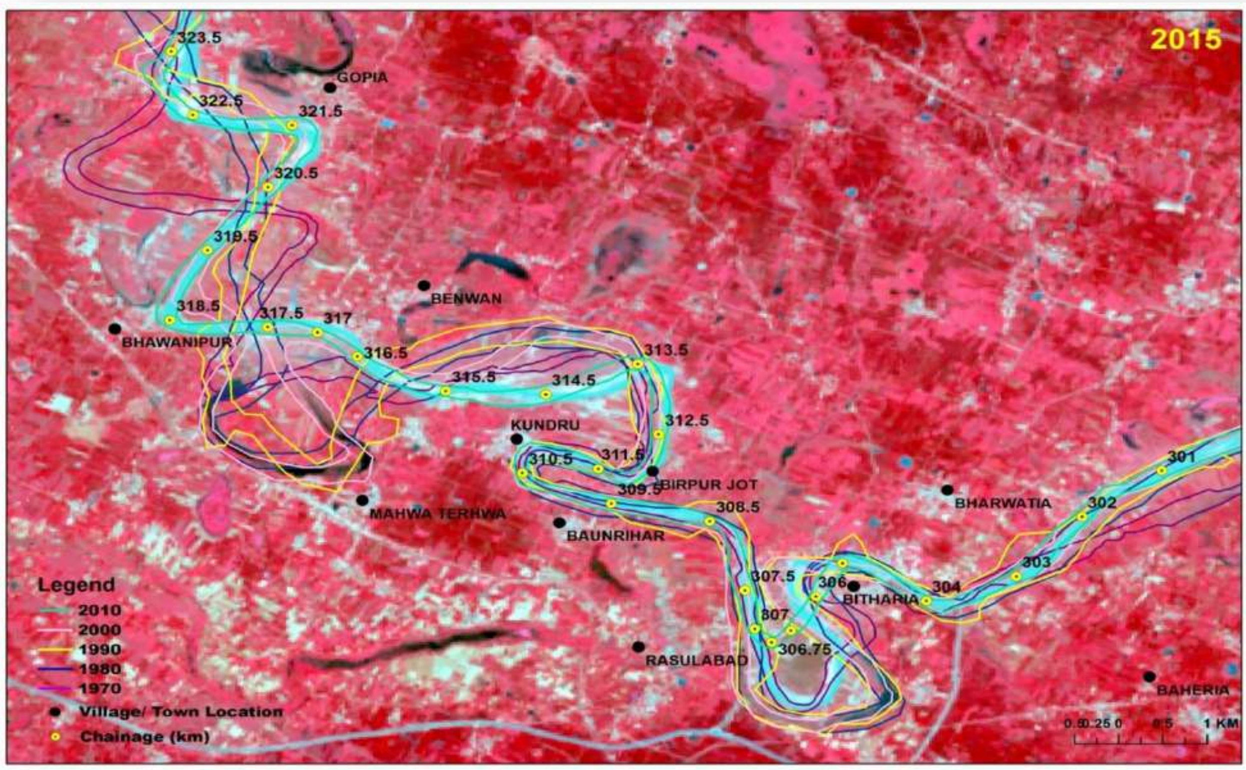
FINAL REPORT

MORPHOLOGICAL STUDY OF RAPTI RIVER USING REMOTE SENSING TECHNIQUES



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Executive Summary

1. River morphology deals with the plan form, cross-section and its dimension, bed forms, aggradation, degradation etc. Such morphology changes due to river hydrodynamics. Indian rivers experience large seasonal fluctuations in discharge and sediment load resulting in significant changes in their morphology. Shifting of the river course is generally accomplished by erosion of habitated and pricey agricultural area that causes tremendous losses. The sediments deposited and eroded in the river have a tremendous effect on the river cross-section and its gradient, sediment transport rate, discharge etc. Understanding of changes in the morphology of the rivers is required in the engineering projects for their planning, design and execution. With this in mind, CWC, New Delhi desires to carry out morphological study of the major Indian rivers. In this direction, CWC awarded a project entitled "Morphological study of rivers Ganga, Sharda and Rapti using remote sensing techniques" to IIT Roorkee.

2. Following were broad objectives of the study

(i) Compilation of river drainage map in GIS; changes in Land use/Land cover, flood affected areas, rainfall-runoff, geology etc.

(ii) Hydrological analysis: Probability curve and flow rates corresponding to return period of 1.5 year and 2 year.

(iii) Decadal stream banks shifting and also changes in its Plan form (Sinuosity & Plan-form Index) from the base year 1970 to 2010.

(iv) Work out erosion and siltation based on the banks shifting.

(v) Evaluate the impacts of major hydraulic structures on the river morphology.

(vi) Identification of critical and other vulnerable reaches and to suggest suitable river training/protection works.

(vii) Reconnaissance survey for ground validation of outcomes of the study.

(viii) Recommendations in the respect of actionable points.

(ix) Suggestions for the further study.

3. Rapti river is the major tributary of Ghaghara river. The Rapti river basin is diverse in its physiography. The lofty mountain, inner and outer Tarai and undulating plain regions constitute the topography of the entire basin. The reach of the Rapti river studied in this project work is from Nepalganj to confluence point of Rapti and Ghaghra. Rapti river covers an area of 25,793 km^2 out of which 44% (11,401 km^2) lies in Nepal and 56% (14,392 km^2) in Uttar Pradesh. Rapti River flows through the districts of Rukum, Salyan, Rolpa, Gurmi, Arghakhanchi, Dang and Banke of Nepal territory;

and Bahraich, Shrawasti, Balrampur, Siddharthnagar, Santkabinagar, Gorakhpur and Deoria districts of the Eastern Uttar Pradesh. Important tributaries of Rapti river in the study reach are Bhakia, Gaura, Kacna, Kunhara, Sunawan. Various aspects of the Rapti river related to topography, soil, climate, geology, meteorological stations, land use land cover, flood map etc. are compiled in this report from the different sources, like GSI, WRIS, NRSC.

4. Hydrological data of Rapti river that comprises of annual maximum and minimum discharges and water levels; ten daily average discharge, sediment, and gauge at different gauging stations, were obtained from CWC, offices, while relevant satellite images were procured from the National Remote Sensing Centre (NRSC), Hyderabad and downloaded from United States Geological Survey (USGS) website. SOI toposheets were obtained from SOI, Dehradun.

5.

6. Planform of the rivers may be described as straight, meandering or braided. There is, in fact, a great range of channel patterns from straight through meandering to braided. Straight and meandering channels are described by sinuosity which is the ratio of channel length to valley length.

7. The computed sinuosity ratio of the Rapti river in the reach under consideration is higher than 1.5 in the years 1970, 1980, 1990, 2000, and 2010, therefore, the Rapti is classified as meandering river. Almost whole reach of the river has meandering pattern, however, it is prominent in the reaches 25-50 km, 75-100 km, 300-375 km, 400-425 km and 450-475 km. The meandering is characterized by acute bend with high amplitude, however, they are relatively stable.

8. The plan form index (PFI) of Rapti River is calculated using the formula given by Sharma (2004). It has been observed that the Rapti River always flows in one channel, so negligible braiding is found in Rapti River.

9. For the computation of shifting of course of the river, center line of the river as in year 2010 is perpendicularly bisected at a regular interval of 1.0 km and shift of left bank, right bank and center line in either directions has been computed for the years 1970, 1980, 1990 and 2000 with respect to year 2010 in GIS software. Remarkable shifting of the course of the Rapti river from 1970 to 2010 has been noticed. The maximum shift is of the order of 2.7 km at some locations. The confluence point of Rapti and Gaghara rivers has shifted 500 m towards left in year 2010 w.r.t. year 1970.

10. Major shifting of the river course in span of year 1970 to 2010 are in the reaches 75 -100 km, 300-375 km, 400-485 km and 500-542 km. At Devpura, Jamuha, Keshwapur, Nandnagar and Chitahari, shifting is from left to right while at Gujarpurwa, Ikauna, Jyonar and Kanchalpur, the shifting is from right to left. No progressive shifting of the course of the river with respect to time has been noticed.

11. Width of the active channel of the river and river width based on the extreme banks have been estimated using the satellite images of years 1970-2010. There is no definite progressive change in the width of the river over the span of year 1970-2010 in the whole studied reach of the Rapti river. From chainage zero to 450 km, the average width of the active channel is almost constant and is equal to about 206 m, however, in the upper reach i.e., Chainage 450 km to 542 km, the average width is about 290 m - which may be attributed to silting in upper reaches and spreading of flow as the river descends from hilly areas.

12. Erosion and siltation studies have been carried out for the Rapti river from Nepalganj to confluence point of Rapti and Ghaghra using SOI toposheets and post-monsoon decadal satellite images from years 1970 to 2010. The extreme left and right banks have been identified based on the sand deposit and vegetation and based on the shifting of these banks, the erosion and deposition are estimated for duration from year 1970 to 2010 and is expressed in the terms of area in km^2.

13. The total eroded, silted, eroded plus silted, and net eroded area in the Rapti river during the period 1970 to 2010 are 79.04 km^2, 57.24 km^2, 107.35 km^2 and 21.80 km^2, respectively. It may be concluded that over a span of 40 years i.e, 1970 to 2010, about 21.80 km^2 area of Rapti River has been eroded by the flowing water.

14. Erosion has been noticed in the entire reach of Rapti River starting from Nepalgunj to its confluence with Ghaghra River. Major erosion has occurred during the period 1970 to 2010 in the upper reaches (chainage 450-542 km) due to constant shifting of river course. At other locations, like Gorakhpur, Balrampur, Utraula, and Domrianganj, the erosion is not so severe. Minor deposition has taken place in the reaches 25 km - 50 km, 150 km - 175 km and 425 km - 450 km that are near Ekauna, Bhaksa and Ikauna, respectively.

15. Provision of embankments and other river training works in the Rapti river has controlled the shifting of the river. There are natural water bodies in the form of ox-bow lakes in vicinity of river due to its meandering nature.

16. Available measured cross sections of the Rapti river for different years at gauging stations of Balrampur, Rigauli and Birdghat have been analysed.

No remarkable changes in the historical cross-sections of the Rapti river at Rigauli and Birdghat are noticed, however, river course has shifted towards left side by about 40 m at Balrampur which has resulted in both erosion and siltation at this location. Cross-section of the Rapti river is shallow at Balrampur, however it is deep at Rigauli and Birdghat.

17. There is one barrage, named as Rapti barrage, in the reach of the river from Nepalgunj to Patana Ghat (confluence point of Rapti and Ghaghra Rivers). The river course has wandering behavior upstream of the barrage. However, no shifting has been observed downstream of the barrage over the years. The Rapti barrage was commissioned in year 2008. Since then no noticeable silting upstream of the barrage has been observed. Nevertheless, river in year 2015 was flowing in two channels upstream of the barrage.

18. There are about 22 bridges on the Rapti river from Nepalgunj to its confluence with Ghaghra river at Patana ghat. Morphological changes have noticed near the major bridges, however, proper river training works have been provided which are working satisfactorily. Protection works are suggested in the vicinity of the bridges at Chainages 160 km, 205 km, 212 km, 251.5 km, 272.5 km and 418 km to train the Rapti river.

19. Nine reaches of the Rapti river have been identified as critical. These reaches are at Chainages 68-80 km (Chhithari), 138-156 km (Mirpur), 304-322.5 km (Rasulabad), 326.5- 378 km (Utraula), 387-392 km (Shankarnagar), 399-433 km (Jyonar), 438-466 km (Ikauna), 470-492 km (Lakshmannagar) and 506-515 km (Jamnaha). In these reaches, river has wandering behaviour in wide width. No progressive shifting in either directions has been noticed over the years.

20. Methodology for the design of various river training works has been discussed and based on the morphological changes of the river, it is suggested to provide embankment/ levees/spurs in critical reaches of the river.

a)	Chainages 2-12.5 km	Embankment on right side
b)	Chainages 75-77 km	Series of spurs on left side
c)	Chainages 304-322.5 km	Embankments on both sides
d)	Chaianges 326.5-378 km	Embankments on both sides

21. In the identified critical reaches, wherever river is striking to the existing embankments, porcupine/ boulder revetment/geo tubes shall be provided to avoid breach in the embankment.

22. Embankments are provided towards both sides of the river in its most of the length, in particular in the lower reaches. In some reaches, embankments

are not continuous and that are to be plugged by construction of new embankment as suggested in this study.

23. Design methodology of conventional river training works and also flexible system are described in the report that can be used for the design of a particular work. A sample design of embankment/levees using flexible system is also mentioned in the report.

24. Field reconnaissance survey was conducted at various locations, like Rapti Barrage, Bansi Bridge, Birdghat, Patana ghat etc., to assess the present condition of the river. The observations made during the site visits have been examined in the perspective of the outcomes of the morphological study carried out in this study.

Recommendations:

(i) It is recommended to implement the suggested measures in the identified four critical reaches of the Rapti and in the vicinity of the identified bridges. It is further suggested that such reaches/locations be studied in more details based on ground survey and analysis of high resolution satellite data.

(ii) Suggested measures are prioritized as follow:

a) Extension of the existing left guide bund of about 90 m downstream at Kodri ghat (Chainage = 418 km, Fig.9.10)
b) Provision of series of spurs towards left side at Dhani (Chainage = 205 km, Fig. 9.6)
c) Boulder revetment/porcupine/series of spurs on right bank over a length of 700 m upstream of the bridge at Peepeganj (Chainage = 160 km, Fig. 9.5)
d) Provision of protection to the left embankment upstream of the bridge (SH5) in the form of boulder revetment/short spurs at Rajendra Nagar (Chainage = 251.5 km, Fig. 9.8)
e) Provision of boulder revetment to the existing both sides embankments at Dhani (Chainage = 212 km)
f) Provision of boulder revetment to both the approach roads at Tighra (Chainage = 272.5 km)
g) Provision of series of spurs on left side in the reach at Chainages 75-77 km
h) Provision of embankment on right side in the reach at Chainages 2-12.5 km
i) Provision of embankment on both sides in the reach at Chainages 304-322.5 km
j) Provision of embankment on both sides in the reach at Chainages 326.5-378 km

(iii) It is recommended to plan hydraulic structures, like barrage, bridge etc. at the identified nodal points (wherein minimum morphology of the river has occurred) on the Rapti river to avoid outflanking of the river and to minimize the protection works.

(iv) Large scale de-silting from the rivers are not recommended. Efforts shall be made to manage the sediment in the river through deploying suitable river training works. However, from the utility consideration like siltation at water intake, minimum draft requirement for navigation, skewed distribution of flow across bridges/barrages etc., it is recommended to desilt the sediment from that location.

(v) River training works or any other structure shall be designed in such a way that it should not encroach the flood plains of the river or it should not delink the lakes, depressed areas, wetlands etc. as such bodies provide additional storage to the river and that results in lowering the peak discharge that controls the flood.

(vi) Sediment management in the vicinity of a barrage shall be explored by operation of the barrage gates. For an example, gates of the barrages shall be operated in such a way that incoming sediment can be passed downstream during the flood time, to maintain the sediment equilibrium.

(vii) Detailed ground survey of the area and data collection/analysis is proposed before implementing the recommendations, so as to incorporate the current ground conditions and river behaviour.

Suggested Further Study:

(i) Unauthorized, unscientific and unplanned mining of sand and gravel from the river has resulted in major morphological changes in river in the terms of stream bank shifting, bed degradation, bank erosion, disrupting the sediment mass balance, danger to the hydraulic structures etc. It is suggested to carry out replenishment study so that quantity of the sand and gravel to be mined can be estimated and morphological changes can be controlled.

(ii) Erosion and siltation in the Rapti river has been studied herein on the basis of the shifting of the banks of the river and analysis of satellite images. This approach of the study is an indicative and does not provide the eroded/silted sediment in the terms of volume/weight. In view of this, it is suggested that the eroded/silted sediment shall be quantified on the basis of the sediment mass balance study i.e., quantity of eroded/silted sediment in a reach of the river is equal to mass of the sediment entered into the reach minus mass of the sediment gone out from the reach during a period.

(iii) Flood zones of the river should be identified and delineated along both the banks of river. Based on flood zone boundaries, habitation and development activities may be prohibited in such areas.

(iv) In future, morphological studies are required to be carried out using 3D data of the terrain, as topography and slope of the region play an important role to study the morphological behavior of the river.

For the dissemination of outcomes of the study carried out under the project to the potential users, a workshop on *Morphological Study of Rivers Ganga, Sharda and Rapti Using Remote Sensing Technique* was organized by Indian Institute of Technology Roorkee in association with Central Water Commission at Library building, CWC, New Delhi during 18-19 Sept. 2017. A brief note on the workshop is given in Annexure-C,

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DISCLAIMER

Utmost care has taken to process the toposheets, satellite images, hydrological data, estimation of erosion and siltation, identification of critical reaches, etc. to meet out the objectives of the study in this report, however, possibility of errors, omissions, etc. cannot be precluded.

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Chapter 1 INTRODUCTION

1.1 INTRODUCTION

The river morphology is concerned with the shapes of river channels and how they change over time. The morphology of a river channel is a function of a number of processes and environmental conditions on multiple spatial and temporal scales. Watershed features that control river morphology include topography, discharge, sediment supply and vegetation. River stability and response to changing environmental conditions are highly dependent on local context i.e., channel type and associated degrees of freedom; the nature of the imposed sediment, hydrologic and vegetation regimes; imposed anthropogenic constraints; and the legacy of past natural and anthropogenic disturbances. Alluvial streams are dynamic landforms subject to rapid change in channel shape and flow pattern. Water and sediment discharges determine the dimensions of a stream channel (width, depth, and meander wavelength and gradient). Characteristics of stream channels and types of pattern (braided, meandering, straight) and sinuosity are significantly affected by changes in flow rate and sediment discharge, and by the type of sediment load in terms of the ratio of suspended to bed load. Dramatic changes in stream bank erosion within a short time period indicate changes in sediment discharge.

River bank erosion is a natural geomorphic process which happens in all streams as modifications of channel size and shape are made to carry the discharge and sediment provided from the drainage basin. The sediments deposited and eroded in the river have a tremendous impact on river cross-sectional area, gradient, intensity of water flow and its discharge. Therefore, due to morphology change, there is overflow in river which causes flood in the neighbourhood. With the remote sensing- GIS integrated approach, morphological mapping of the river for the pre and post monsoon images can be easily done. Data supplied by the optical and radar satellites can be employed to invoke maps of morphological changes and flood inundation in a short period of time which is cost effective.

Chapter-1: Introduction

Radar images can be used in all type of weather conditions as they can penetrate clouds, they are quite beneficial in mapping flood and are ideal for flood monitoring, especially in complex hydraulic conditions.

Plan form of the rivers may be described as straight, meandering or braided. There is in fact a great range of channel patterns from straight through meandering to braided. Straight and meandering channels are described by sinuosity which is the ratio of channel length to valley length or the ratio of valley slope or channel gradient as measured over the same length of valley (Schumm, 1977). Braiding pattern of the rivers is characterized in different ways; however, most common is Plan Form Index (PFI).

The river geomorphology is the knowledge and interpretation of river processes, which generate and modify landscape's shapes (Marchetti, 2000). By flowing in a river bed composed of non-cohesive loose substances, the current modifies shape of the sections and its planimetric and altitudinal structure, thus originating morpho-dynamics processes.

The preservation of morphological shape, the change of an already-existing balance or the tendency to establish a new shape of the watercourse are the result of both varied and different river processes (erosion/deposition, sedimentation) and geological, climatic, hydrologic, hydraulic, vegetative and biological factors that could trigger, control or wipe out various river phenomena. Such processes characterize every type of river bed, therefore are not typical of any particular morphological configuration. In fact, there are in nature varied river forms corresponding to different stability conditions of beds. The river beds are to be modelled, in relation to the geometric characteristics of the valley and as a response to a certain hydrometric status, to particular flow conditions and depending on the particle size of material transported that forms the bed and on soil composition forming the banks (Lenzi et al., 2000).

Indian rivers always divulge certain special features since they experience large seasonal fluctuations in discharge and sediment load. The rivers are accustomed to a range of discharges and most rivers exhibit morphologies that are related to high-magnitude floods. The key themes in Indian river geomorphology includes the hydrology of monsoonal rivers, and its forms and processes in alluvial channels; causes of avulsion, channel migration; anomalous variations in channel patterns; dynamics of suspended sediments; and the geomorphic impacts of floods. Researches indicate that the Himalayan Rivers are occupying a highly dynamic environment with extreme variability in discharge and sediment load.

Earthquakes and landslides also have a great impact on these rivers from time to time. Consequently, the rivers are characterized by frequent changes in shape, size, position and planform.

There are no clear limits among the various morphological typologies but there is a continuous shift from one form to the other. For this reason, in order to be able to define the morphology of a watercourse and the typologies it is made of, one single parameter is not enough, therefore different factors must be examined and taken into consideration, such as:

- ***Sinuosity*:** it expresses the ratio between the length of the river and the length of the valley axis (Leopold et al., 1964);
- ***Grain distribution*:** it pertains to analyzing the particle size of the material forming the bed;
- ***Total sediment transportation*:** defined as the sum of two components, i.e. bed load and suspended load transportation;
- ***Braiding*:** it is the number of bars or islands situated along a given reach. It is defined as the ratio between the main channel width under flood conditions (when bed sediments are completely flooded) and its width under standard flow conditions;
- ***Vertical running off*:** it specifies whether the stream flows deeply incised in the valley's plain or in its sediments. It is normally expressed by the ratio between the width of the flooded area and the width of the open channel, which corresponds to the bankfull discharge (Kellerhals et al., 1976; Rosgen, 1994);
- ***Width-Depth ratio*:** it describes the size and the form factor as the ratio between bank width of the channel, and the corresponding mean depth (Rosgen, 1994);
- ***Planimetry*:** it explains how a watercourse flows into its drainage area;
- ***Gradient*:** it is a very important aspect in the determination of the hydraulic, morphological and biological characteristics relating to a watercourse;
- ***Longitudinal section*:** it is the change in height of a stream which explains how the river can be divided up into morphological categories according to the gradient;
- ***Cross section*:** it indicates the incision degree of a channel and the extent of the most important hydraulic variables.

A stream can have various channel patterns (as shown in Figure 1.1), such as braided channels, meandering channels, and straight channels. These various patterns are a response to the above variables, in particular the slope/gradient and the friction in the channel (related to grain sizes).

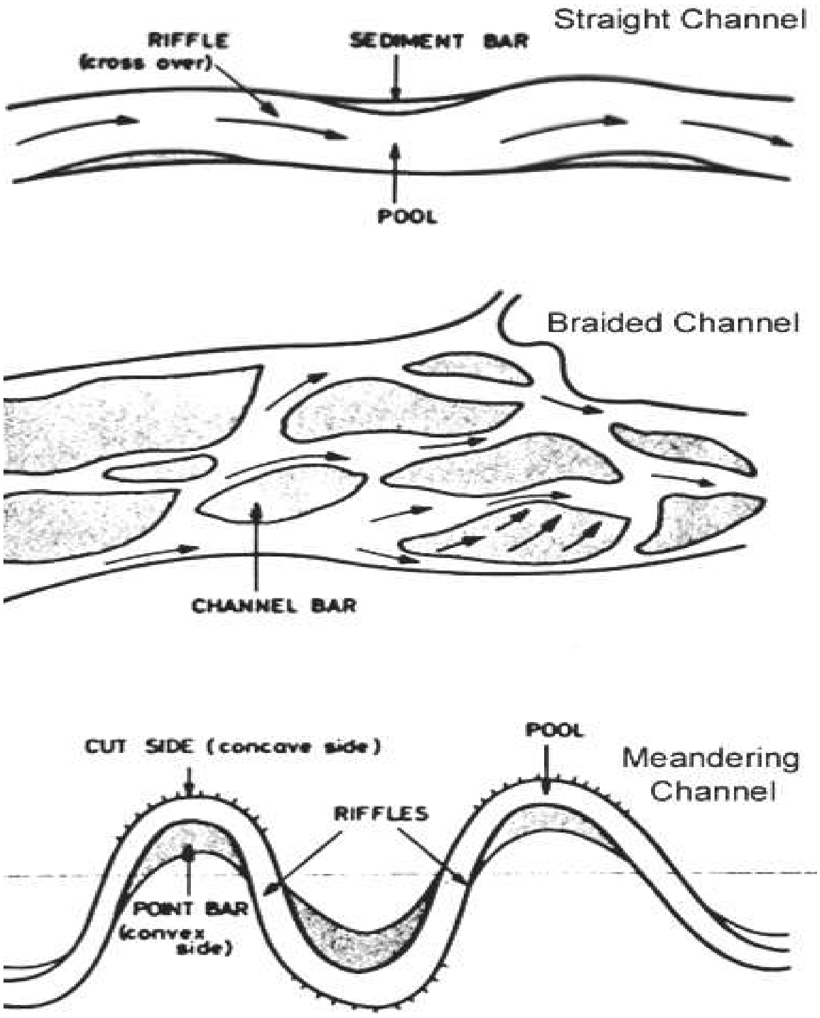


Figure 1.1 Channel Patterns

1.2 OBJECTIVES & TERMS OF REFERENCE

The specific objectives of works are:

i. Compile complete river drainage map in GIS by integrating available secondary maps in WRIS of CWC. Collect additional required information on major flood protection structures, existing water resources projects, important cities/ towns, CWC H.O. sites, airport, island etc., and to be integrated with final river drainage maps.

ii. Study shifting of river course and also changes in its Plan form from the base year (say 1970) till 2010, by collecting 4 sets of satellite imageries at 10 years interval in addition to one set of Survey of India toposheets for the base year on a scale of 1:50,000. In case toposheets are available for older period say 1950, the base year may be shifted accordingly.

iii. Compile Changes in Land Use/Land cover, and study of its impact on river Morphology.

iv. Channel Evolution Analysis to describe the status of the river channel. The analysis of the channel dimension, pattern, and longitudinal profile identifying distinct river reaches i.e. channel in upper reaches, channel in flood plain with bank erosion etc. This segregation of the reaches is to be determined by using Channel Evolution Analysis.

v. Work out the rate of bank erosion/deposition in terms of erosion length & erosion area w.r.t. base year at 50 km interval.

vi. The present condition of critical reaches of the main channel of river may be assessed by conducting ground reconnaissance. Field recon trips may be taken, if required.

vii. Evaluate the impacts of major hydraulic structures on morphological behavior of river course and its impacts on river morphology.

viii. Evaluate braiding pattern of river by using Plan -Form Index (PFI) criteria along with its threshold classifications.

ix. Compile information (if any) on flood affected areas in the vicinity of river course prepared by NRSC using Multi-temporal satellite data of IRS WiFS (188 m) & Radarsat ScanSAR Wide & Narrow (100 m & 50 m) for flood images of Bihar and Assam.

x. Plot probability curve (Exceedance Probability vs. Flow rate) and show flow rates corresponding to return period of 1.5 year and 2 years for different CWC H.O. locations. The observed flows need to be normalized before using for analysis.

xi. Relate the morphological changes in river on the basis of available peak discharges of different years in the time domain considered in this study. Study impact of changes in annual rainfall in the basin on river morphology.

xii. Identify critical and other vulnerable reaches, locations. Analysis of respective rate of river course shifting and based on it, future predication of river course behaviors.

xiii. Suggest suitable river training works for restoration of critical reaches depending on site conditions.

