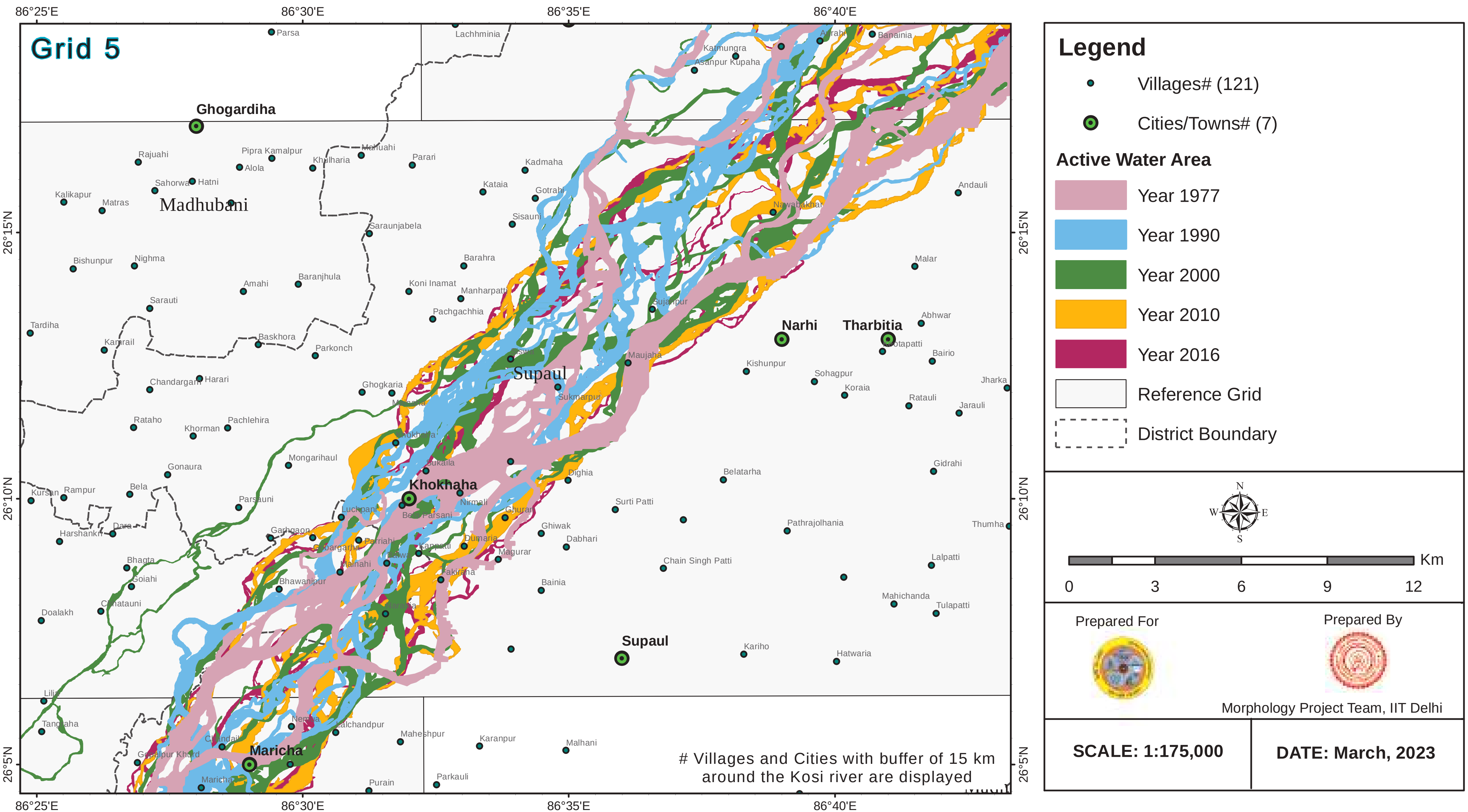
Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 3



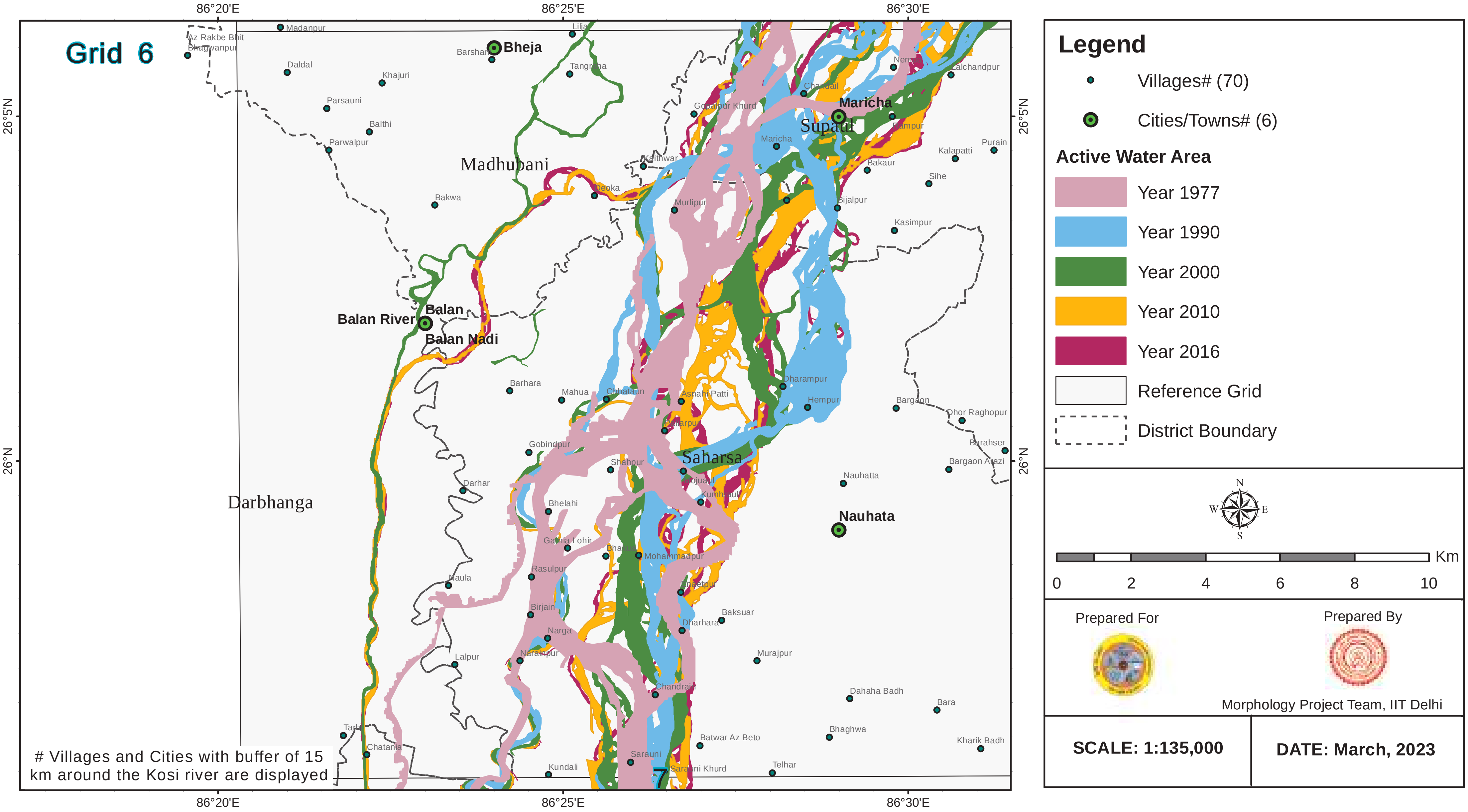
Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 4



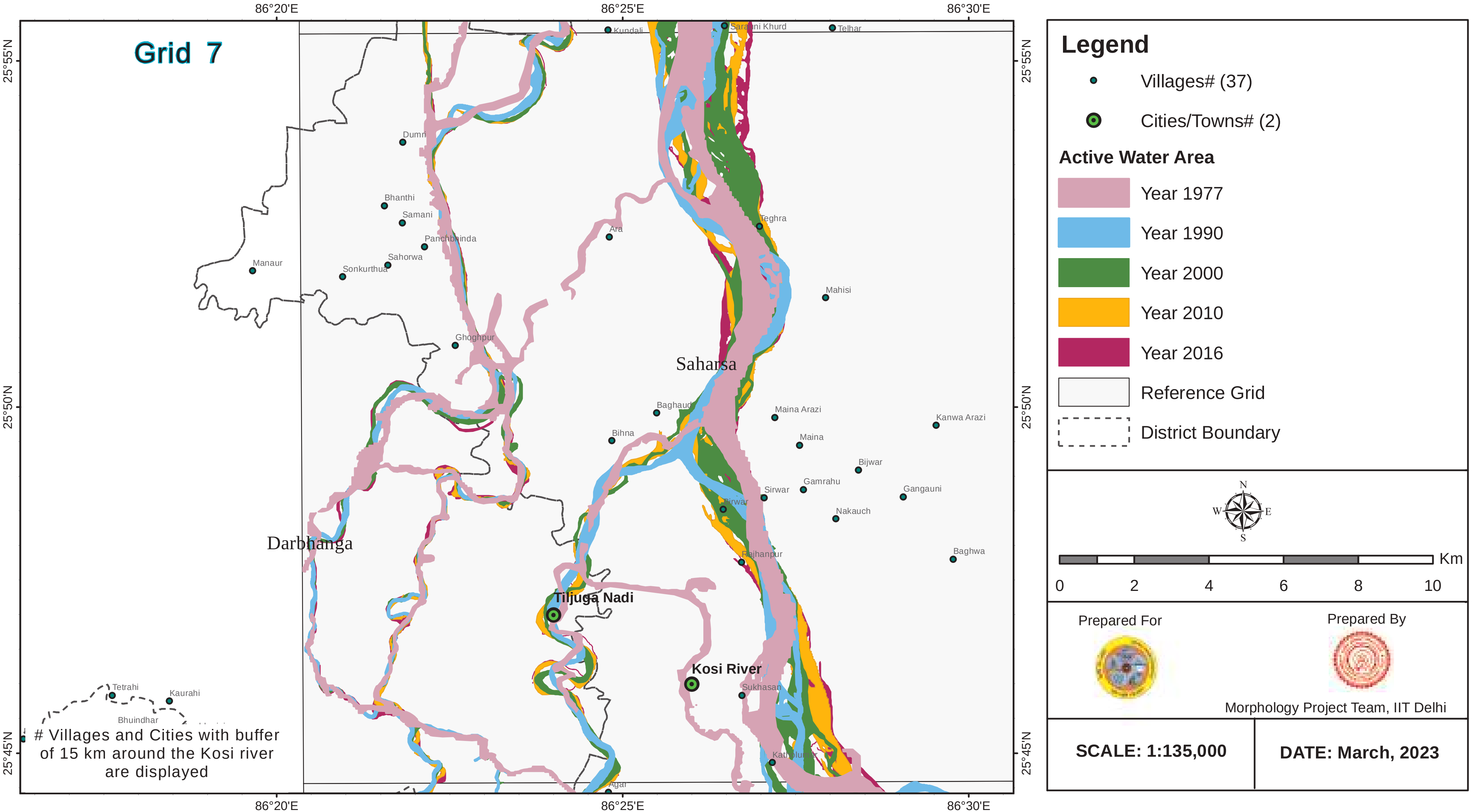
Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 5



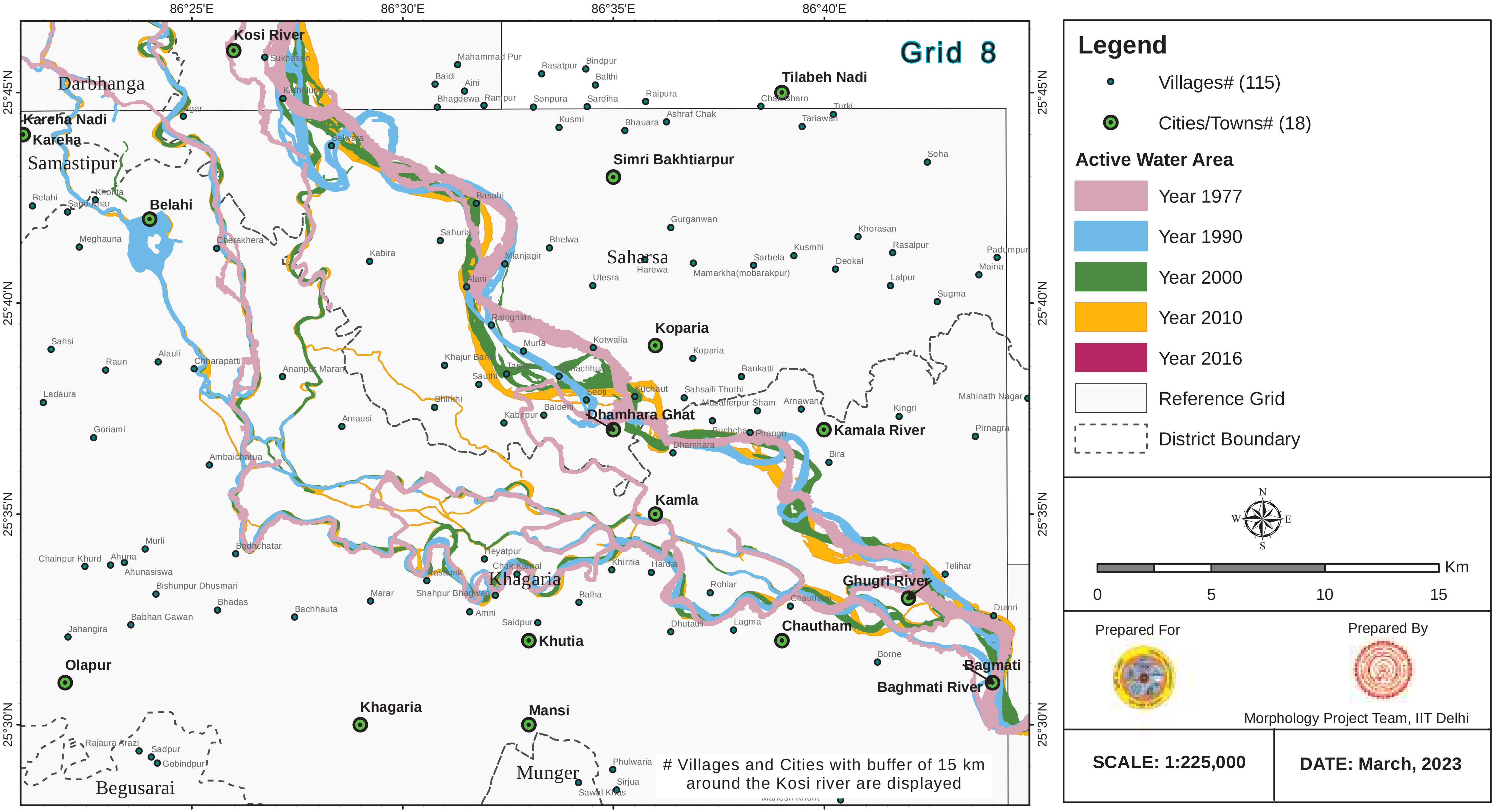
Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 6



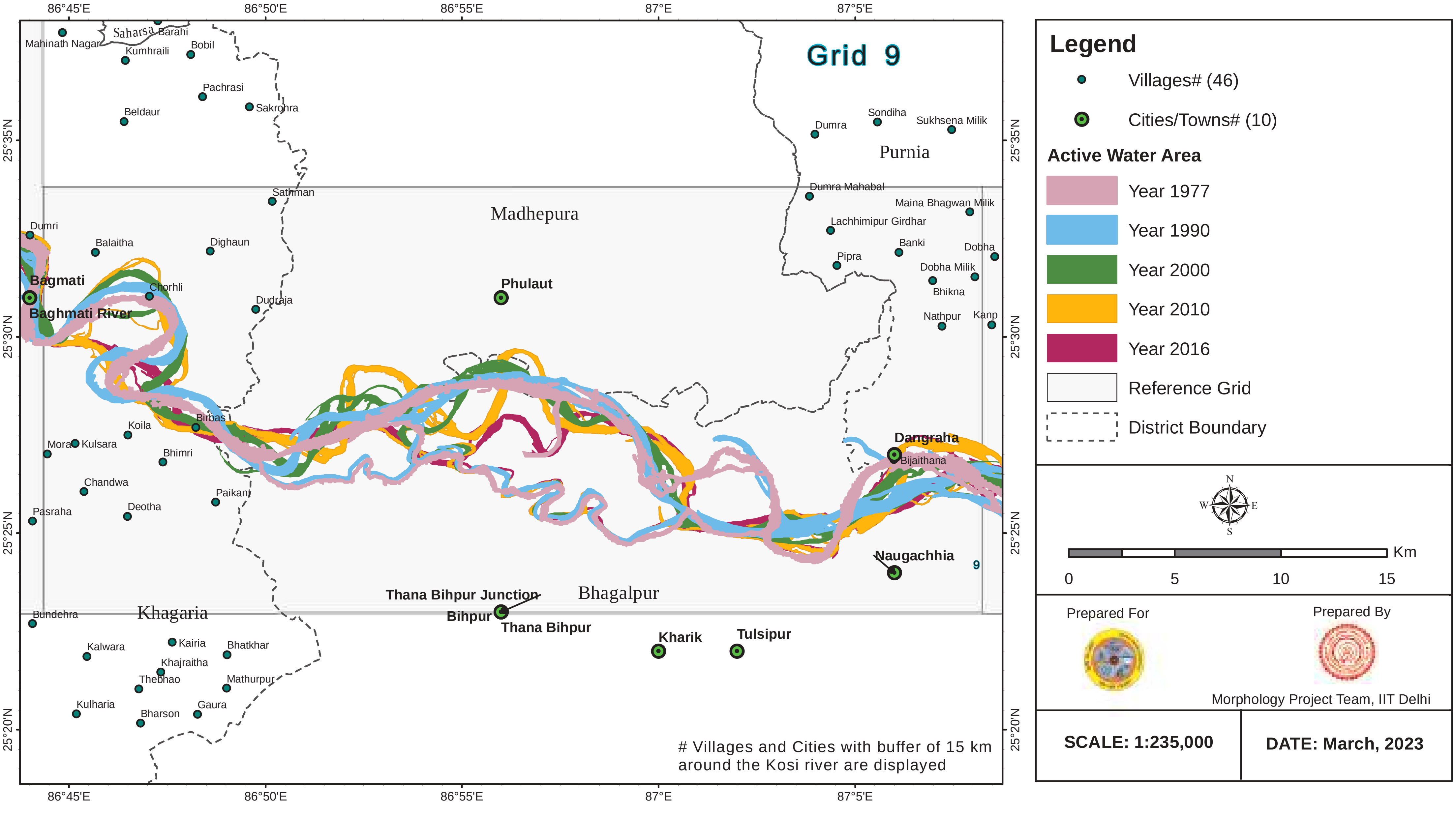
Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 7



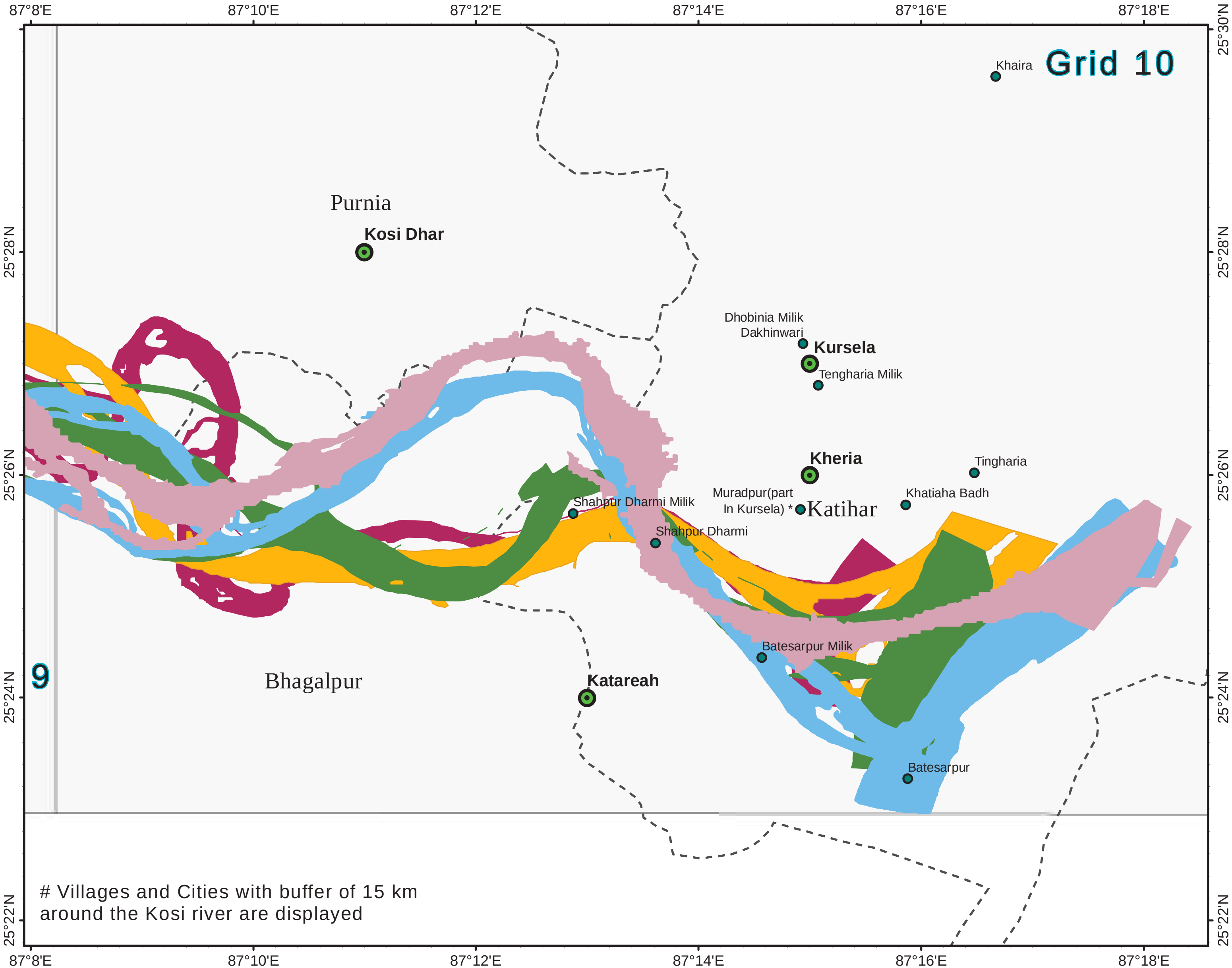
Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 8



Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 9



Temporal Changes in Active Water Area of Kosi River over 5 Time Slices - Grid 10



Villages and Cities with buffer of 15 km
around the Kosi river are displayed

Legend

- Villages# (10)
- Cities/Towns# (4)

Active Water Area

- Year 1977
- Year 1990
- Year 2000
- Year 2010
- Year 2016
- Reference Grid
- District Boundary

N W E S

0 2 4 6 Km

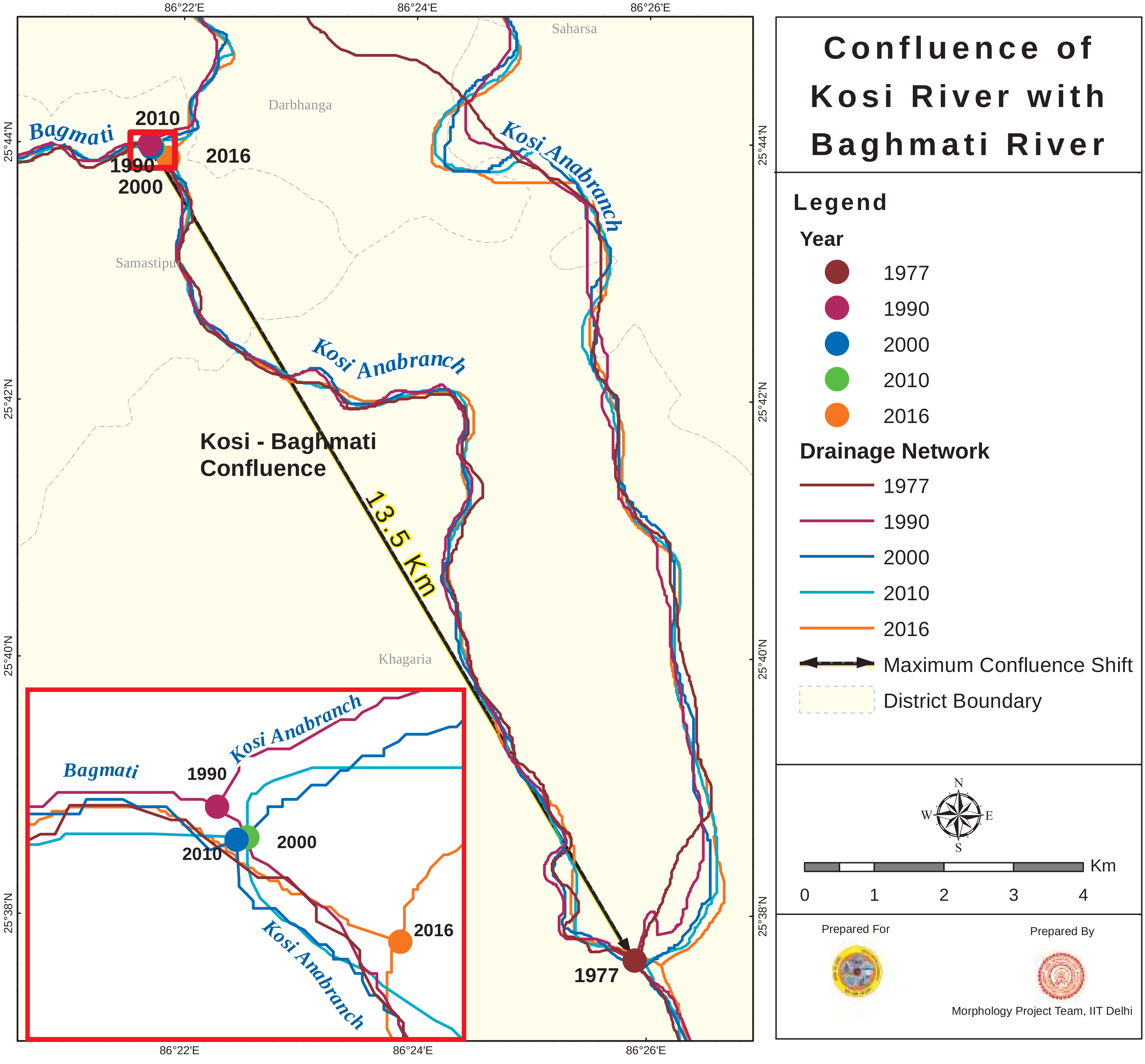
Prepared For

Prepared By

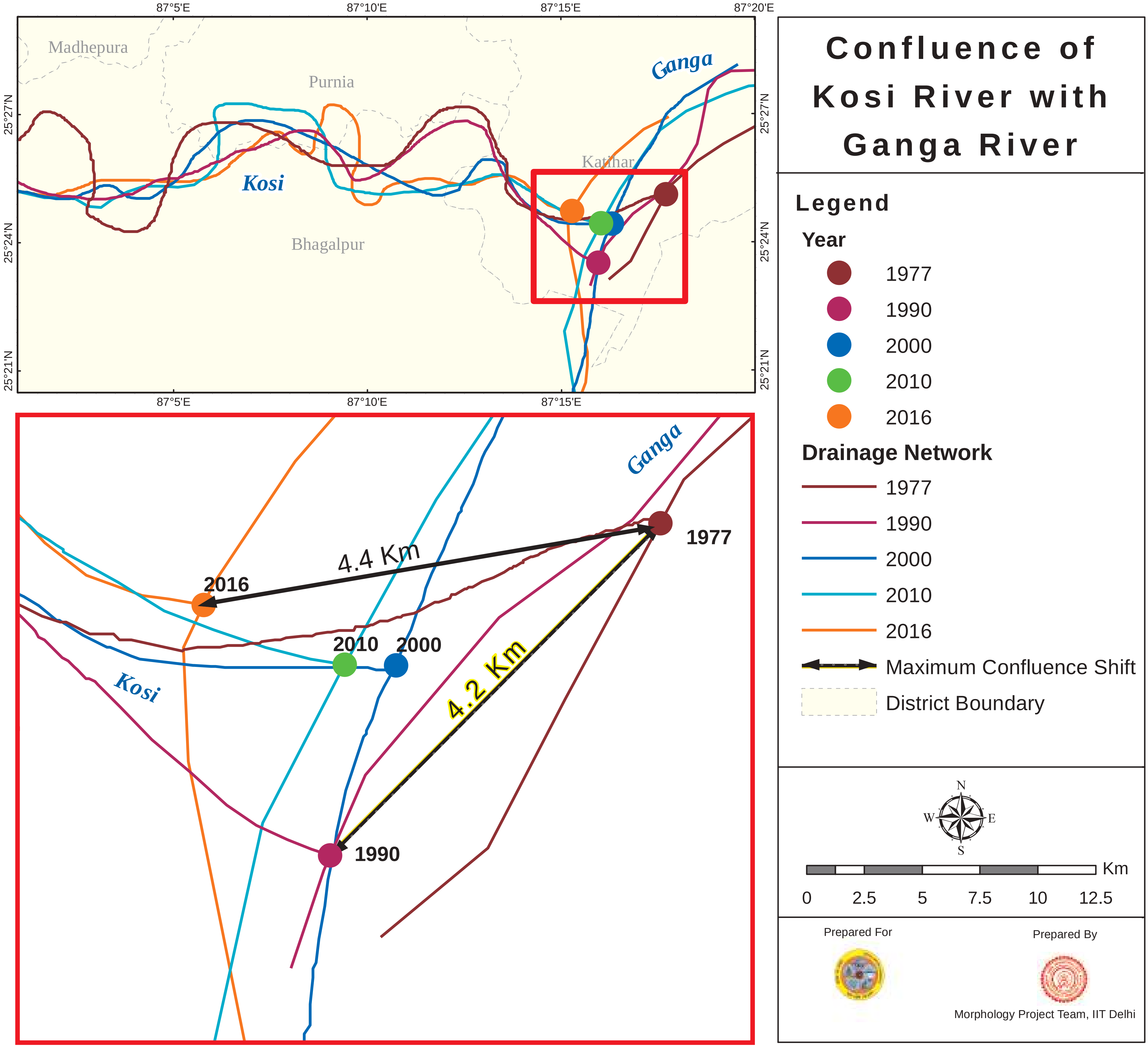
Morphology Project Team, IIT Delhi

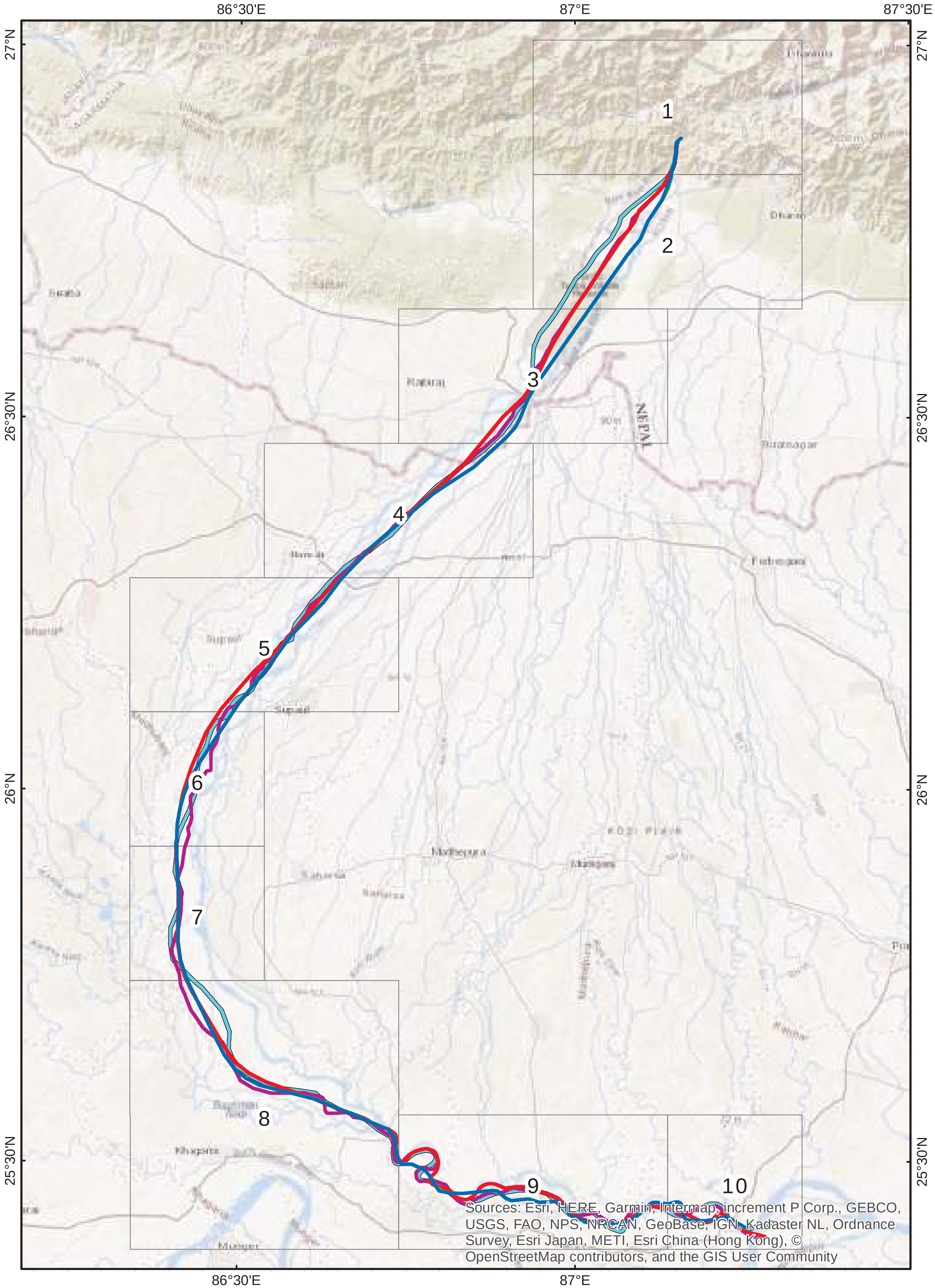
SCALE: 1:100,000

DATE: March, 2023



Confluence of Kosi River with Baghmati River
Legend
Year
1977
1990
2000
2010
2016
Drainage Network
1977
1990
2000
2010
2016
Maximum Confluence Shift
District Boundary
N
S
E
W
Km
0 1 2 3 4
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
86°22'E
86°24'E
86°26'E
25°44'N
25°42'N
25°40'N
25°38'N
Saharsa
Darbhanga
Samastipur
Khagaria
Bagmati
Kosi Anabranch
Kosi Anabranch
2010
2016
1990
2000
Kosi - Baghmati
Confluence
13.5 Km
1977
Bagmati
Kosi Anabranch
1990
2010
2000
2016
Kosi Anabranch


Confluence of Kosi River with Ganga River
87°5'E
87°10'E
87°15'E
87°20'E
25°27'N
25°24'N
25°21'N
Madhepura
Purnia
Katihar
Bhagalpur
Kosi
Ganga
2016
2010
2000
1990
1977
4.4 Km
4.2 Km
Legend
Year
1977
1990
2000
2010
2016
Drainage Network
1977
1990
2000
2010
2016
Maximum Confluence Shift
District Boundary
N
W
E
S
Km
0
2.5
5
7.5
10
12.5
Prepared For
Prepared By
Morphology Project Team, IIT Delhi



Shifting of Centre Lines of Kosi River

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N
W E
S

Km
0 10 20 30 40 50

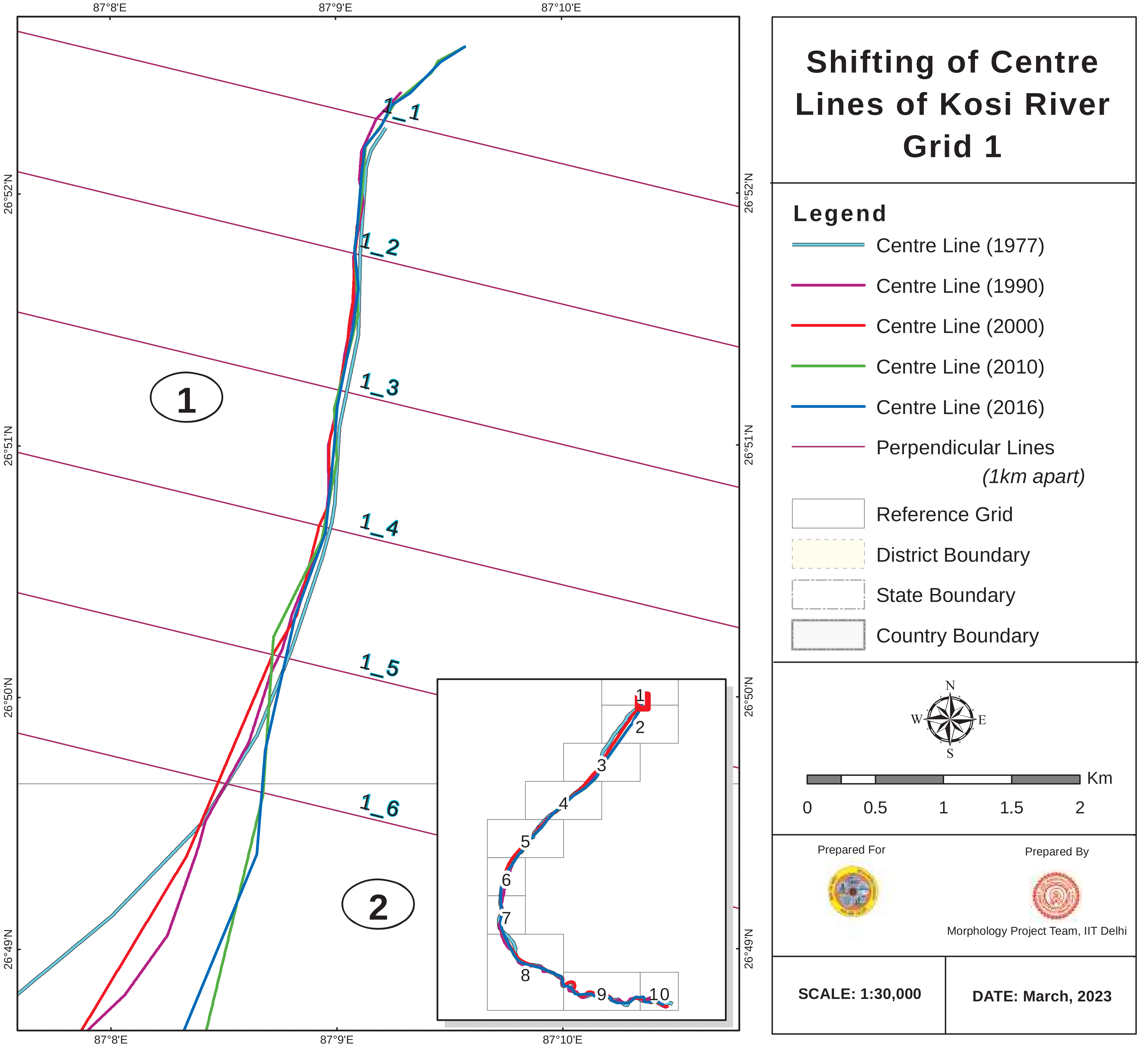
Prepared For

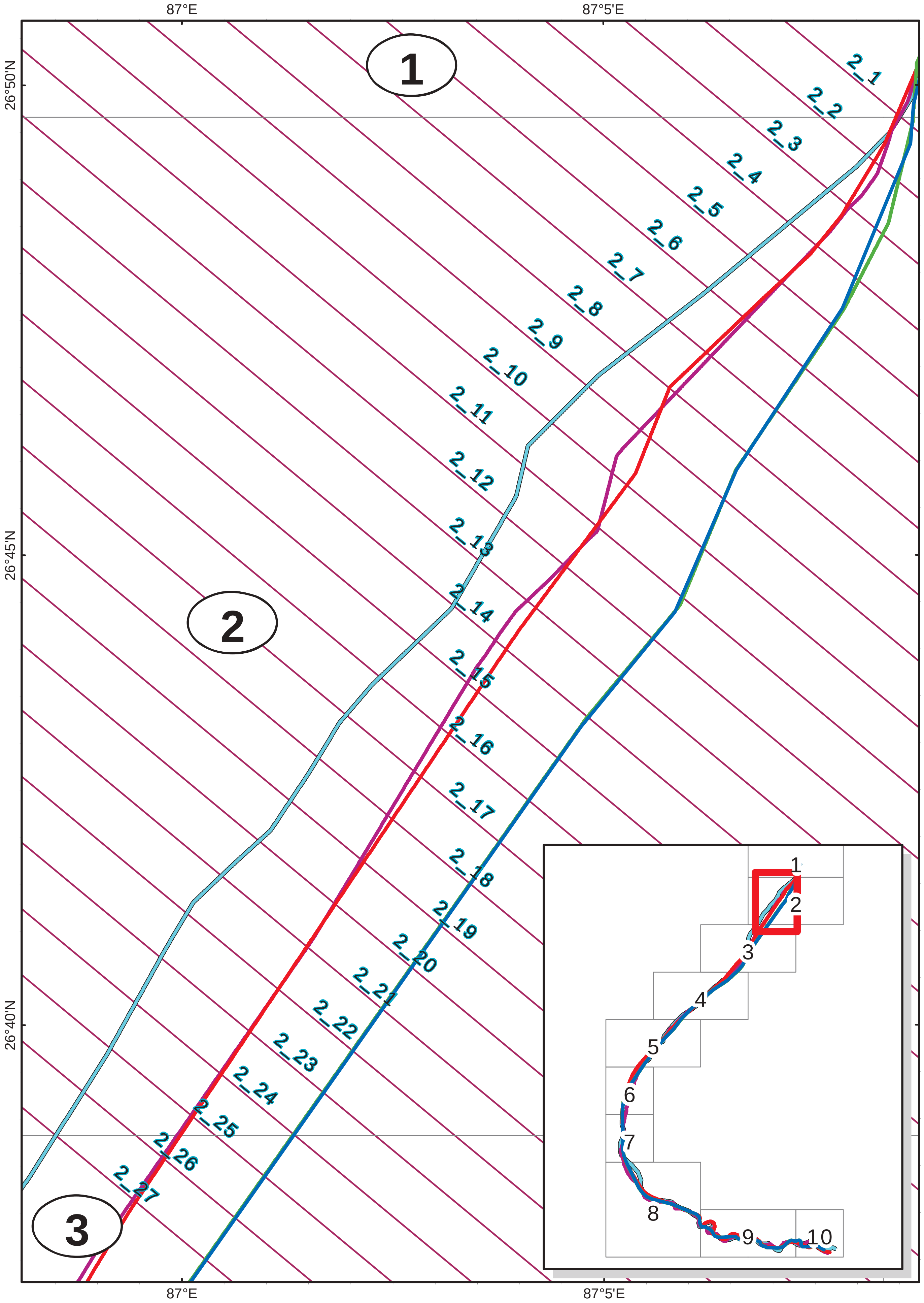
Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:750,000