1.3 NEED/SCOPE OF STUDY

Following are the scope of the intended study:

i. The required inventory of one set of Survey of India (SOI) toposheets in respect of reference time datum on a scale of 1:50,000 are to be procured from SOI by the Consultant. The inventory of satellite imageries having spatial resolution of 23.5 m , IRS LISS-I, LISS-II, LISS-III may be worked out covering the study area, and to be procured from NRSC.

ii. One set of SOI toposheets (say year 1970) and digital satellite imageries of IRS LISS-I, LISS-II and LISS-III sensors, comprising scenes for the years 1980, 1990, 2000 and 2010 are to be used for the present study. In case of non-availability of above data, the foreign satellite data of similar resolution may also be used. The maps and imagery are to be registered and geo-referenced with respect to Survey of India (1:50,000 scale) toposheets w.r.t. to base year by using standard technique & GIS tool.

iii. Delineation of River Bank Line, River Centre Line along with generation of important GIS layers of river banks, major hydraulic structures, embankments/levees, railway bridge line, island, airport, cities/towns/villages, and important monuments etc. located in the vicinity of river banks for the selected years of the studies are to be part of studies.

iv. Estimation of left & right banks shifting amount(s) w.r.t. base year & appropriate graphical plotting of these shifting.

v. Evaluation of braiding of different river course reaches by using Plan Form Index (PFI) criteria along with its threshold classification, wherever required.

vi. Estimation and comparison of each bank erosion for different reaches in term of erosion length & erosion area of the river w.r.t. base year by using appropriate GIS tool, accordingly vulnerability index for different reaches may be evolved & prioritized along with causative factors detail for this erosion may be worked out.

vii. Comparison of delineated different river courses on the same graphical plot on A0 size, and all plots may be arranged in a separate volume.

viii. The most critical reaches may be shown separately with appropriate suitable stream reach(s) restoration with a recommendation of suitable bank stabilization technique(s) depending upon the channel planform and condition.

ix. The cross section data available may be used for identifying riffle locations, and measure topography changes. The cross sectional data provided may be used to extract necessary information to analyze the channel, which ultimately led to identifying the channel stage or condition.

x. The plan view of various stream patterns may be used to define the geometric relationship that may be quantitatively defined through measurement of meander wavelength, radius of curvature, amplitude, and belt width. It may be done by separating river reaches based on change in valley slopes into different RDs, estimation of sinuosity, no. of bends for different RDs, average radius of curvature for each segment of the rivers defined. Based on this channel pattern analysis, proper interpretation may be given.

xi. River Channel Dimension; river channel width and the representative cross section are a function of the channel hydrograph, suspended sediments, bed load, and bank materials, etc. The future river channel dimensions may be evaluated based on the available cross-section detail for vulnerable/critical reaches of the rivers.

xii. Maximum Flow Probability curves at CWC H.O. sites located on concern river, may be developed to predict the channel discharge corresponding to 1.5 year and 2 year Return Interval (RI). These values i.e. 2 year Return Interval is widely accepted as the "Channel Forming Discharge" or "Bankfull". These are the flows that contribute most to the channel dimension. These parameters may be used to determine the Channel Evolution Stage based on the Channel Evolution Analysis. Comparison of channel forming discharge and the maximum channel capacity may be done; accordingly interpretation about the channel carrying capacity is to be presented.

xiii. Channel profile; channel profile is commonly referred to channel slope or gradient. The channel profile may be developed for river reach under consideration. The proper interpretation w.r.t. bed formations, aggradations, degradation etc. may be made part of studies.

xiv. Impaired stream analysis; as part of the scope of work, part of impaired streams to be identified along with the causes and sources by the consultant. Based on the causes of stream impairment, stream restoration mechanism/methods to be recommended. While stream restoration and bank stabilization techniques do improve water quality, land use practices may also be discussed, which is typically the main culprit of chemical pollution.

xv. Results & Recommendations are to be separate chapters. A proper discussion about results in respect of different reaches i.e. upper reach, middle reach & lower reach of river along with appropriate suggestions to be given.

xvi. Collection of a dditional information like Topography, Climate, Soils, Geology and Hydrology etc. required to be incorporated in the Morphological report.

xvii. Analysis of shifting of left and right banks of the rivers at about 50 kilometer interval as well as covering critical reaches of the river irrespective of river RDs interval.

xviii. Identification of flood affected areas in the vicinity of river course which have experienced frequent flooding in the past and suggesting suitable remedial measures for flood proofing for the river reaches. It was informed by NRSC representatives that NRSC derived inundation from 10 years of multi-temporal satellite data (1998-2007). Based on the frequency and extent of inundation, the flood hazard is categorized into 5 classes - Very High, High, Moderate, Low and Very Low. This helps the concerned authorities in planning developmental works in these areas. NRSC used Multi-temporal satellite data of IRS WiFS (188 m) & Radarsat ScanSAR Wide & Narrow (100 m & 50 m) for flood images. The flood hazard along with flood annual layers mapping has been done for Assam & Bihar. It includes complete flood hazard statistics district wise. This published information can be utilized by IIT Roorkee to cover flood affected aspects in the study.

xix. The entire satellite data used in the study by the IIT Roorkee, all analysis, results, maps, charts etc. and the subsequent report prepared shall be the exclusive property of CWC and the IIT Roorkee has no right whatsoever to divulge the information/data to others without the specific written permission of CWC.

xx. In order to ensure the desired quality of the generated outputs as well as to ensure that the GIS layers are hydrologically, hydraulically, and scientifically reasonable approximations. It was decided that the standards used for WRIS, as well as “Standards for Geomorphological Mapping Project” and “Standards for Land Degradation Mapping Project” given in manuals of NRSC may be referred.

xxi. The compilation of Changes in Land Use/Land cover, and study of its impact on river Morphology is to be incorporated in the study report. The NRSC’s published information about land use and land cover maps under NRSC Bhuvan thematic service on a scale of 1:50,000 as well as 1:2,50,000 for all states can be used for this purpose.

Chapter 2 LITERATURE REVIEW

2.1 LITERATURE REVIEW

The dynamics of river and associated problems like erosion/deposition floods in particular have been studied by many researchers around the world. The physical based research in the area of river geomorphology has pointed out the historical trends in river processes and flooding. Pioneering study in river geomorphology by Leopold and Wolman (1957) is the most noteworthy along with the work of Schumm (1963), Chorley (1969), Gregory and Walling (1973), Brice (1981) and Hooke (2006). The following section deals with the literature survey to streamline the present work.

Leopold and Wolman (1957) grouped the alluvial rivers into straight, braided and meandering on the basis of their plan form, and calculated the characteristics of each of these patterns. Braided river was found to be the one that flows into two or more anastomosing channels (anabranches) around alluvial island, and in a winding course. The continuum of channel patterns from unbranched to highly braided has been quantified by the braiding index introduced by Brice (1974), which is the ratio of twice of the channel length of the islands in the reach of stream divided by the length of the reach.Channels have also been classified based on the relative percentage of bed load and suspended load they transport (Schumm, 1969).

Brice (1981) studied the meandering pattern of three reaches of the white river, Indiana. He demarcated the centroid of each bend to find out the movement in the meanders. To find out the potential of erosion in each meander bend a plot was created between angular movements of centroids and meander length. Further, he plotted the eroded area and the meander length on a scatter diagram to find out the average meander length which triggers erosion. He concluded that the erosion along straight segments of a highly sinuous channel is negligible.

Hooke (1987) stated that channel planform changes by erosion of the banks (growth of meanders), by deposition within the channel (braiding), or by cutoffs and avulsions that involve switching of channel position. Hooke (2006) elaborated the spatial pattern of instability and the mechanism of change in an active meandering river, the Dane. Nearly 100 meandering bends of the Dane river have been analyzed using historical maps and aerial photographs for the period 1981-2002. More than 20 years of monitoring of these bends provided a unique insight into the link between erosion, deposition and maximum discharge.

Sarma and Phukan (2004) studied the origin and geomorphological changes of Majuli Island of the Brahmaputra River in Assam, India using SOI toposheets (1917, 1966 and 1972) and satellite data (IRS-1B LISS II data of 1996 and IRS-1D LISS III data of 2001). This study reveals that erosion is predominant in the southern boundary of Majuli Island owing to the river Brahmaputra while rate of erosion is more prominent in the south western part of the island. Increase in rate of erosion is noticeable during 1917-2001 due to this Brahmaputra has widened its channel by eroding both of its banks, particularly after the Great Assam earthquake of 1950. An increase in channel width from 35.8% to 61.2% has been measured around Majuli during the period from 1917 to 1996 due to overall northward migration of the Brahmaputra.

Lauer and Parker (2008) stated that erosion from the banks of meandering rivers causes a local influx of sediment to the river channel. Most of the eroded volume is usually replaced in nearby point bars. However, the typical geometry of river bends precludes the local replacement of all eroded material because (i) point bars tend to be built to a lower elevation than cut-banks and (ii) point bars tend to be shorter than the eroding portion of cut-banks because of channel curvature. In a floodplain that is in equilibrium (i.e., neither increasing nor decreasing in volume), sediment eroded from cut banks must be replaced elsewhere on the floodplain. The local imbalance caused by differences in bank height should be balanced primarily by overbank deposition, while the local imbalance caused by curvature should be balanced primarily by deposition in abandoned stream courses or oxbow lakes.

Nicoll and Hickin (2010) examined the planform geometry and migration behavior of confined meandering rivers at 23 locations in Alberta and British Columbia. Relationships among planform geometry variables are generally consistent with those described for freely meandering rivers with small but significant differences because of the unique meander pattern of confined meanders. Migrating confined meandering rivers do not develop cutoffs, and meander bends appear to migrate downstream as a coherent waveform.

Luchi *et al.* (2010) stated that high spatial resolution of the topographical survey allows capture of significant variations in the cross-sectional morphology at the meander wavelength scale. The width-curvature behavior is correlated with the pattern of bed and banks morphology, which is different in bend apices and in meander inflections. The survey shows that the bed-form morphology can be characterized by a mid-channel bar pattern that is initiated at the inflection section and that the bed-form dynamics can be closely associated with channel width variations.

Rozo *et al.* (2014) stated that bank erosion is essential in the proper functioning of river ecosystem and it also happens in densely forested system. The identification of pixel class-change was carried out and the following changes were acknowledged: a) Deposition: when there is formation of island or floodplain from water feature; b) Erosion: when floodplain or island changes to water body; c) Erosion-Deposition: when there is change from floodplain or island to water and again to recent deposition; d) Changes between various land forms; and e) No change.

Ghosh (2014) quantifies planform of the river Teesta after Gazaldoba barrage using satellite images of years 1997, 1990, 1999 and 2008 in the GIS environments and found that the river braiding has drastically increased in the year 1999 just after the dam/barrage operation in comparison of pre barrage operations year 1977 and 1990 where Plan Form Index (PFI) values have shown an increasing trend in most of the reaches indicating less braiding of the river planform. His study highlights that Gazaldoba barrage is not solely responsible for altered river flow but several other upstream factors are also responsible for this changes. Thus the river Teesta planform pattern has been changed from low braided to highly braided after the human induced changes in the river.

Hazarika *et al.* (2015) quantified the planform and land use changes of Gai and Simen tributaries of the Brahmaputra River, Assam, India for last 40 years using remote sensing and GIS techniques. Quantification of bank line migration shows that the river courses are unstable. A reversal in the rate of erosion and deposition is also observed. Land use change shows that there is an increase in settlement and agriculture and a decrease in the grassland. The area affected by erosion–deposition and river migration comprises primarily of the agricultural land. Effect of river dynamics on settlements is also evident. Loss of agricultural land and homestead led to the loss of livelihood and internal migration in the floodplains. The observed pattern of river dynamics and the consequent land use change in the recent decades have thrown newer environmental challenges at a pace and magnitude way beyond the coping capabilities of the dwellers.

Dewan et al. (2016) used geospatial techniques to quantify the channel characteristics of two major reaches of the Ganges system in Bangladesh over 38 years. It has covered the section of the Ganges River, from the India–Bangladesh border and the Padma, from Aricha to Chandpur. They also examined the nature and extent of bankline movements of the Ganges and Padma rivers and estimated the volume and location of both erosion and deposition in the river channel. Channel planform maps of the Ganges over 38 years revealed that the river experienced contraction and expansion as well as adjustment to its planform. Analysis of the left and right bank movement showed that each bank has particular stretches where movement is high and low.

Fluvial geomorphological studies in India have mostly focused on the river response to climate and tectonic force at Quaternary time scale (Chamyal et al., 2003; Juyal et al., 2006; Sinha et al., 2007). Recently, studies of the hydro geomorphic behavior of river systems at modern time scale have also been initiated to understand the impact of anthropogenic force on geomorphic processes for some of the Indian river systems. Such studies at modern time scale have not only highlighted anthropogenic impacts on river systems but have provided significant insights to river hazards, particularly flooding and river dynamics.

Jain et al. (2012) reviewed the major geomorphic studies on the Indian rivers and highlighted various research questions. One of the major research concerns is the development of hydrology morphology ecology relationship in the river system and the assessment of the anthropogenic disturbances on this or a part of this relationship. Anthropogenic disturbances cause flux or slope variability in the channel, which alter the morphology and ecology of the river system.

Channel morphology is a manifestation of the river characteristics and river behavior (Gregory and Lewin, 2014). Its spatial variability not only represents the variability in hydrology and channel processes but also governs the ecological diversity in the channel. In order to understand the spatial variability, a geomorphic diversity framework has been developed for the Ganga River and its tributaries (Sinha et al., 2016). The geomorphic features at different spatial scales were used in a hierarchical framework to divide the Ganga River system into different reach types.

Rivers support human population in villages and are therefore of significant interest to different workers.

The Majuli Island has been shrinking with an average erosion rate of 3.2 km^2/yr. A recent study showed that the erosion trend closely correlates with the various geomorphic parameters of the Brahmaputra River, which includes channel belt area (CHB), channel belt width (W), braid bar area (BB), channel area (CH), thalweg changes and bank line migration, which highlights the role of channel processes on the evolution and erosion of the island (Lahiri and Sinha, 2014). It was also suggested that subsurface tectonic processes also governed its evolutionary trajectory. This new understanding of the evolutionary trajectory of the Majuli Island highlights the complexity in the management of this mega geomorphic feature.

A recent study on the stream network connectivity structure in longitudinal and lateral dimensions had shown its utility for the prediction of inundation areas in the scenario of avulsion driven flooding (Sinha et al., 2013). The connectivity structure was quantified by a connectivity index defined as a function of the length and slope properties of the channel network. This topography-driven connectivity model was successfully used to simulate the avulsion pathway of the Kosi River during the August 2008 breach (Sinha, 2009). In general, avulsion prone reach of the Kosi River is characterised by different palaeo channels, which makes it difficult to predict the inundation zone due to avulsion event. However, such an approach provides a priori information about possible inundation zones and could be used to predict flood risk in populated and vulnerable regions. This study demonstrated that the mapping of connectivity structure for a stream network on a part of a fan surface can be used as an important tool in the management of flood hazards.

Formation of various barriers across the rivers like dams and barrages has also caused significant disconnectivity in the system. A number of major dams constructed on the Himalayan and Peninsular rivers in India have disturbed the water and sediment fluxes. In the Mahanadi River basin, the time series data of the rainfall at different monthly and seasonal scales show that the rainfall trend is spatially variable (Panda et al., 2013).

Large dams have caused more pronounced disconnectivity on the sediment fluxes. The Peninsular rivers were characterized by significant decrease in sediment supply during the last few decades. Using hydrological data from 1986 to 2006, Panda et al. (2011) had shown that all the Peninsular rivers were characterized by decrease in sediment supply to ocean in response to decrease in rainfall and anthropogenic impact. The source-sink disconnectivity was more explicit in the highly regulated Narmada and Krishna rivers, where climate (rainfall variability) had no significant control on sediment flux variability. The sediment supply in the ocean had decreased by 70% in these regulated river basins.

Gupta and Subramanian (1994 and 1998) analyzed water and sediment samples collected from the Gomti river during the post-monsoon season. The results indicated almost monotonous spatial distribution of various chemical species, especially because of uniform presence of alluvium dun gravels throughout the basin. The river annually transports 0.34×10^6 tonnes of total suspended material (TSM) and 3.0×10^6 tonnes of total dissolved solids (TDS), 69% of which is accounted for by bicarbonate ions only.

Shukla and Asthana (2005) studied the inter linking of river in India. The interlinking river project was separated into two primary components i.e. Himalayan and Peninsular Rivers. The Himalayan component proposes 14 canals and the Peninsular component 16. In the Himalayan component, many dams are slated for construction on tributaries of the Ganga and Brahmaputra in India, Nepal and Bhutan. The project intends to link the Brahmaputra and its tributaries with the Ganga and the Ganga with the Mahanadi River to transfer surplus water from east to west. The scheme envisages flood control in the Ganga and Brahmaputra basins and a reduction in water deficits for many states. In the Peninsular component, river interlinks were envisaged to benefit the states of Orissa, Karnataka, Tamil Nadu, Gujarat, Pondicherry and Maharashtra. The linkage of the Mahanadi and Godavari rivers was proposed to feed the Krishna, Pennar, Cauvery, and Vaigai rivers. Transfer of water from Godavari and Krishnaentails pumping 1,200 cusecs of water over a crest of about 116 meters. Interlinking the Ken with the Betwa, Parbati, Kalisindh and Chambal rivers was proposed to benefit Madhya Pradesh and Rajasthan.

Latrubesse et al. (2005) presented an overview of tropical river systems around the world and identifies major knowledge gaps. They focused particularly on the rivers draining the wet and wet–dry tropics with annual rainfall of more than 700 mm/year. The size of the analyzed river basins varies from 104 to 6×10^6 km^2. They also computed the intensity of floods and discharge variability in tropical rivers. The relationship between sediment yield and average water discharge for orogenic continental rivers of South America and Asia was also plotted. Insular Asian rivers show lower values of sediment yield related to mean annual discharge than continental orogenic rivers of Asia and South America. Rivers draining platforms or cratonic areas in Savanna and wet tropical climates are characterized by low sediment yields. Tropical rivers exhibit a large variety of channel form. In most cases, and particularly in large basins, rivers exhibit a transition from one form to another so that traditional definitions of straight, meandering and braided may be difficult to apply.

Schwenk et al. (2016) studied the planform changes of large, active meandering rivers at high spatiotemporal resolutions. Through mapping of annual planforms at Landsat-pixel scale of 30 m, their results provided a basis for determining controlling factors on local planform changes and contextualizing them within the broader reach. They also introduced the RivMAP toolbox, which provides intuitive, easily-customized, and parallelizable Matlab codes for analyzing meandering river masks derived from satellite imagery, aerial photography. Based on estimates of uncertainty associated with classifying and compositing Landsat data, their techniques can provide meaningful annual morphodynamic insights in large rivers from Landsat imagery. With current Landsat data, over a dozen large, tropical meandering rivers, e.g. the Mamoré, Beni, Juruá, Fly, and Sepik Rivers, were ideal candidates for quantifying morphodynamic changes and identifying process controls on planform adjustments from Landsat imagery.

Kumar et al. (2013) focused on the fluvial geomorphic features within the valley margin of Rapti river. The study revealed that the floodplain was formed due to lateral migration of channel and associated scroll bars in accordance with unit stream power varying from ~10 Wm^{-2} to 23 Wm^{-2}. They also studied the hydrometeorological conditions of 2011 monsoon season and its effect on channel instability. Lateral expansion, translation of meander and cut-offs formation were responsible for altering the planform of the channel. Based on the proportion of bar area to channel belt area and channel area, they identified reach-wise aggradational and degradational processes.

Gautam and Phaiju (2013) presented an overview of flood problems in the West Rapti River basin, causes and consequences of recent floods and the applicability and effectiveness of the community based approach to flood early warning in Nepal. A community based flood early warning system has been set up with a collaborative effort of the Department of Hydrology and Meteorology, Practical Action, local government and non-governmental organisations. Community level disaster management committees have been formed in each of the disaster prone villages. These committees have been brought into a network of District Disaster Relief Committee, local media, the Red Cross, local police, the military units and the flood monitoring and forecasting station of the Department of Hydrology and Meteorology. The disaster management committees have been equipped and trained for warning dissemination, preparedness and immediate response. This proved to be a very effective mechanism to disseminate flood warning and respond immediately during times of disaster.

Talchabhadel and Sharma (2014) presented an overview of flood problems in the West Rapti River basin, causes and consequences of recent floods and the applicability and effectiveness of the real time data to flood early warning in Nepal. The west Rapti River basin is one of the most flood prone river basins in Nepal. The real-time flood early warning system together with the development of water management and flood protection schemes play a crucial role in reducing the loss of lives and properties and in overall development of the basin. The non-structural mitigating measure places people away from flood. This method was designed to reduce the impact of flooding to society and economy.

Singh et al. (2015) studied the threshold limits of discharge, sediment load and water level, which creates the flood and helps to identify the recurrence interval, flood inundation map and geomorphic features for flood forecasting and risk management in the Gorakhpur region. The construction and preservation of retaining ponds should be popularized which would mitigate the flood risk and also solve the problem of depleting ground water table in the Gorakhpur region.

Shrestha (2016) focused on various storage project related to development of main course of Rapti (West), Nepal. In the case of Nepal, river waters are the basic sources of all these elements and are the only resources available indigenously in Nepal for these purposes. Rapti (West), being medium size river of rain-fed nature, the dry spell continues long from December up to the end of May; at the same time the flood waters available particularly in July, August and September create havoc by flooding in the downstream reaches. The Kapilvastu area which can be commanded by the Rapti (West) river does not have other dependable sources for fulfilling its requirements. The only way to fulfill its requirements without affecting downstream users is, thus, to capture a portion of flood water of Rapti behind a storage dam aimed at diversion to Kapilvastu for use during dry season. An appropriate site for such purpose is located at Bhalubang. Hence, this site needs to be developed first to ensure the diversion to Kapilvastu and then a much higher storage dam site at Naumore could, later at appropriate time but within 25 to 30 years after development of Bhalubang site, be developed for increasing the flow regulation potential of the Rapti River so that the hydropower generation, flood control and intensification of irrigated agriculture at its commandable areas, could be maximized.

2.2 CONCLUDING REMARKS

Review of the available literature related to morphology of the rivers indicates that various investigators have investigated the morphology of the rivers in the respect of its planform change, river shifting, changes in land use and land pattern, erosion and siltation, impact of the structures on the morphology, measures for training the rivers etc. However, a comprehensive morphological study of Rapti river is not available in the literature. In view of this gap, this study has been taken up.

Chapter 3 RIVER BASIN

3.1 RAPTI RIVER BASIN

Rapti River, basically originates as a small river draining the Chitwan (Inner Terai) valley in Nepal, flowing west to join the Narayani (Gandaki) river at a short distance towards north of the Indian border and form Rapti zone (Fig 3.1). Rapti zone falls in Nepal's Middle Hills between the Karnali and Gandaki basins, cutting through the Mahabharat range, flowing west through Deukhuri valley, then south-east down the Indo-Gangetic plains to join the Sharda (Ghaghara) river. Rapti river is the major tributary of Ghaghara river. The Rapti river basin is diverse in its physiography. The lofty mountain, inner and outer Tarai and undulating plain regions constitute the topography of the entire basin. Figure 3.2 shows sample map of Rapti river basin layers procured from WRIS.

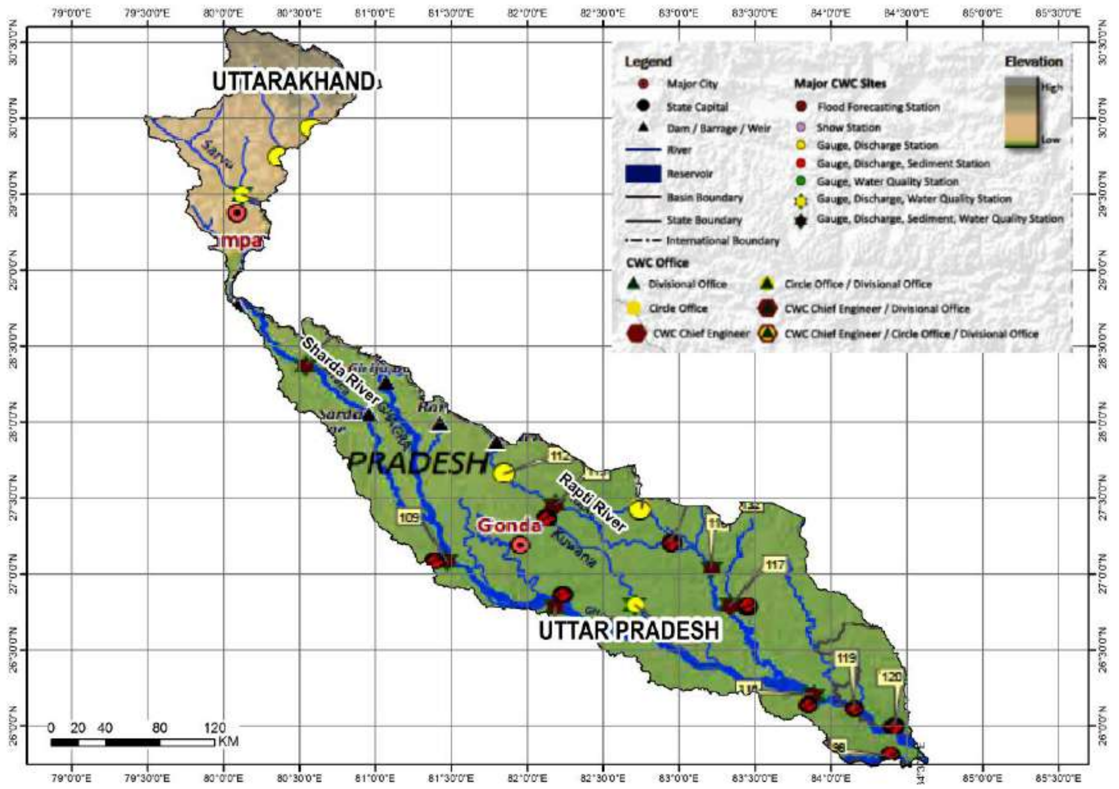


Figure 3.1 River basin map of Rapti - Sharda - Ghaghra basin (Source: WRIS)

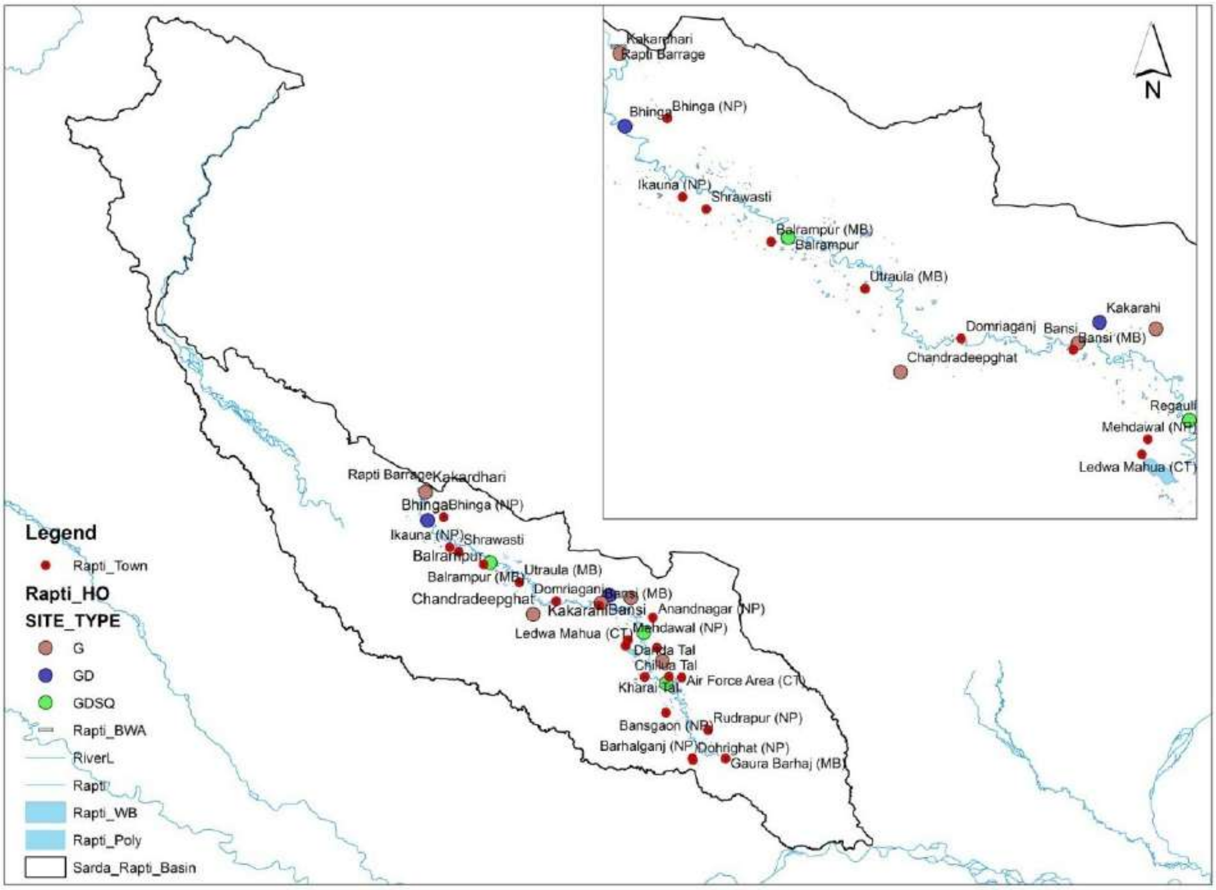


Figure 3.2 Rapti River basic layers (Source: WRIS)

3.2 CLIMATE

Due to difference in altitude, the Rapti River has two distinct climatic regions - the temperate climate prevails in the mountainous region while the plain region has subtropical climate. Himalayas have a temperate climate. Summers are warm and winters are cold. Subtropical climate plain region experiences typical monsoon type of climate with dry winter season. The weather is very hot in summers. Daily maximum temperature goes upto 46.5°C. The western part is hotter than the eastern part.

Like most of northern India, Rapti Basin has an extreme Humid Subtropical with dry winter (CWa) type of climate. Summers are hot with temperatures rising up to 40 °C. During winters from mid-October to mid-March, temperatures hover between 20 to 30 °C. Prevalent winds are westerly. The hot wind Loo blows strongly from mid-April up to end of May. Monsoon starting in mid-June and lasting up to September accounts for 90% of the rainfall of 150 cm. Temperatures range from a minimum of 9 °C in winter to a maximum of up to 45°C in peak summer.

3.3 METEOROLOGICAL STATIONS

Meteorological sites (Raingauge) of the Indian Meteorological Dept. located in the basin of the Rapti river are shown in Fig. 3.3.

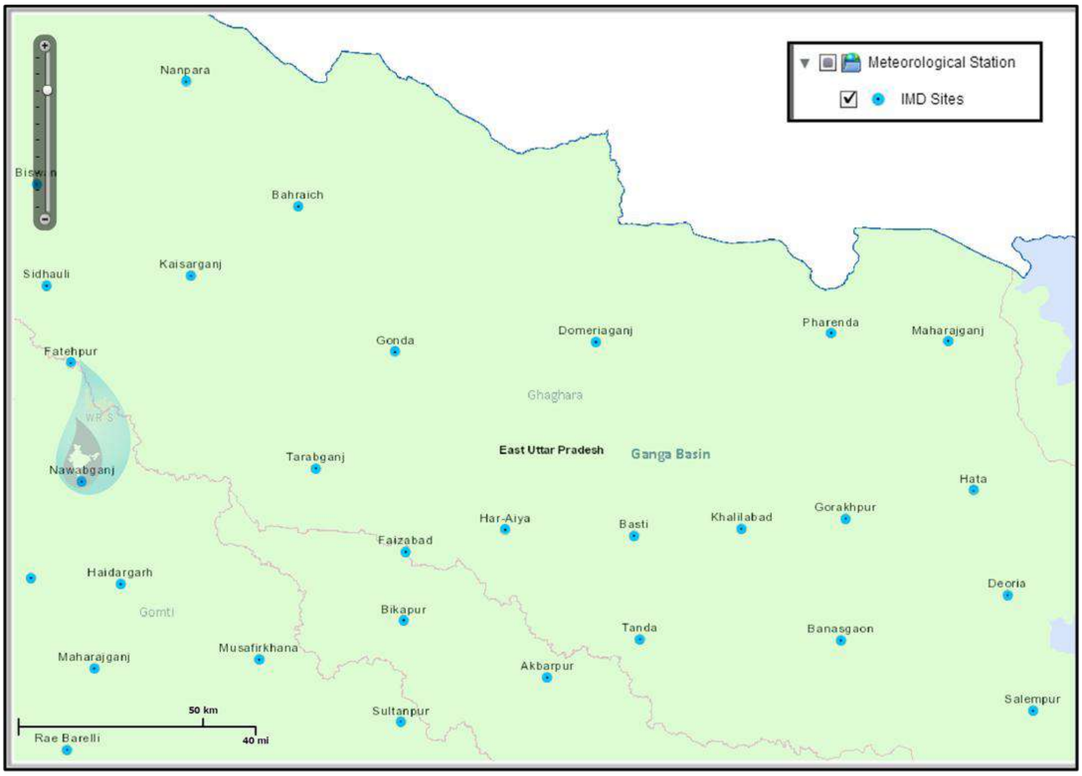


Figure 3.3 Rain gauge stations of Rapti basin (Source: WRIS)

3.4. BASIN GEOLOGY

Geologically, the Rapti river basin may be divided into three zones:

- The northern mountain zone or Shiwalik Himalaya,
- The *tarai* zone, and
- The plain zone.

The Northern Mountain Zone or Shiwalik Himalaya: It forms the foothills of the Himalayan Range and is essentially composed of Miocene to Pleistocene molassic sediments derived from the erosion of the Himalaya. These molasse deposits, known as the Muree and Siwaliks Formations, are internally folded and imbricated. The Sub Himalaya is thrust along the Main Frontal Thrust over the Quaternary alluvium deposited by the rivers coming from the Himalaya (Ganga, Indus, Brahmaputra and others), which demonstrates that the Himalaya is still a very active orogen.

The Tarai Zone: The Tarai is crossed by the large perennial Himalayan rivers Yamuna, Ganga, Sharda, Karnali, Narayani and Kosi that have each built alluvial fans covering thousands of square kilometres below their exits from the hills. Medium rivers such as the Rapti rise in the Mahabharat Range. The geological structure of the region consists of old and new alluvium, both of which constitute alluvial deposits mainly of sand, clay, silt, gravels and coarse fragments. The new alluvium is renewed every year by fresh deposits brought down by active streams, which engage themselves in fluvial action. Old alluvium is found rather away from river courses, especially on uplands of the plain where silting is a rare phenomenon.

The Plain Zone: The reduction in slope as rivers exit the hills and then transition from the sloping Bhabhar to the nearly level Tarai causes current to slow and the heavy sediment load to fall out of suspension. This deposition process creates multiple channels with shallow beds, enabling massive floods as monsoon-swollen rivers overflow their low banks and shift channels. Many areas show erosion such as gullies. This area consists of highly fertile and arable land.

Geology of Rapti - Sharda - Ghaghra Basin as obtained from GSI is shown in Fig. 3.4.

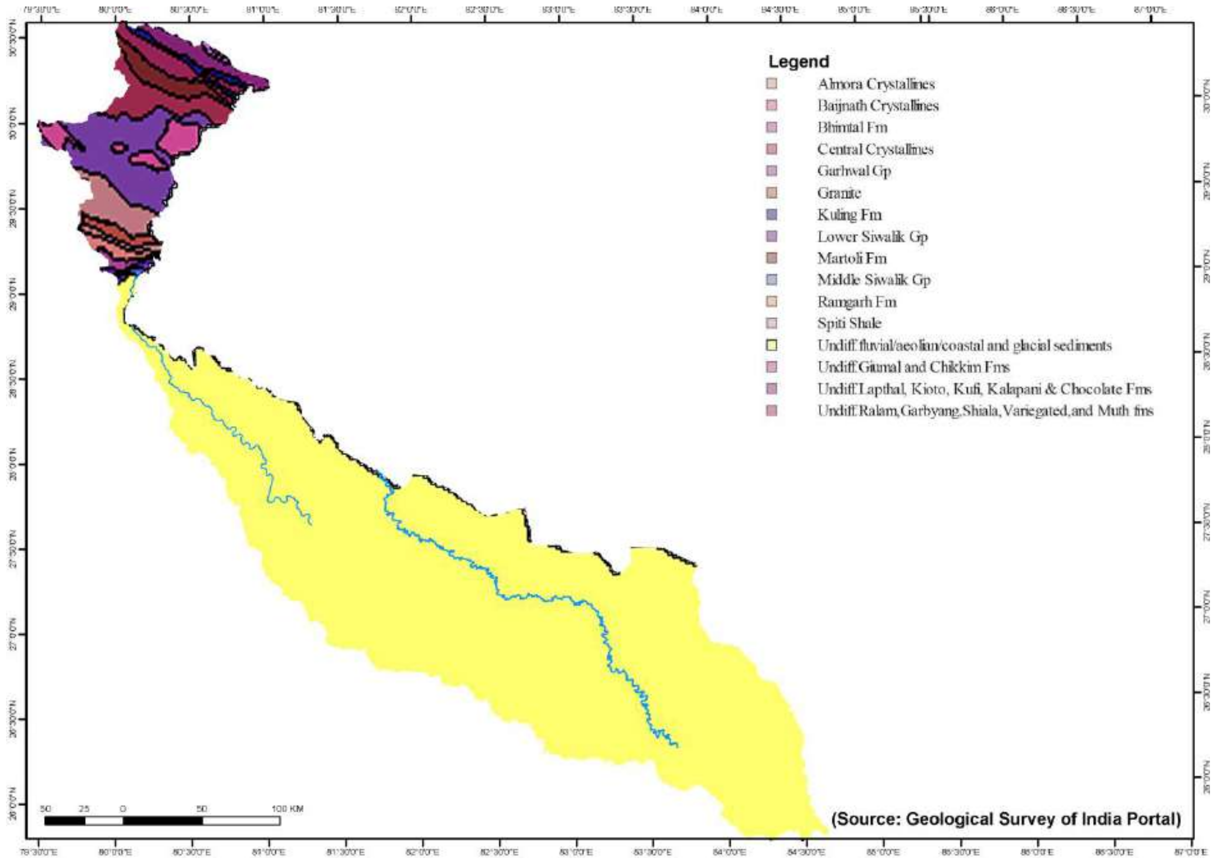


Figure 3.4 Geology of Rapti - Sharda - Ghaghra basin (Source: GSI)

3.5 LAND USE & LAND COVER

Land use land cover map of Rapti - Sharda - Ghaghra Basin as obtained from WRIS is shown in Fig. 3.5, while Fig. 3.6 shows land use land cover map of Rapti basin explicitly.

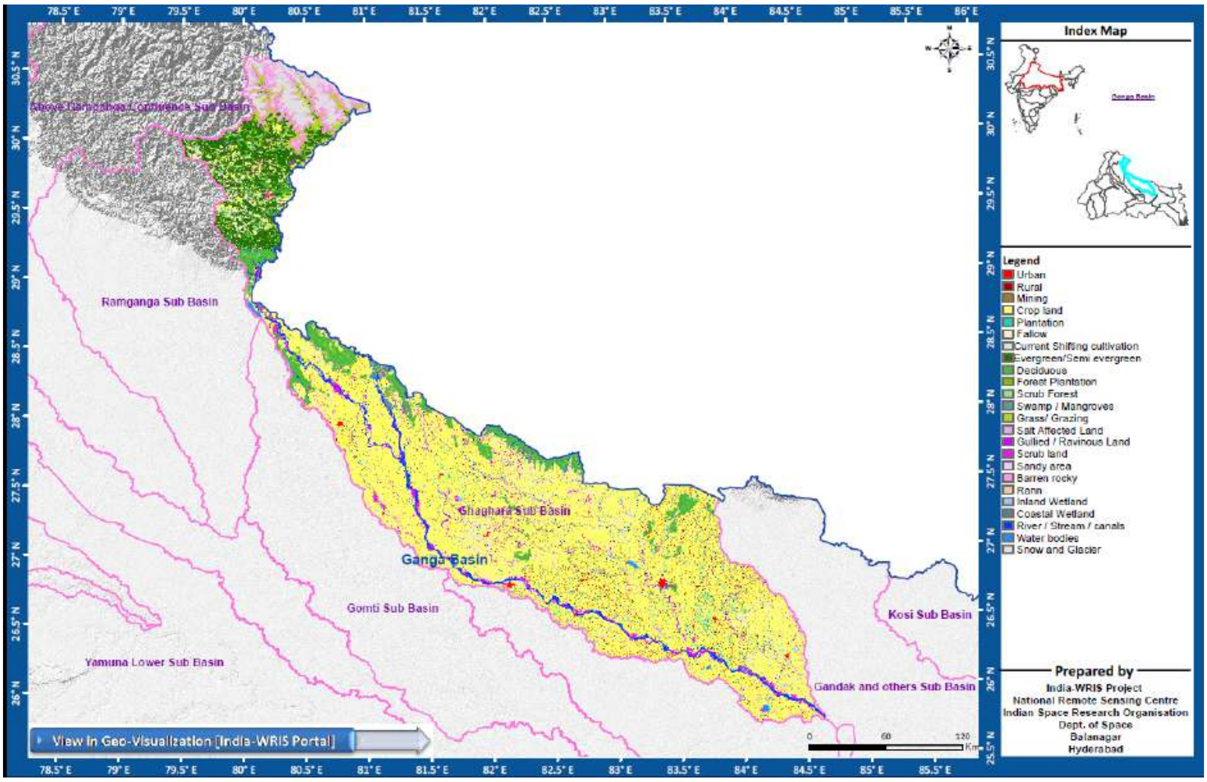


Figure 3.5 Land Use Land Cover map of Rapti - Sharda - Ghaghra basin (Source: WRIS)

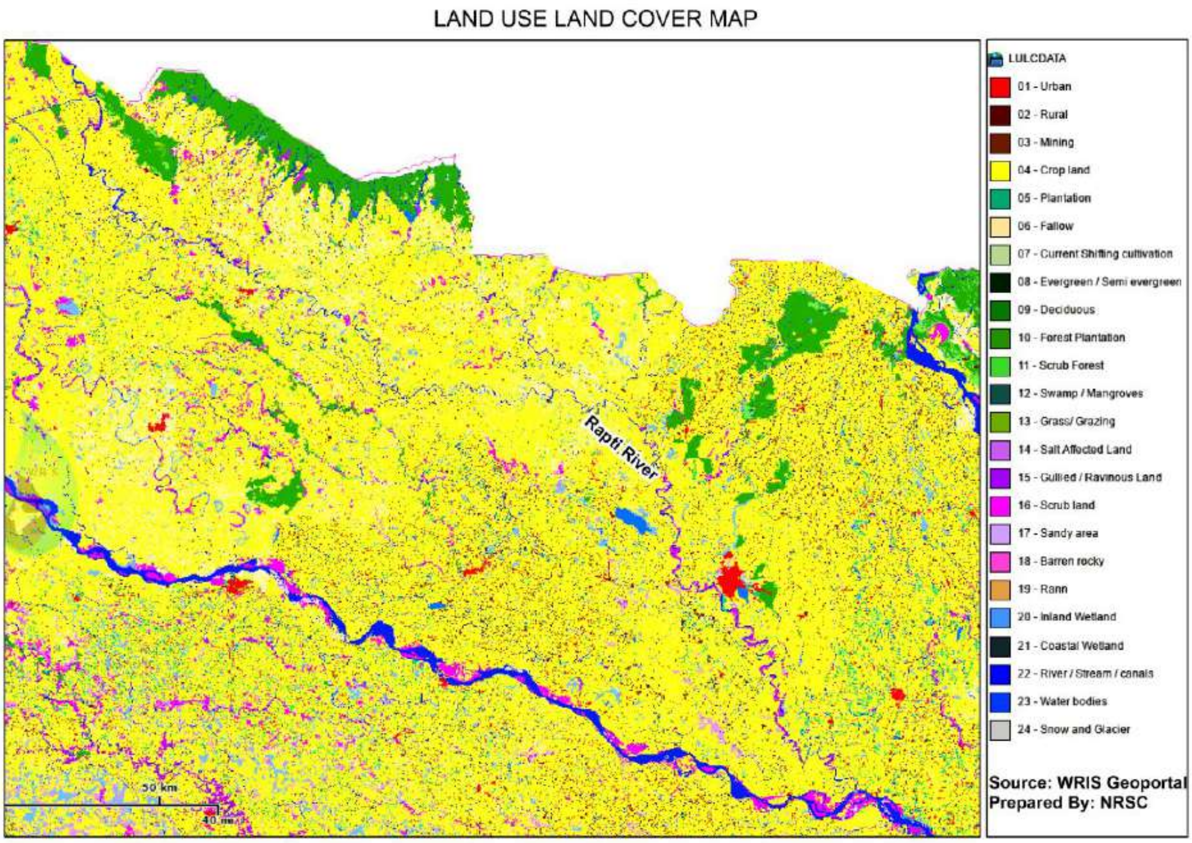


Figure 3.6 Land Use Land Cover map of Rapti basin (Source: WRIS)

3.6 FLOOD AFFECTED AREA

The Indo-Gangetic and Brahmaputra river basins are the most chronic flood prone areas and are regarded as the worst flood affected region in the world (Agarwal and Sunita, 1991). Every year states like Assam located in Brahmaputra basin and Bihar, Uttar Pradesh and West Bengal located in Indo-Gangetic basin face severe flood problems due to the huge amount of discharge and large volume of sediments brought down from the Himalayan Rivers and their tributaries during the monsoon season. The recurring floods cause loss of life, destruction and damages to existing infrastructure, including roads, bridges, embankments and agricultural land and stress the need for identification of flood prone areas in the country. Identification of flood prone areas is one of the most important non-structural measures for mitigation of floods (Jain et.al. 2005).

Flood hazard zonation facilitates appropriate regulation, and development of floodplains thereby reducing the flood impact. The recurrent flood events at frequent intervals demand the need for identification of flood hazard prone areas for prioritizing appropriate flood control measures. In this context, satellite remote sensing plays an important role in delineating such flood hazard zones.

Generation of the Flood hazard zones was done based on the analysis of multi-temporal satellite data acquired during the floods of 2003-2013. Three major steps are involved in preparation of flood hazard zonation maps.

i. **Satellite data Planning and Acquisition**: Data from Indian Remote Sensing Satellites (IRS) and Landsat satellites was acquired during the floods. The water levels observed at different gauge stations were closely monitored during floods and attempts were made to program the satellite data during peak/near peak situations.
ii. **Rectification**: The acquired satellite datasets were geo-rectified to Lambert Conformal Conic projection system with Modified Everest Datum for achieving positional accuracy.
iii. **Flood inundation layer preparation**: Using image processing classification algorithms, water layer was extracted from the satellite data and integrated with the pre-flood river and water bodies layer to derive flood inundation layer.

Flood hazard zone map of Rapti - Sharda - Ghaghra Basin as obtained from NRSC is shown in Fig. 3.7, while Fig. 3.8 shows flood hazard zone map of Rapti basin.

FLOOD HAZARD ZONES

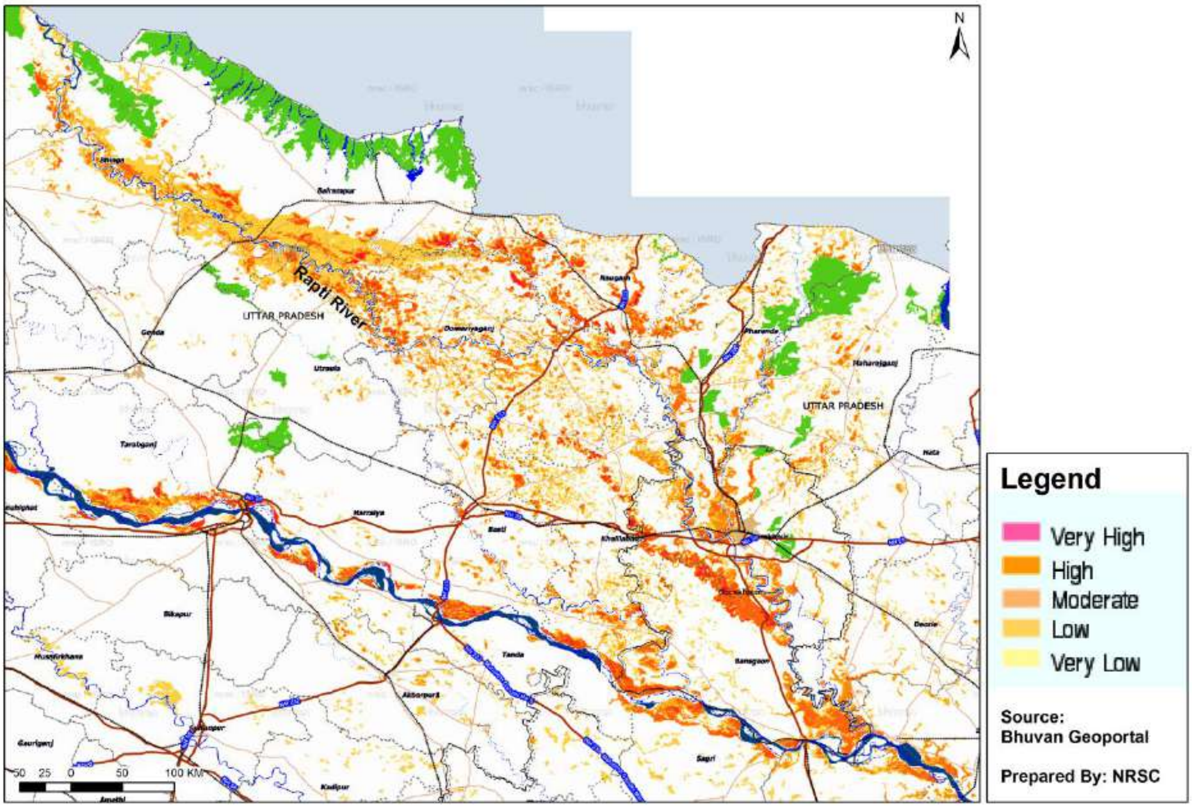


Figure 3.7 Flood hazard zone map of Rapti - Sharda - Ghaghra basin (Source: NRSC)

AGGREGATED FLOOD MAP (2003-2013)

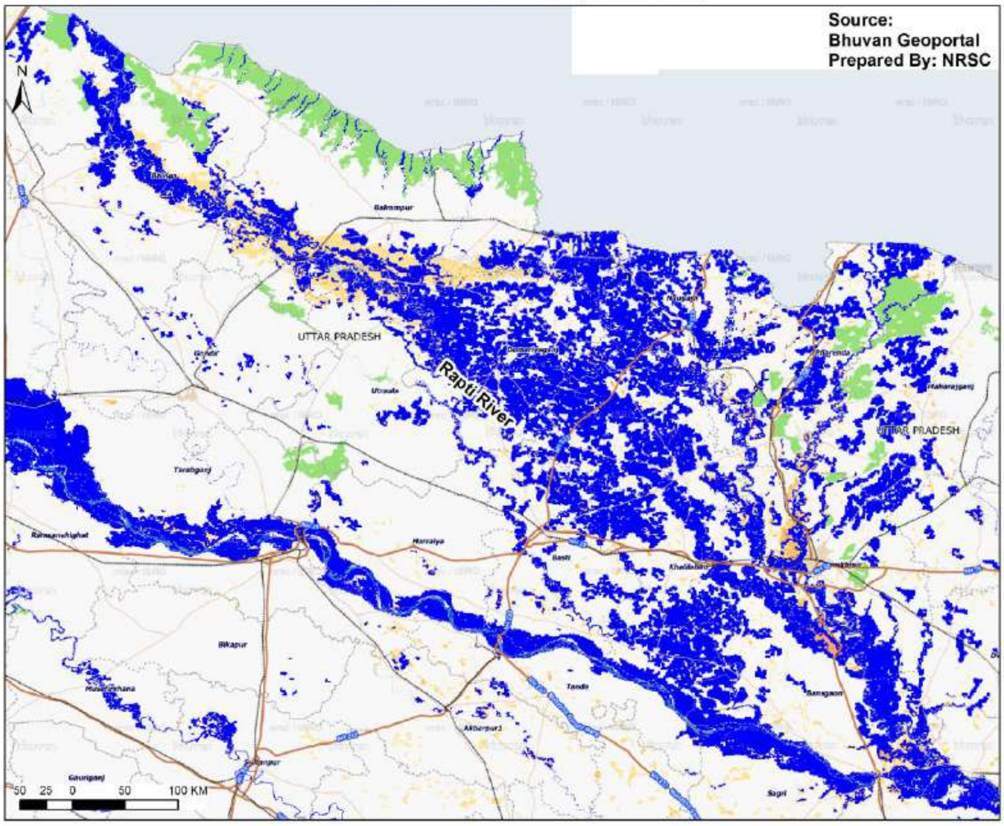


Figure 3.8 Aggregated flood map of Rapti basin from 2003-2013 (Source: NRSC)

3.7 CONCLUDING REMARKS

Various aspects of the Rapti basin related to topography, soil, climate, geology, meteorological stations, land use land cover, flood map etc. are compiled in this chapter from the different sources like GSI, WRIS and NRSC.

Chapter 4 STUDY REACH

4.1 THE STUDY AREA

The reach of the Rapti river studied in this project work is from Nepalganj to confluence point of Rapti and Ghaghra which lies between longitudes 81°03'00" E to 83°45'06" E and latitudes 26°18'00" N to 28°05'00" N as shown in Fig. 4.1. Rapti river covers an area of 25,793 km^2 out of which 44% (11,401 km^2) lies in Nepal and 56% (14,392 km^2) in Uttar Pradesh. A photograph of confluence point of Rapti and Ghaghra rivers is shown in Fig. 4.2. The Rapti river flows in the sub-humid to humid monsoon region of the middle Ganga plain. It is the largest tributary of river Ghaghra, which itself is one of the major tributaries of the Ganga River. Rapti River flows through the districts of Rukum, Salyan, Rolpa, Gurmi, Arghakhanchi, Dang and Banke of Nepal territory; and Bahraich, Shrawasti, Balrampur, Siddharthnagar, Santkabinagar, Gorakhpur and Deoria districts of the Eastern Uttar Pradesh.

The Rapti river basin is diverse in its physiography. The lofty mountain, inner and outer tarai and undulating plain regions constitute the topography of the entire basin. Due to difference in altitude, the Rapti river has two distinct climatic regions, the temperate climate prevails in the mountainous region while the plain has subtropical climate. Himalayas has a temperate climate. Summers are warm and winters are cool to severe. Subtropical Climate plain region experiences typical monsoon type of climate with dry winter season. The weather is very hot in summers. Daily maximum temperature goes upto 46.5°C. The western part is hotter than the eastern part.

The Rapti River was historically known as Iravati. The river originates in the Siwalik Himalayas of Nepal at an elevation of 3050 m. After flowing through Nepal, it enters eastern Uttar Pradesh in Chanda Pargana, east of the Kundwa village of Bahraich District. It flows in a very sinuous course with shallow depth and causes heavy flooding in the districts of eastern Uttar Pradesh. The Rapti River has a total length of about 776 km from its origin to its confluence with the Ghaghra at Barha. Out of this, 290 km lie in Nepal territory. After the hair pin bend just above the Indo-Nepal border, the river maintains a south-easterly direction passing through a number of lakes and swamps and some abandoned water courses.

The course of the Rapti River can be divided into three sections. The first section is mountainous, in this section, the river runs in a longitudinal valley. It receives the combined waters of Madi, Lungi and Jhirmuk. The altitude drops from 3000 m to 1500 m and the slope of this section is steep.

The second section of the river is called Rapti Dun. This section of the river flows up to Nepalganj. Here, the river turns south presenting an elbow towards Nepalganj. The altitude of this section varies from 300 m to 150 m.

In the third section, the Rapti River enters the tarai region of eastern Uttar Pradesh. In this tarai region, the gradient is very low throughout its easterly. The altitude of this section varies from 100 m to 80 m. Other salient features of the Rapti basin are as follow:

Drainage Area	: 25,793 km^2
Important Tributaries within Study Reach	:Bhakia, Gaura, Kacna, Kunhara, Sunawan
Important Habitat	:Gorakhpur, Bansi, Balrampur, Baharaich,
Water Resources Projects	: Rapti Barrage, Rapti Sarayu Canal (Fig. 4.3)

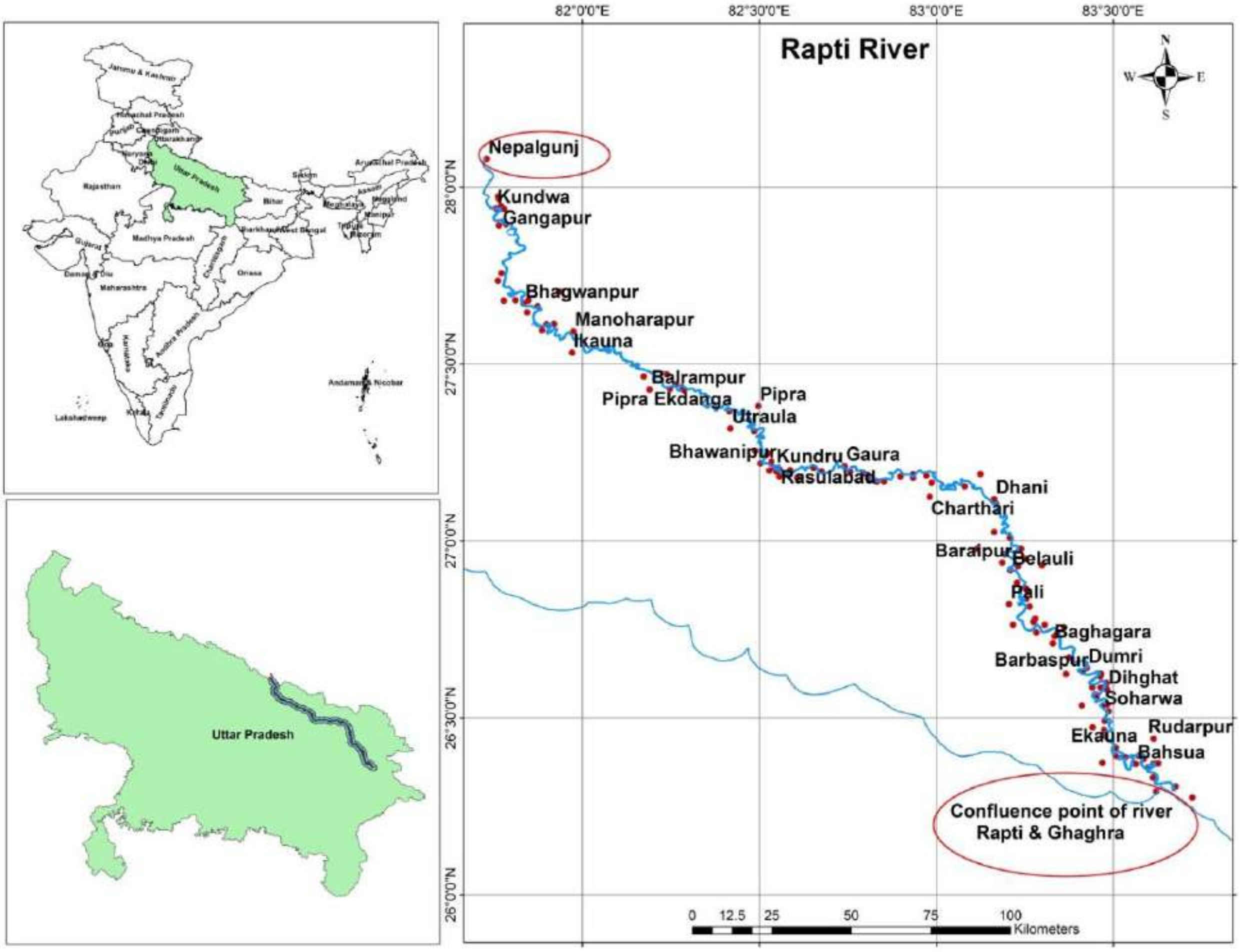


Figure 4.1 River Rapti from Nepalgunj to confluence point of Rapti and Ghaghra

Figure 4.2 Confluence point of Rapti and Ghaghra river

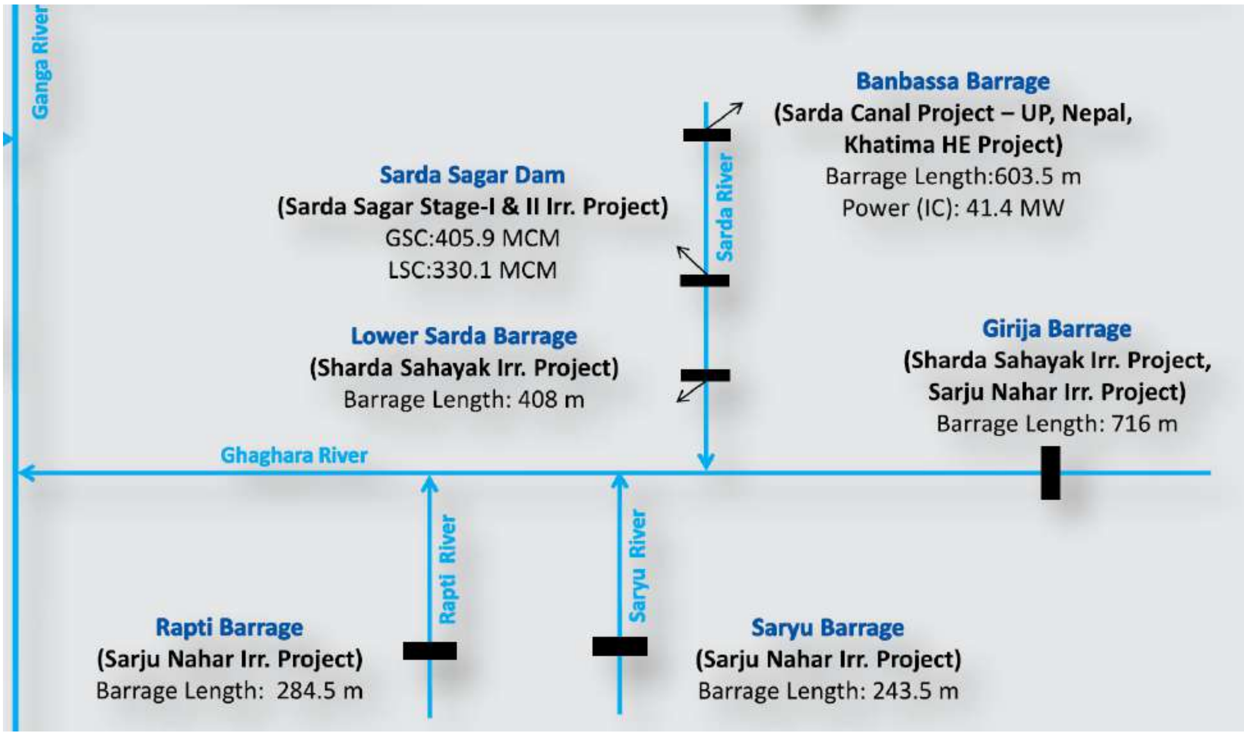


Figure 4.3 Major water resources projects (Source: INDIA-WRIS, 2012)

4.2 CONCLUDING REMARKS

Morphological changes of the rivers are more pronounced in the plain area. Therefore considered reach of the Rapti river in this study is relatively flat and varies from elevation 150 m to 80 m. It starts from Nepalganj and ends at Confluence point of Rapti river with Ghaghra river.