DATE: March, 2023


Shifting of Centre Lines of Kosi River Grid 1
Legend
Centre Line (1977)
Centre Line (1990)
Centre Line (2000)
Centre Line (2010)
Centre Line (2016)
Perpendicular Lines (1km apart)
Reference Grid
District Boundary
State Boundary
Country Boundary
N
S
E
W
0
0.5
1
1.5
2
Km
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
SCALE: 1:30,000
DATE: March, 2023
87°8'E
87°9'E
87°10'E
26°52'N
26°51'N
26°50'N
26°49'N
1_1
1_2
1_3
1_4
1_5
1_6
1
2
3
4
5
6
7
8
9
10



Shifting of Centre Lines of Kosi River Grid 2

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N W E S

0 2 4 6 Km

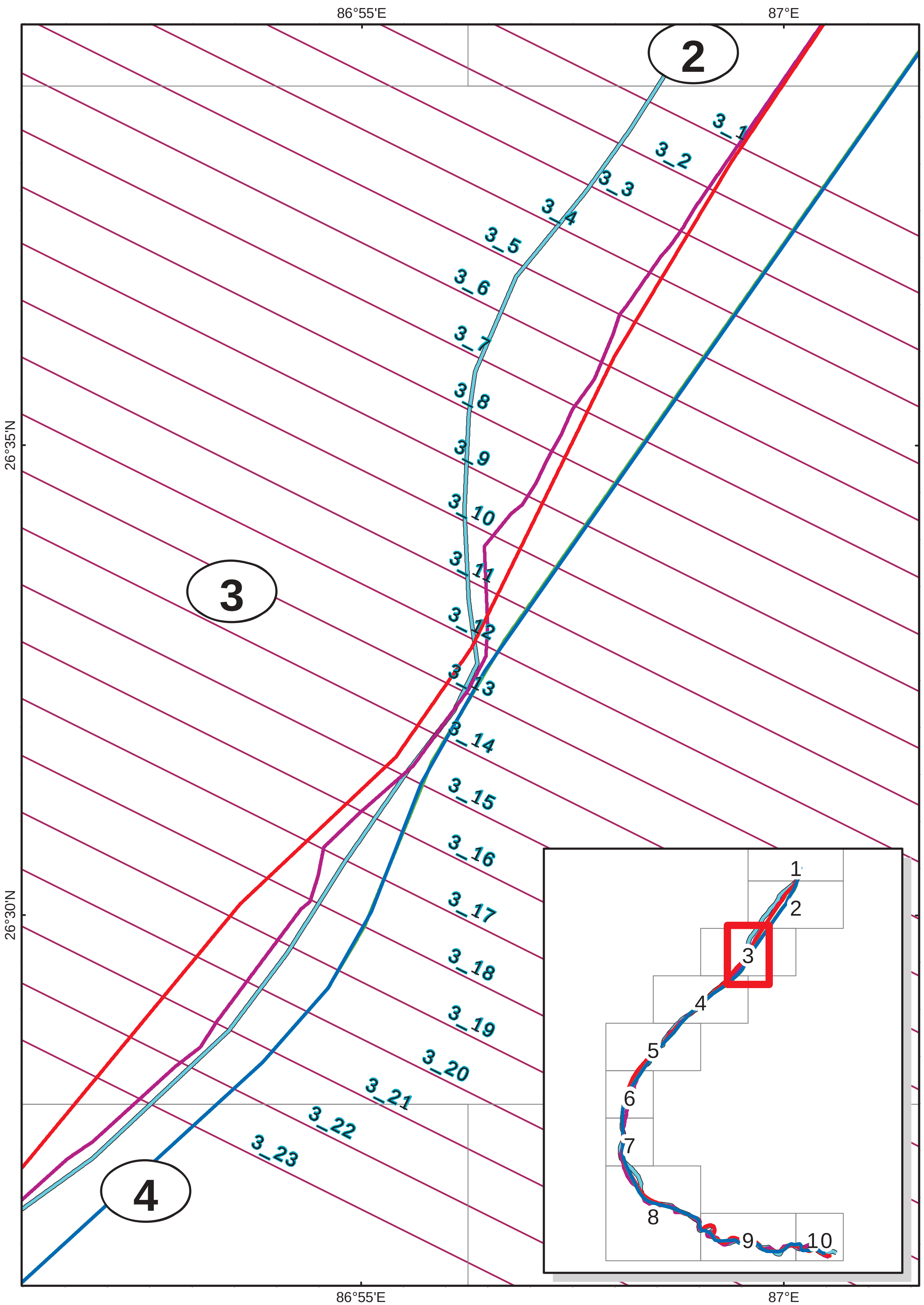
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:100,000

DATE: March, 2023



Shifting of Centre Lines of Kosi River Grid 3

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N
W E
S

0 2 4 6 Km

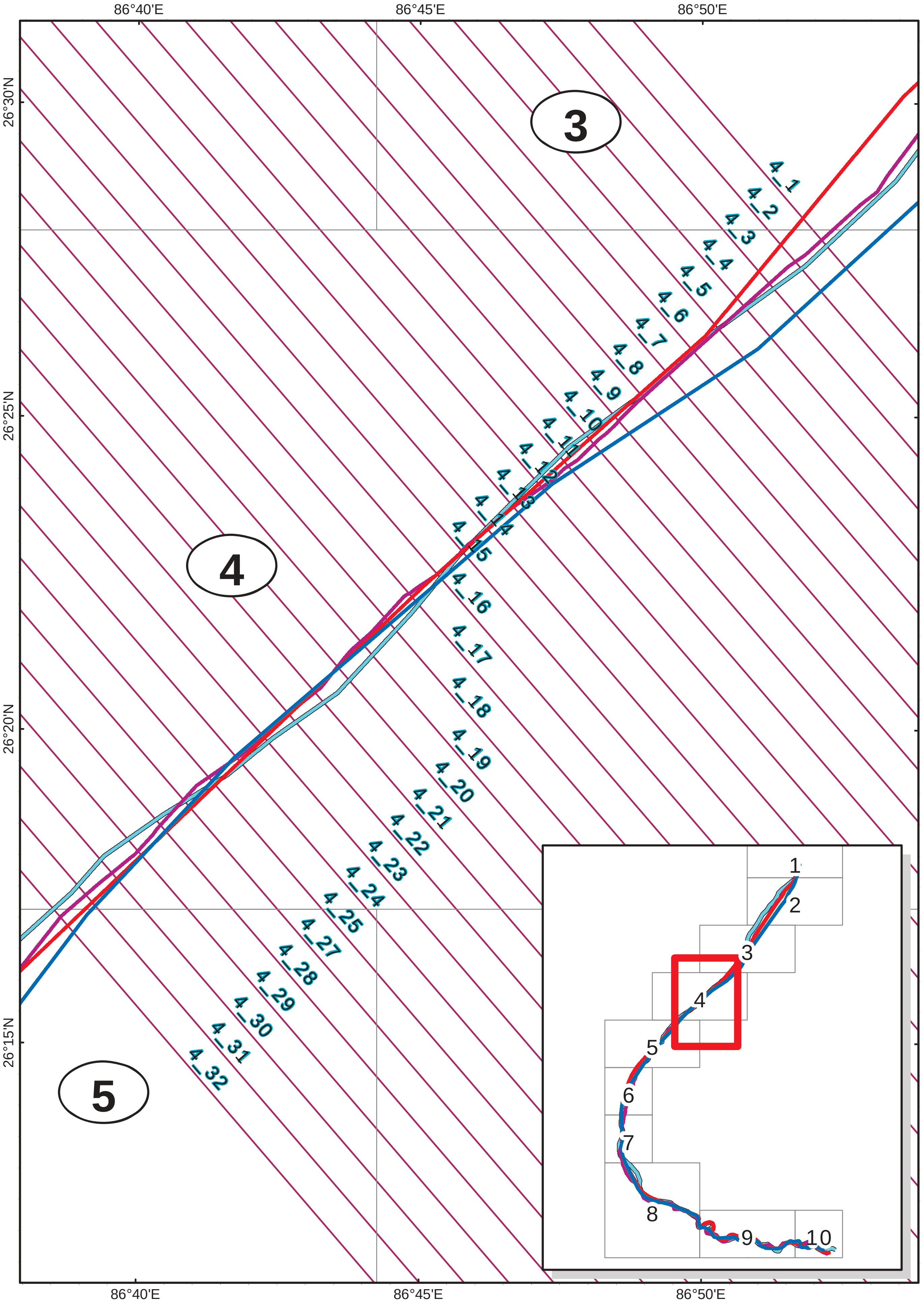
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:100,000

DATE: March, 2023



Shifting of Centre Lines of Kosi River Grid 4

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N
W E
S

Km
0 2 4 6 8 10

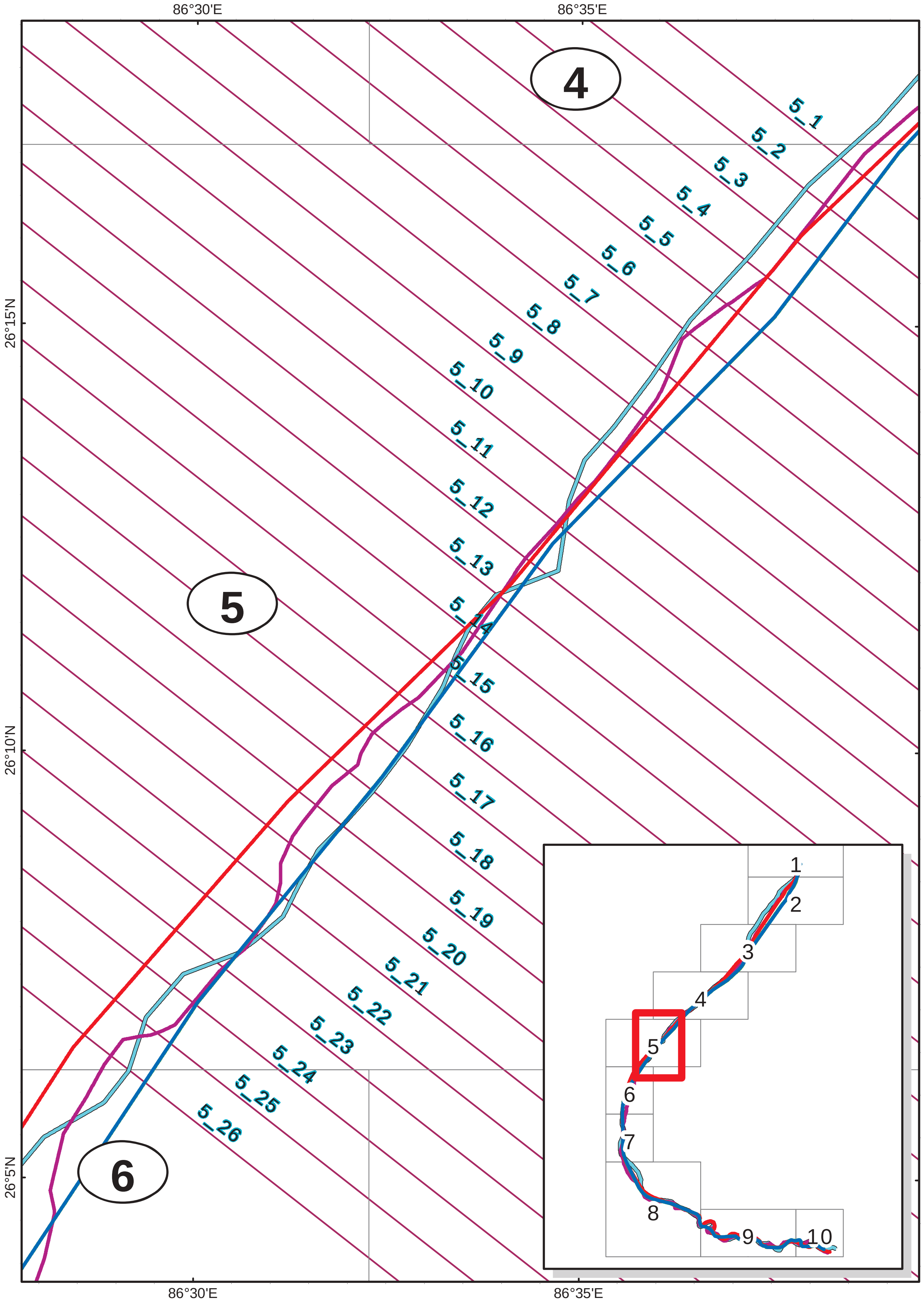
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:150,000

DATE: March, 2023



Shifting of Centre Lines of Kosi River Grid 5

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N
W E
S

Km
0 2 4 6 8

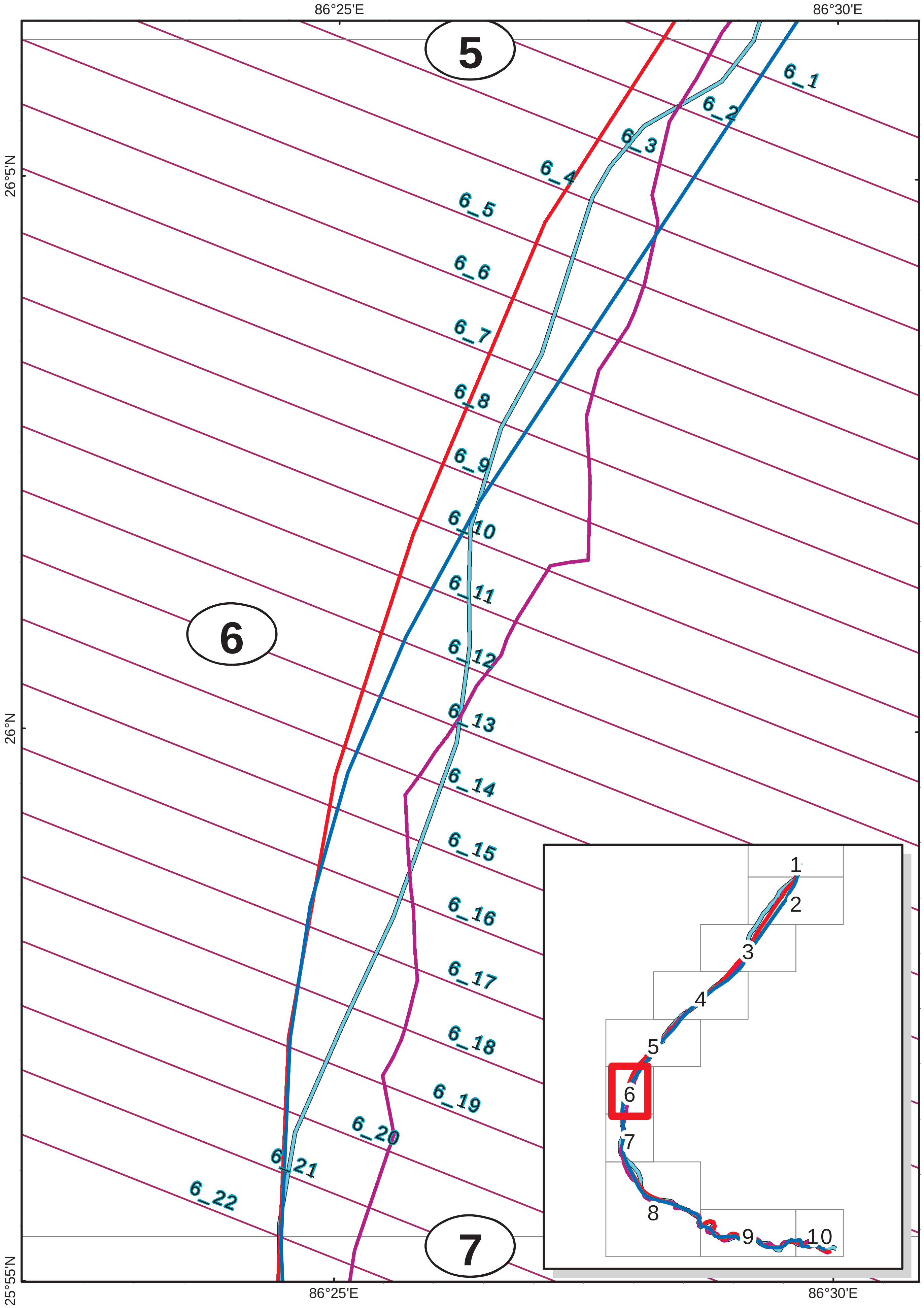
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:110,000

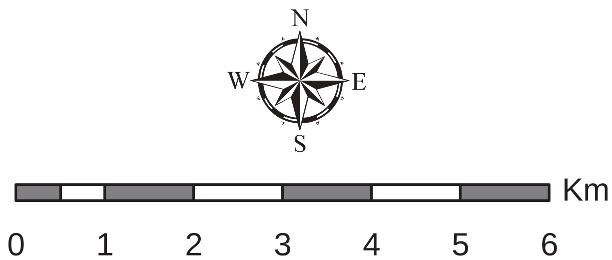
DATE: March, 2023



Shifting of Centre Lines of Kosi River Grid 6

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

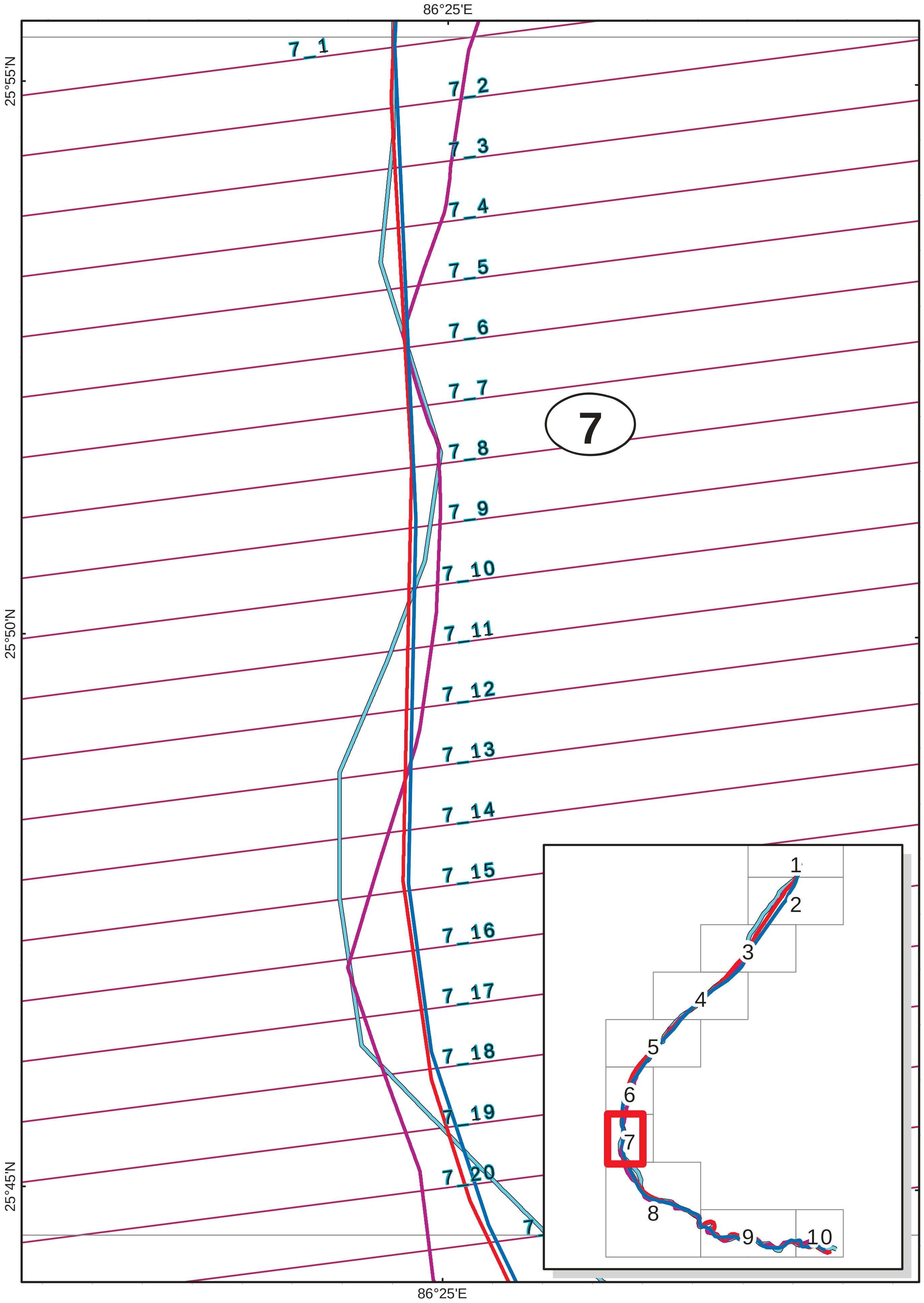


Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:85,000	**DATE: March, 2023**