Chapter 5 INPUT DATA & METHODOLOGY

5.1 HYDRO-METEOROLOGICAL DATA

The various gauging sites on Rapti River as given in Table 5.1 and shown in Fig. 5.1 were identified and requisition was sent to concerned Chief Engineers of CWC for the procurement of the data comprising of annual maximum and minimum discharge and water level, 10-daily water level, discharge and silt data and also cross-section data.

Table 5.1 Hydro-meteorological data

S. No.	Name of River	Name of G&D Sites	District	Chainage (km)	Concerned Agency
1.	Rapti	Kakardhari	Gonda, UP	517	CWC (MGD-I), Lucknow
2.	Rapti	Balrampur	Gonda, UP	396	CWC (MGD-I), Lucknow
3.	Rapti	Bansi	Basti, UP	250	CWC (MGD-I), Lucknow
4.	Rapti	Rigauli	Gorakhpur, UP	183	CWC (MGD-I), Lucknow
5.	Rapti	Gorakhpur (Birdghat)	Gorakhpur, UP	120	CWC (MGD-I), Lucknow

Following data have been received:

a) Gauging Site: Kakardhari

Maximum water level from year 1971-2015

b) Gauging Site: Balrampur

Maximum water level from year 1971-2015

Maximum discharge from year 1971-2015

10-daily silt data year 1985-2015

Cross-sectional data: Pre-monsoon 2010 to 2014

Post-monsoon 2013 to 2014

c) Gauging Site: Bansi

Maximum water level from year 1971-2015

d) Gauging Site: Rigauli

Maximum water level from year 1975-2015

Maximum discharge from year 1975-2015

10-daily silt data from year 1975-2015

Cross-section data: Pre-monsoon 2010 to 2014

Post-monsoon 2010, 2012, 2013

e) Gauging Site: Birdghat

Maximum water level from year 1960-2015

Maximum discharge from year 1960-2015

10-daily silt data from year 1964-2015

Cross-sectional data: Pre-monsoon 2010 to 2014

Post-monsoon 2010, 2012, 2013

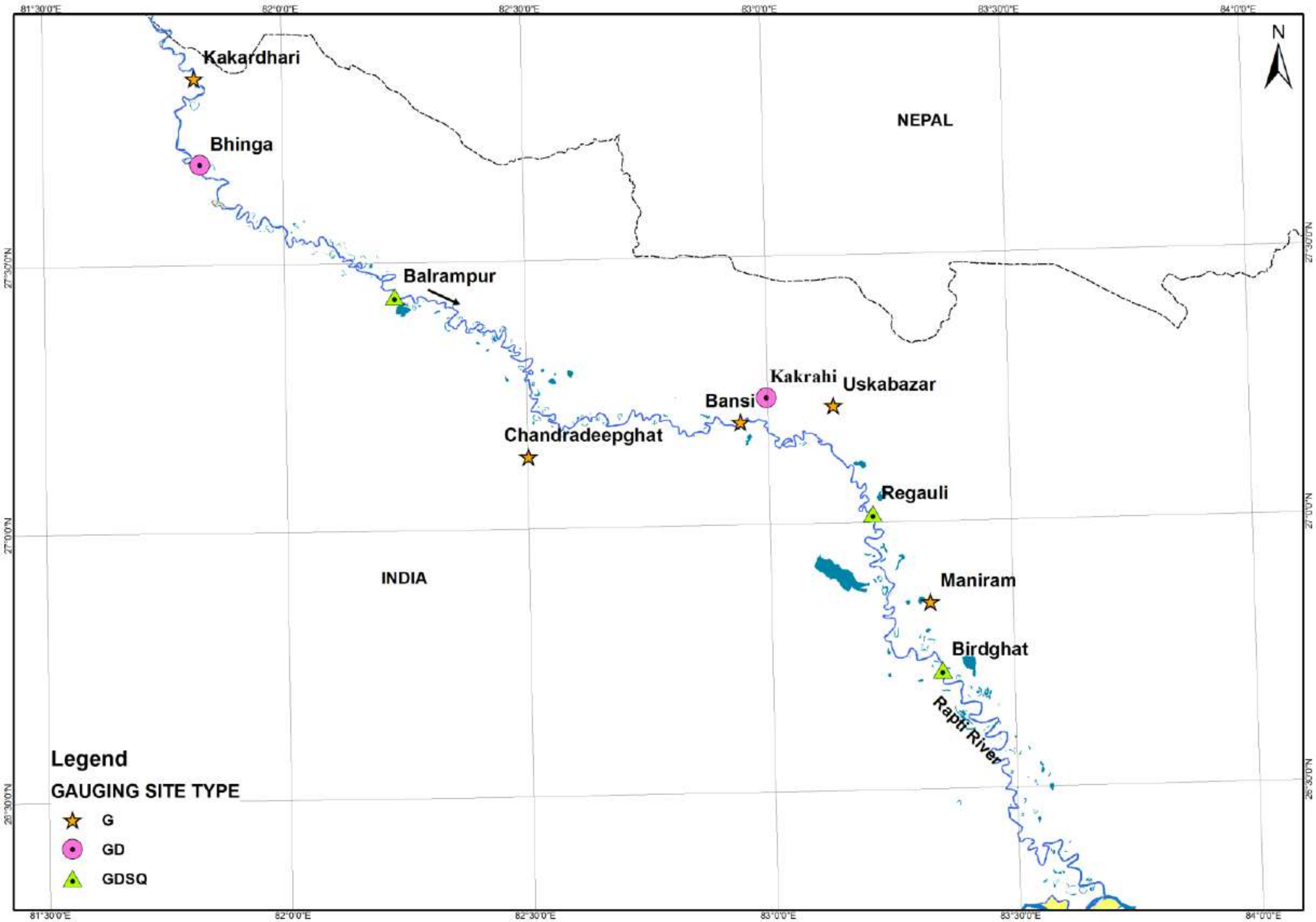


Figure 5.1 Location of gauging Sites

5.2 TOPOSHEETS AND SATELLITE DATA

For the present study, data have been collected from Government agencies and organizations, like National Remote Sensing Centre (NRSC), Survey of India (SOI) etc. Details regarding topographical maps and remote sensing data used herein are given in Table 5.2 and the specifications of sensors are given in Table 5.3.

Table 5.2 Data used and their sources

Toposheets						
S. No.	**Data**			**Data Source**	**Date/Year**	**Scale**
1	Toposheets			SOI, Dehradun	1970 onwards	1:50,000
	63 E/9	63 E/13	63 E/14			
	63 I/2 (1970)	63 I/3 (1970)	63 I/7 (1915)			
	63 I/8 (1970)	63 I/11 (1970)	63 I/12			
	63 I/16 (1915)	63 M/4	63 N/1 (1973)			

Remote Sensing Digital Data					
2	**Sensor**	**Data Source**	**Date/Year**	**Path**	**Row**
	Landsat MSS	GLCF & USGS website	26/01/1979	153	41
			10/17/1980	153	42
			30/09/1980	154	41
	IRS 1A LISS II (Each Scene of LISS II contains 4 satellite images A1, A2, B1, and B2)	NRSC Hyderabad	25/11/1990	23	49
			18/12/1990	24	48
			05/11/1990	25	48
	IRS 1C LISS III	NRSC Hyderabad	13/10/2000	100	52
			18/10/2000	101	52
			29/09/2000	102	52
			23/10/2000	102	53
	IRS P6 LISS III	NRSC Hyderabad	02/11/2010	100	52
			18/10/2010	101	52
			12/11/2010	102	52
			12/11/2010	102	53
	Resource 2 LISSIV	NRSC Hyderabad	09/11/2011 12/11/2015	100	52 B
			18/02/2012 24/10/2015	101	52 A
			18/02/2012 24/10/2015	101	52 B
			26/10/2011 05/10/2015	102	52 C
			26/10/2011 05/10/2015	102	52 D
			05/10/2011 16/12/2015	103	53 A
			05/10/2011 16/12/2015	103	53 B

Table 5.3 Sensors specifications

Specifications	LANDSAT MSS	IRS 1A LISS II	IRS 1C LISS III	IRS P6 LISS III
Spectral Bands	1-5	1-4	1-4	1-4
Spatial Resolution (m)	60	36.25	23.5	23.5
Swath Width (km)	185×185	141	141	141
Radiometric Resolution (bits)	8	7	7	7

5.3 SOFTWARE

The flowing softwares have been used in this study

- ArcGIS 10.2
- ERDAS Imagine 10.1
- Microsoft Office & Excel
- Sigma Plot
- Matlab

5.4 ACQUISITION OF DATA AND GEO-REFERENCING OF IMAGES

Firstly, the Survey of India toposheets (1:50000 scale) which covers the area of interest are procured. Then, these toposheets have been geo-referenced and ortho-rectified using first order polynomial and Lambert Conformal Conic (LCC) projection type with the help of ERDAS Imagine 2014 software, before initiating the analysis. After geo-referencing, clipping and mosaicing have been done.

Relevant satellite images were procured from the NRSC (National Remote Sensing Centre), Hyderabad or downloaded from United States Geological Survey (USGS) website. Pre-processing of the satellite images have been carried out using filters such as histogram equalization and matching etc. to improve and equalize the brightness levels of similar features and provide uniform information. After mosaicing the toposheets, all the satellite images were geo-referenced using image to image method by selecting several control points. The RMS error has been kept below the half pixel size. After geo-referencing, images have been mosaiced to cover the entire study area. For mosaicing feather option of the software has been used to get the seamless boundaries between different images of the same year.

5.5 METHODOLOGY FOR PLAN FORM CHANGES

Plan form of the rivers may be described as straight, meandering or braided. There are in fact a great range of channel patterns from straight through meandering to braid. Methodology adopted to fulfil the objective in respect of planform changes of the river is shown in Fig. 5.2 in a form of a methological flowchart:

In the present study of morphology of Rapti River, sinuosity ratio and PFI index of the river shall be estimated using the satellite images for different years. The temporal and spatial variation of sinuosity ratio and PFI index for different reaches shall be shown graphically.

5.6 FLOW PROBABILITY CURVES

Flood frequency analysis shall be carried out for the recorded discharge data at various CWC gauging sites on the river for the estimation of discharges for 1.5 to 2 year return periods. Discharge for higher return periods shall also be estimated using frequency analysis to correlate the peak discharges with the morphological parameters of the rivers. Details of the frequency analysis are given below:

Frequency analysis of recorded maximum stream flow data is an important flood-runoff analysis tool. The objective of flood frequency analysis is to infer the probability of exceedance of all possible discharge values (the parent population) from observed discharge values (a sample of the parent population). This process is accomplished by selecting a statistical model that represents the relationship of discharge magnitude and exceedance probability for the parent population. The parameters of the models are estimated from the sample.

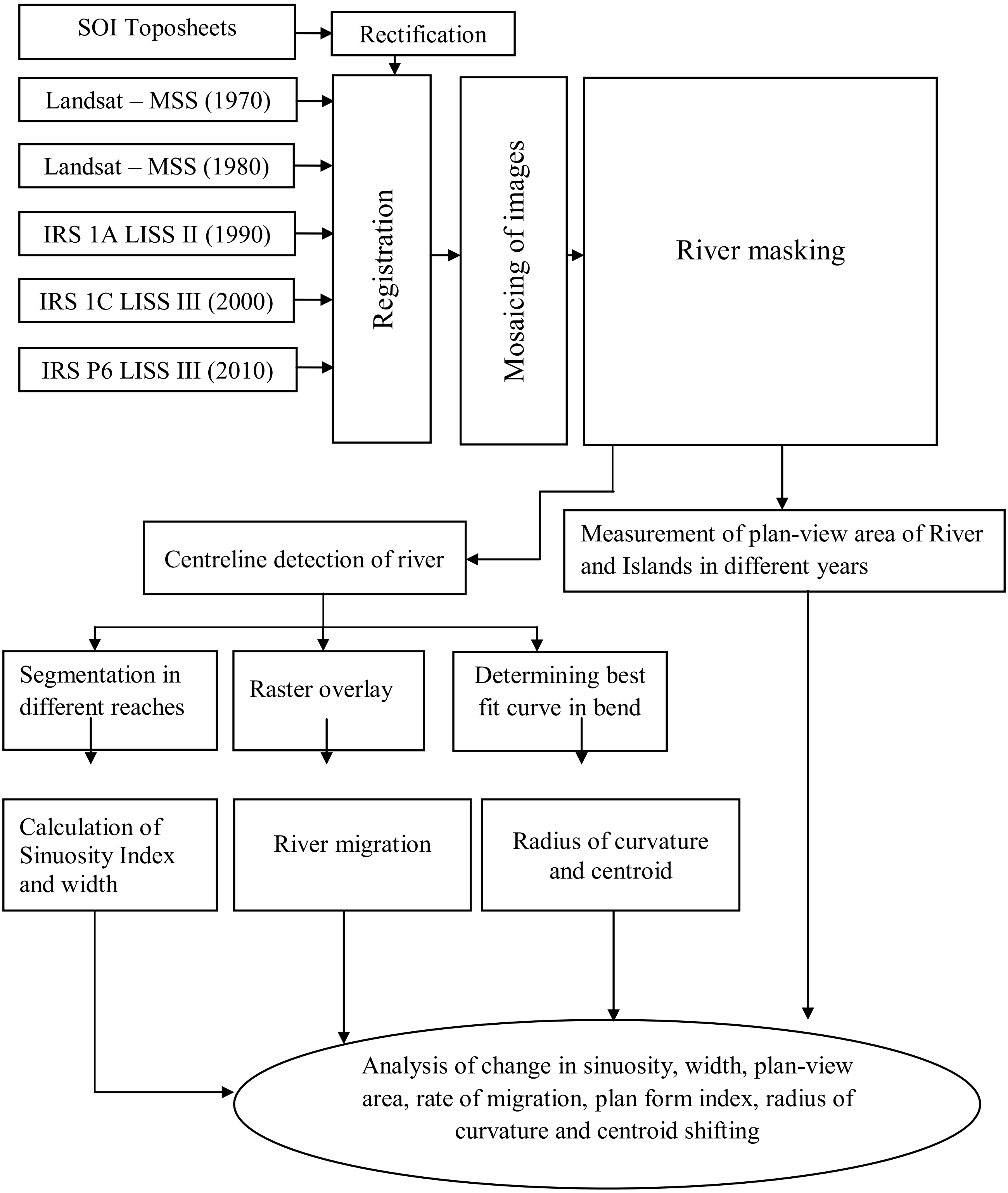


Figure 5.2 Flowchart of the methodology

Commonly used methods for the frequency analysis are

(a) Graphical methods

In this method, the annual maximum flood data are arranged in descending order and rank is assigned to each data. The highest flood data is assigned a rank 1 second highest 2 and like-wise others. This arrangement of data gives an estimate of the exceedance probability, that is, the probability of a value being equal to or greater than the ranked value. The probability of a data being equal to or exceeded is calculated by Weibull formula

$$P = \frac{m}{N+1} \tag{5.1}$$

where m is the rank of the data and N is the total number of the data. The return period for the event

$$T=1/P \tag{5.2}$$

A plot of discharge Q vs time T yields the probability distribution. Return period for any discharge can be read from the fitted data on the probability plot.

(b) Analytical methods

Commonly used frequency distribution functions for the prediction of extreme flood values analytically are

i. Gumbel's extreme value distribution method

ii. Log-Pearson Type-II distribution

iii. Log normal distribution

The best fitted probability distribution shall be used to estimate the discharge for higher return period.

In addition to the above, hydraulic structures constructed across and along the rivers like barrages, bridges etc shall be identified from Google Earth images and details of those structures shall be collected from concerned department. The morphological changes of the river in the vicinity of the structure shall be studied using high resolution images and changes in morphology due to construction of the structure shall be assessed in the form of shifting of banks and erosion/deposition of the sediments.

5.7 CONCLUDING REAMRKS

The following tasks shall be performed in this study

- Reach-wise temporal analysis of main (deeper channel), left and right bank of river.
- Estimation of eroded/deposited area of the river, and their presentation in a graphical form, with length of the river on x-axis and erosion & deposition on y-axis.
- Length-wise variation of sinuosity ratio and Plan Form Index (PFI) for the evaluation of meandering and braiding patterns of the river.
- Identification of levels of braiding using Plan Form Index threshold values.
- Detailed analysis of the shifting of river in the critical reaches using high resolution satellite images.
- Plotting of probability curve for discharge at various gauging sites of the river using the recorded flow data for 1.5 years and 2 years return period.
- Flood discharge for higher return periods shall also be computed using the frequency analysis.
- After the identification of critical reaches, that will be characterized by major left and right bank shifting inserting heavy erosion/deposition, river training works in the form of flood walls, guide bunds, sparse submerged vanes, porcupines etc. shall be suggested.
- Reconnaissance survey shall be carried out near the major hydraulic structures and also the critical reaches to assess the morphological changes of the river onset of the construction of the hydraulic structures.

Chapter 6 HYDROLOGICAL DATA PROCESSING & ANALYSIS

6.1 INTRODUCTION

In this chapter, available discharge and water level data at the various gauging sites of the Rapti river have been analysed. Trend analysis of the maximum discharge and maximum water level has been carried out to investigate the trend of variation of the data. Further, peak discharge for different return periods have also been estimated using frequency analysis.

6.2 HYDROLOGICAL DATA

The various gauging sites on Sharda River as given in Table 6.1 were identified and requisition was sent to concern Chief Engineers of CWC for the procurement of the data.

Table 6.1 Hydrological data of Rapti river

S. No.	Name of River	Name of G&D Sites	District	Chainage (km)	Concerned Agency
1.	Rapti	Kakardhari	Gonda, UP	517	CWC (MGD-I), Lucknow
2.	Rapti	Balrampur	Gonda, UP	396	CWC (MGD-I), Lucknow
3.	Rapti	Bansi	Basti, UP	250	CWC (MGD-I), Lucknow
4.	Rapti	Rigauli	Gorakhpur, UP	183	CWC (MGD-I), Lucknow
5.	Rapti	Gorakhpur (Birdghat)	Gorakhpur, UP	120	CWC (MGD-I), Lucknow

Following data have been received:

a) Gauging Site: Kakardhari

Maximum water level from year 1971-2015

b) Gauging Site: Balrampur

Maximum water level from year 1971-2015

Maximum discharge from year 1971-2015

10-daily silt data year 1985-2015

Cross-sectional data: Pre-monsoon 2010 to 2014

Post-monsoon 2013 to 2014

c) Gauging Site: Bansi

Maximum water level from year 1971-2015

d) Gauging Site: Rigauli

Maximum water level from year 1975-2015

Maximum discharge from year 1975-2015

10-daily silt data year 1975-2015

Cross-section data: Pre-monsoon 2010 to 2014

Post-monsoon 2010, 2012, 2013

e) Gauging Site: Birdghat

Maximum water level from year 1960-2015

Maximum discharge from year 1960-2015

10-daily silt data year 1964-2015

Cross-sectional data: Pre-monsoon 2010 to 2014

Post-monsoon 2010, 2012, 2013

6.3 TEMPORAL VARIATION OF MAXIMUM DISCHARGE AND MAXIMUM WATER LEVEL

Temporal variation of maximum observed discharge and maximum observed water level on various gauging sites on Rapti river has been carried out using the available data. Temporal variation of the maximum observed discharge during period 1971-2015 at Balrampur, during 1975-2015 at Rigauli, during 1960-2015 at Birdghat are shown in Figs. 6.1a-c, respectively. It may be concluded that maximum discharge at Balrampur has decreasing trend, however, no trend has been found at Rigauli and Birdghat gauging sites. Like-wise Figs 6.2a-e show process is accomplished by selecting a statistical model that represents the relationship of discharge magnitude and exceedance probability for the parent population. The parameters of the models are estimated from the sample.

Annual maximum observed discharge data at gauging sites Balrampur (1971-2015), Rigauli (1975-2015), Birdghat (1960-2015) on Rapti river have been used to estimate the flood discharge for different return periods. Following distribution methods have been used herein.

(a) **Gumbel's Extreme Value Distribution method**

The annual maximum discharge for T year returns period Q_T is defined as

$$Q_T = \overline{Q} + K\sigma$$

Where $\overline{Q}$ = average of annual maximum discharge

σ = standard deviation of available annual maximum discharge data

K = Frequency factor and expressed as

$$K = \frac{y_T - \overline{y}_n}{S_n}$$

y_T = reduced variate and function of return period T

$$y_T = -\left[\ln.\ln\frac{T}{T-1}\right]$$

$\overline{y}_n$ = mean and function of sample size, N

S_n = reduced standard deviation and function of N

T = Return period in year

(b) Log-Pearson Type III Distribution method

In this method, the variate is first transformed into logarithmic form and the transformed data is then analysed. For any return period T

$$Z_T = \overline{Z} + K_z\sigma_z$$

and Z = log (Q)

Where Q = variate of available flood data

σ_Z= standard deviation of the Z variate== $\sqrt{\frac{(Z-\bar{Z})^2}{N-1}}$

K_z = Frequency factor and function of return period T and the coefficient of skewness, C_s of variate Z.

$$C_s = \frac{N\sum(Z-\bar{Z})^3}{(N-1)(N-2)\sigma_z^3}$$

$\bar{Z}$ = mean of the variate Z

N = number of sample, i.e. discharge data

(c) Log Normal Distribution method

Log-Pearson Type III distribution reduces to Log normal distribution when the coefficient of skewness of variate Z is zero, i.e., C_s =0. Procedure for estimation of peak discharge would be same as the Log pearson Type III distribution method.

Estimated peak discharge at Palia kalan using different probability methods are given in Table 6.2.

Table 6.2 Peak discharge of various return periods from various distributions

Method	Station	Peak Discharge (m^3/s)		
		Return period		
		25 yr	50 yr	100 yr
Gumbel's Extreme Value	Birdghat			
	Rigauli			
	Balrampur			
Log Normal	Birdghat			
	Rigauli			
	Balrampur			
Log Pearson Type III	Birdghat			
	Rigauli			
	Balrampur			
Average value-->	Birdghat			
	Rigauli			
	Balrampur			

6.5 PROBABILITY EXCEEDANCE CURVE

Probability exceedance curve for estimation of the discharges for 1.5 to 2 year return periods using 10-daily discharge data have not been carried out due to unavailability of the data.

6.6 CONCLUDING REMARKS

Analysis of maximum observed discharge and maximum observed water level at different gauging sites on Rapti river using the available data indicates that there is no remarkable trend of temporal variation of maximum discharge and maximum water level at the gauging sites Kakardhari, Balrampur, Bansi, Rigauli and Birdghat over a long period of time.

However, maximum discharge at Balrampur has decreasing trend, however, no trend has been found at Rigauli and Birdghat gauging sites. The maximum water level has increasing trend at Kakardhari and Balrampur and decresing trend at Bansi, however, no trend was found at gauging sites of Rigauli and Birdghat.

Chapter 7 RIVER MORPHOLOGY

7.1 DELINEATION/DIGITIZATION OF RIVER BANK LINES

The river bank lines have been identified and delineated from mosaics for all the satellite images of year 1970, 1980, 1990, 2000 and 2010 as shown in Figs. 7.1 to 7.5. The identified river bank lines for the left, right and center (main channel) have been digitized using ArcMap software. The left bank, right bank and centerline have been prepared for the years 1970, 1980, 1990, 2000 and 2010. The length of arcs of the left bank, right bank and centerline for all the above years has been calculated using GIS software. Shifting of centerline, left bank, right bank of the river has been evaluated with respect to river course of year 2010.

Figure 7.1 Mosaic of SOI toposheets of Rapti river of year 1970 (Scale 1:50,000)

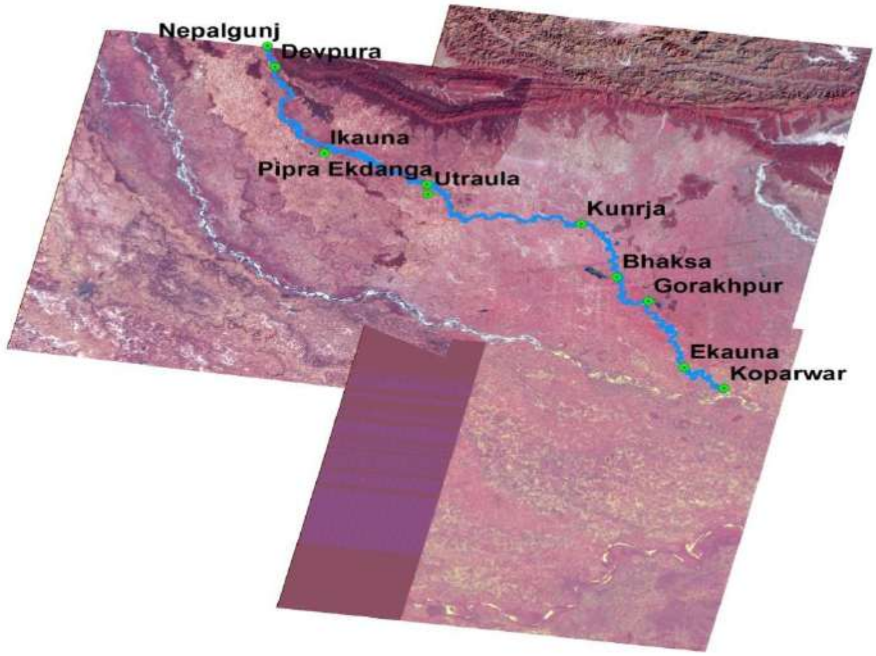


Figure 7.2 Mosaic of FCC of Rapti river of year 1980 (Landsat-MSS Images)

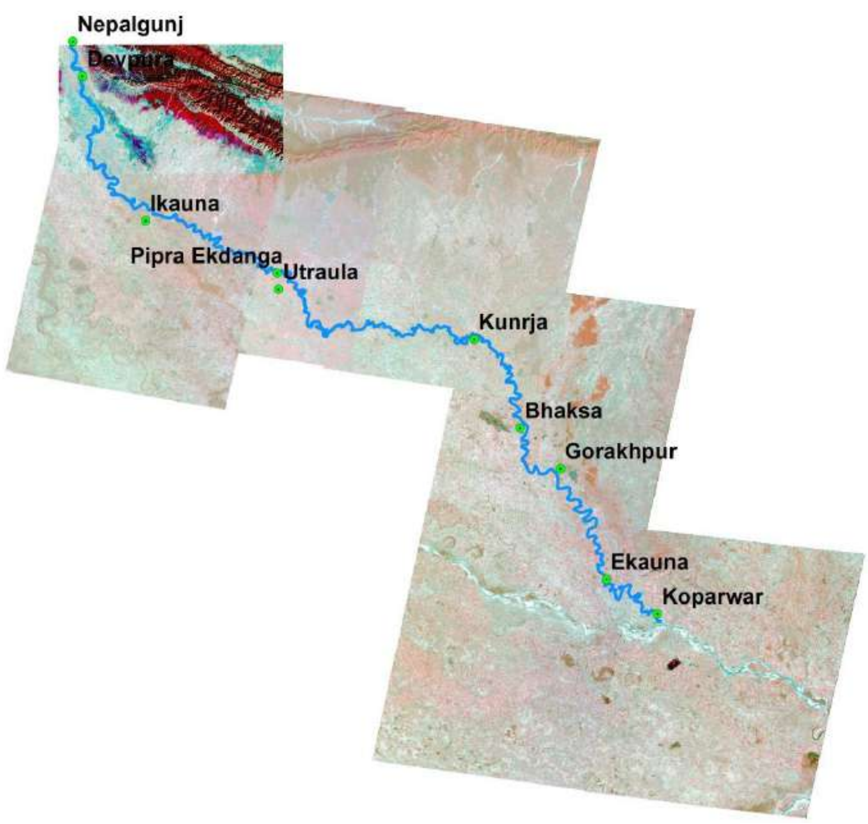


Figure 7.3 Mosaic of FCC of Rapti river of year 1990 (IRS 1A LISS II Images)

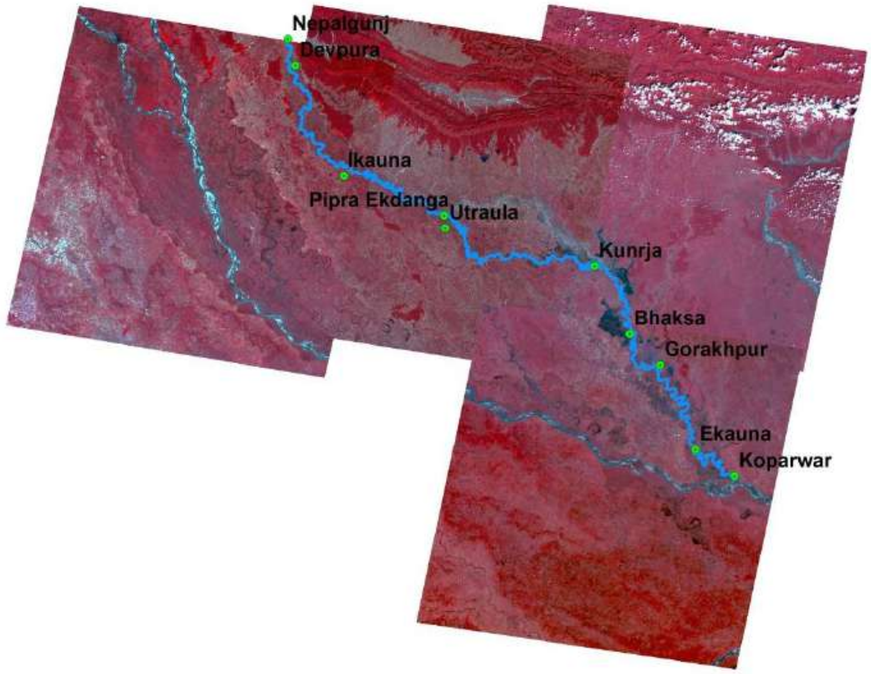


Figure 7.4 Mosaic of FCC of Rapti river of year 2000 (IRS 1C LISS III Images)

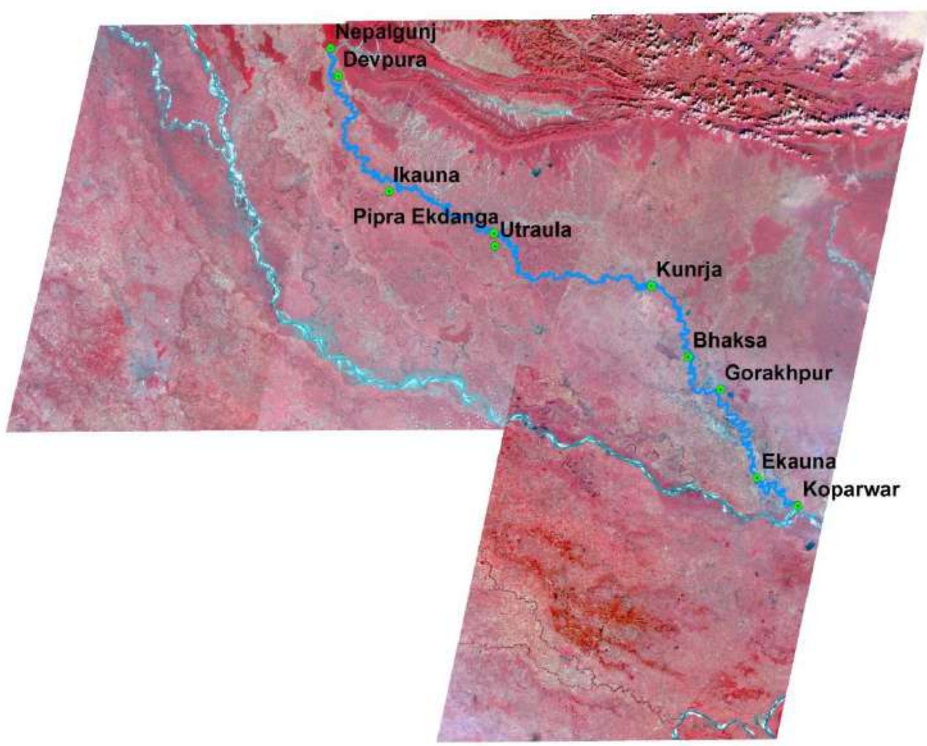


Figure 7.5 Mosaic of FCC of Rapti river of year 2010 (IRS P6 LISS III Images)

Total length of the Rapti river from Nepalganj to the confluence point of Rapti and Ghaghra is divided into eleven reaches, ten reaches of 50 km length each and last one reach of 42 km length. Such reaches are described below:

Table 7.1 Reaches of the Rapti River

Chainage in km	Start to end location	Start to end location
0 - 50	Reach A	Koparwar to Ekauna
50 - 100	Reach B	Ekauna to Barbaspur
100 - 150	Reach C	Barbaspur to Mirpur
150 - 200	Reach D	Mirpur to Garlana
200 - 250	Reach E	Garlana to Narkatha
250 - 300	Reach F	Narkatha to Domariaganj
300 - 350	Reach G	Domariaganj to Utraula
350 - 400	Reach H	Utraula to Balrampur
400 - 450	Reach I	Balrampur to Manhorapur
450 - 500	Reach J	Manhorapur to Lachhmanpur
500 - 542	Reach K	Lachhmanpur to Devpura

7.2 PLAN FORM PATTERN OF THE RIVER

a) Sinuosity Ratio

Plan form of the rivers may be described as straight, meandering or braided. There is in fact a great range of channel patterns from straight through meandering to braided. The straight and meandering channels are described by sinuosity which is ratio of channel length to valley length or the ratio of valley slope or channel gradient as measured over the same length of valley (Schumm, 1977). A sinuosity ratio of 1.50 was considered by Leopold and Wolman (1957) to differentiate sinuous from meandering. Rivers having a sinuosity of 1.5 or greater refer to meandering, and below 1.5 straight or sinuous. Definition of the sinuosity ratio, as suggested by various investigators, is given in the Table 7.2, however, definition proposed by Leopold and Wolman (1957) is commonly used.

Table 7.2 Definition of sinuosity ratio

Sinuosity Ratio	Source
$\frac{\text{Thalweg length}}{\text{Valley length}}$	Leopold and Wolman, 1957
$\frac{\text{Channel length}}{\text{Length of Meander belt axis}}$	Brice, 1964
$\frac{\text{Stream length}}{\text{Valley length}}$	Schumm, 1963

The modified sinuosity parameter, P, as defined by Friend and Sinha (1993) has been used for this study.

$$P = L_{cmax}/L_R \tag{7.1}$$

Where, L_R is overall length of the channel belt reach measured along a straight line, or the valley length, and L_{cmax} is the mid channel length for the same reach or the stream length. The sample map that depicts the computation of river sinuosity is shown in Fig. 7.6a. Fig 7.6b shows channel patterns for different Sinuosity ratio.

It is apparent from Fig. 7.7 that there is no definite progressive change in the sinuosity ratio of the Rapti river in the span of time 1970 to 2010 in the studied reach. High sinuosity ratio was noticed in the reach of Chainage 25-50 km, 75-100 km and 300-425 km. Rapti river possess lower sinuosity ratio in upper reaches.

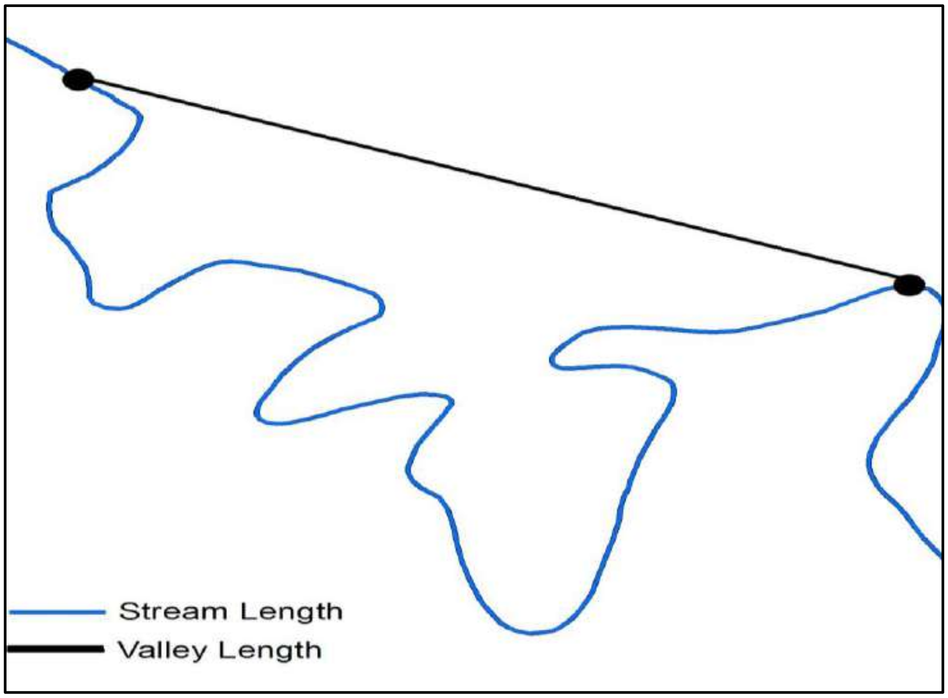


Figure 7.6a Diagram representing the calculation of the sinuosity

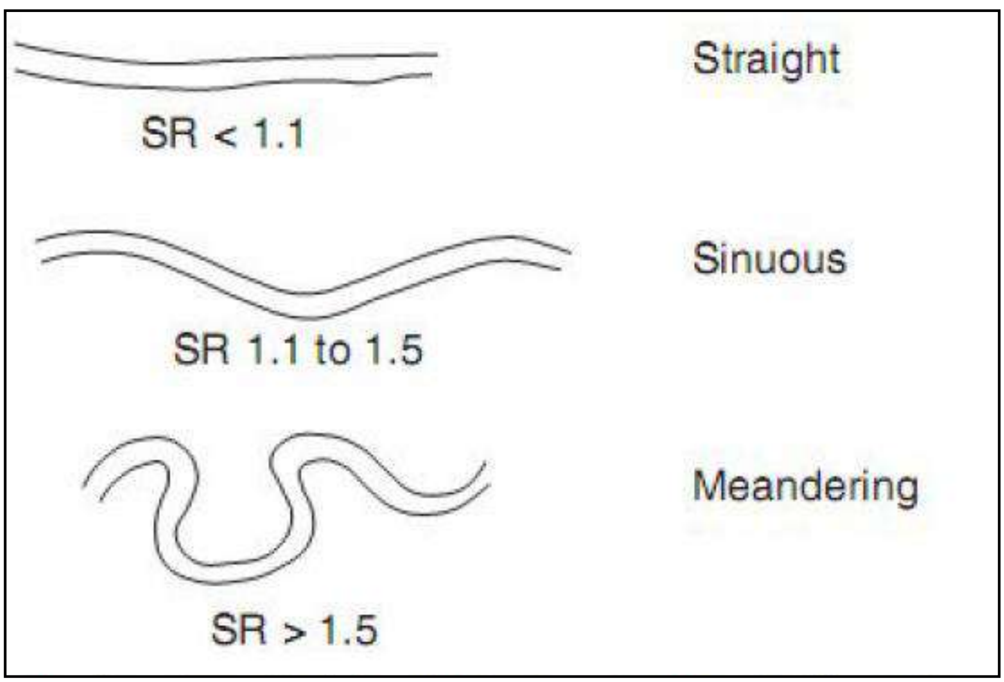


Figure 7.6b Channel patterns for different Sinuosity ratio

Rapti river with a length of 542 km has been divided into reaches 50 km each in length. For calculating sinuosity ratios, the river reach has been further divided into 25 km long reaches. The total length of the river has been subdivided into 21 reaches of 25 km length, the last one being 15.68 km. Equation (7.1) has been used for the computation of sinuosity ratio. The calculated values of sinuosity ratio are given in Table 7.3 and graphically shown in Fig 7.7.

The following data as given in Table 7.4 have been extracted from the computed sinuosity ratio of the Rapti river:

Table 7.4a Sinuosity ratios of the Rapti river for different years

S.No.	Year	Maximum Sinuosity	Minimum Sinuosity	Average Sinuosity
1.	1970	3	1.37	1.8
2.	1980	2.9	1.11	1.88
3.	1990	2.83	1.14	1.79
4.	2000	2.79	1.42	1.87
5.	2010	2.8	1.55	1.92

It is apparent from Table 7.3 & 7.4a and Fig. 7.7a that the sinuosity ratio of the Rapti river in the reach under consideration is higher than 1.5 in the year 1970, 1980, 1990, 2000, and 2010, therefore, the Rapti is classified as meandering river.

Table 7.3 Sinuosity ratios for Rapti river of year 1970, 1980, 1990, 2000 and 2010

Chainage (km)	Section	2010			2000			1990			1980			1970		
		L_{max}	L_R	Sinuosity	L_{max}	L_R	Sinuosity	L_{max}	L_R	Sinuosity	L_{max}	L_R	Sinuosity	L_{max}	L_R	Sinuosity
12.5	1	25.00	14.53	**1.72**	24.48	14.44	**1.70**	25.93	14.49	**1.79**	25.55	14.44	**1.77**	27.53	14.40	**1.91**
37.5	2	25.00	8.87	**2.82**	24.76	8.88	**2.79**	25.15	8.87	**2.83**	25.75	8.89	**2.90**	26.56	8.85	**3.00**
62.5	3	25.00	14.55	**1.72**	23.94	14.53	**1.65**	23.03	14.44	**1.59**	21.90	14.48	**1.51**	22.49	14.41	**1.56**
87.5	4	25.00	9.70	**2.58**	24.15	9.75	**2.48**	23.37	9.74	**2.40**	22.75	9.64	**2.36**	26.75	9.81	**2.73**
112.5	5	25.00	14.96	**1.67**	25.17	15.05	**1.67**	25.12	15.26	**1.65**	23.76	15.19	**1.56**	22.65	15.32	**1.48**
137.5	6	25.00	12.41	**2.01**	24.60	12.20	**2.02**	23.01	12.08	**1.91**	24.90	12.24	**2.04**	23.31	12.11	**1.92**
162.5	7	25.00	14.51	**1.72**	24.70	14.33	**1.72**	23.96	14.37	**1.67**	22.79	15.00	**1.52**	24.60	15.37	**1.60**
187.5	8	25.00	12.44	**2.01**	23.58	12.41	**1.90**	23.52	12.44	**1.89**	22.72	11.81	**1.92**	24.13	11.88	**2.03**
212.5	9	25.00	13.92	**1.80**	24.05	13.96	**1.72**	24.84	14.00	**1.77**	24.80	13.95	**1.78**	25.21	14.00	**1.80**
237.5	10	25.00	11.77	**2.12**	22.88	11.74	**1.95**	23.11	11.71	**1.97**	20.34	11.70	**1.74**	19.01	11.86	**1.60**
262.5	11	25.00	16.16	**1.55**	24.79	16.23	**1.53**	24.71	16.29	**1.52**	24.13	16.47	**1.47**	23.43	15.67	**1.50**
287.5	12	25.00	15.83	**1.58**	24.11	15.75	**1.53**	24.07	15.67	**1.54**	23.99	15.52	**1.55**	22.19	15.95	**1.39**
312.5	13	25.00	12.88	**1.94**	32.49	12.94	**2.51**	29.41	12.94	**2.27**	29.66	13.00	**2.28**	29.20	13.48	**2.17**
337.5	14	25.00	10.50	**2.38**	22.00	10.49	**2.10**	17.79	10.48	**1.70**	19.86	10.48	**1.89**	17.45	10.46	**1.67**
362.5	15	25.00	11.49	**2.18**	19.86	11.42	**1.74**	22.42	11.12	**2.02**	27.33	10.99	**2.49**	24.77	10.92	**2.27**
387.5	16	25.00	15.22	**1.64**	27.55	15.05	**1.83**	24.73	14.98	**1.65**	23.45	15.41	**1.52**	23.45	15.97	**1.47**
412.5	17	25.00	13.22	**1.89**	29.45	13.43	**2.19**	21.21	13.84	**1.53**	37.67	13.79	**2.73**	28.17	12.82	**2.20**
437.5	18	25.00	15.00	**1.67**	26.50	15.11	**1.75**	19.02	14.85	**1.28**	25.51	14.43	**1.77**	23.62	14.45	**1.63**
462.5	19	25.00	11.04	**2.27**	18.84	10.90	**1.73**	24.85	11.34	**2.19**	24.81	12.15	**2.04**	24.28	11.99	**2.03**
487.5	20	25.00	15.00	**1.67**	23.05	14.96	**1.54**	22.51	14.80	**1.52**	25.35	14.24	**1.78**	20.16	14.68	**1.37**
512.5	21	25.00	14.00	**1.79**	21.55	13.71	**1.57**	21.92	13.58	**1.61**	21.80	13.92	**1.57**	23.63	14.14	**1.67**
537.5	22	15.68	9.79	**1.60**	13.69	9.64	**1.42**	10.18	8.92	**1.14**	9.95	9.00	**1.11**	13.19	8.58	**1.54**
Maximum		**2.82**			**2.79**			**2.83**			**2.90**			**3.00**		
Minimum		**1.55**			**1.42**			**1.14**			**1.11**			**1.37**		
Average		**1.92**			**1.87**			**1.79**			**1.88**			**1.84**		

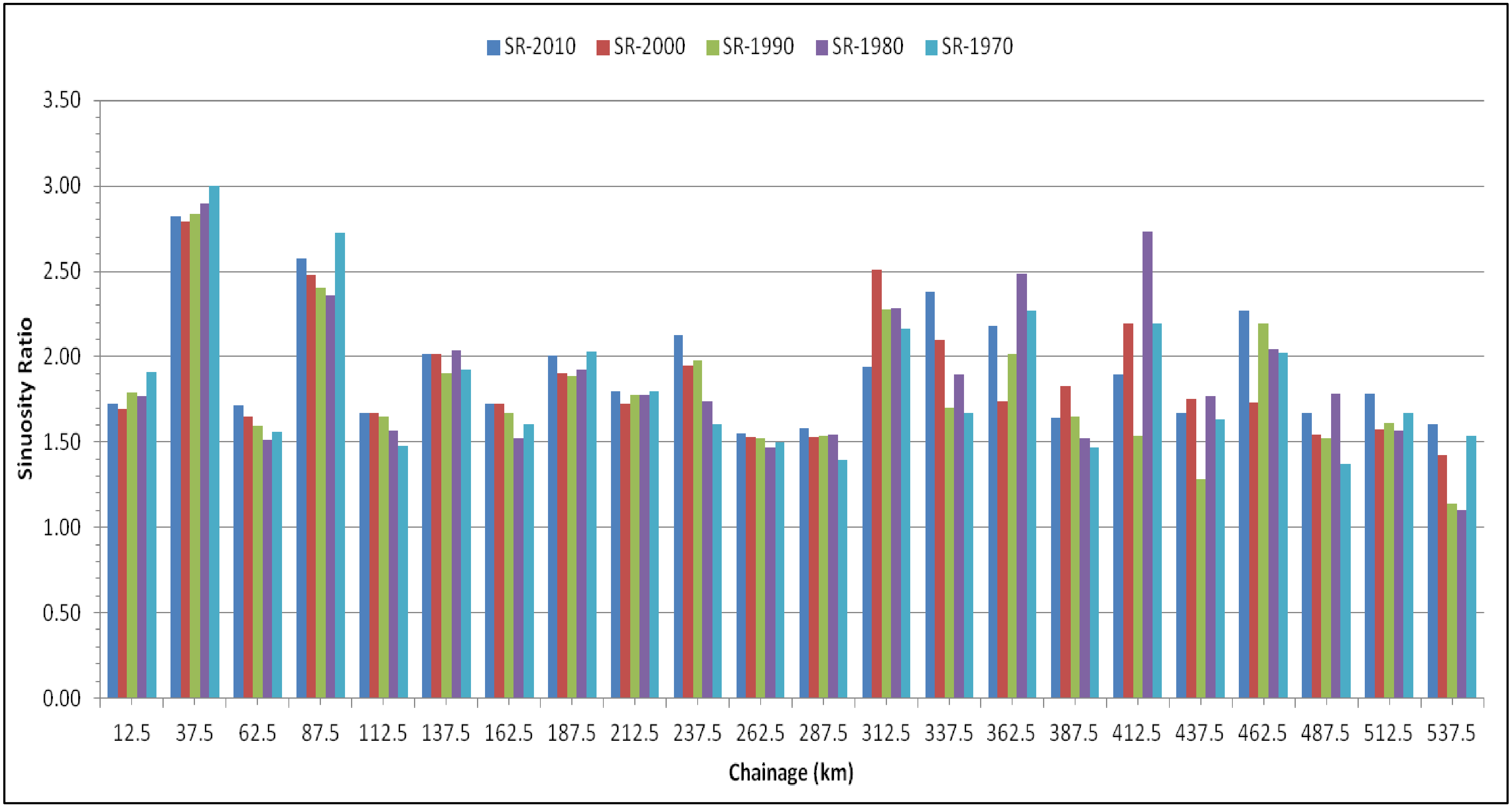


Figure 7.7a Sinuosity ratio of Rapti river of year 1970, 1980, 1990, 2000 and 2010

Geometrical parameters of the prominent meanders such as axial wavelength, amplitude and radius of curvature as shown in Fig. 7.7b have been calculated and listed in the Table 7.4b. Prominent meanders are numbered as M-1 to M-16 and shown in Figures 7.7c-h.

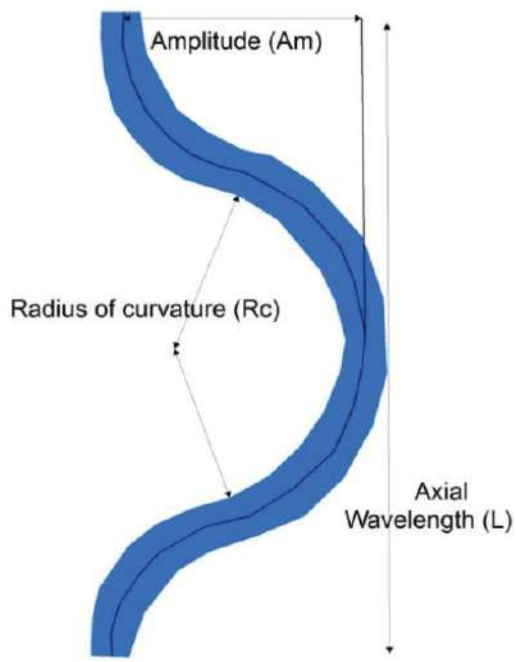


Figure 7.7b Geometrical parameters of a river meander (Sinha 2012)

Table 7.4b Geometrical parameters of the prominent meanders in the Rapti river

Meander No.	Chainage (km)	Location	Year	Axis wave length (km)	Amplitude (km)	Radius of Curvature (km)
M-1	8	Sareya	1970	1.5	2.8	0.8
			1980	SR~1		
			1990	SR~1		
			2000	SR~1		
			2010	SR~1		
M-2	35	Bahsua	1970	2	3.5	0.9
			1980	2	3.5	0.9
			1990	2	3.5	0.9
			2000	2	3.5	0.9
			2010	2	3.5	0.9
M-3	83	Kanail	1970	3.5	3.7	1.3
			1980	3.3	3.5	1.3
			1990	3.3	3.5	1.3
			2000	3.3	3.5	1.3
			2010	3.3	3.5	1.3

M-4	93	Choppra	1970	1.8	3.1	1.3
			1980	2.1	3.5	1.3
			1990	2.9	3.6	1.4
			2000	2.9	3.6	1.4
			2010	2.9	3.6	1.4
M-5	100	Barbaspur	1970	3.7	3.4	1.3
			1980	3.7	3.4	1.3
			1990	3.7	3.4	1.3
			2000	3.7	3.4	1.3
			2010	3.7	3.4	1.3
M-6	305	Rasulabad	1970	0.8	1.7	0.4
			1980	1	2	0.6
			1990	0.5	1.3	1.3
			2000	0.5	1.3	1.3
			2010	1.3	1.2	0.4
M-7	315	MahwaTerhwa	1970	SR~1		
			1980	1.2	1.3	0.5
			1990	1.7	1.4	0.7
			2000	0.7	1.3	0.5
			2010	SR~1		
M-8.	335	MahuaDhani	1970	3.6	1.8	1.7
			1980	0.4	9.4	0.2
			1990	0.6	1.7	0.4
			2000	1.7	2.0	0.7
			2010	1.7	2.1	0.7
M-9	350	Misraula	1970	0.5	1.1	0.5
			1980	1.2	2.3	0.7
			1990	1.3	2.0	0.5
			2000	1.3	2.1	0.5
			2010	1.1	1.9	0.5
M-10	375	Nandnagar	1970	1.3	2.4	0.5
			1980	1.2	2.2	0.6
			1990	1.1	1.6	0.4
			2000	2.5	2.6	1.1
			2010	2.3	2.9	1.0
M-11	390	Bilha	1970	1.8	1.6	0.5
			1980	2.3	1.1	0.6
			1990	2.5	1.3	0.8
			2000	0.5	1.3	0.3
			2010	1.1	1.1	0.4
M-12	400	Jyonar	1970	SR~1		
			1980	1.6	1.9	0.7
			1990	1.7	3.0	1.3
			2000	0.8	2.4	0.4
			2010	0.7	3.0	0.6
M-13	413	KanlanderpurKhurd	1970	0.5	1.2	0.3
			1980	1.2	2.4	0.6
			1990	1.9	1.0	0.9

			2000	0.9	1.7	0.4
			2010	0.5	0.7	0.4
M-14	430	Shravasti	1970	2.0	2.6	0.8
			1980	1.8	0.8	0.9
			1990	2.2	1.4	1.0
			2000	1.3	2.4	0.6
			2010	1.9	1.3	0.6
M-15	450	Itwariya	1970	1.2	1.5	0.4
			1980	2.0	0.8	0.7
			1990	4.8	2.0	1.9
			2000	2.0	2.0	0.8
			2010	2.8	1.9	1.8
M-16	485	Lakshman Nagar	1970	3.1	1.6	1.5
			1980	2.6	1.5	1.0
			1990	2.0	1.6	0.8
			2000	1.7	1.6	0.7
			2010	1.9	1.6	0.8

From the Table 7.4b and Figures 7.7c-h, it may be concluded that in general the meanders are relatively stable. Close examination of these figures indicate that almost whole reach of the river has meandering pattern, however, it is prominent in the reaches 25-50 km, 75-100 km, 300-375 km, 400-425 km and 450-475 km. The meandering is characterised by acute bend with high amplitude.