Shifting of Centre Lines of Kosi River Grid 7

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N
W E
S

Km
0 1 2 3 4 5 6

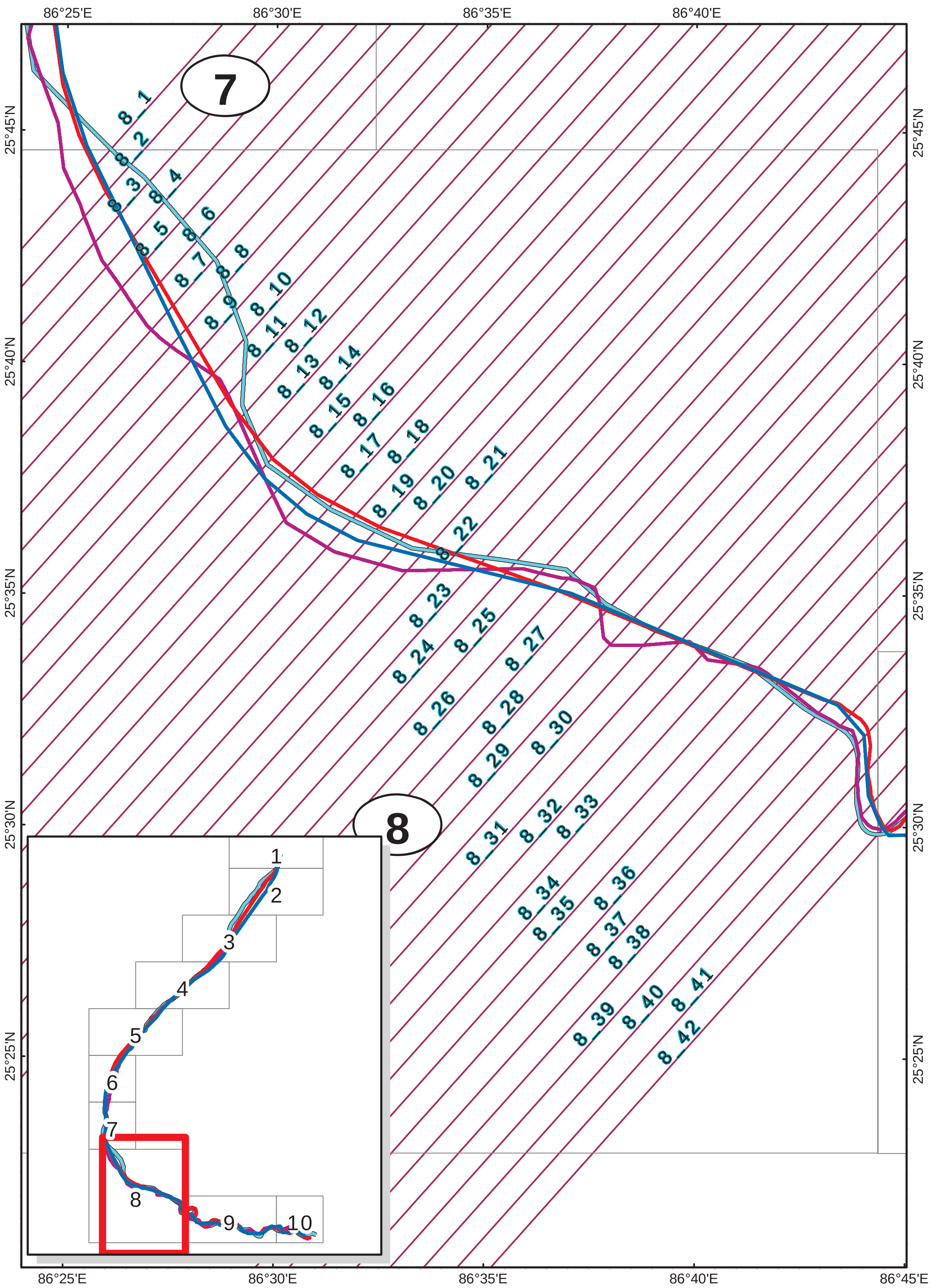
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:85,000

DATE: March, 2023



Shifting of Centre Lines of Kosi River Grid 8

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N
W E
S

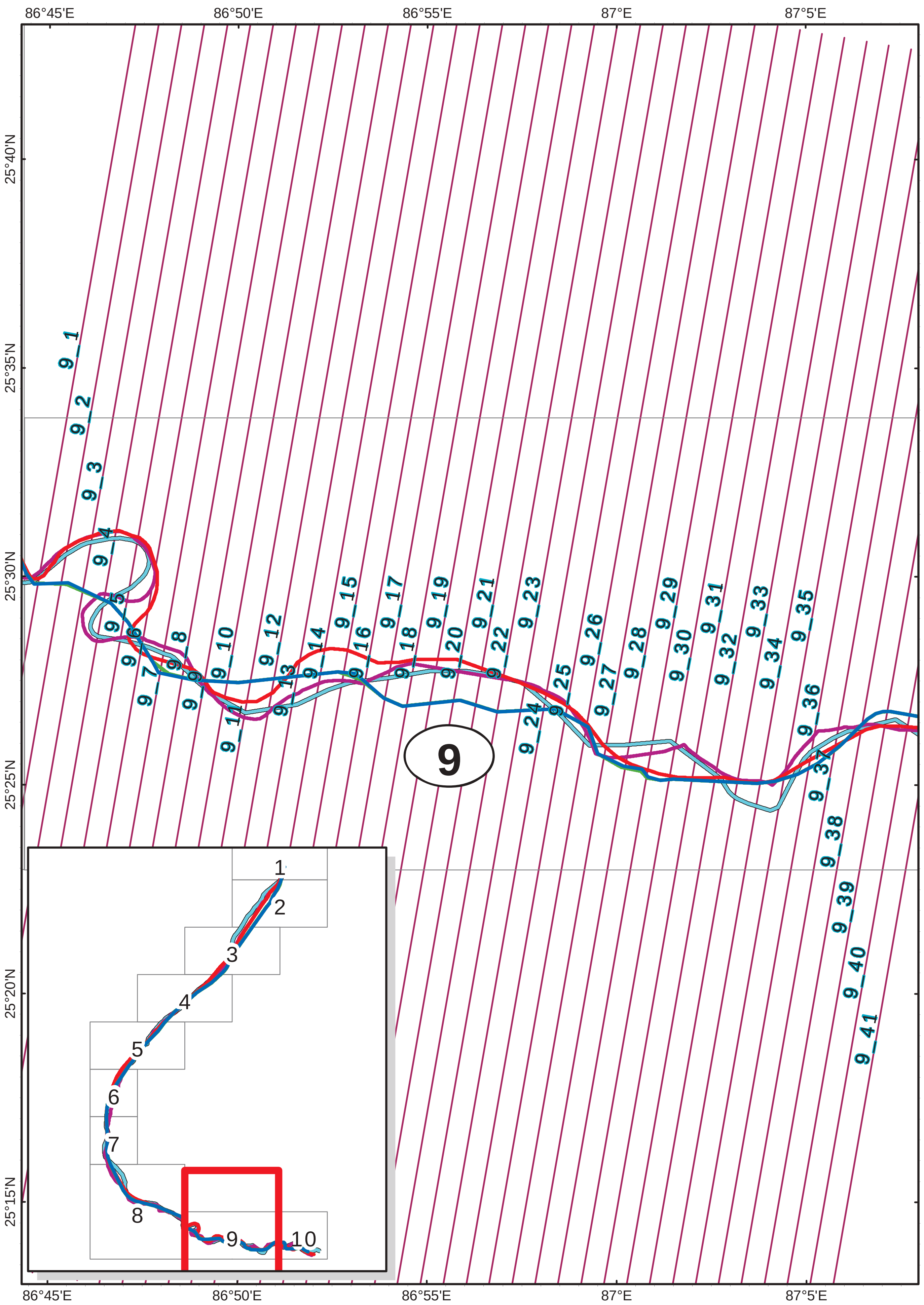
Km
0 3 6 9 12 15

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:200,000	**DATE: March, 2023**



Shifting of Centre Lines of Kosi River Grid 9

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N E S W

0 4 8 12 16 Km

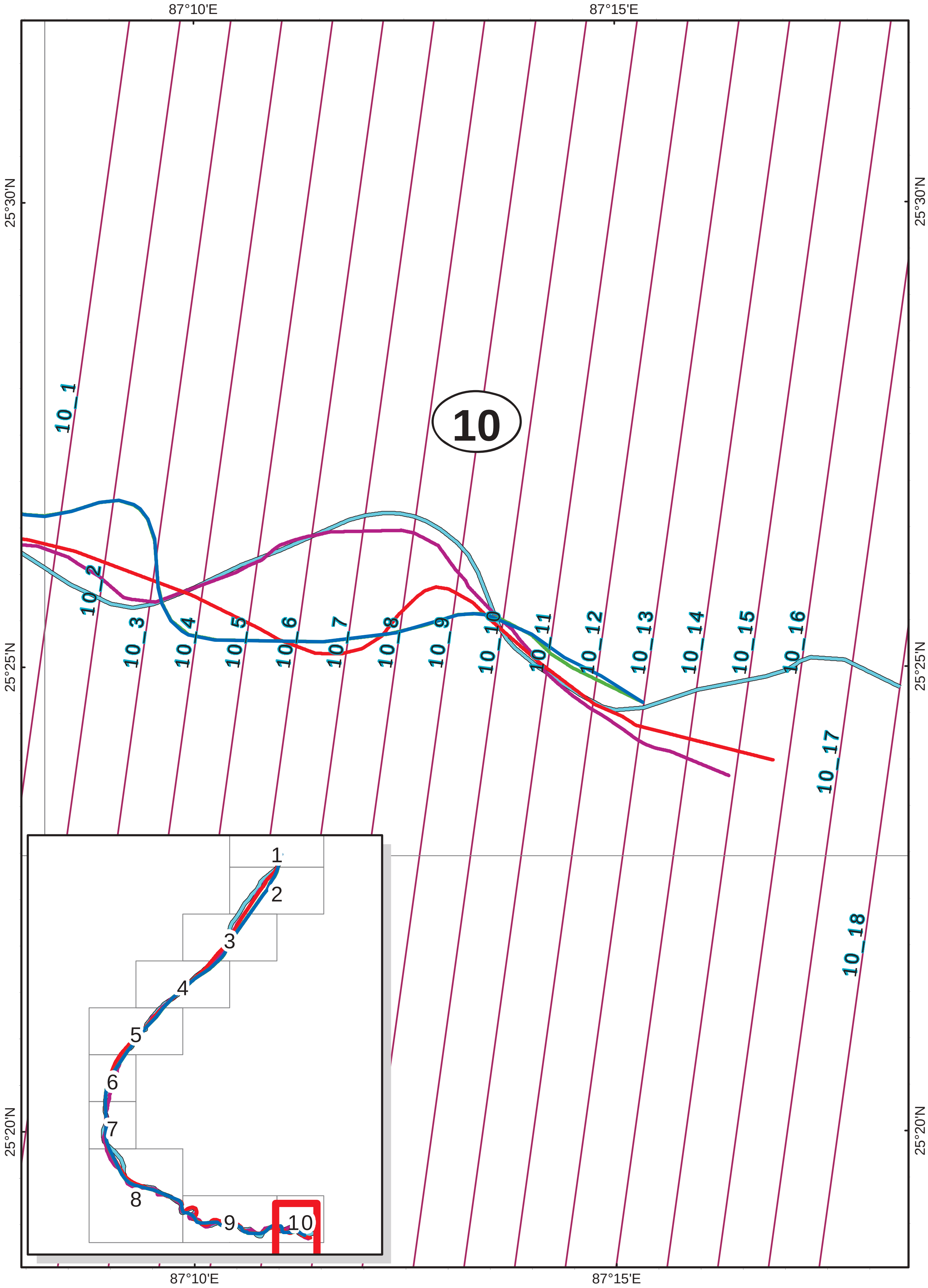
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:225,000

DATE: March, 2023



Shifting of Centre Lines of Kosi River Grid 10

Legend

- Centre Line (1977)
- Centre Line (1990)
- Centre Line (2000)
- Centre Line (2010)
- Centre Line (2016)
- Perpendicular Lines *(1km apart)*
- Reference Grid
- District Boundary
- State Boundary
- Country Boundary

N
W E
S

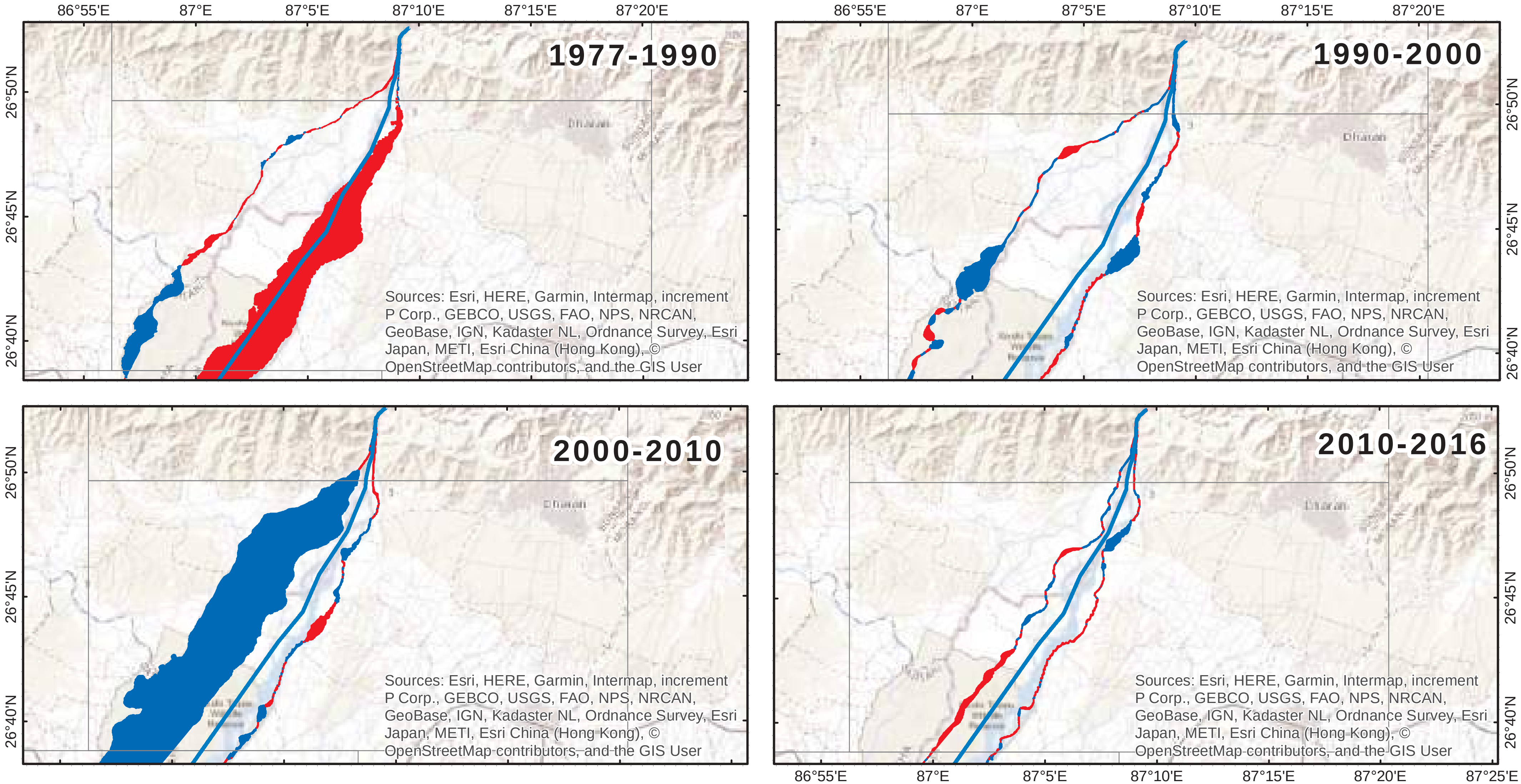
0 2 4 6 8 Km

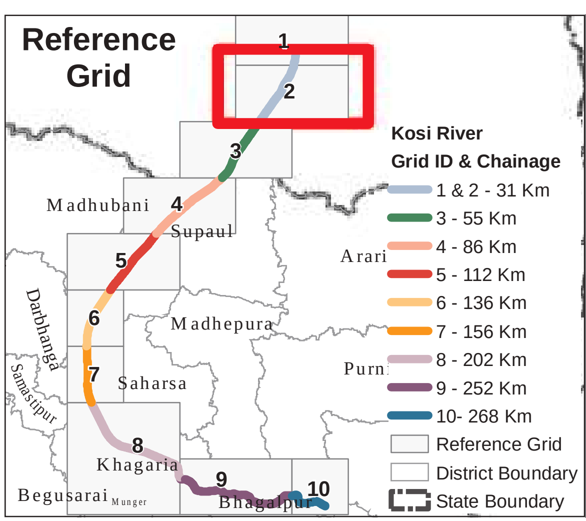
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:100,000	DATE: March, 2023





Channel Bank Retreat on Account of Erosion and Deposition for Grid No 1 & 2 (From Chainage 0 - 31 Km)

Prepared For

Prepared By

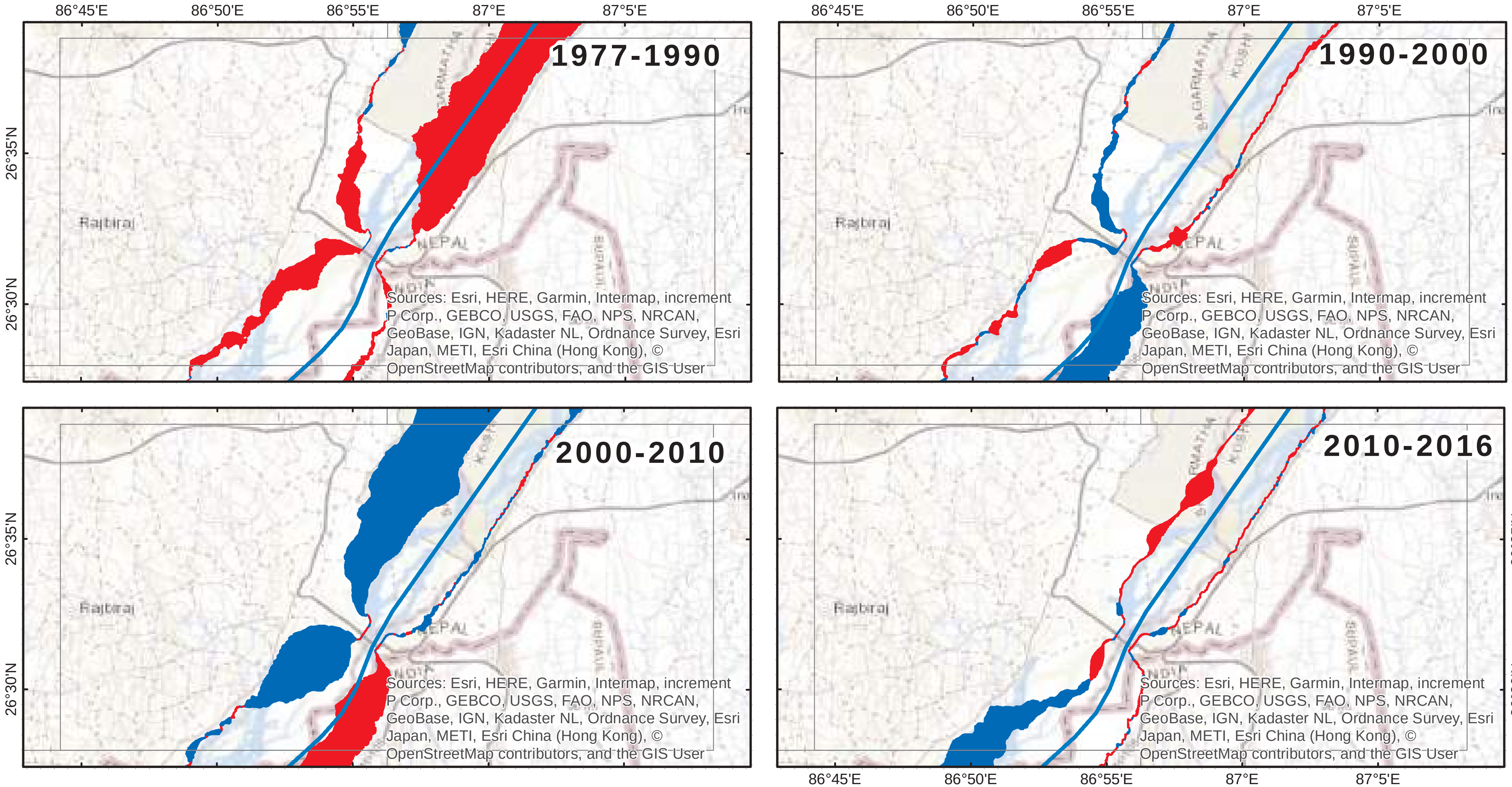
Morphology Project Team, IIT Delhi

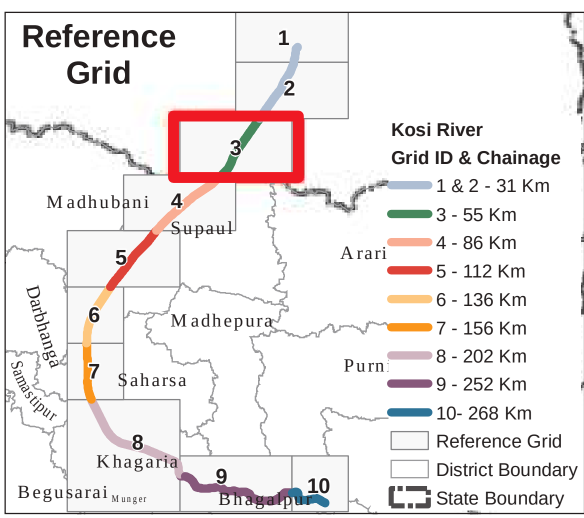
Legend

- Erosion
- Deposition
- Kosi River
- Grid

N

0 10 20 30 km





Channel Bank Retreat on Account of Erosion and Deposition for Grid No 3 (From Chainage 31 - 55 Km)

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

Legend

Erosion

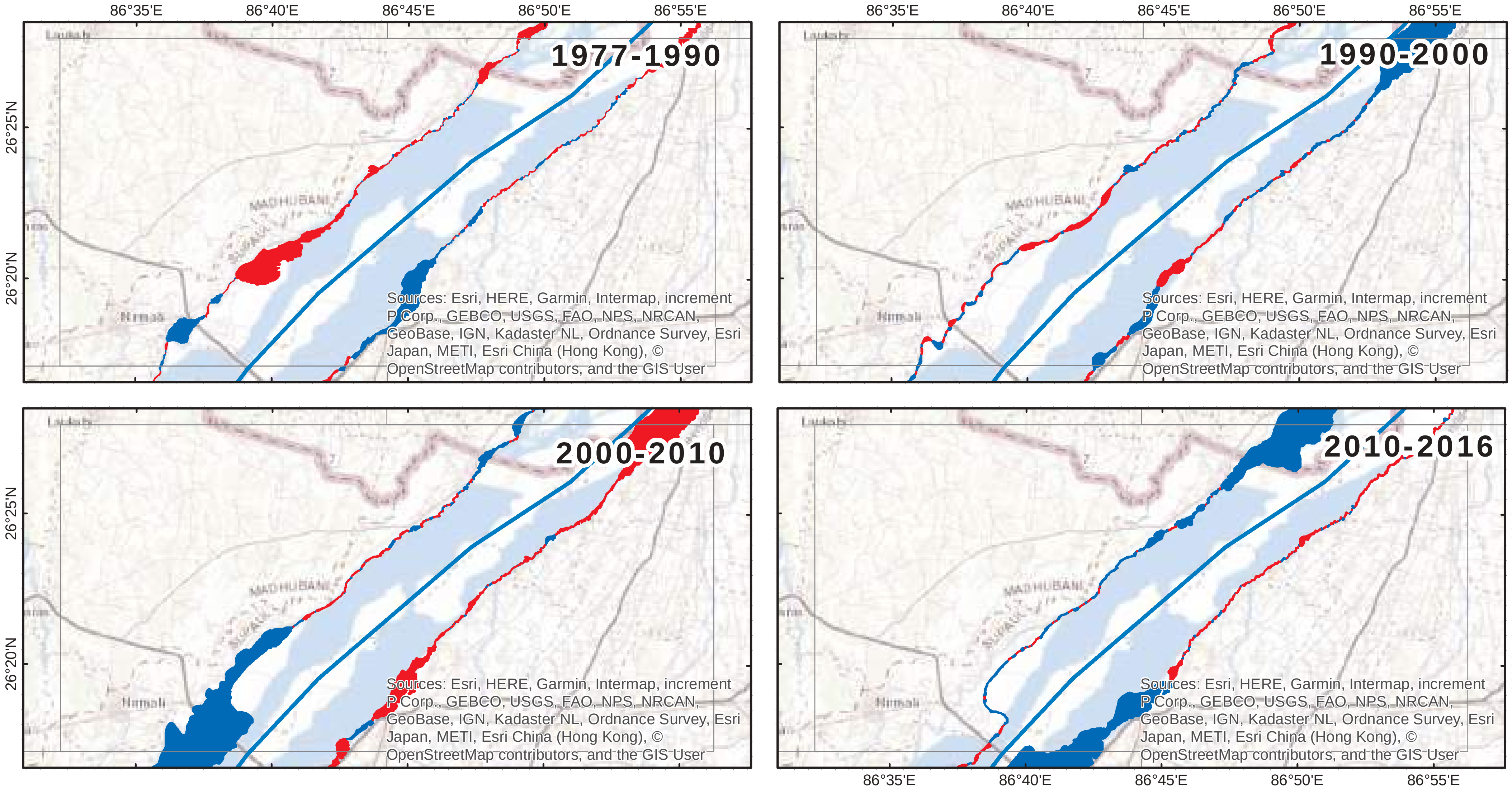
Deposition

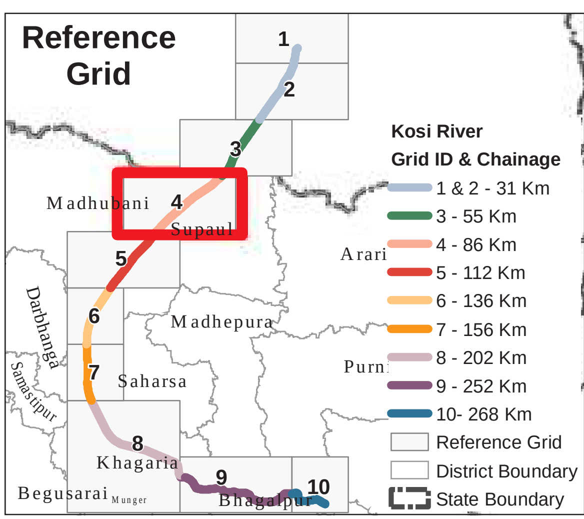
Kosi River

Reference Grid

N

0 5 10 15 20 25 km





Channel Bank Retreat on Account of Erosion and Deposition for Grid No 4 (From Chainage 55 - 86 Km)

Prepared For

Prepared By

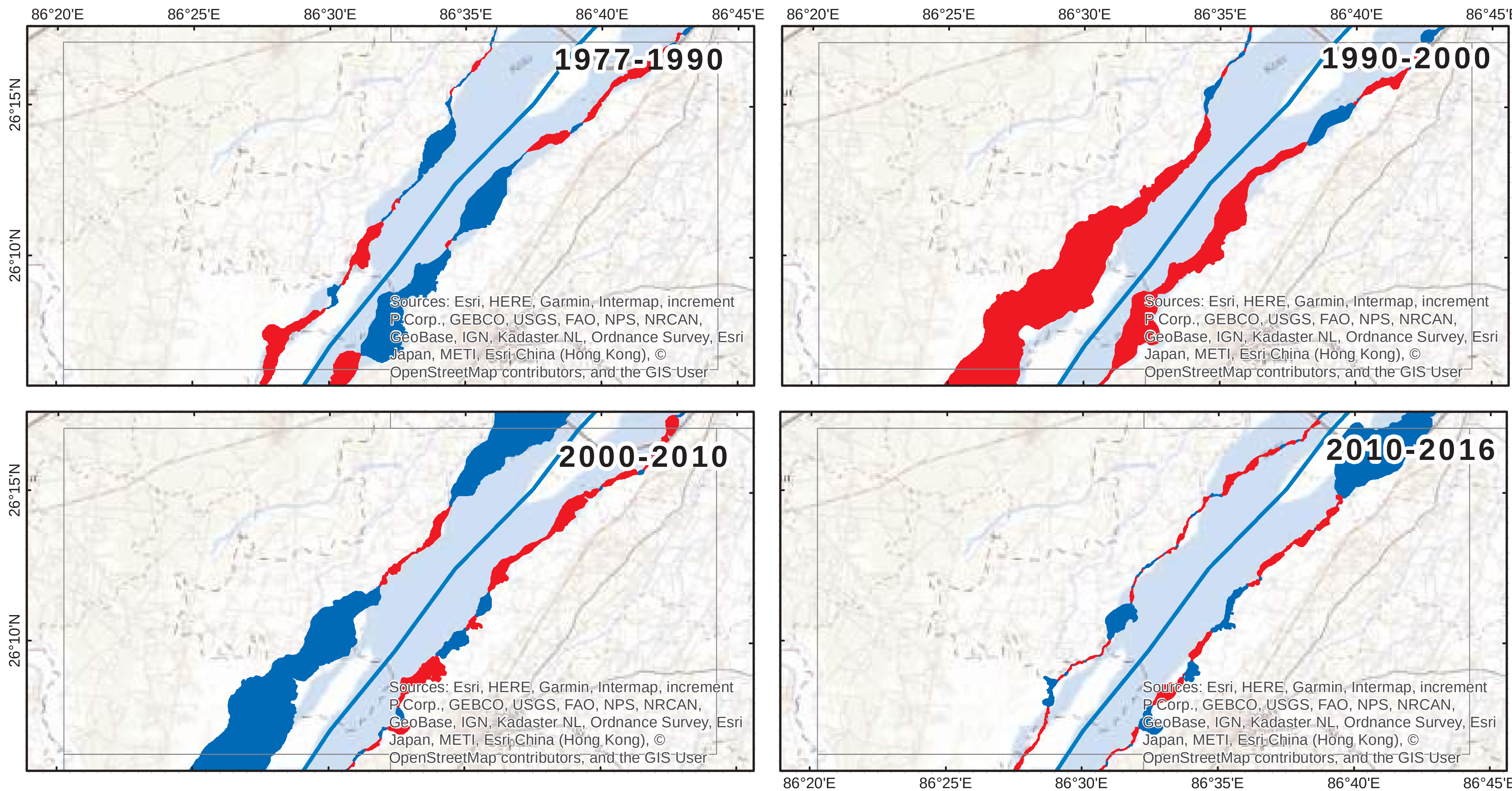
Morphology Project Team, IIT Delhi

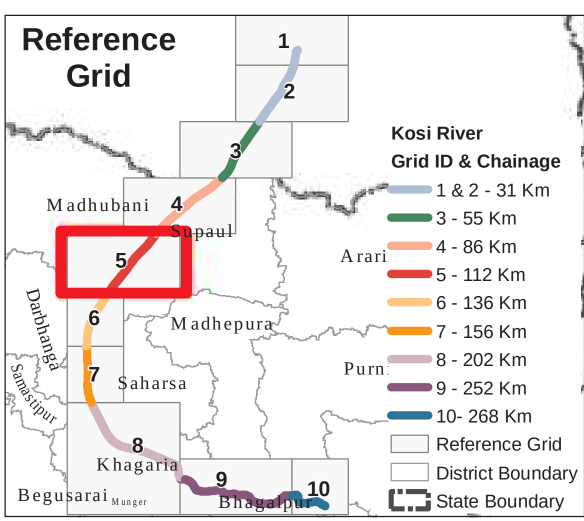
Legend

- Erosion
- Deposition
- Kosi River
- Reference Grid

N

0 5 10 15 20 25 km





Channel Bank Retreat on Account of Erosion and Deposition for Grid No 5 (From Chainage 86 - 112 Km)

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

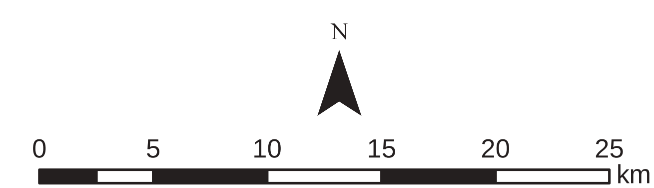
Legend

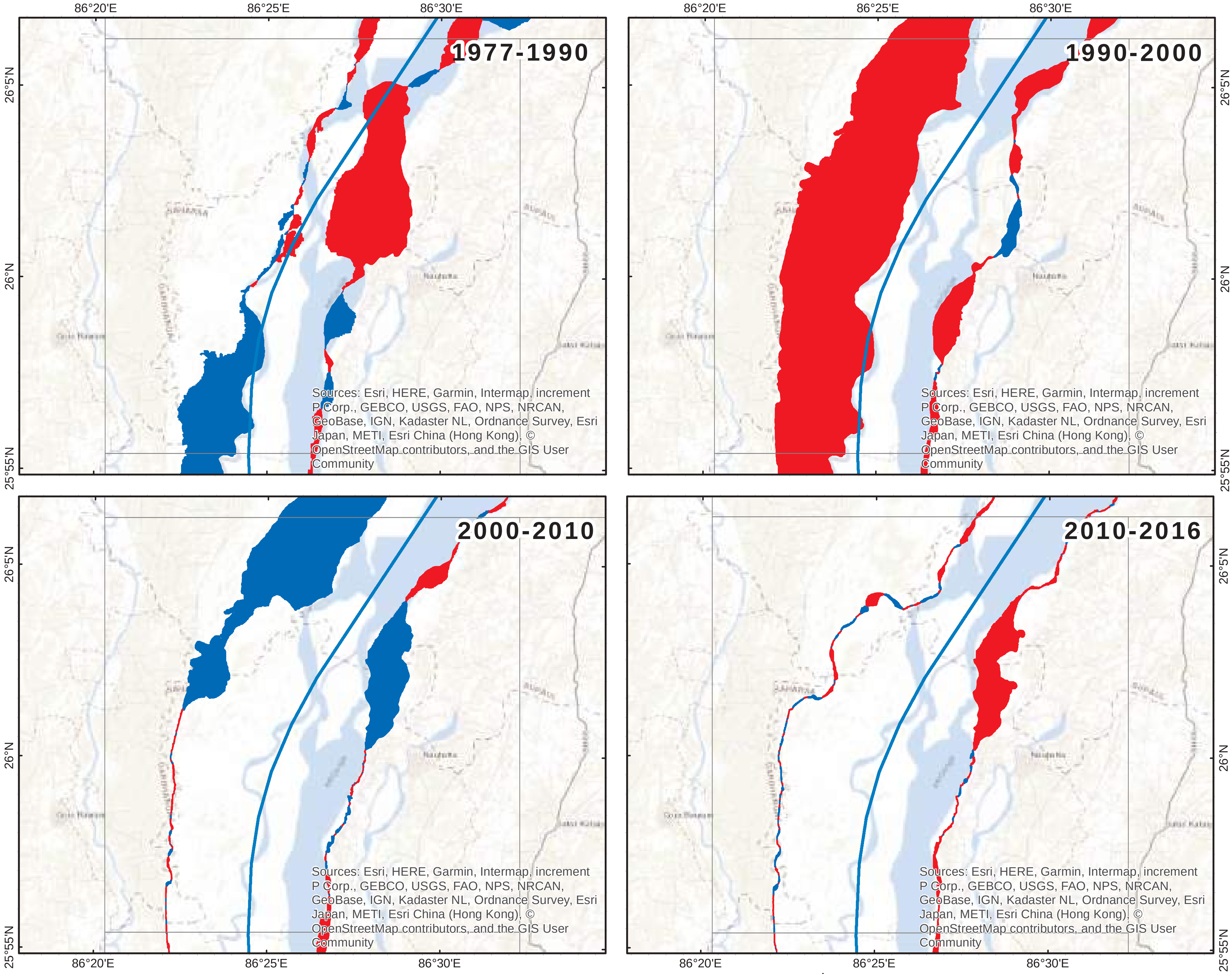
Erosion

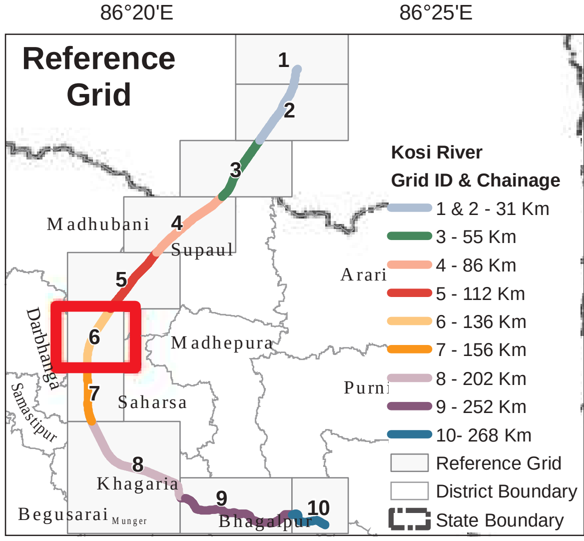
Deposition

Kosi River

Reference Grid







Channel Bank Retreat on Account of Erosion and Deposition for Grid No 6 (From Chainage 112 - 136 Km)