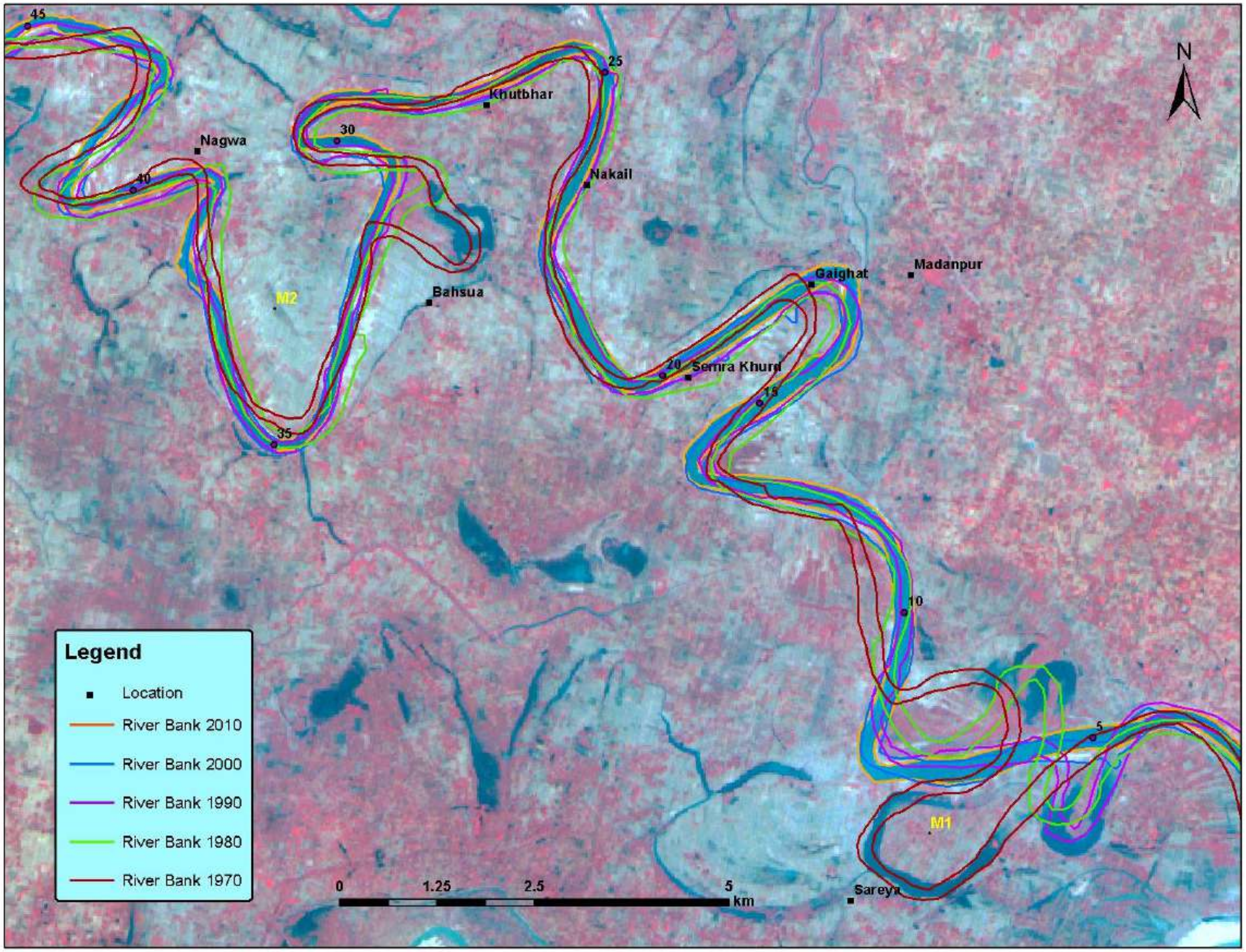


Figure 7.7c Meandering pattern of the Rapti river in the reach from chainage 5 km to 45 km

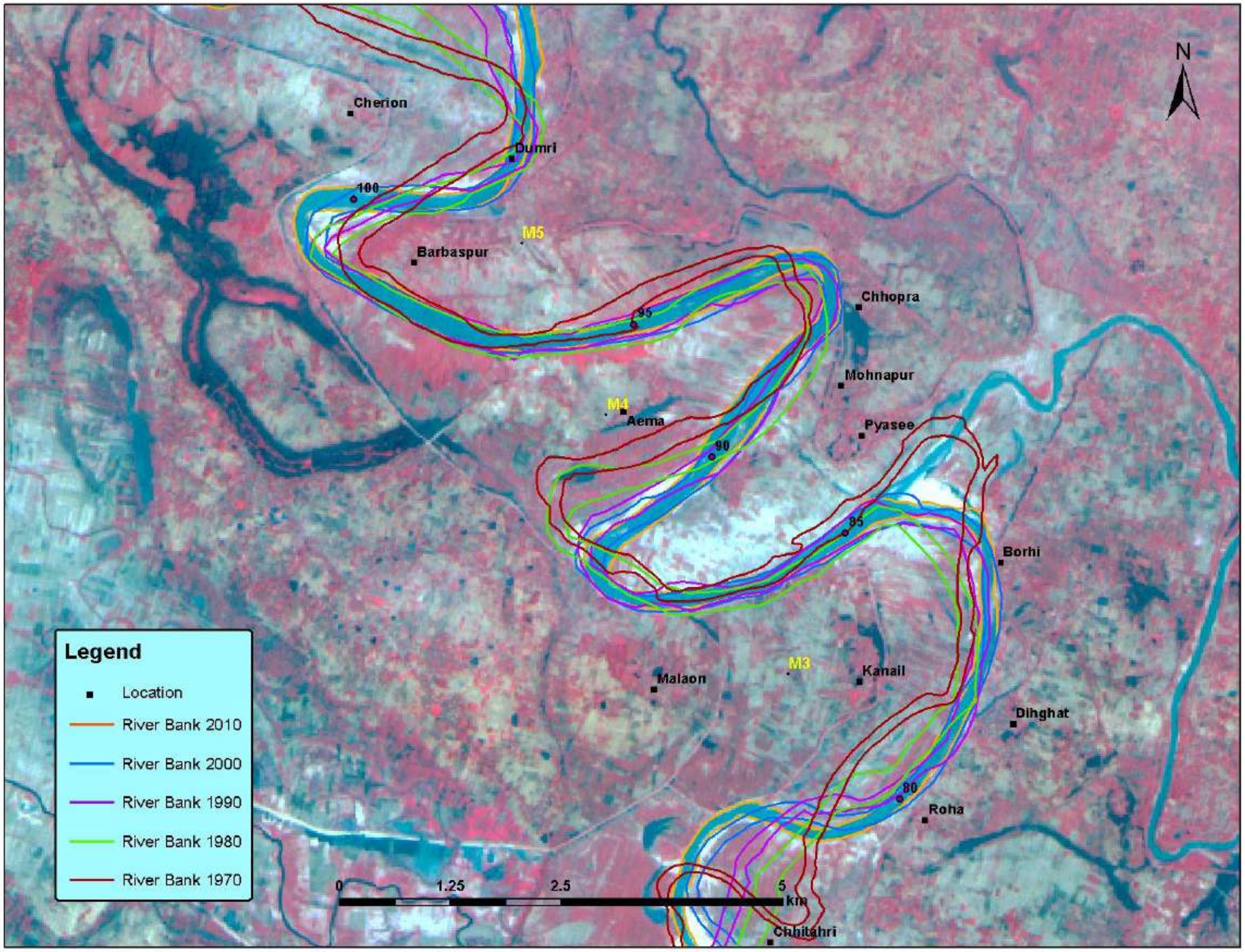


Figure 7.7d Meandering pattern of the Rapti river in the reach from chainage 80 km to 100 km

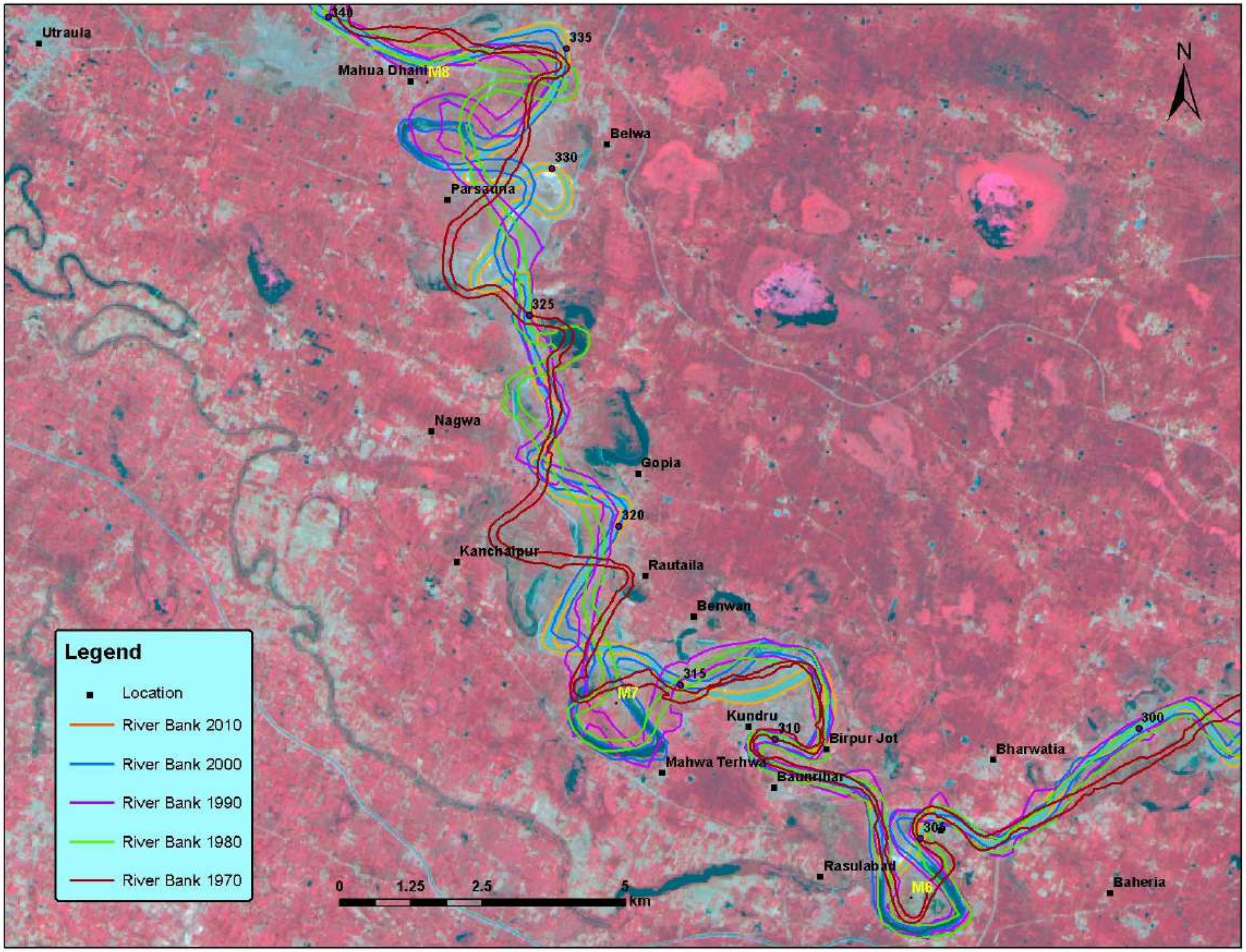


Figure 7.7e Meandering pattern of the Rapti river in the reach from chainage 300 km to 340 km

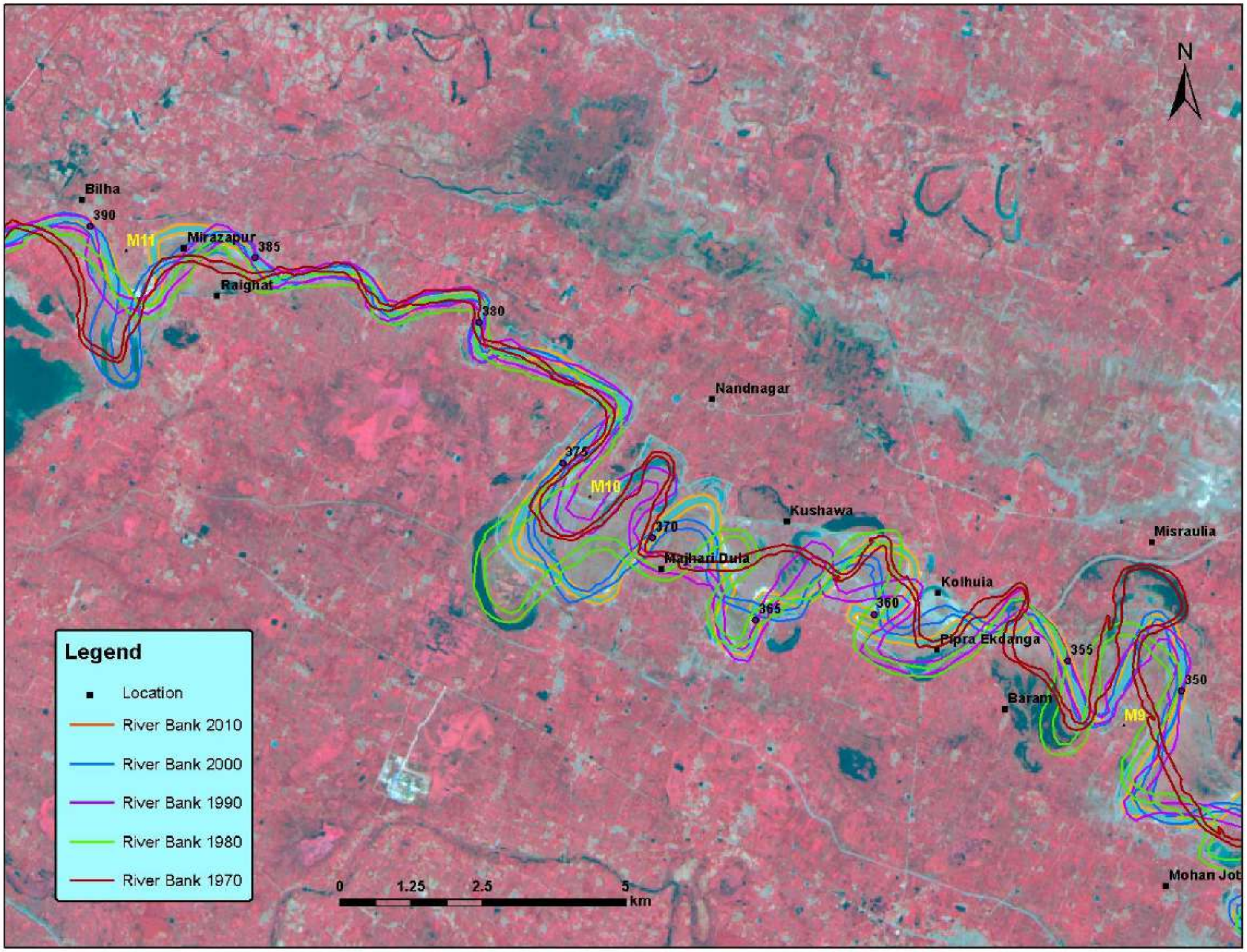


Figure 7.7f Meandering pattern of the Rapti river in the reach from chainage 350 km to 390 km

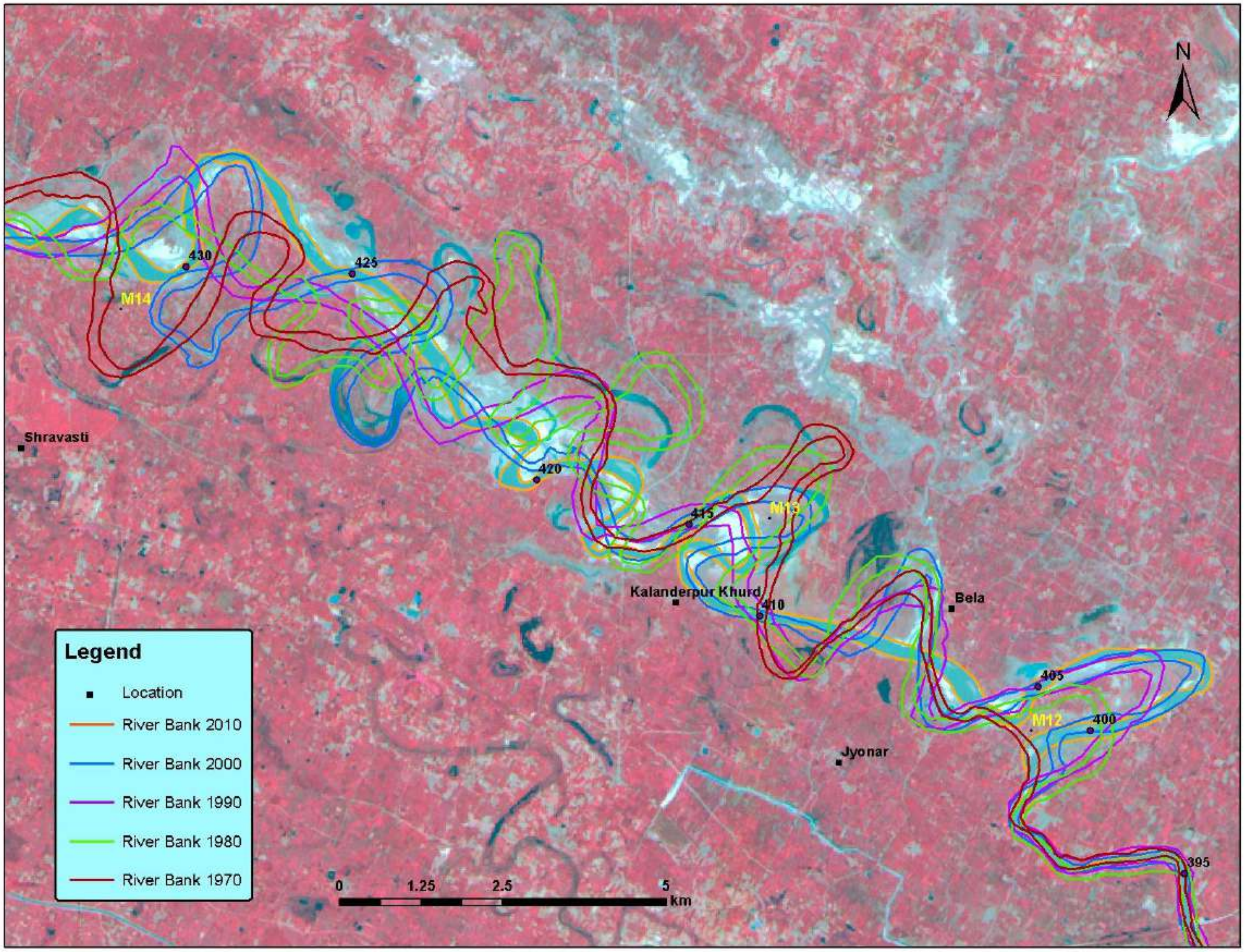


Figure 7.7g Meandering pattern of the Rapti river in the reach from chainage 395 km to 430 km

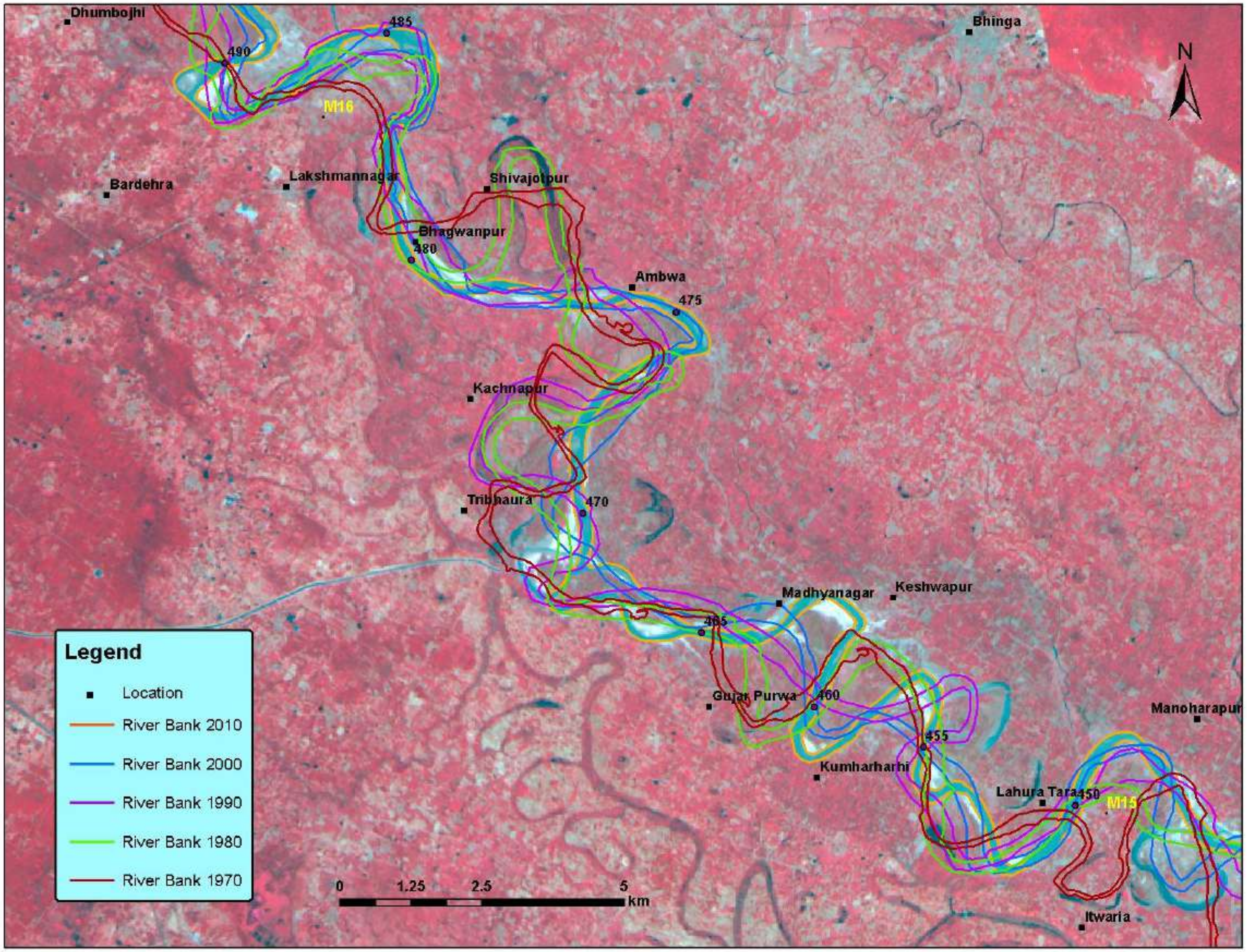


Figure 7.7h Meandering pattern of the Rapti river in the reach from chainage 210 km to 240 km near Madho Tanda

b) Planform Index

Braiding pattern of the rivers has been characterized in different ways. Three parameters which are mentioned in the literature and commonly being used to characterize the braided pattern are proposed by Brice (1964), Rust (1978) and Friend and Sinha (1993) (Fig 7.8).

$$\text{Brice Index (BI)} = 2\ \Sigma L_i / L_r \tag{7.2}$$

where ΣL_i is the length of the islands or bars in a reach and L_r is the reach measured midway between the banks of the channel. The factor 2 in the Eq. (7.2) accounts for the total length of the bars.

Braiding parameter as given by Rust (1968)

$$\text{RI} = 2\ \Sigma L_b / L_m \tag{7.3}$$

where ΣL_b is the sum of the braid lengths between the channel thalweg divergences and confluences in a reach, and L_m is the average of meander wave lengths in the reach. Friend and Sinha (1993) proposed braid–channel ratio BR as

$$\text{BR} = L_{\text{ctot}} / L_{\text{cmax}} \tag{7.4}$$

where L_{ctot} is the sum of mid-channel lengths of all the segments of primary channels in a reach, and L_{cmax} is the mid-channel length of the widest channel through the reach. The ratio BR is a measure of tendency of the channel belt to develop multiple channels in a reach. If the reach has a single channel, BR will be unity.

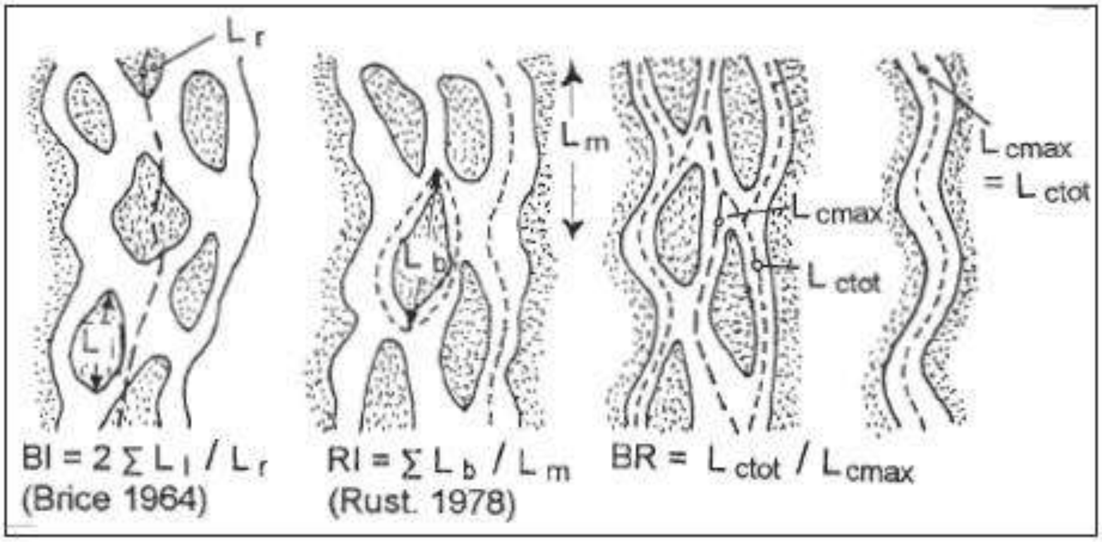


Figure 7.8 Braiding indices

Sharma et al. (2004) introduced a Plan Form Index (PFI), cross-slope ratio and Flow Geometry Index (FGI) for identifying the level of braiding in a highly braided river. The Plan Form Index, Flow Geometric Index and Cross-Slope ratio can be expressed as (Fig 7.9)

$$\text{Plan Form Index} = \frac{\frac{T}{B}\times 100}{N} \tag{7.5}$$

$$\text{Flow Geometry Index} = \left[\frac{\sum d_i\, x_i}{RT}\right] \times N \tag{7.6}$$

$$\text{Cross-Slope ratio} = \frac{\frac{B_L}{2}}{(Bank\, level - Av.\, bed\ level)} \tag{7.7}$$

where, T = flow top width; B= overall width of the channel; N = number of braided channels; R = hydraulic mean depth; d_i and x_i are depth and width of submerged sub-channels. B_L = transect length across river width.

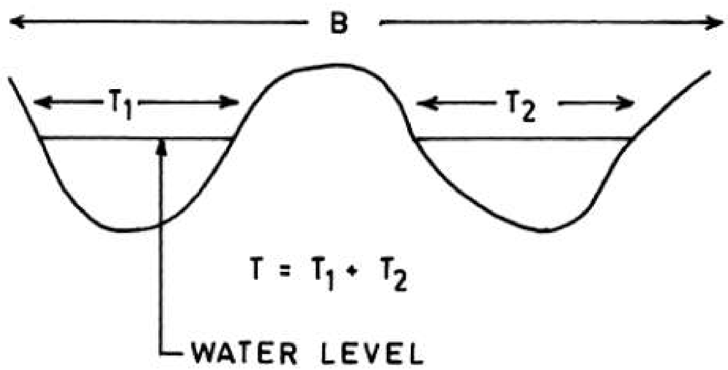


Figure 7.9 Definition sketch of PFI

PFI reflects the river landform disposition with respect to a given water level. Low value of PFI indicates higher degree of braiding. For the classification of the braiding intensity, the following threshold values for PFI are proposed by Sharma (2012).

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

The plan form index (PFI) of Rapti River is calculated using the formula given by Sharma (2004). It has been observed that the Rapti River always runs bankfull, so no braiding is found in Rapti river.

7.3 SHIFTING OF MAIN COURSE OF THE RIVER

Shifting of river is calculated on the basis of center line of year 2010. Center line of year 2010 is perpendicularly bisected at a regular interval of 1 km and it's further bisected at an interval of 0.5 km on the places where river taking sharp turn. The shift of left bank, right bank and center line in left and right direction has been computed for the year 1970, 1980, 1990 and 2000 with respect to base year 2010 in GIS software. The sample map of computation of river shifting is shown in Fig 7.10 and results of the river shifting are given in Table 7.5.