Prepared For

Prepared By

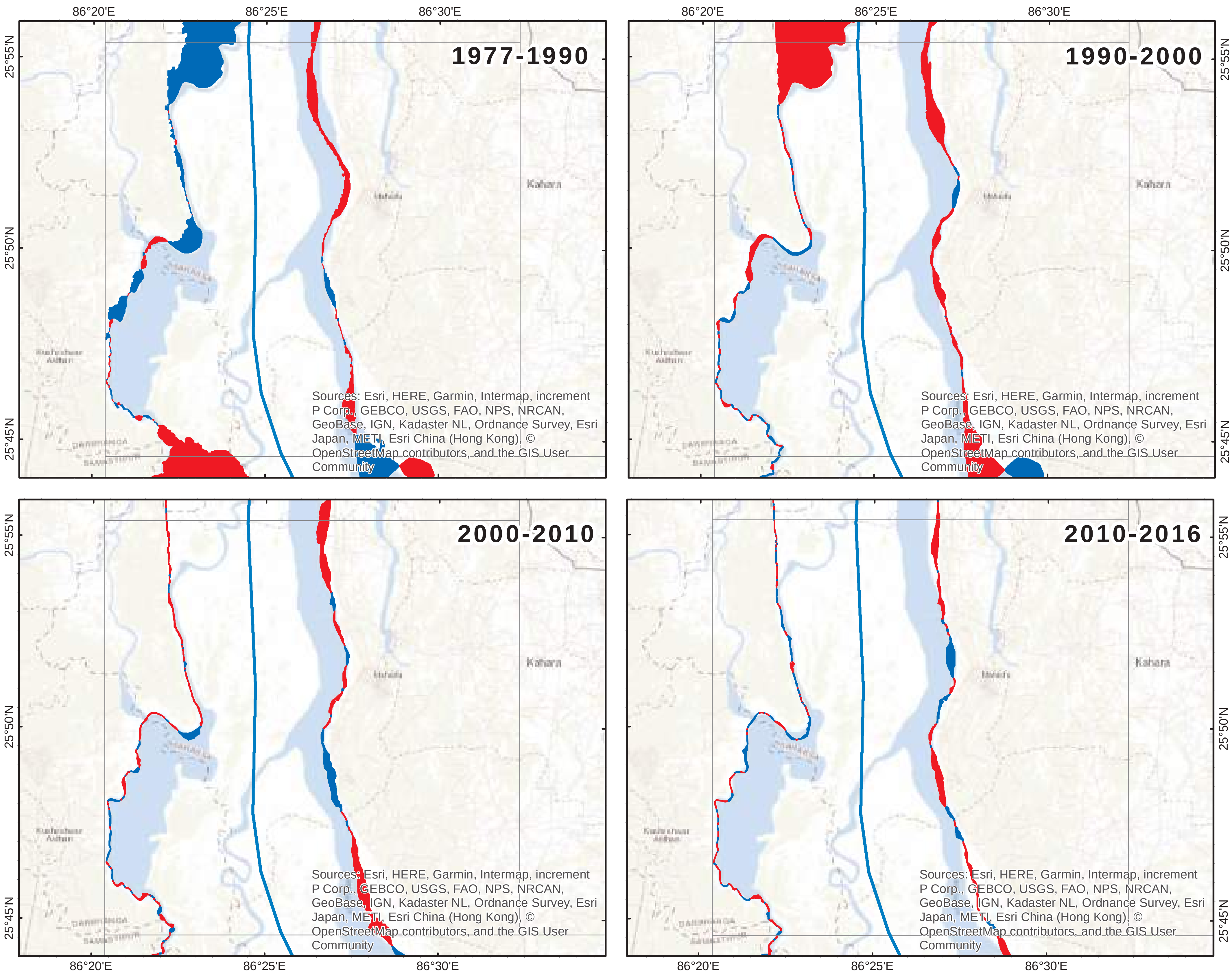
Morphology Project Team, IIT Delhi

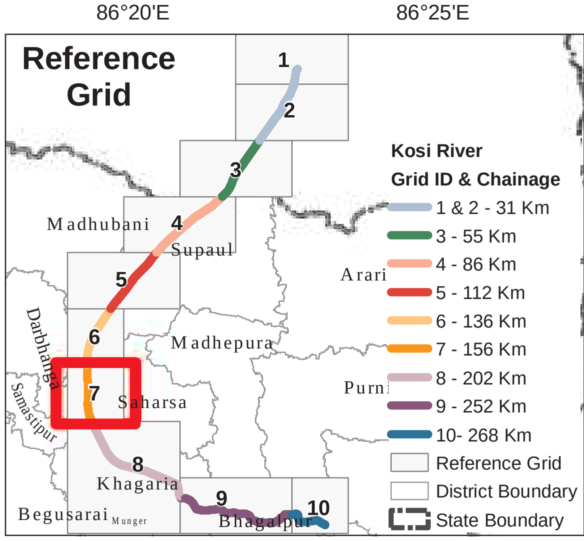
Legend

- Erosion
- Deposition
- Kosi River
- Reference Grid

N

0 5 10 15 km





Channel Bank Retreat on Account of Erosion and Deposition for Grid No 7 (From Chainage 136 - 156 Km)

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

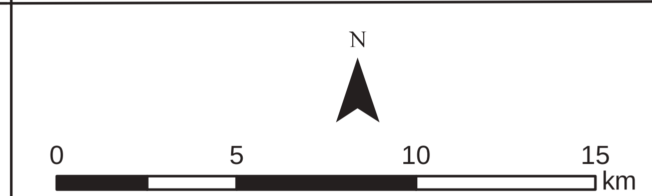
Legend

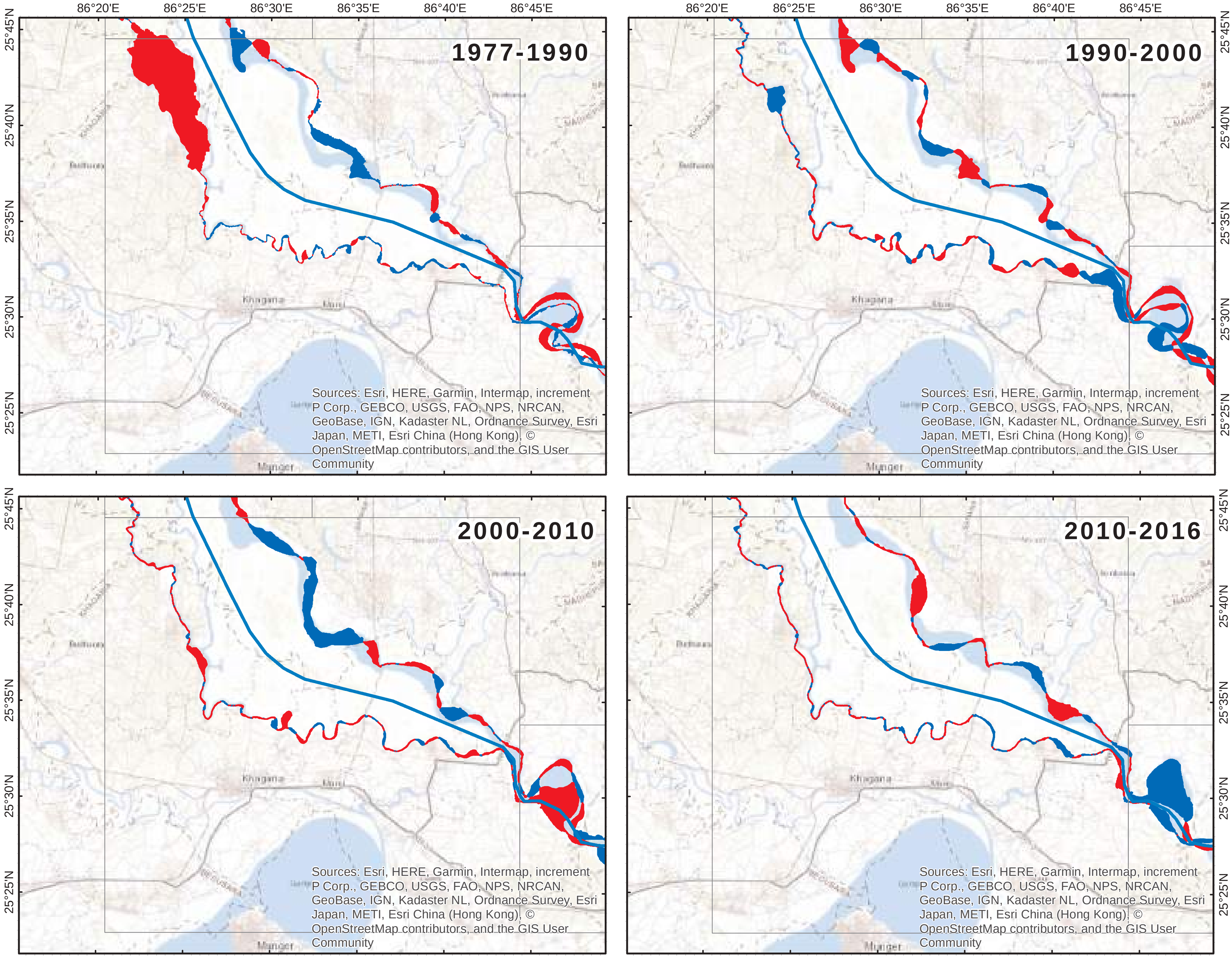
Erosion

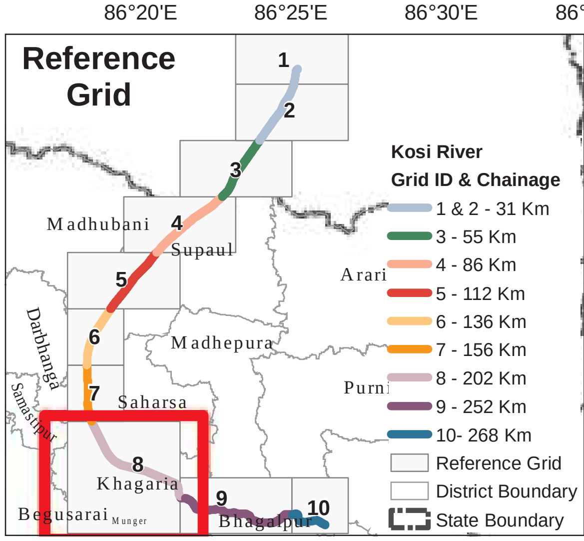
Deposition

Kosi River

Reference Grid







Channel Bank Retreat on Account of Erosion and Deposition for Grid No 8 (From Chainage 156 - 202 Km)

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

Legend

Erosion

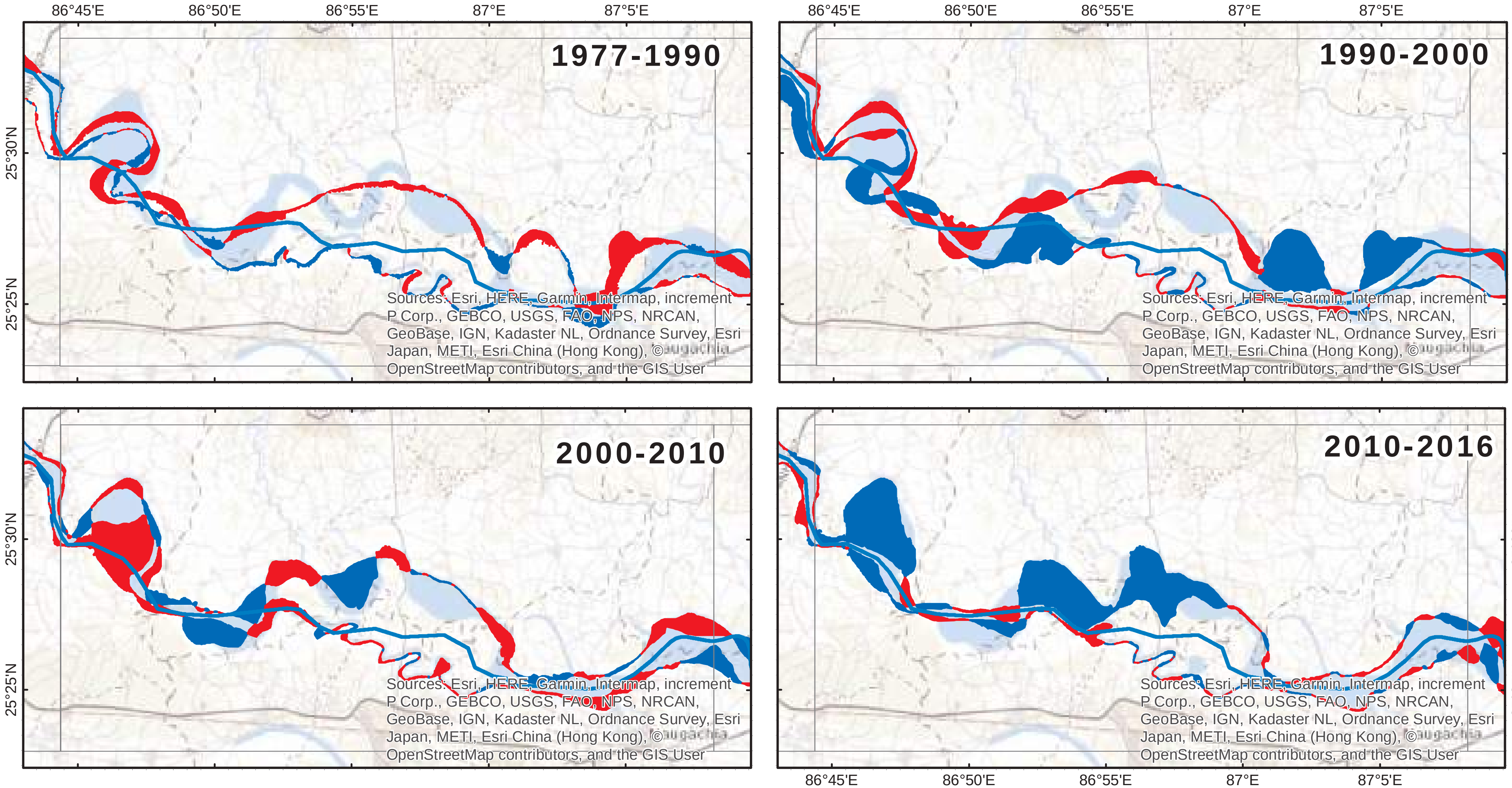
Deposition

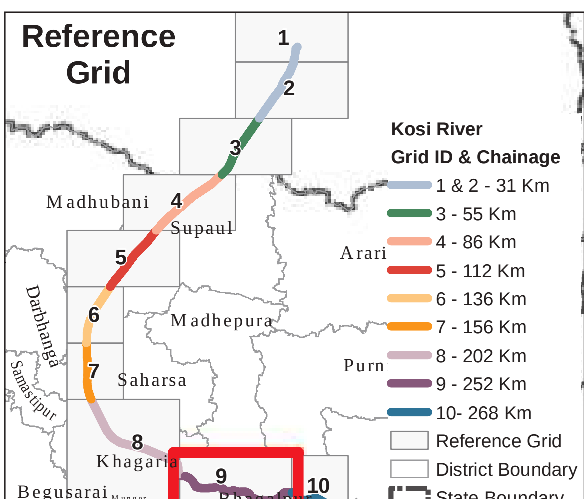
Kosi River

Reference Grid

N

0 10 20 30 km





Channel Bank Retreat on Account of Erosion and Deposition for Grid No 9 (From Chainage 202 - 252 Km)

Prepared For

Prepared By

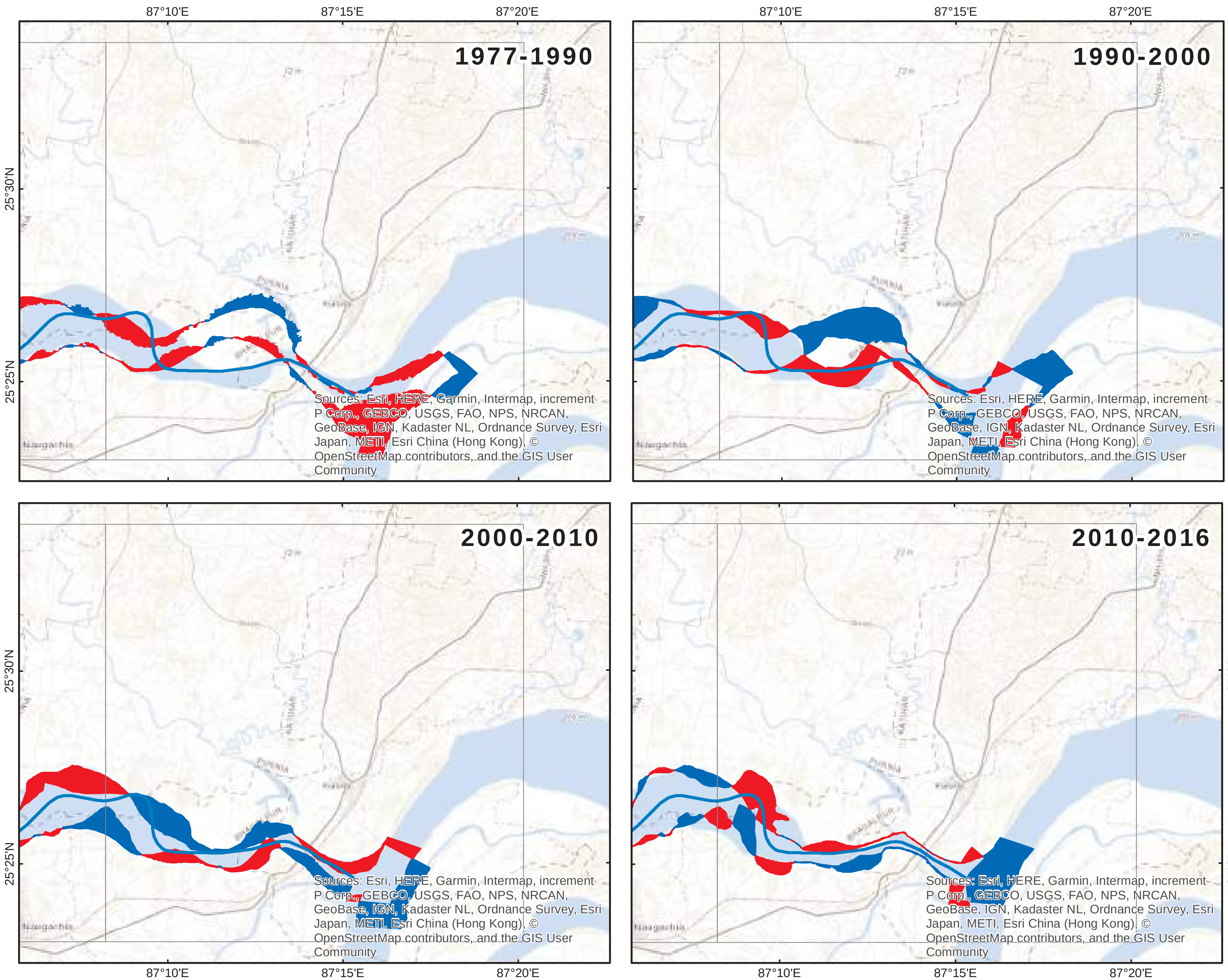
Morphology Project Team, IIT Delhi

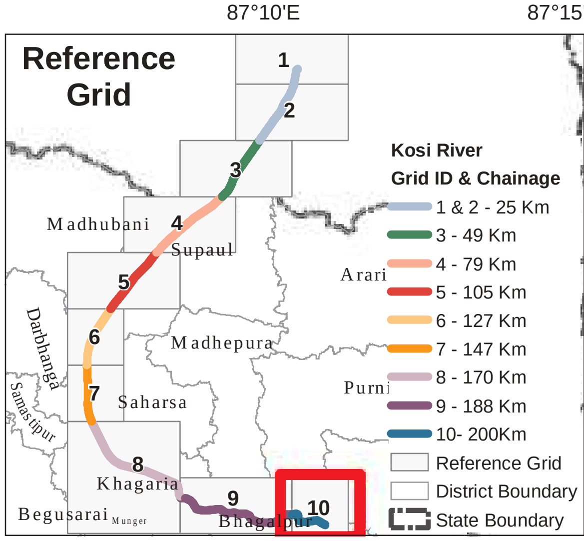
Legend

- Erosion
- Deposition
- Kosi River
- Reference Grid

N

0 5 10 15 20 25 km





Channel Bank Retreat on Account of Erosion and Deposition for Grid No 10 (From Chainage 188 - 200 Km)

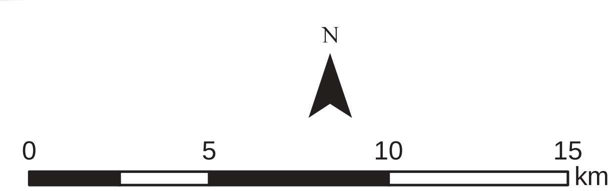
Prepared For

Prepared By

Morphology Project Team, IIT Delhi

Legend

- Erosion
- Deposition
- Kosi River
- Reference Grid



Kosi River Barrages and Embankment

Legend

Kosi Barrage

Embankments

Kosi RIver

Country Boundary

District Boundary

State Boundary

N W E S

Km

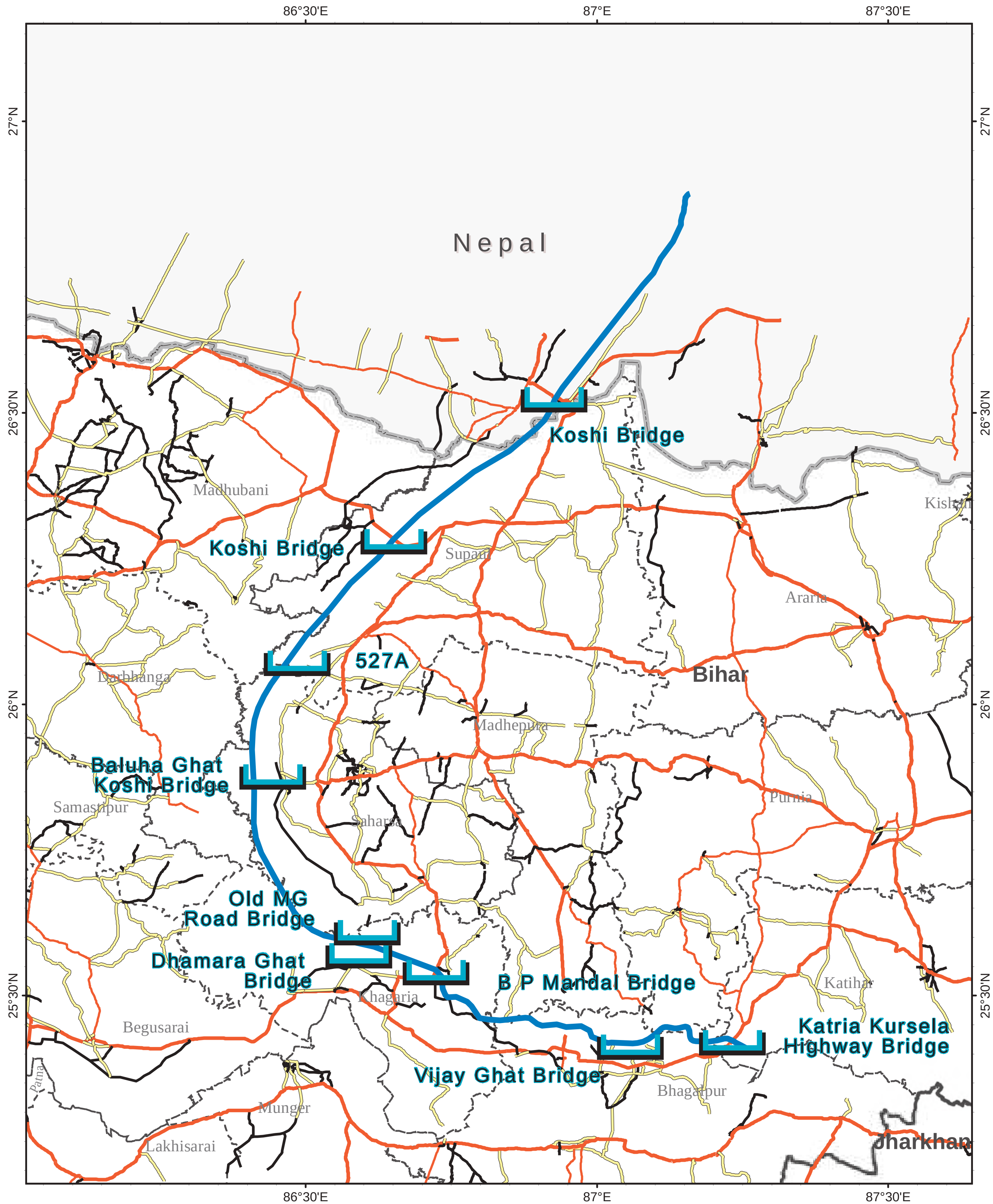
0 20 40 60 80

Prepared For

Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,000,000	DATE: March, 2023



Road Network Map for Kosi River

Legend

Bridge (9)

Kosi RIver

Road Type

National Highwways

Primary Roads

Secondary Roads

Tertiary Roads

Country Boundary

District Boundary

State Boundary

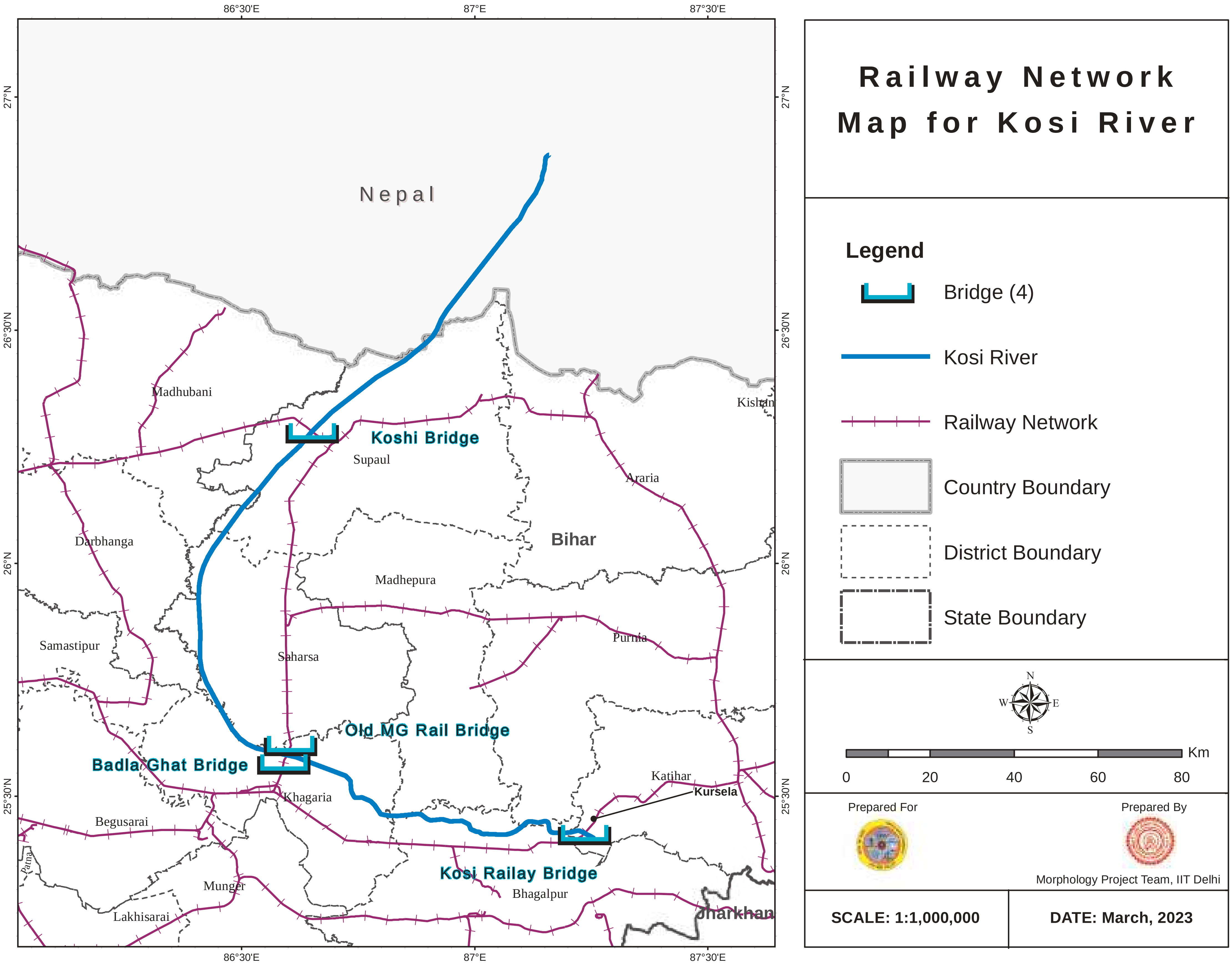
Km
0 20 40 60 80

Prepared For

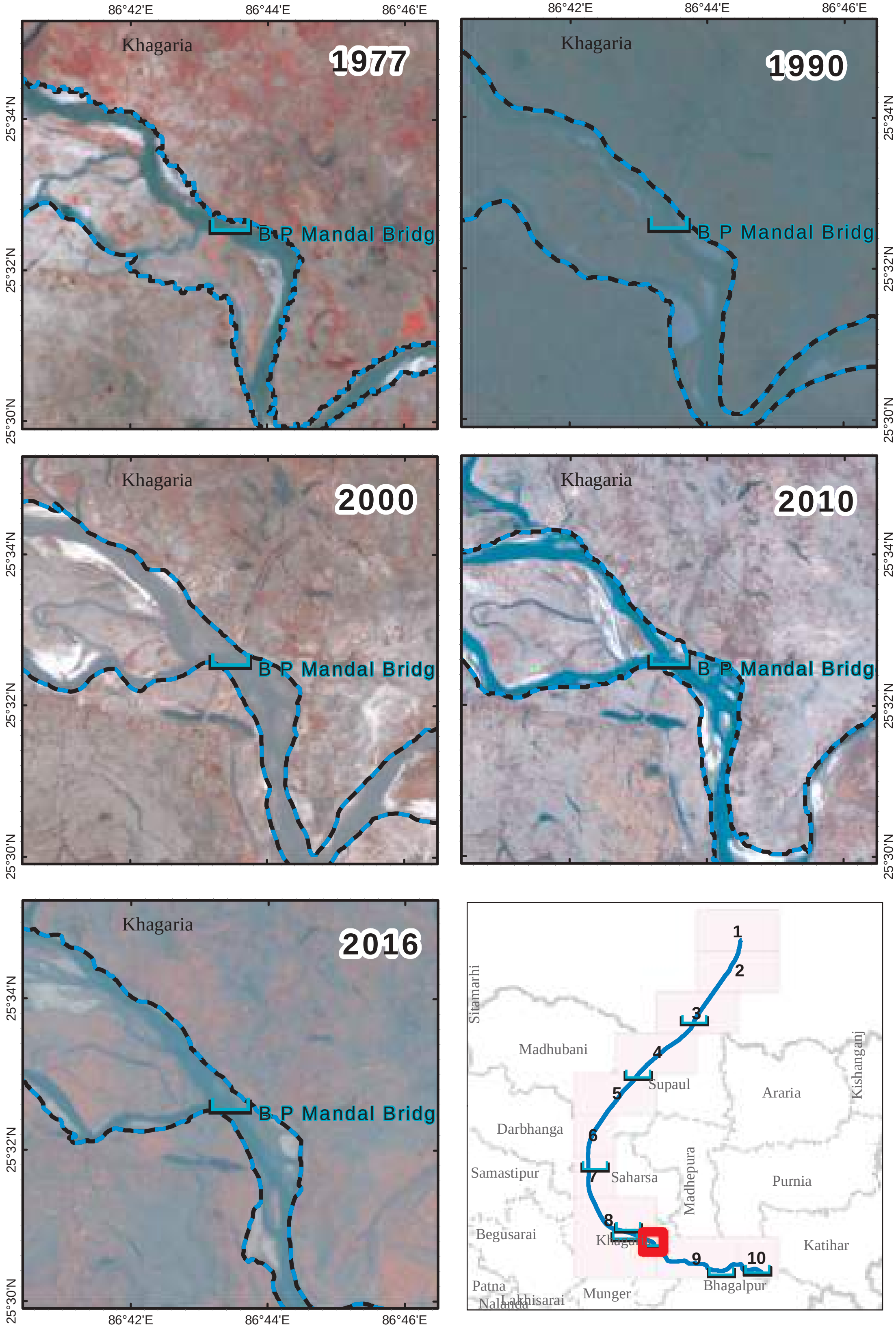
Prepared By

Morphology Project Team, IIT Delhi

SCALE: 1:1,000,000	**DATE: March, 2023**



Railway Network Map for Kosi River
86°30'E
87°E
87°30'E
27°N
26°30'N
26°N
25°30'N
Nepal
Madhubani
Koshi Bridge
Supaul
Araria
Kishan
Darbhanga
Bihar
Madhepura
Samastipur
Saharsa
Purnia
Old MG Rail Bridge
Badla Ghat Bridge
Khagaria
Katihar
Kursela
Begusarai
Kosi Railay Bridge
Patna
Munger
Bhagalpur
Lakhisarai
Jharkhan
Legend
Bridge (4)
Kosi River
Railway Network
Country Boundary
District Boundary
State Boundary
N
S
E
W
Km
0
20
40
60
80
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
SCALE: 1:1,000,000
DATE: March, 2023



Change in River Course Near

B P Mandal Bridge on Mahesh Khunt Saharsa Punia Road

Legend

Bridge

Kosi River (Channel Area)

District Boundary

State Boundary

N W E S

0 2 4 6 8 km

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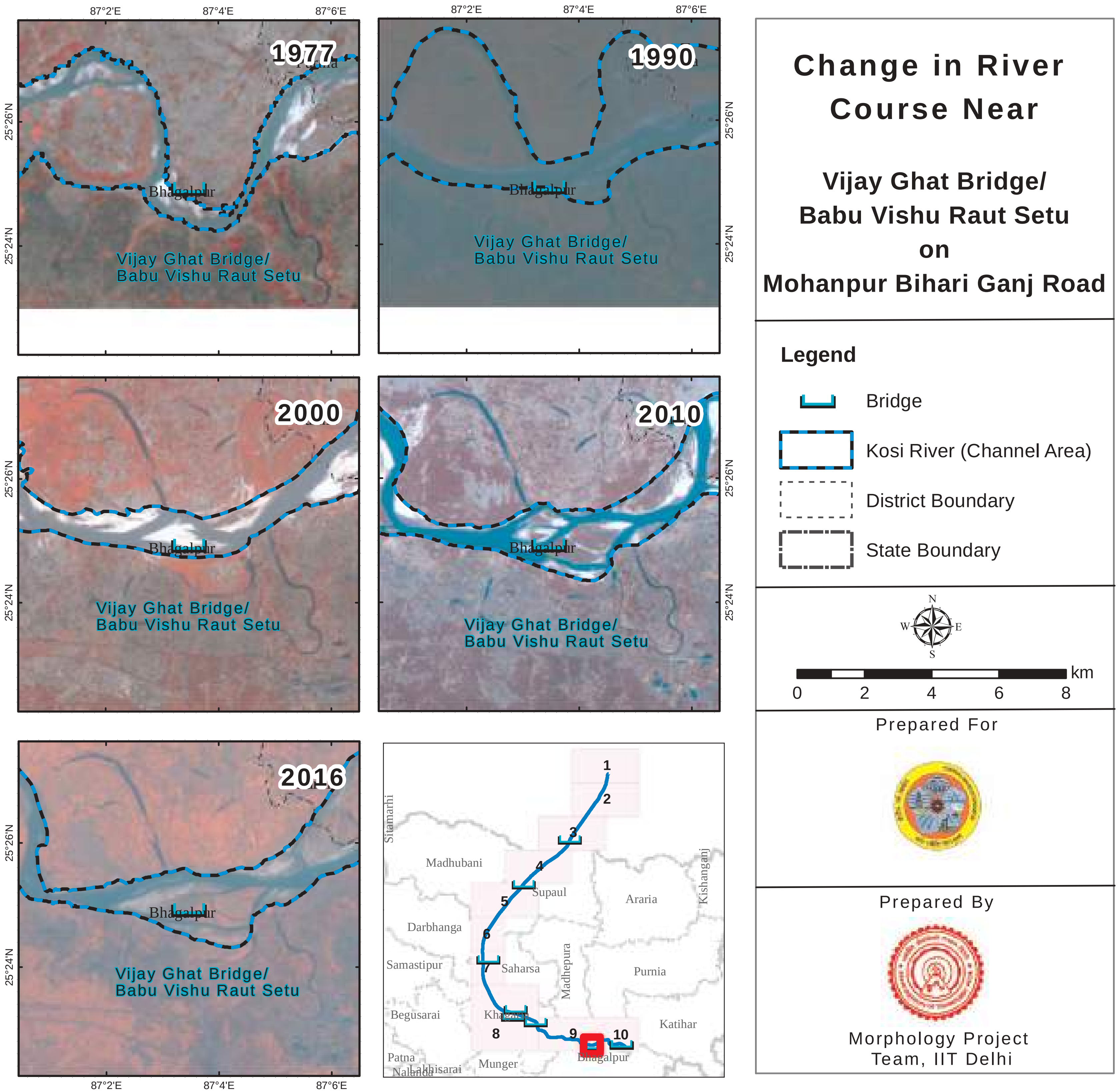
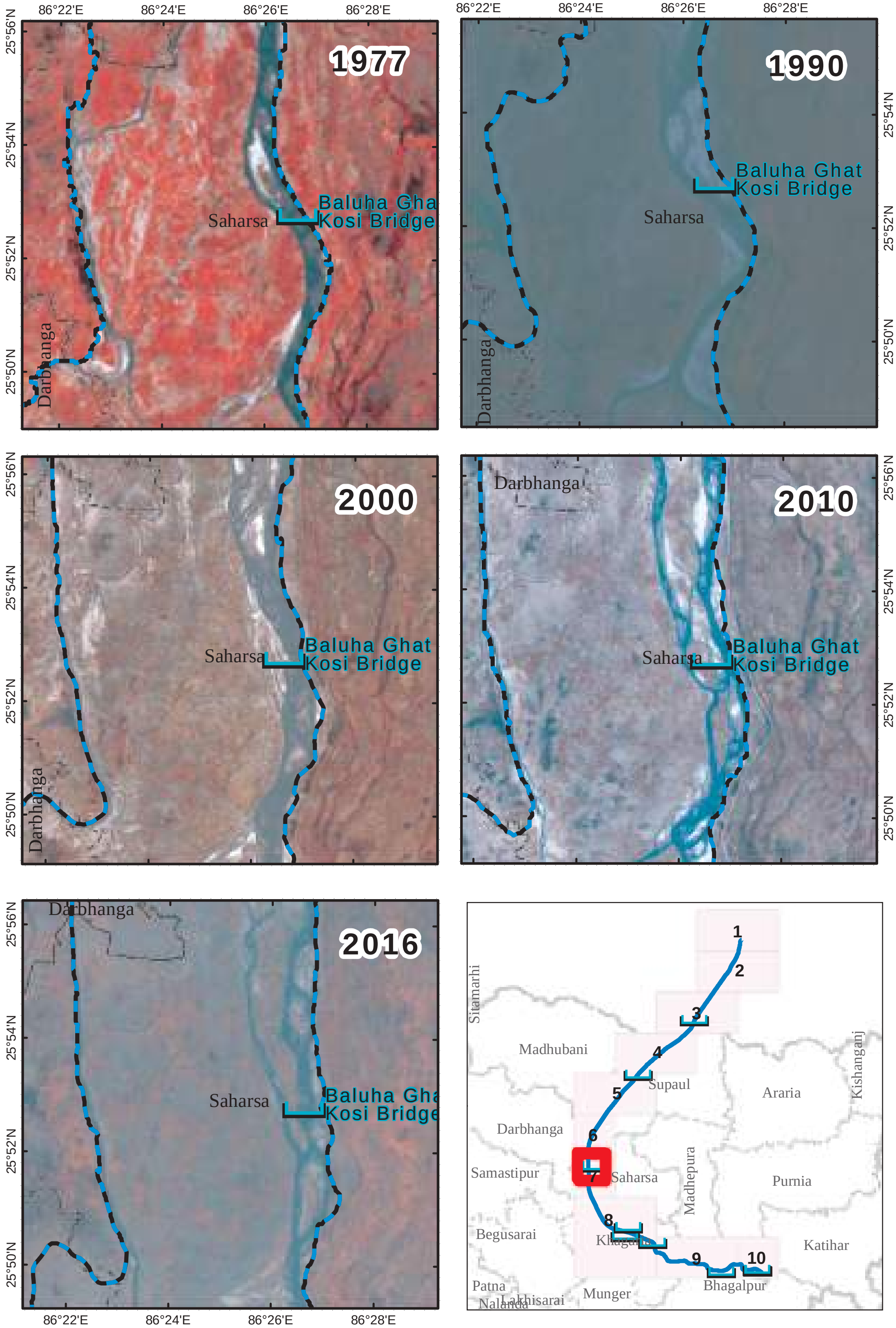
Morphology Project Team, IIT Delhi


Change in River Course Near
Vijay Ghat Bridge/ Babu Vishu Raut Setu on Mohanpur Bihari Ganj Road
1977
1990
2000
2010
2016
Bhagalpur
Vijay Ghat Bridge/ Babu Vishu Raut Setu
87°2'E
87°4'E
87°6'E
25°26'N
25°24'N
Legend
Bridge
Kosi River (Channel Area)
District Boundary
State Boundary
N
S
E
W
0 2 4 6 8 km
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Sitamarhi
Madhubani
Kishanganj
Supaul
Araria
Darbhanga
Samastipur
Saharsa
Madhepura
Purnia
Begusarai
Khagaria
Katihar
Patna
Lakhisarai
Nalanda
Munger
1
2
3
4
5
6
7
8
9
10