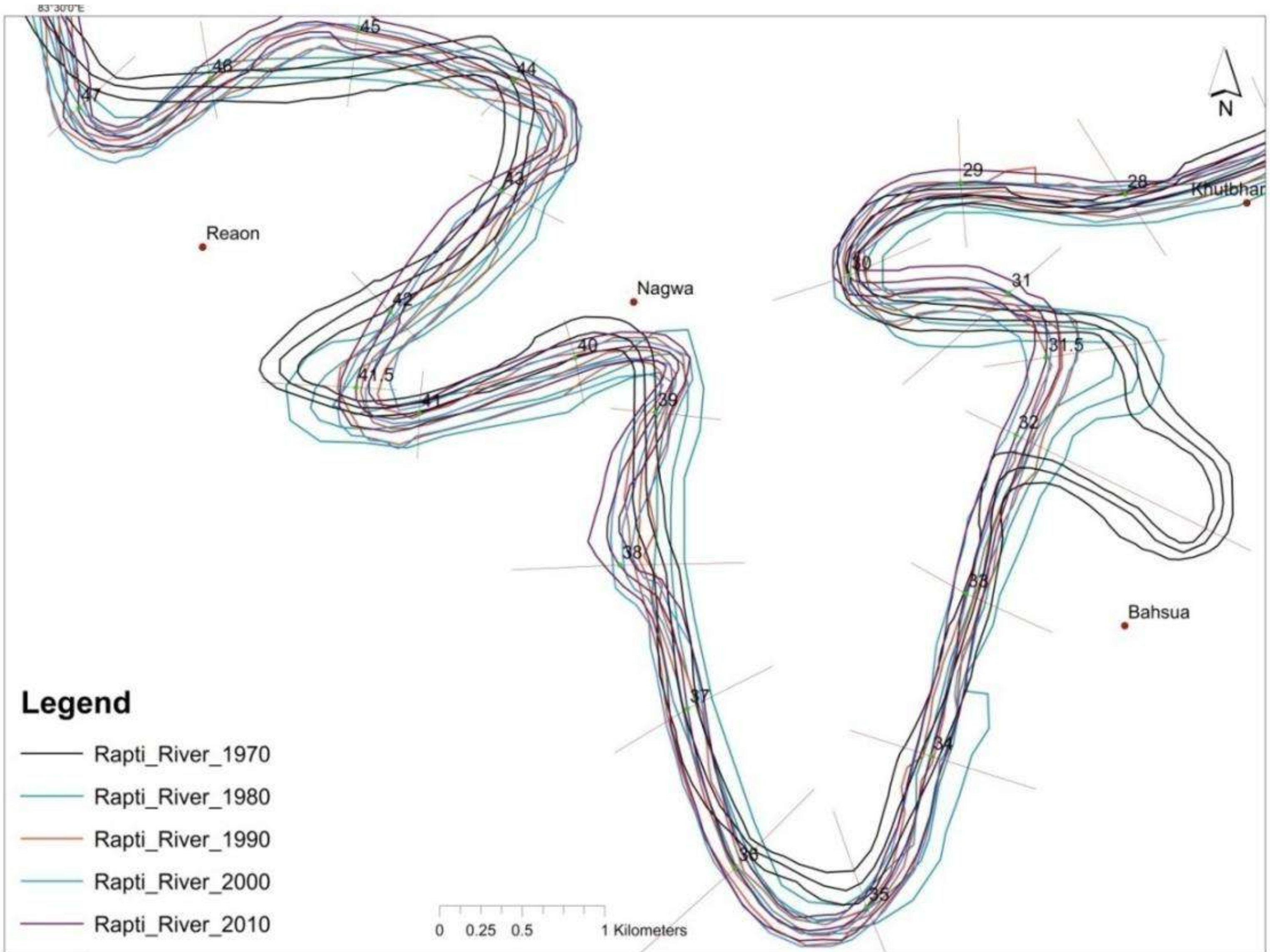


Figure 7.10 Sample map of river shifting

Table 7.5 Changes in the course of Rapti river of year 1970, 1980, 1990 and 2000 with respect to year 2010

Chainage	1970			1980			1990			2000		
	Left Bank	Center Line	Right Bank	Left Bank	Center Line	Right Bank	Left Bank	Center Line	Right Bank	Left Bank	Center Line	Right Bank
(km)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
0.00												
1.00	350.84	414.03	523.11	159.47	202.85	263.49	75.80	127.85	225.34	247.86	265.89	332.27
2.00	112.21	124.16	130.30	-78.06	-100.98	-98.85	-120.03	-121.30	-108.52	-7.03	-17.89	-20.28
3.00	150.31	120.95	102.91	-49.52	-55.97	-66.58	-159.02	-157.22	-139.68	4.17	5.00	0.86
4.00	67.89	82.47	103.87	103.01	97.63	94.09	-58.07	-52.09	-53.11	95.65	75.43	60.00
5.00	-60.18	-44.08	7.34	-95.69	74.06	95.54	12.24	-33.70	-34.99	-29.26	14.28	13.48
6.00	706.87	572.10	459.34	807.00	793.41	-258.25	68.52	127.75	181.80	81.16	93.60	101.81
7.00	-111.50	131.68	391.48	-474.17	-442.82	-399.82	-182.56	-122.06	-82.66	20.39	19.78	54.58
8.00	217.67	548.85	895.84	-455.13	-456.08	-448.90	-187.47	-146.97	-100.26	-56.62	-70.35	-62.27
9.00	-681.75	-476.36	-36.12	-555.27	-365.10	79.19	-312.73	-82.32	356.63	-73.53	-40.32	165.30
10.00	302.62	327.11	370.20	232.65	212.95	196.46	-12.50	21.60	52.14	10.84	9.33	-11.12
11.00	450.86	444.43	438.23	-34.27	-21.78	-4.65	-101.24	-56.81	-18.39	-8.82	28.60	6.63
12.00	153.62	208.19	260.00	228.33	181.81	163.20	28.16	44.43	85.00	112.56	91.55	80.19
13.00	163.82	238.79	356.44	82.75	82.28	99.75	-22.64	1.34	37.88	100.59	97.22	94.35
14.00	-196.92	-181.68	-52.71	-237.04	-208.33	-75.64	-167.52	-107.33	20.65	24.20	48.39	135.25
15.00	-191.01	-100.09	-41.73	-268.99	-249.62	-222.45	-172.88	-87.83	-2.22	-72.18	-55.54	-77.47
16.00	92.89	201.94	284.00	-116.07	-106.44	83.46	-75.50	-79.10	-18.49	-119.99	-97.03	-114.89
17.00	485.16	518.67	580.42	138.31	104.86	113.65	-45.01	-13.43	32.90	-31.59	-43.14	-58.18
18.00	281.77	425.03	447.55	133.34	273.94	271.13	47.81	180.72	197.82	164.35	175.11	128.54
19.00	-109.09	-98.29	-71.82	99.79	91.09	87.49	86.41	75.82	75.01	85.79	68.47	58.31
20.00	-88.85	-48.66	-0.84	317.67	199.71	160.09	91.54	108.29	123.00	69.49	61.60	58.39
21.00	-25.29	12.31	61.36	23.82	-4.33	-8.97	54.63	49.53	39.16	45.19	29.47	34.48
22.00	122.46	150.64	185.84	4.15	-13.52	-6.53	-29.25	-11.84	16.74	31.30	13.14	-12.79
23.00	-77.27	-40.21	1.63	-96.67	-141.07	169.54	-57.97	-59.34	49.01	-2.10	-21.94	36.11
24.00	142.70	166.41	178.07	-46.77	-79.04	-102.66	7.57	-16.57	-27.30	-24.04	-52.31	-59.17

25.00	50.89	81.05	118.61	-118.24	-121.17	-118.89	-38.19	-50.24	37.83	-68.52	-47.45	-38.62
26.00	51.45	72.09	83.48	68.93	75.66	84.57	27.90	18.54	80.92	50.80	57.50	76.48
27.00	-43.42	-64.68	-71.22	89.59	74.72	44.09	52.34	40.51	22.31	80.75	51.66	24.17
28.00	7.31	33.32	79.77	129.00	88.66	58.38	60.50	55.13	69.13	73.86	52.37	30.26
29.00	58.13	84.02	113.20	109.82	94.50	92.89	54.27	68.05	74.64	66.21	72.81	79.51
30.00	-23.17	-2.23	26.07	145.21	-106.63	86.78	30.87	-6.54	50.72	-15.69	9.18	-15.50
31.00	-225.54	251.63	276.16	-177.59	298.05	420.65	-107.49	88.16	84.82	-92.08	108.89	127.29
31.50	488.37	-483.47	481.71	585.83	-545.02	489.29	104.19	-96.47	103.94	108.83	-26.43	-29.39
32.00	1322.49	-1324.82	1364.22	253.60	-211.32	175.83	86.23	-105.12	120.67	45.63	-37.97	35.02
33.00	62.49	-72.24	70.96	100.00	-129.85	133.68	-6.61	-55.00	90.05	-0.26	-11.88	-4.46
34.00	-35.27	63.27	-74.00	151.58	-101.63	52.21	0.00	-16.99	49.98	-17.52	5.41	6.74
35.00	-266.20	144.15	-169.08	45.91	-13.76	-17.08	42.45	-50.41	62.86	35.07	-18.30	-17.83
36.00	-196.64	153.32	-115.11	-90.95	-112.22	-144.14	-16.27	17.58	39.98	7.85	5.90	5.42
37.00	-6.12	23.24	45.97	-55.69	-57.46	-51.20	12.92	29.62	40.38	31.78	26.38	15.17
38.00	-280.01	-264.58	-260.43	-301.70	-310.77	-306.85	-178.86	-131.48	-90.79	-51.08	-24.65	-12.80
39.00	26.89	62.50	85.52	-167.52	-187.76	-192.11	-61.95	-46.08	-10.43	-21.97	-24.10	-39.20
40.00	-102.36	-117.46	-124.92	167.85	163.97	157.01	57.85	51.38	64.49	103.89	77.27	39.44
41.00	-84.57	-65.03	-33.87	113.11	53.41	6.49	73.68	77.40	89.07	61.35	43.35	36.26
41.50	428.35	388.60	307.55	320.06	233.21	140.00	14.52	-32.82	-60.90	-20.78	-64.13	-140.03
42.00	135.77	128.14	102.14	-119.35	-143.45	-146.14	-134.60	-125.93	-121.43	-104.27	-116.00	-130.84
43.00	-27.19	7.17	20.61	-225.52	-205.75	-170.91	-106.80	-74.17	-59.47	-89.73	-85.86	-87.03
44.00	15.99	15.46	15.74	-19.23	-27.18	-74.36	64.27	69.79	66.96	96.72	62.34	18.54
45.00	274.72	284.24	276.33	174.30	235.08	266.21	27.26	82.07	112.81	24.94	95.08	76.12
46.00	52.37	49.05	69.68	58.65	14.00	24.65	73.19	84.03	127.79	72.86	63.47	62.06
47.00	-258.80	-232.78	-193.37	-32.92	-11.25	-10.36	44.77	47.97	44.06	55.00	61.93	52.41
48.00	55.85	1.03	-38.59	-43.38	-61.14	-87.72	-178.64	-173.86	-177.51	-81.21	-93.45	-100.89
49.00	403.06	311.64	248.95	294.21	246.44	209.02	350.55	376.83	389.28	225.11	178.79	136.59
50.00	8.34	-7.84	-46.36	-88.97	-130.33	-144.07	-30.93	-58.62	-99.68	16.68	-18.15	-33.11
51.00	-67.30	-46.25	-51.48	30.82	8.61	-7.13	-20.50	-1.47	12.63	-24.30	-4.86	21.19

52.00	67.83	60.33	38.34	-21.15	-13.80	-17.59	-2.65	10.52	3.04	34.37	34.03	23.24
53.00	-112.57	-181.16	-236.67	-38.67	-90.33	-133.43	8.06	0.25	2.46	42.73	32.62	32.32
54.00	-36.68	11.72	65.29	4.64	2.98	-5.35	12.03	27.80	55.40	50.42	64.80	42.97
55.00	29.55	37.25	17.57	-115.77	-111.34	-115.92	-133.05	-110.97	-133.65	-80.34	-62.60	-46.03
56.00	132.50	-128.10	-144.27	120.93	-79.83	-45.08	-51.17	45.93	36.50	-12.23	24.68	33.03
57.00	123.84	178.75	215.39	-16.00	5.27	19.28	-23.48	8.65	36.03	-10.97	9.52	21.25
58.00	31.19	27.59	29.73	-140.01	-148.11	-155.14	-101.53	-100.06	-87.64	-54.26	-60.88	-77.59
59.00	-151.96	-142.98	-151.93	-131.65	-171.26	-215.56	-50.52	-21.99	16.37	-19.44	-45.82	-66.73
60.00	46.40	73.25	68.23	-22.46	-76.35	-147.41	-63.94	-42.38	-23.62	-53.45	-61.71	-112.65
61.00	48.42	92.69	135.54	-58.04	-75.94	-96.88	-22.51	-39.07	-52.46	-2.47	-19.80	-52.88
62.00	208.38	192.28	175.87	219.63	192.62	171.66	144.03	134.94	107.90	100.66	44.16	18.05
63.00	-89.59	-109.47	-94.75	-72.48	-97.40	-97.17	39.96	52.75	72.70	35.42	-27.18	-53.41
64.00	-72.10	-58.36	-56.37	84.86	65.63	42.97	43.65	147.05	157.89	18.40	3.92	-37.05
65.00	251.74	239.06	245.96	54.44	21.58	27.47	25.26	15.86	24.22	18.77	-6.83	-3.46
66.00	45.31	57.73	65.99	103.63	78.20	-41.63	22.18	14.42	9.39	83.40	52.49	0.04
66.50	-621.38	-1162.08	-1130.03	65.24	62.76	49.55	16.07	21.84	38.55	40.42	34.56	36.75
67.00	33.64	34.42	43.02	103.53	109.57	106.77	59.44	46.85	20.95	50.04	23.81	19.63
68.00	-251.69	-233.23	-227.92	-27.58	-51.90	-69.47	-12.66	-41.07	-95.05	44.46	30.98	43.29
69.00	-128.52	-104.05	-106.55	-499.71	-510.55	-535.37	-285.99	-301.43	-315.21	-235.70	-248.31	-274.19
70.00	360.06	462.04	588.20	243.55	273.24	333.74	-43.66	50.13	189.95	-51.03	-68.42	-31.00
71.00	1063.12	1098.88	1105.92	1035.93	1029.26	1019.29	592.74	596.33	571.94	143.31	163.53	173.61
72.00	910.81	970.80	996.24	885.12	930.62	950.85	555.33	559.32	549.53	264.27	288.58	299.29
73.00	289.85	338.69	379.08	299.89	312.26	293.69	35.45	55.09	87.95	38.16	20.97	12.35
74.00	-172.82	-126.21	-79.73	-13.32	-23.87	-44.04	17.33	3.41	-10.16	40.78	37.42	23.05
75.00	114.13	94.25	90.36	924.14	856.91	815.10	721.40	724.74	764.35	802.72	926.30	489.26
76.00	683.58	701.31	755.50	504.84	172.18	37.56	568.77	543.26	552.74	15.19	35.45	81.05
77.00	84.53	72.36	44.05	-767.76	-832.14	-883.61	-506.15	-501.84	-507.68	-326.88	-377.06	-419.22
78.00	-226.72	-1147.39	-1225.01	-125.98	-1080.70	-1162.07	-629.89	-663.02	-702.55	-141.89	-159.58	-172.70
79.00	-1313.52	-1278.14	-1253.55	-436.01	-462.69	-495.82	-95.57	-41.26	-7.95	65.46	99.28	103.71

80.00	685.49	667.14	660.20	469.36	418.98	291.00	197.62	222.92	273.95	38.79	32.15	55.20
81.00	600.24	631.41	651.95	241.20	226.37	203.68	-17.84	11.92	39.59	-20.56	-41.28	-87.70
82.00	208.25	214.28	225.92	154.88	88.89	48.90	51.96	19.00	1.87	5.08	8.65	-3.59
83.00	263.80	263.85	269.61	326.32	309.38	316.39	59.51	65.04	93.19	-34.90	-47.94	-51.07
84.00	-8.04	-44.56	0.21	558.07	568.05	625.18	140.39	173.76	265.02	210.45	157.79	144.06
85.00	-949.01	-922.28	-844.47	270.42	344.00	291.27	131.27	215.16	138.19	106.63	157.79	92.54
85.50	-370.65	-379.48	-304.79	57.66	34.71	94.33	65.66	-1.65	67.36	80.83	-13.29	-49.03
86.00	-126.33	-75.69	-13.32	120.19	129.92	115.20	-2.27	4.24	10.57	48.01	30.39	7.71
87.00	-54.66	-40.41	-32.49	115.32	93.62	74.73	-0.58	20.02	41.67	16.71	5.34	-4.10
88.00	-301.25	-267.19	-233.57	-81.49	-121.93	-183.73	-7.39	0.96	14.25	42.09	41.49	53.12
89.00	910.41	847.50	-102.12	711.70	712.11	700.05	187.41	242.01	250.65	116.08	119.08	106.59
90.00	681.49	656.86	589.18	-315.64	191.42	308.64	105.26	120.29	123.13	-19.77	-12.16	0.14
91.00	-45.40	101.94	247.30	-213.89	-158.58	-79.02	-176.41	-118.12	-58.29	-149.11	-98.52	-38.77
92.00	-115.51	-29.85	25.33	-179.63	-185.68	213.14	-67.17	-30.29	1.61	-37.10	-40.94	83.90
93.00	379.56	384.50	390.51	262.95	224.24	210.97	54.75	40.17	46.02	11.12	-6.07	-15.36
94.00	421.48	-229.43	-149.49	32.68	43.21	48.63	101.13	78.37	57.71	71.75	70.79	70.58
95.00	-356.13	-327.74	-267.56	83.34	64.76	68.82	-2.87	-7.34	7.82	78.77	59.39	68.60
96.00	-80.50	-138.18	-167.12	55.60	22.20	-10.23	4.73	-5.20	-42.52	12.20	-4.26	-16.51
97.00	-35.75	-3.70	49.34	30.05	54.19	23.35	59.51	21.91	19.43	27.42	28.68	36.92
98.00	-3.63	-11.60	-23.49	-3.58	1.57	32.04	-7.50	-5.75	16.47	2.08	0.81	19.20
99.00	-142.21	-189.75	-203.14	-38.76	-48.44	-54.57	-26.39	-23.54	-15.83	13.92	2.16	-2.33
100.00	-572.69	-630.68	-644.27	-459.30	-482.94	-473.02	-452.93	-417.57	-357.92	-220.13	-219.20	-198.53
101.00	11.62	81.60	118.75	-80.28	-65.15	43.81	-67.83	-0.54	-67.35	41.34	31.90	12.27
102.00	478.05	437.67	410.75	178.19	163.01	161.62	197.17	185.59	194.97	18.63	4.41	-14.26
103.00	77.36	79.37	82.79	-7.12	-86.06	-106.25	0.21	-10.32	3.18	-31.46	-21.04	-14.54
104.00	847.34	788.64	712.99	723.07	708.15	674.57	454.07	398.35	365.71	109.52	128.27	130.04
105.00	1070.31	1054.72	1016.95	868.08	870.21	876.61	237.77	253.84	260.12	60.98	5.97	83.63
106.00	783.12	803.85	810.53	419.38	446.10	452.73	-38.34	36.15	96.28	20.51	12.03	31.33
107.00	102.59	167.23	224.59	-1.12	49.06	85.03	-1.08	17.35	24.82	10.17	10.94	-6.03

108.00	-196.17	-207.18	-179.20	-99.40	-77.13	-62.51	-98.75	-70.22	-30.03	-63.93	-55.61	-24.23
109.00	557.24	594.81	613.13	517.96	456.28	429.62	481.25	471.02	465.32	449.22	422.84	363.25
110.00	166.94	108.33	37.55	-212.38	-306.80	-336.89	-177.55	-195.88	-218.37	-199.02	-223.90	-255.08
111.00	-301.05	-281.59	-263.37	-445.74	-469.73	-492.83	-417.81	-450.19	-481.73	-58.24	-36.13	-9.01
112.00	645.16	649.18	584.51	20.62	85.02	103.95	27.17	79.78	87.33	10.51	65.05	61.28
113.00	1015.50	97.60	928.64	626.28	580.57	548.39	64.92	79.20	82.96	18.73	21.68	-19.01
114.00	469.55	1491.68	586.85	226.19	272.11	309.50	-58.54	-16.25	48.03	2.03	-29.41	-18.95
115.00	-225.35	-149.20	-71.78	-54.99	-18.70	-12.92	-89.86	-54.89	-19.59	-13.89	-26.89	-42.04
116.00	-264.73	-235.88	-211.32	33.62	44.55	19.66	7.35	26.24	18.02	7.52	12.31	8.68
119.00	221.61	298.81	108.00	2.88	-1.12	-164.13	-61.46	-35.22	154.64	-22.84	-25.54	16.60
120.00	3.84	68.43	328.76	-149.26	-145.00	165.35	-52.24	118.19	173.54	-12.83	-26.75	76.36
121.00	-103.28	-146.22	-157.34	-81.14	-100.07	-106.08	-109.77	-96.57	-68.77	-90.78	-113.06	-145.09
122.00	592.59	645.50	691.03	-363.23	-345.07	-316.93	-360.68	-313.95	-291.86	-107.36	-143.29	-204.00
122.50	856.35	888.45	919.47	-404.45	-415.15	-428.47	-133.58	-80.40	-40.18	-36.23	-87.46	-144.77
123.00	659.53	751.30	833.51	-128.36	-98.77	-97.28	111.04	124.58	110.07	2.66	1.57	7.22
124.00	632.14	613.76	675.18	-74.66	-71.95	-21.49	-131.08	-126.90	-56.70	-107.69	-153.59	-166.98
125.00	-530.65	-509.25	-502.17	-444.91	-493.47	-540.22	-404.54	-418.81	-435.04	-178.73	-257.23	-327.23
126.00	-405.99	-332.66	-232.19	-52.56	-16.63	25.86	-99.16	-162.05	-94.03	-51.21	-66.24	-61.99
127.00	-98.16	-49.25	-7.95	126.65	125.02	112.05	19.19	47.29	51.00	-5.18	21.46	44.55
128.00	541.22	646.72	728.91	667.85	720.19	768.89	723.63	756.90	766.87	695.46	698.87	659.60
129.00	1159.72	1182.78	1190.90	1129.92	1089.03	1046.27	1176.72	1158.04	1098.13	601.63	579.16	549.48
130.00	1004.15	1013.45	1006.14	922.81	887.25	839.41	959.14	947.96	912.05	312.64	306.90	265.08
131.00	150.98	376.38	632.26	-11.15	153.55	365.41	110.22	301.10	475.06	-451.11	-170.59	87.27
132.00	-1793.74	-1756.09	-1717.17	-1500.80	-1512.36	-1502.27	-1165.75	-1243.06	-1350.25	-334.05	-461.14	-665.63
133.00	-304.46	-257.76	-228.04	-129.64	-128.94	-141.59	-185.70	-151.56	-121.08	-112.59	-93.58	-66.63
134.00	119.76	-64.92	-29.46	74.46	84.45	55.05	38.16	54.38	74.15	-38.48	-35.12	-37.96
135.00	-171.73	-136.33	-193.50	-108.15	-99.40	-93.05	-47.02	-50.01	-62.19	-3.68	-11.07	-29.65
136.00	-21.98	-25.69	-13.45	-21.83	-37.24	-21.75	22.15	8.76	8.73	-4.48	-31.81	-56.79
137.00	27.20	4.24	-23.49	-90.00	-90.14	-101.98	-50.99	-66.97	-71.66	-7.69	-39.95	-67.12

138.00	-130.19	-281.76	-306.33	-58.43	-51.57	-76.80	82.68	83.89	53.30	-61.75	-84.80	-103.17
139.00	-566.41	-661.37	-743.10	8.41	-1.94	-5.51	-369.87	-386.15	-394.71	-203.89	-226.09	-257.89
140.00	16.79	1.55	-87.75	-528.43	-448.02	-438.26	-0.62	157.58	234.91	122.19	193.77	159.82
141.00	-407.95	-564.33	-685.18	-294.99	-299.69	-301.85	161.85	171.24	175.89	-36.26	-71.28	-130.16
142.00	-1132.25	-1132.92	-1138.94	-1442.67	-1491.21	-1515.84	319.86	293.98	282.06	106.23	63.77	24.68
143.00	453.07	440.15	447.65	565.80	469.53	359.52	258.45	309.68	349.52	124.27	88.90	74.70
144.00	1002.66	972.17	936.15	1136.39	1117.19	1101.89	615.47	606.16	563.27	66.36	49.85	26.30
145.00	748.11	507.41	706.78	953.91	924.28	986.51	231.07	167.17	202.17	-13.48	-56.03	-32.56
146.00	-204.88	-191.19	-125.85	-806.55	-827.71	-793.50	-553.11	-570.15	-513.86	-144.38	-228.38	-427.84
147.00	-532.66	-225.69	314.67	-1289.69	-997.77	-469.27	-173.06	146.06	697.95	-68.39	396.33	952.38
148.00	806.96	787.81	783.09	17.94	-75.01	-149.50	714.53	739.15	766.80	833.27	664.02	495.59
149.00	1202.11	1155.85	1149.04	478.44	460.12	418.81	148.48	96.45	81.16	81.37	68.14	18.60
150.00	1243.55	1321.12	1301.53	55.45	159.55	187.95	-125.49	-7.03	36.11	-203.51	-101.60	-83.25
151.50	-354.96	-462.27	-556.68	-967.33	-1018.26	-1071.39	-948.29	-1011.24	-1028.92	-482.05	-556.22	-614.70
152.00	-730.70	-786.52	-836.89	-1008.05	-1064.95	-1121.80	-806.61	-887.72	-928.23	-392.26	-439.38	-490.88
153.00	-177.38	-170.74	-154.90	-195.44	-223.02	-272.07	204.92	261.96	330.07	335.78	374.02	414.39
154.00	381.36	341.58	297.62	587.35	509.68	438.70	80.23	-20.60	-140.49	-168.99	-264.36	-351.40
155.00	1766.95	1699.31	1691.69	-570.94	-626.56	-596.16	-633.49	-591.02	-555.93	-706.85	-701.91	-685.46
156.00	-238.93	-284.83	-314.59	-581.45	-618.20	-649.53	-476.30	-463.21	-440.11	-345.23	-336.10	-309.82
157.00	72.45	48.82	36.98	-148.54	-170.71	-179.15	-72.52	-63.57	-34.42	-24.04	-22.67	-31.25
158.00	179.47	157.26	154.99	-36.58	-2.19	-16.29	-160.45	-147.12	-110.19	-61.68	-104.97	-149.34
159.00	-544.38	-537.75	-513.89	-527.16	-687.38	-733.05	-441.22	-455.84	-467.20	-138.96	-138.26	-122.42
160.00	-503.35	-531.94	-577.10	-634.28	-654.40	-664.23	-273.24	-285.18	-325.54	-60.27	-73.72	-88.54
161.00	89.28	52.69	27.29	138.84	48.38	-34.43	260.30	225.24	161.85	131.47	81.65	24.54
162.00	480.19	222.51	242.42	559.69	241.42	214.53	380.18	103.74	115.62	323.41	19.56	-5.48
163.00	301.83	220.41	152.29	-220.56	93.11	48.70	149.30	66.26	0.43	187.26	103.04	22.17
164.00	-517.60	-555.06	-523.83	-94.25	-124.78	-109.24	2.58	-34.75	-92.43	-0.44	-69.60	-79.65
165.00	-697.44	-771.38	-850.54	-323.39	-351.25	-396.20	-135.82	-97.94	-63.92	-517.60	-59.28	-141.91
166.00	232.71	226.05	219.44	-3.32	-48.12	-75.85	3.04	23.13	46.32	26.93	7.10	-14.29

167.00	222.71	189.56	141.86	84.36	21.67	-43.14	112.69	106.54	90.14	119.79	74.42	34.06
168.00	98.44	68.16	10.66	-160.16	-138.50	-8.83	7.48	23.00	30.81	6.75	-49.16	-101.07
169.00	201.94	201.63	153.67	10.56	12.57	7.91	25.12	25.73	15.17	-50.79	-36.71	-58.20
170.00	305.32	243.14	192.70	94.45	48.73	10.12	65.46	-97.45	-126.27	-54.11	-129.64	-204.97
171.00	38.72	-3.56	-63.89	-128.09	-174.00	-220.51	-47.56	-55.13	-68.12	-46.05	-129.97	-233.24
172.00	-16.49	-59.55	-101.77	29.93	10.41	5.62	14.86	11.48	27.38	-40.02	-44.46	-61.15
173.00	-77.15	-81.90	-71.43	-379.44	-397.07	-394.69	63.09	53.81	73.39	13.54	6.89	10.45
174.00	-234.02	-191.16	-130.18	-318.62	-328.20	-352.86	-77.52	-53.67	-9.08	45.14	41.85	41.03
175.00	579.38	564.10	472.33	478.66	445.43	392.34	159.20	139.95	133.29	225.68	145.48	66.52
176.00	786.70	730.66	703.00	780.27	703.78	655.82	94.59	77.07	79.11	143.33	76.34	41.31
177.00	558.65	502.73	443.13	347.32	214.82	158.03	-46.59	-38.46	-23.61	2.20	-23.84	-51.10
178.00	-246.00	-340.68	-424.88	126.99	51.10	-37.09	141.18	97.92	64.15	143.82	58.19	-29.34
179.00	-468.71	-492.90	-518.52	62.96	53.00	34.91	55.85	47.64	24.12	20.71	4.91	-15.00
180.00	-238.81	-338.50	-517.09	-132.15	-143.90	-157.87	50.68	29.78	9.01	-22.64	-30.42	-46.29
181.00	337.41	355.95	372.14	155.30	95.96	36.12	148.14	95.92	40.83	88.12	45.86	-4.30
182.00	113.62	138.70	159.68	12.97	-14.29	-46.19	114.24	86.38	79.32	21.76	11.76	-2.29
183.00	-175.12	-145.68	-136.52	-203.31	-177.19	-173.55	-55.25	-42.95	-67.53	-58.37	-78.85	-111.46
184.00	-34.08	-101.57	-87.18	-153.25	-175.95	-202.60	-62.99	-79.46	-86.21	-12.83	-41.36	-99.43
185.00	-615.87	-686.97	-673.05	-75.26	-66.82	-64.91	19.99	44.95	39.73	-53.34	-53.59	-52.19
186.00	18.04	84.76	107.34	75.80	110.78	91.90	76.61	101.08	65.92	41.07	12.14	-40.20
187.00	364.41	-328.29	-263.40	96.23	-113.22	-103.94	255.85	-257.22	-267.19	167.22	-170.94	-192.00
188.00	-291.73	-251.89	-218.70	-159.80	-202.02	-241.31	-41.05	-88.32	-114.94	-39.20	-75.00	-113.20
189.00	49.72	64.18	84.47	-89.11	-131.16	-172.30	1.09	-12.82	-9.04	25.24	17.11	-1.66
190.00	69.59	93.35	106.13	-104.65	-107.46	-117.37	-7.47	17.19	44.13	3.90	15.35	21.50
191.00	-39.62	-6.40	0.93	-71.25	-109.09	-136.27	49.50	15.45	-27.22	32.95	-24.65	-77.46
192.00	11.95	-4.13	-31.52	47.01	18.30	-19.12	83.90	44.55	-3.50	3.11	6.01	-13.28
193.00	-608.60	-648.38	-452.12	-567.12	-516.25	-340.63	-351.34	-237.76	-10.05	-247.44	-197.76	-18.80
194.00	26.62	40.12	22.66	-331.87	-384.72	-405.20	-35.75	-74.27	-117.76	-21.72	-115.00	-199.53
195.00	72.99	98.01	132.00	41.52	-23.92	-61.24	90.43	67.24	65.40	99.27	52.75	44.71