Change in River Course Near

Baluha Ghat Road Bridge on Nahuna Gandaul Hanti Road

Legend

- Bridge
- Kosi River (Channel Area)
- District Boundary
- State Boundary

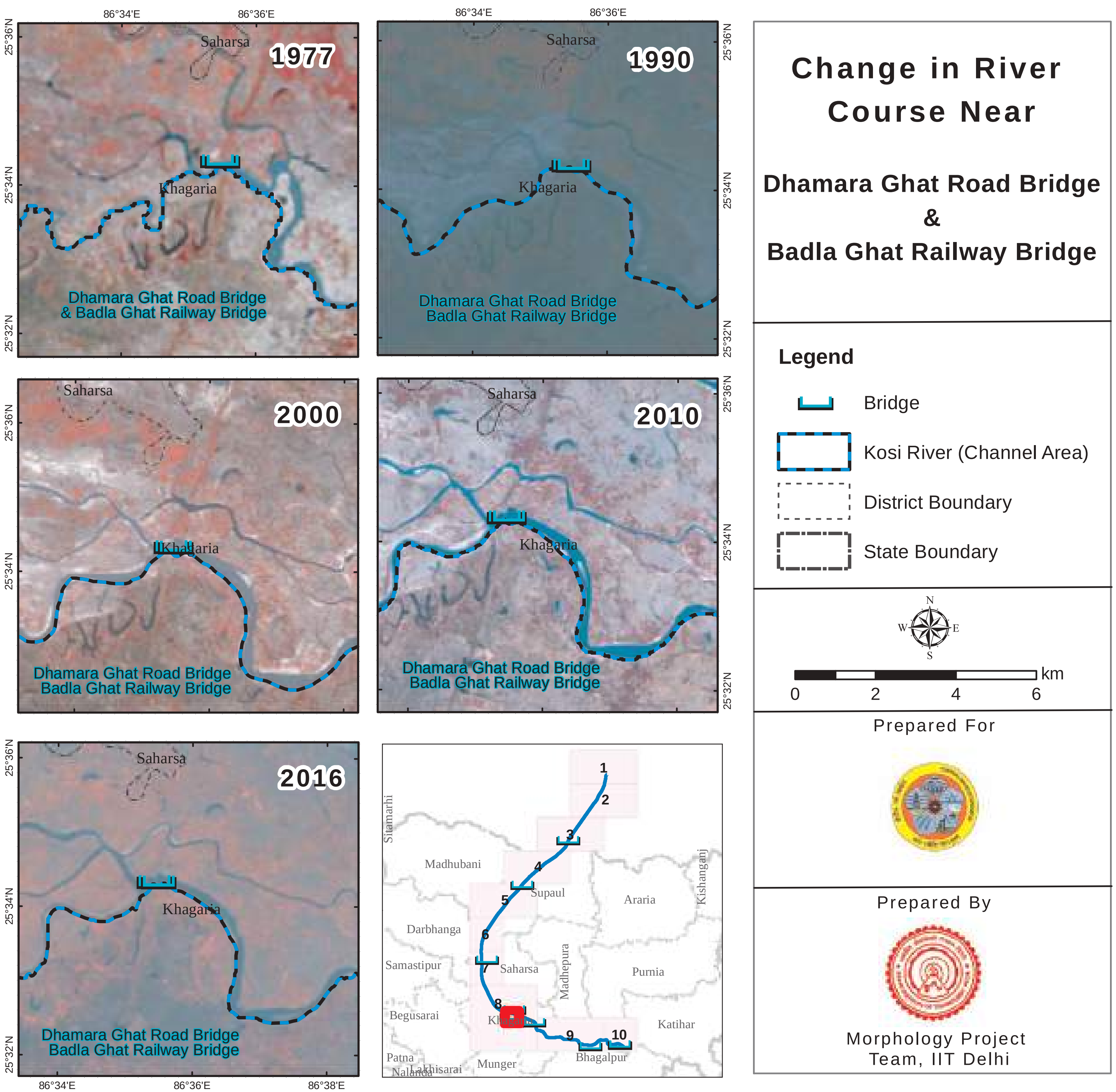
N W E S

0 2 4 6 km

Prepared For

Prepared By

Morphology Project Team, IIT Delhi



Change in River Course Near
Dhamara Ghat Road Bridge
&
Badla Ghat Railway Bridge
1977
1990
2000
2010
2016
Saharsa
Khagaria
Dhamara Ghat Road Bridge
& Badla Ghat Railway Bridge
Dhamara Ghat Road Bridge
Badla Ghat Railway Bridge
86°34'E
86°36'E
86°38'E
25°36'N
25°34'N
25°32'N
Legend
Bridge
Kosi River (Channel Area)
District Boundary
State Boundary
N
S
E
W
km
0
2
4
6
Sitamarhi
Madhubani
Supaul
Araria
Kishanganj
Darbhanga
Samastipur
Madhepura
Purnia
Begusarai
Katihar
Bhagalpur
Patna
Nalanda
Lakhisarai
Munger
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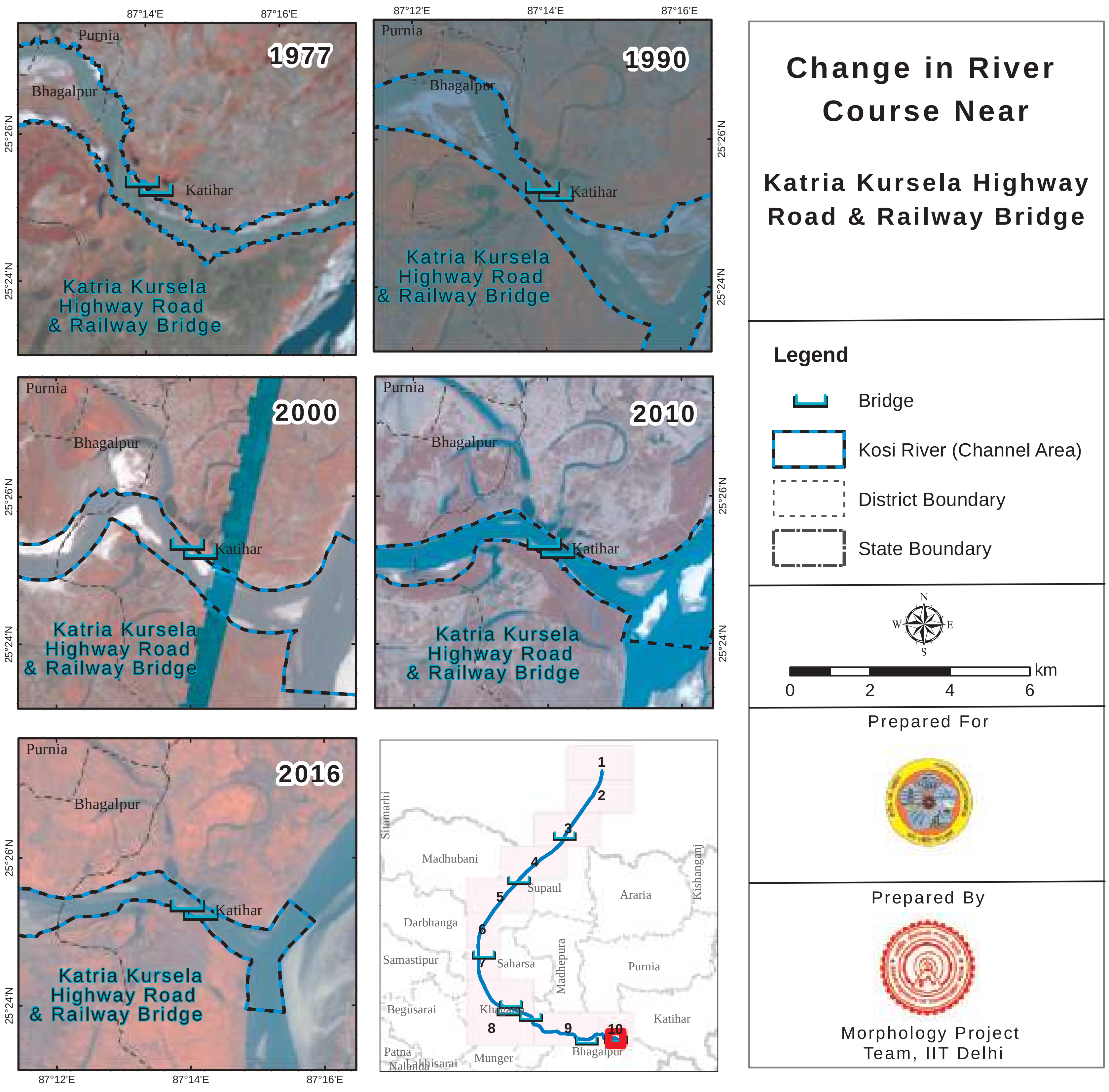
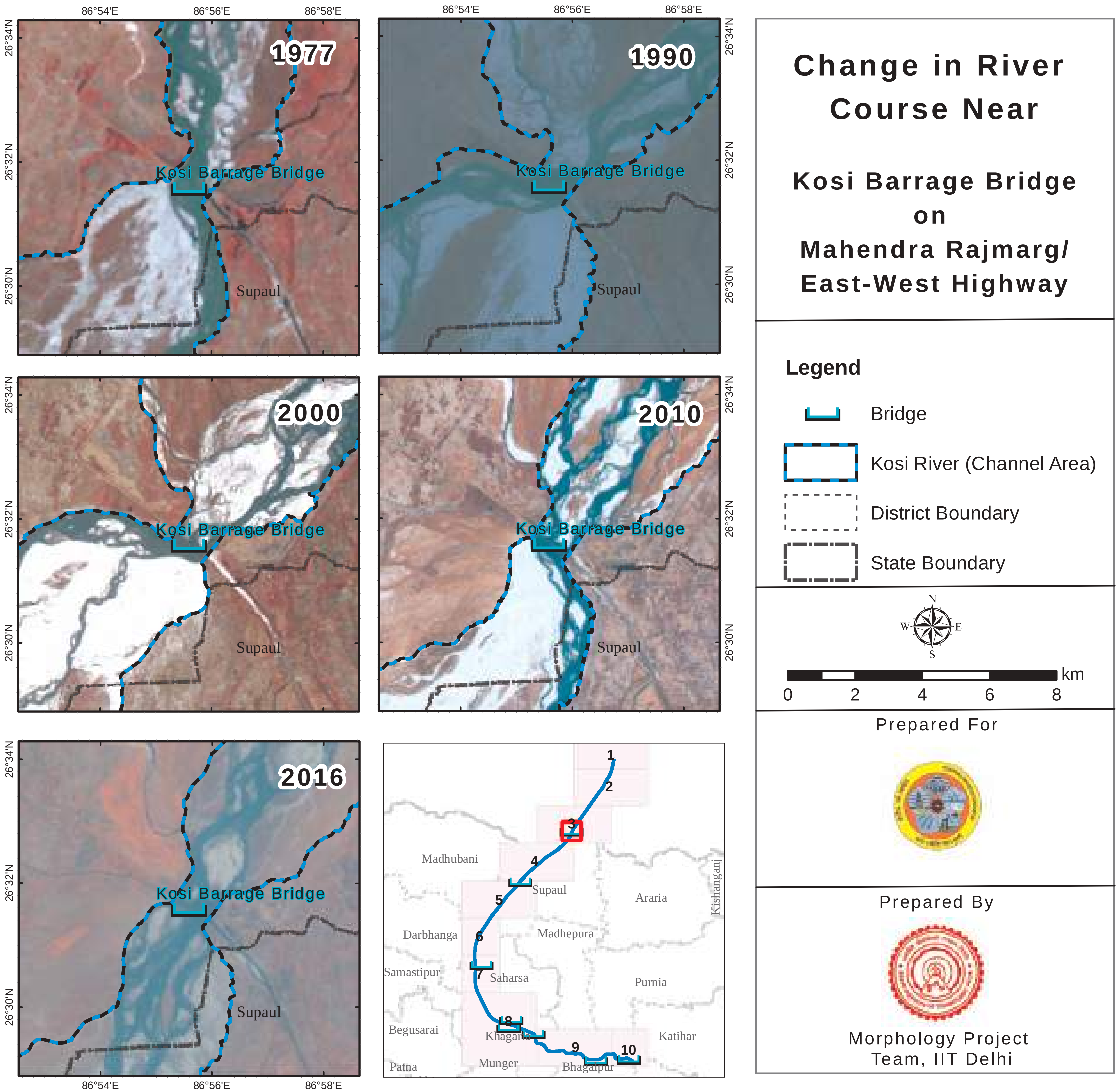
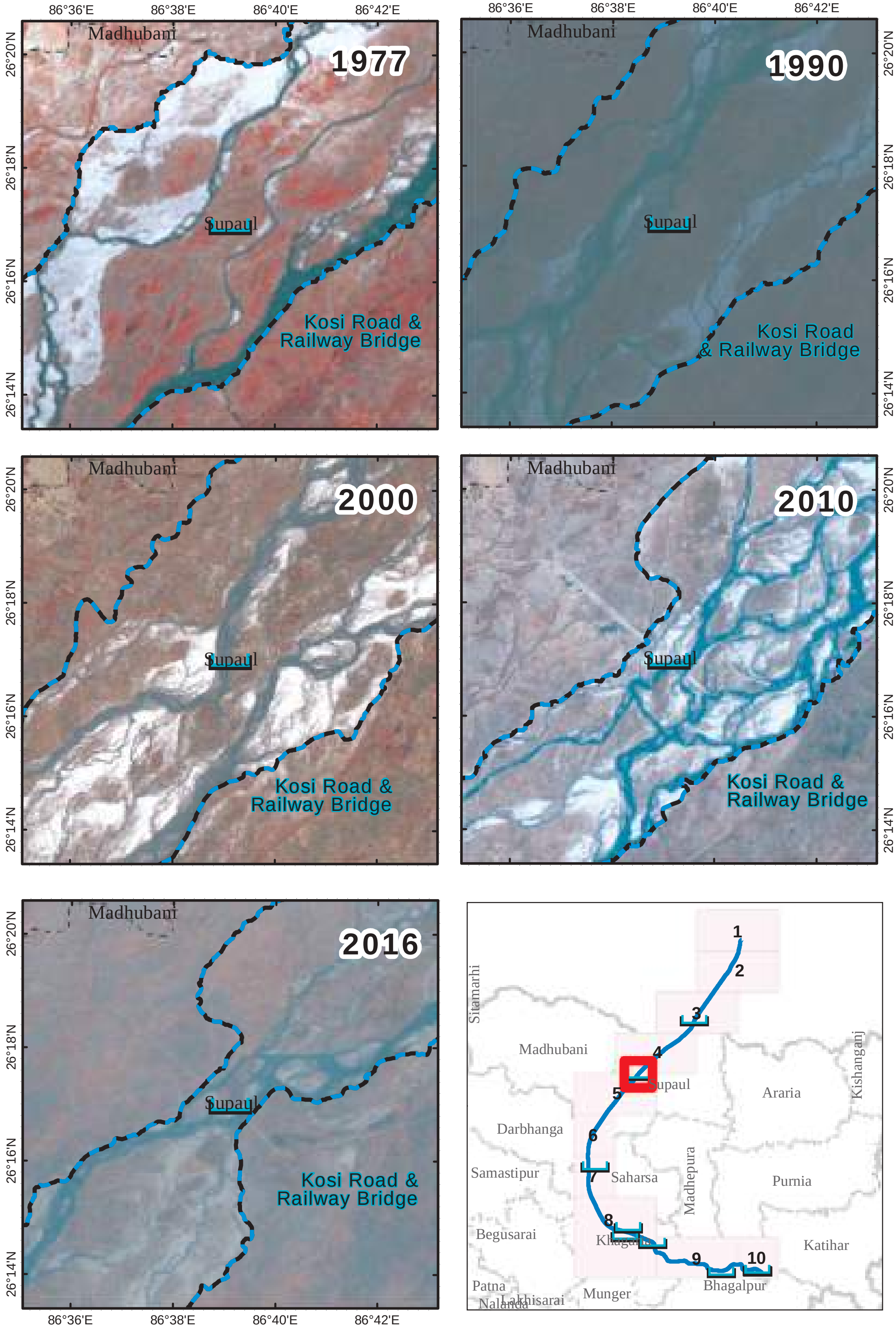


Change in River Course Near
Katria Kursela Highway Road & Railway Bridge
1977
1990
2000
2010
2016
Purnia
Bhagalpur
Katihar
Katria Kursela Highway Road & Railway Bridge
87°12'E
87°14'E
87°16'E
25°24'N
25°26'N
Legend
Bridge
Kosi River (Channel Area)
District Boundary
State Boundary
N
S
E
W
km
0
2
4
6
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
Sitamarhi
Madhubani
Supaul
Araria
Kishanganj
Darbhanga
Samastipur
Saharsa
Madhepura
Purnia
Begusarai
Khagaria
Katihar
Patna
Nalanda
Lakhisarai
Munger
Bhagalpur
1
2
3
4
5
6
7
8
9
10



Change in River Course Near
Kosi Barrage Bridge on Mahendra Rajmarg/ East-West Highway
Legend
Bridge
Kosi River (Channel Area)
District Boundary
State Boundary
N
S
E
W
km
0
2
4
6
8
Prepared For
Prepared By
Morphology Project Team, IIT Delhi
1977
1990
2000
2010
2016
Kosi Barrage Bridge
Supaul
86°54'E
86°56'E
86°58'E
26°34'N
26°32'N
26°30'N
Madhubani
Supaul
Araria
Kishanganj
Darbhanga
Madhepura
Samastipur
Saharsa
Purnia
Begusarai
Khagaria
Katihar
Patna
Munger
Bhagalpur
1
2
3
4
5
6
7
8
9
10



Change in River Course Near

Kosi Bridge (Maha Setu) on East-West Corridor Road and Railway Bridge

Legend

- Bridge
- Kosi River (Channel Area)
- District Boundary
- State Boundary

N
W E
S

0 2 4 6 8 10 km

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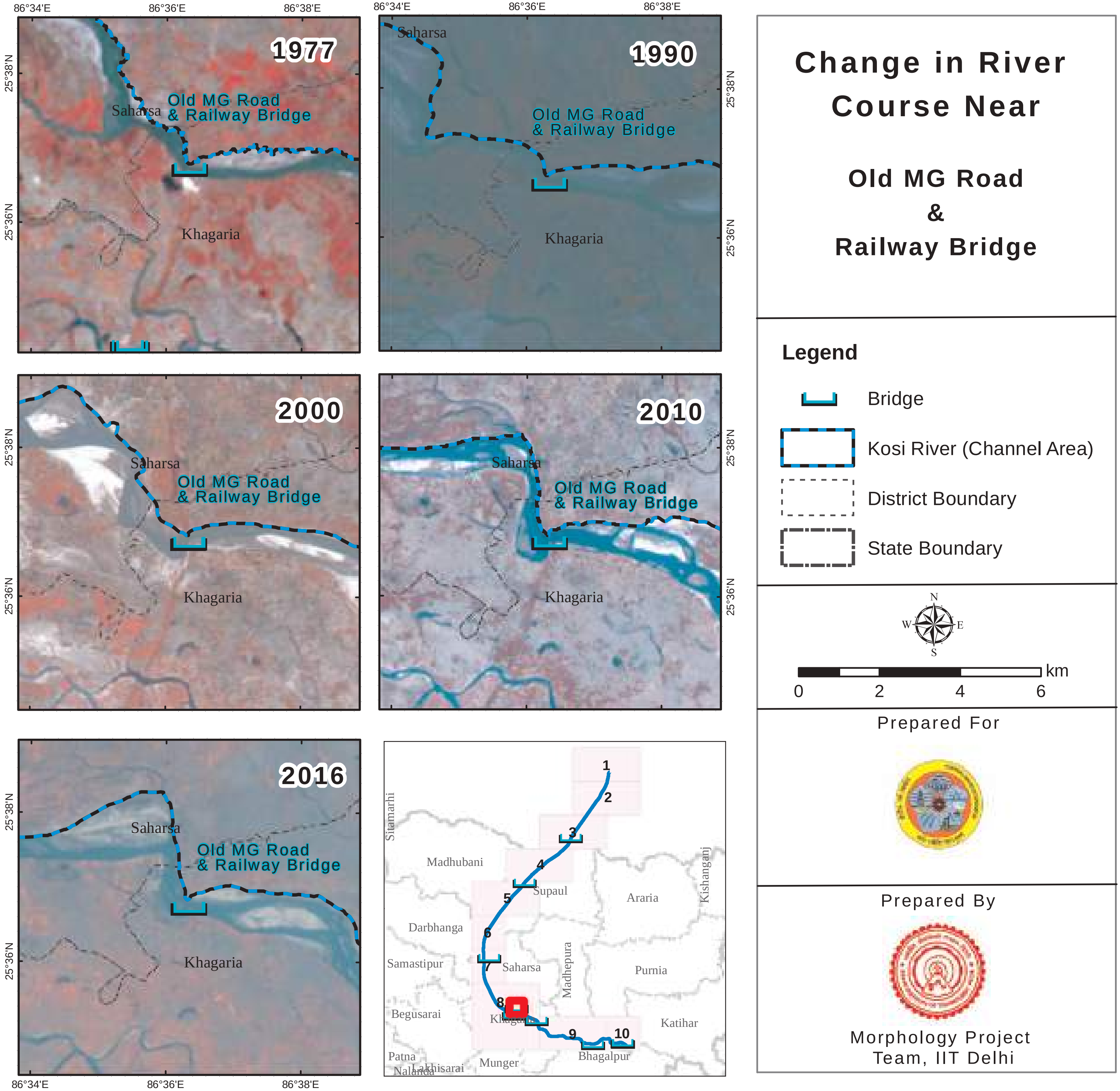
Change in River Course Near
Old MG Road
&
Railway Bridge
1977
1990
2000
2010
2016
Saharsa
Khagaria
Old MG Road
& Railway Bridge
86°34'E
86°36'E
86°38'E
25°38'N
25°36'N
Legend
Bridge
Kosi River (Channel Area)
District Boundary
State Boundary
N
S
E
W
km
0
2
4
6
Sitamarhi
Madhubani
Supaul
Araria
Kishanganj
Darbhanga
Samastipur
Saharsa
Madhepura
Purnia
Begusarai
Katihar
Bhagalpur
Munger
Patna
Nalanda
Lakhisarai
1
2
3
4
5
6
7
8
9
10
Prepared For
Prepared By
Morphology Project
Team, IIT Delhi