196.00	-31.47	6.82	26.19	-74.07	-71.95	-77.06	62.12	47.40	14.96	85.33	32.91	-18.83
197.00	-229.53	-178.27	-118.98	-86.32	-118.69	-108.65	-115.10	-178.60	-148.74	-14.09	-110.54	-180.42
198.00	-108.35	-94.35	-83.32	36.06	20.06	-16.06	8.58	-19.99	-8.02	45.31	-12.34	-88.07
200.00	-153.09	-119.29	-79.06	119.83	44.91	-8.60	64.60	-14.03	-70.78	78.33	18.75	-31.76
201.00	-223.89	-171.92	-114.23	-90.09	-79.93	-56.40	-100.27	-72.94	-51.96	-65.83	-119.26	-107.66
202.00	-41.74	23.94	70.88	-17.59	-30.95	-45.26	86.03	63.03	41.59	13.36	0.85	-19.02
203.00	-90.43	-55.60	-38.53	-18.71	-19.84	-14.82	52.00	49.20	39.33	14.26	10.01	9.79
204.00	-38.64	-41.28	-36.96	-13.26	-36.90	-62.25	58.84	22.42	-17.15	39.64	7.93	-30.27
205.00	-163.99	-122.90	-69.87	-25.02	-36.62	-32.87	-9.65	-58.02	-79.78	71.05	-33.08	-60.38
206.00	1037.81	999.93	1023.70	907.87	881.53	841.46	674.58	611.01	587.65	85.09	20.96	-34.00
207.00	175.92	172.31	164.20	142.05	98.22	56.08	147.28	113.00	-69.62	35.00	31.30	14.86
208.00	-152.03	-135.58	-115.09	84.72	54.05	40.63	67.86	28.26	-14.94	1.30	0.50	-8.62
209.00	-196.61	-199.76	-190.80	51.92	36.63	10.70	39.22	19.19	5.02	-18.82	-22.38	-36.13
210.00	-168.26	-145.22	-139.88	2.61	-40.33	-74.64	40.58	19.30	16.66	0.65	-38.00	-60.07
211.00	-1.91	10.02	19.74	35.70	6.40	-45.68	44.02	14.22	6.58	50.57	33.33	19.48
212.00	-129.98	-162.81	-208.56	-69.22	-87.59	-97.93	9.56	-27.18	-50.04	-31.95	-56.41	-80.12
213.00	-131.80	-146.63	-146.84	92.72	54.93	1.21	3.96	-19.93	-45.87	-19.87	-28.76	-38.05
214.00	-101.86	-112.02	-110.04	85.82	60.70	20.39	48.59	35.37	14.89	-14.31	-15.70	-20.71
215.00	-221.81	-230.67	231.60	-20.49	16.18	-0.39	-16.05	-30.48	45.72	-23.07	-34.39	41.36
216.00	-95.20	-120.31	-162.67	79.17	29.17	-3.83	41.03	19.21	6.25	10.48	-0.90	-7.31
217.00	-29.45	-56.14	-99.78	109.31	61.78	3.30	89.65	52.95	24.24	12.59	4.60	-5.89
218.00	-49.41	-65.42	-81.73	156.07	96.49	41.06	114.48	78.90	30.60	31.66	26.63	15.70
219.00	-139.42	-190.01	-232.51	46.39	-18.77	-60.86	31.37	-7.58	-76.73	-9.66	-53.70	-81.64
220.00	71.58	75.13	97.47	307.21	226.32	149.32	312.22	235.04	142.76	147.66	94.79	30.06
221.00	-20.28	-11.14	24.15	54.02	-7.80	-67.17	-58.25	-81.04	-106.07	21.22	-1.19	-10.61
222.00	-227.38	-189.78	-185.35	-177.71	-249.96	-337.06	-65.39	-114.77	-173.70	-79.80	-123.16	-206.93
223.00	-26.62	-36.45	-49.53	83.18	42.52	-13.77	98.45	70.04	39.13	52.44	16.70	-11.74
224.00	-390.76	429.20	-503.97	431.31	377.45	-396.45	241.57	218.92	-203.55	95.43	90.32	-106.50
225.00	-67.00	-47.44	-37.43	174.89	156.72	141.54	-8.43	-21.87	-32.74	50.10	2.66	-43.16

226.00	-270.70	-277.34	-280.29	-97.58	-133.64	-174.56	-76.88	-77.06	-91.09	-8.44	-23.82	-52.65
227.00	-76.22	-70.39	-60.94	412.95	360.63	297.20	444.97	384.48	344.07	308.75	209.25	144.22
228.00	-314.39	-257.47	-174.23	0.00	0.00	0.00	-55.34	-65.37	-92.94	-8.06	-39.02	-35.83
229.00	-447.04	-388.56	-342.56	-6.29	-909.71	-897.27	-275.07	-219.24	-174.87	-254.78	-211.23	-169.42
232.00	1241.05	529.02	1313.58	812.28	404.19	631.03	56.54	188.59	-56.80	146.73	139.92	-11.06
233.00	457.97	-188.05	599.16	414.03	59.61	378.26	278.31	6.90	181.58	197.07	-27.76	78.63
234.00	-214.10	-71.47	-134.78	119.85	38.12	26.33	104.24	14.39	2.91	7.70	-12.95	-39.26
235.00	-97.42	-71.47	-40.05	84.77	38.12	11.72	59.69	14.39	-21.33	14.67	-12.95	-24.36
236.00	-121.68	-88.65	-47.35	-7.08	-64.64	-134.12	17.97	-42.09	-78.04	19.28	-20.75	-38.27
237.00	32.53	115.69	218.61	-123.46	-38.49	70.36	-140.10	10.05	149.63	-53.81	13.98	41.78
238.00	-157.27	-136.73	-135.43	27.97	33.40	32.76	13.88	59.72	11.03	30.66	21.83	12.15
239.00	-56.46	-67.62	-86.05	109.75	51.77	15.82	99.47	55.11	7.57	29.84	2.33	-12.03
240.00	-148.06	-140.90	-117.16	90.85	51.49	27.13	31.94	38.63	-15.10	86.57	20.88	-30.52
241.00	-14.45	26.12	37.44	-17.44	-14.13	-51.17	85.49	43.48	34.32	35.89	50.07	38.35
242.00	-128.34	-79.95	-34.64	69.15	31.62	-23.30	4.08	-7.25	-33.78	33.87	4.01	-29.21
243.00	21.17	149.00	226.98	-84.47	-2.93	-54.95	65.13	60.42	29.75	19.88	4.31	-8.64
244.00	-125.11	-99.29	-69.47	138.94	92.72	49.81	28.72	8.54	-18.99	35.22	16.03	8.97
245.00	-59.09	-32.75	-3.31	115.45	85.42	59.26	24.88	6.82	-10.83	49.16	29.45	6.31
246.00	-337.37	-301.19	-268.30	142.59	100.91	38.81	-27.32	-36.69	-50.47	35.82	21.96	10.31
247.00	-219.83	-200.12	-184.81	60.52	3.66	-46.95	45.53	22.20	-69.13	32.08	-0.79	-47.29
248.00	117.68	141.33	175.83	46.96	-3.11	2.25	50.78	21.51	-11.41	82.21	34.98	5.00
249.00	54.21	82.79	117.34	151.46	124.13	110.81	1.28	-3.04	-8.72	39.04	24.78	10.31
250.00	19.78	-17.05	-13.06	65.97	50.73	81.14	-22.69	-36.20	-48.53	-7.03	-32.70	-47.78
251.00	-80.27	-55.13	-97.09	45.84	20.47	-32.52	30.44	35.08	-0.78	40.29	49.09	37.71
252.00	-130.97	-77.25	-34.52	47.37	10.89	-33.75	42.04	25.74	-2.26	23.64	30.49	22.84
253.00	-92.72	-58.92	-27.19	125.30	67.33	14.54	48.46	26.45	-5.31	43.55	44.36	36.99
254.00	-207.77	-152.66	-131.90	4.15	-5.52	-38.12	12.94	8.70	17.04	34.96	22.54	9.50
255.00	36.18	74.74	-87.31	-6.06	-21.20	-20.59	20.77	22.03	20.79	27.38	30.32	41.81
256.00	-132.03	-66.69	-18.91	35.52	22.82	1.02	0.94	28.13	38.19	51.95	63.04	64.22

257.00	-99.05	-53.38	10.42	79.90	41.55	22.56	-36.75	-28.56	-4.07	-11.17	-23.91	-25.26
258.00	-112.81	-92.11	-75.83	60.65	27.05	-10.07	0.00	0.00	0.00	-3.35	9.80	8.14
259.00	22.22	53.55	15.43	63.01	-40.81	-0.82	-8.46	-2.80	11.94	39.39	35.43	22.37
260.00	209.81	-248.05	121.66	47.50	-1.63	-13.00	-37.21	29.28	-19.96	-17.09	33.73	-47.47
261.00	32.14	-72.67	66.60	100.16	-69.48	55.06	-8.45	14.87	-6.39	-19.07	21.58	-9.84
262.00	-64.95	64.31	-86.82	182.34	-74.65	-26.09	9.75	23.30	-52.05	-31.90	31.66	-27.88
263.00	24.33	-20.50	-12.36	25.12	-7.80	-26.49	64.40	40.44	34.62	21.45	11.48	21.62
264.00	-85.28	-63.87	-66.63	80.71	62.73	52.04	12.35	22.02	19.76	-36.43	-21.62	0.95
265.00	36.91	33.35	34.20	82.91	51.88	28.10	54.82	55.40	57.90	9.12	21.01	16.89
266.00	-18.18	0.60	17.40	119.74	65.20	-9.83	-17.33	-18.51	-42.51	-12.90	-21.87	-56.66
267.00	-66.87	-71.57	-60.48	-36.70	-67.92	-87.72	0.99	19.14	29.13	53.43	27.87	6.98
268.00	7.60	32.82	26.75	146.61	93.22	49.47	39.74	20.39	8.98	29.77	14.45	-11.00
269.00	-138.08	-97.15	-319.25	51.61	-111.41	-251.67	-25.89	-15.34	9.22	1.58	1.95	10.93
270.00	110.56	106.97	90.13	-25.44	-56.18	-86.61	2.83	-23.28	-36.27	34.83	31.88	17.94
271.00	-140.59	-111.91	-93.79	88.03	75.93	42.93	4.53	-16.85	-44.30	-17.69	-12.38	-12.04
272.00	-5.76	-32.79	-57.61	-48.12	-64.65	-81.19	21.41	-35.35	-63.58	38.64	32.64	38.72
273.00	31.51	53.61	66.70	111.64	62.00	-0.32	97.19	78.84	73.09	53.37	50.69	43.00
274.00	113.84	114.22	102.62	235.23	168.92	107.94	118.93	77.02	52.50	43.54	35.06	38.85
275.00	-672.06	-732.66	-719.28	-8.21	-42.32	-96.10	48.93	38.41	5.99	28.37	2.37	-24.95
276.00	275.67	105.90	58.36	402.54	334.77	284.12	211.94	192.13	163.37	81.03	89.10	88.38
277.00	410.32	404.11	406.18	160.56	119.25	74.65	112.26	75.44	32.50	48.97	51.34	42.22
278.00	148.93	131.98	137.12	207.66	158.84	134.10	114.13	59.02	13.87	12.07	-6.18	18.59
279.00	65.78	90.07	104.69	115.29	63.96	32.75	93.54	68.03	54.90	72.43	50.80	44.79
280.00	-186.81	-182.14	-172.23	142.25	60.93	-0.78	-8.95	-27.96	-51.97	-5.03	-20.98	-22.03
281.00	85.59	126.31	168.33	-50.64	-56.68	-97.65	15.06	17.93	33.43	11.73	23.19	22.62
282.00	105.10	142.89	147.71	253.72	158.14	66.39	36.30	25.53	26.37	33.98	45.07	41.75
283.00	-155.46	-155.18	-151.26	135.86	117.26	109.79	7.18	16.76	6.01	-1.50	-6.17	-33.99
284.00	272.33	261.48	227.72	-0.45	-54.43	-110.45	-10.75	-17.60	-38.59	55.37	28.50	-8.14
285.00	387.68	412.65	449.86	333.64	215.89	232.42	230.03	68.49	45.20	110.71	63.73	-0.84

285.50	-321.97	-340.39	-385.69	179.43	123.02	62.48	151.62	109.66	50.88	41.29	29.10	7.00
286.00	-285.48	-276.29	-255.87	297.70	236.40	202.63	106.60	91.35	56.70	22.69	1.18	1.97
287.00	-182.61	-153.03	-114.87	126.22	59.87	20.12	-2.67	-36.06	-53.85	-44.43	-56.77	-43.09
288.00	-173.86	-193.93	-224.81	74.51	30.73	-16.64	52.26	28.25	-13.69	16.86	3.26	5.70
289.00	-63.92	-120.40	-115.34	157.59	79.75	6.72	65.41	61.53	33.81	-3.18	-22.08	-24.87
290.00	-64.76	-38.50	-22.01	125.63	82.01	32.09	47.27	54.05	18.52	8.48	11.06	7.38
291.00	-71.87	-68.63	-70.41	109.13	-46.34	-21.25	5.84	-28.67	-84.15	-7.90	-3.72	12.09
292.00	-20.36	9.00	4.11	-80.62	-88.12	-130.97	-29.04	-29.17	-66.41	-0.32	-5.40	-6.88
293.00	-30.25	38.45	88.99	88.74	22.49	-36.01	1.18	-12.01	-46.19	29.75	26.82	4.98
294.00	-63.30	-63.35	-83.48	9.98	-13.13	-39.62	-22.04	-81.71	-144.29	-17.16	15.12	20.52
295.00	383.66	358.89	268.07	115.80	80.18	45.46	76.71	-1.96	-56.57	32.53	19.39	2.86
296.00	-58.43	-46.71	-50.61	60.63	0.39	-94.85	-14.26	-105.69	-188.50	-120.63	-138.49	-181.10
297.00	-293.95	-307.71	-404.18	351.70	291.30	229.71	379.47	272.58	119.55	225.69	153.59	102.60
298.00	-797.52	-885.30	-926.78	-124.58	-164.97	-227.10	-132.58	-220.13	-643.03	-222.47	-262.96	-310.50
299.00	-237.34	-150.42	-153.86	-24.46	37.84	5.46	-5.26	14.94	-206.41	19.34	58.62	48.53
300.00	581.53	625.72	662.90	56.82	16.68	-9.79	20.66	12.60	-36.91	-10.74	-23.50	-26.10
301.00	558.67	534.03	493.90	98.43	86.44	65.69	56.80	14.60	-42.26	24.95	5.62	-30.83
302.00	395.25	376.83	391.27	158.69	118.23	70.94	157.13	94.18	40.52	-2.21	-6.67	-4.95
303.00	12.90	-81.31	-60.00	89.88	41.28	-19.19	61.86	-63.59	-157.12	26.36	-12.15	-43.72
304.00	100.13	125.54	-27.42	54.62	-4.17	-64.85	51.97	-21.04	-87.95	-10.42	-13.70	-17.37
305.00	-105.42	-73.50	-41.70	41.84	-1.18	-45.88	31.83	15.25	-178.24	88.31	84.36	90.68
306.00	-40.92	-53.42	-42.03	234.41	65.84	-29.22	-279.52	-381.68	-525.81	-457.00	-500.52	518.46
306.50	653.34	639.98	599.09	1435.19	1401.97	1324.14	1340.64	1285.74	1215.22	1279.77	1257.92	1219.02
306.75	668.17	601.71	477.32	1015.55	938.47	920.83	990.51	943.29	104.90	1005.06	966.33	981.54
307.00	-0.30	18.49	27.42	102.98	37.22	-14.41	107.49	88.33	-29.48	200.58	166.54	126.37
307.50	-53.62	-34.71	-31.50	38.37	-14.49	-69.33	9.01	14.70	16.22	109.38	85.21	56.61
308.50	-1.04	43.62	33.81	147.95	55.42	-32.07	237.49	38.19	-229.25	57.24	43.80	12.03
309.50	-35.63	-28.38	-31.30	81.87	67.40	50.46	-2.49	14.34	3.38	-16.66	-12.68	-19.59
310.50	-71.57	-41.91	-26.30	-9.19	-67.86	-110.06	-0.15	-31.60	-51.75	13.61	18.06	22.67

311.50	86.13	80.71	99.11	1.19	-25.18	-56.72	61.19	36.30	11.83	21.23	5.04	-2.40
312.50	94.81	132.41	169.43	123.90	136.65	146.87	134.68	84.57	15.90	102.26	85.82	68.23
313.50	18.79	64.31	114.27	44.54	16.26	24.12	8.21	-25.16	-30.78	-30.04	2.84	31.28
314.50	-434.38	-403.06	-365.17	-697.68	-718.75	-710.01	-781.75	-813.34	-822.60	-848.29	-821.12	-791.93
315.50	-105.28	-81.51	-47.24	-404.59	-455.04	-487.35	-478.82	-586.84	-698.69	-154.32	-162.28	-160.21
316.50	234.70	294.28	327.14	559.41	578.72	597.80	411.83	373.54	279.37	-34.98	-12.40	-9.68
317.00	543.75	544.95	438.95	1665.44	1617.40	1579.37	1873.92	1755.24	1604.33	97.94	69.52	36.51
317.50	889.19	894.66	917.98	184.09	71.49	-6.64	1527.08	1175.28	1095.31	1506.54	1508.57	1257.40
318.50	-1356.00	-1396.44	-1594.41	-876.76	-886.60	-920.97	-703.76	-757.28	-833.01	-287.09	-341.65	-394.83
319.50	-1180.43	-1084.35	-1002.15	-408.05	-400.72	-440.67	-422.57	-429.54	-431.27	-25.79	-29.65	-34.63
320.50	1098.73	991.09	778.03	74.85	108.44	151.01	-8.60	3.16	31.34	15.57	21.15	37.82
321.50	1883.78	1955.76	2009.99	474.83	530.73	597.47	110.37	174.68	239.18	16.52	31.35	105.68
322.50	1403.21	1414.65	1403.35	-223.55	-362.98	-378.47	-357.86	-416.89	-488.37	-240.17	-267.26	-287.99
323.50	36.69	54.35	78.85	66.60	-13.08	-93.60	479.45	244.32	82.21	276.70	118.21	67.06
324.50	-133.33	-109.92	-89.24	678.25	603.31	590.23	-81.56	-168.34	-194.08	-143.73	-126.98	-121.59
325.50	-652.75	-637.91	-624.74	-139.43	-258.54	-762.60	34.33	38.36	-153.28	64.10	76.95	94.42
326.50	439.68	427.75	395.48	45.61	19.46	-4.43	146.99	44.91	-51.17	129.27	119.85	102.84
327.50	200.91	137.48	34.06	-881.81	-922.74	-972.69	-1008.06	-1119.86	-1284.02	-548.20	-551.81	-563.38
328.50	851.86	880.46	894.88	-283.14	-293.85	-319.51	-366.11	-459.94	-570.49	-73.25	-41.41	-30.03
329.00	854.05	771.99	719.92	174.80	108.46	48.75	59.39	-10.06	-88.46	-133.48	-190.85	-213.15
331.00	1846.42	1767.27	1673.09	1362.65	1307.52	1261.30	1276.40	1211.09	1153.15	745.37	751.82	748.62
332.00	286.65	577.03	912.07	323.31	744.50	1125.45	262.01	712.98	1114.76	-430.83	6.56	409.95
333.00	-734.89	-779.73	-816.08	-220.67	-192.13	-156.85	-124.31	-155.43	-83.99	-701.56	-721.64	-759.67
334.00	-622.09	-542.94	-500.25	268.78	315.18	334.44	1051.54	871.73	823.14	1307.51	1382.57	1421.32
334.50	-252.63	-247.84	-244.12	925.30	908.88	902.52	1332.70	1312.18	102.78	103.81	56.34	-0.65
335.00	103.01	132.76	170.21	916.37	895.40	885.16	308.40	259.50	242.04	56.47	34.56	26.96
336.00	-38.67	-37.43	-39.49	560.49	65.90	-94.73	468.79	401.21	340.08	24.08	24.49	28.61
337.00	437.72	447.22	458.26	843.56	755.73	668.93	684.45	630.62	585.82	223.42	194.13	141.13
338.00	1.80	57.46	116.12	251.01	211.23	192.26	58.79	74.58	69.58	5.91	-1.30	17.82

339.00	-608.58	-580.08	-566.78	-125.33	-188.17	-279.35	26.35	-32.26	-69.06	39.45	25.18	2.67
340.00	-204.54	-204.90	-304.74	12.51	-56.84	-115.73	82.78	18.20	-48.07	52.75	33.36	23.22
341.00	-180.51	-254.61	-186.72	99.80	56.05	53.36	-152.81	-194.84	-188.22	12.25	9.05	26.25
341.50	-434.94	734.06	-397.14	-124.29	-69.32	10.32	-377.64	-402.73	-368.12	106.55	165.35	246.64
342.00	-38.31	-20.68	-13.65	185.24	177.91	169.32	132.91	107.67	28.36	197.35	135.92	119.52
343.00	700.26	734.05	775.90	41.89	-83.60	-124.75	742.81	697.95	656.22	48.25	55.92	47.09
344.00	-281.04	359.25	513.99	-979.87	-415.04	-308.60	-261.04	286.25	360.17	-559.51	68.34	208.38
345.00	-752.40	-902.26	-854.39	-54.86	-109.90	-138.34	-441.18	-426.58	-421.16	-528.18	-505.20	-489.62
346.00	250.64	604.34	441.89	922.69	1186.93	1166.24	165.52	496.26	524.06	51.84	368.31	400.12
347.00	801.63	839.14	859.36	1277.03	1244.40	1202.31	459.33	475.24	456.79	199.79	250.96	267.69
348.00	-78.53	147.02	-227.47	-142.23	179.90	-253.66	-175.49	230.21	-261.71	-148.18	-164.55	-176.54
349.00	-832.12	-846.75	-847.50	-318.60	-325.83	-325.88	95.70	-77.94	-176.37	-100.82	-149.38	-168.88
350.00	-423.08	-383.05	-319.27	307.79	356.25	431.17	-160.13	-197.75	-185.86	-214.23	-191.86	-140.83
351.00	272.86	317.49	355.66	377.24	292.01	216.10	51.58	23.45	3.34	131.59	111.49	64.49
352.00	800.25	828.46	355.66	175.01	165.39	216.10	-5.77	-27.03	3.34	35.82	23.29	64.49
353.00	87.29	209.72	854.53	446.32	416.90	155.83	887.29	460.77	-52.67	23.56	-36.66	12.26
354.00	132.49	-772.60	351.15	-755.70	-679.27	396.75	2.49	-17.88	227.41	-31.03	-13.12	-69.45
355.00	-400.63	-416.07	-758.86	-377.72	-424.22	-609.99	-29.69	-22.50	-94.08	-3.65	-22.50	-56.46
356.00	415.00	463.21	-445.31	415.00	1067.61	-506.34	61.14	33.21	-9.12	80.05	47.83	-51.30
357.00	743.73	790.54	524.03	94.22	73.74	-188.31	108.96	64.59	36.73	73.74	53.12	44.38
358.00	291.99	265.99	835.02	-480.47	-532.56	49.91	-525.75	-656.59	29.86	-382.17	-501.97	26.75
359.00	41.33	66.61	-23.91	478.25	467.67	-588.08	397.65	409.21	-757.80	-293.31	-298.26	-571.75
360.00	-259.66	-255.17	103.31	570.48	541.78	454.28	503.93	494.79	422.84	-323.15	-391.59	-336.29
361.00	-1131.32	-1094.90	-270.32	-177.74	-272.44	516.19	-802.92	-862.37	471.29	-510.41	-518.12	-558.89
362.00	-514.43	-379.45	-1077.64	287.89	308.08	-376.35	-329.79	-268.73	-925.99	136.67	224.01	-532.44
363.00	371.35	393.59	-284.38	568.47	422.27	300.55	955.07	897.46	-209.99	824.37	799.32	273.83
364.00	199.51	216.32	410.28	-92.16	-139.92	380.46	812.73	852.10	612.01	152.83	180.58	784.73
365.00	-704.38	-729.56	175.09	-103.43	-121.47	-170.31	-263.41	-701.79	795.62	-117.08	-157.84	203.50
366.00	-749.46	-759.12	-737.89	291.26	208.37	-129.94	148.47	91.57	-735.33	376.97	-327.49	-190.52

367.00	-1540.00	-1550.27	-763.06	-265.56	-387.67	163.63	-9.91	-77.36	-4.44	-624.16	-613.41	282.50
368.00	-1179.32	-1088.22	-562.23	-1233.65	164.24	-14.66	-90.63	-15.11	476.16	-559.46	-397.85	229.70
369.00	-24.04	-15.98	-100.23	-727.58	-725.00	-728.31	290.98	258.96	217.67	250.67	204.63	119.08
370.00	1014.65	980.84	1015.96	1104.08	1013.73	910.47	1137.55	1155.03	1129.15	354.38	384.21	401.57
371.00	682.21	720.52	756.73	995.62	993.93	975.42	919.55	898.73	870.73	154.42	184.50	217.35
373.50	-2003.33	-2790.68	-2771.62	-889.21	-946.87	-982.65	-2128.10	-2293.02	-2435.25	134.78	74.19	32.00
374.00	-740.09	-713.59	-704.96	1004.97	944.29	-27.35	-877.83	-946.27	-1027.68	-52.87	-91.12	133.23
374.50	-660.82	-654.92	-649.49	1022.94	990.32	944.64	-883.42	-982.39	-1080.11	-275.30	-280.70	-302.86
375.00	-562.97	-516.61	-458.44	589.79	465.13	207.50	-842.92	-898.64	-928.63	-341.93	-291.49	-228.22
376.00	-86.85	-53.02	-17.43	-150.53	-152.85	-163.32	-414.18	-447.46	-463.52	-25.97	-66.13	-110.54
377.00	-227.53	-147.00	-86.29	-348.08	-303.59	-284.86	-233.70	-204.70	-185.60	-24.17	-18.84	-64.36
378.00	251.16	291.14	319.23	192.22	193.07	201.50	50.27	36.18	2.21	52.89	32.27	-5.03
379.00	186.35	230.68	261.50	227.06	171.61	65.90	132.72	40.74	-48.33	62.68	58.74	43.75
380.00	28.07	57.98	81.33	260.83	259.09	254.62	164.87	121.33	53.19	53.40	37.42	16.18
381.00	-228.31	-194.44	-174.13	-94.19	-148.36	-167.17	13.66	-34.32	-66.41	56.54	19.35	24.46
382.00	63.40	47.39	31.85	243.72	153.19	84.80	23.56	12.71	-3.62	-12.33	-34.84	-36.86
383.00	-65.68	-111.66	-98.17	123.78	93.30	62.50	-21.86	-36.08	-65.20	-6.09	-22.60	-34.87
384.00	182.44	198.89	184.53	176.42	177.99	171.31	247.42	161.03	33.56	77.93	60.64	50.87
385.00	-81.54	-53.21	124.67	160.82	142.44	11.66	8.28	-4.22	-59.92	29.11	11.31	3.78
386.00	-190.95	-132.99	-62.21	109.53	133.17	152.60	34.59	-33.39	-62.47	24.34	9.52	-4.39
387.00	487.82	459.12	462.00	112.12	98.35	103.99	-86.86	-90.57	-88.05	-106.16	-98.62	-98.79
388.00	538.19	561.49	578.55	651.76	646.10	634.79	630.79	574.53	496.35	400.33	403.32	386.41
389.00	-30.60	27.82	4.51	351.84	370.28	386.66	239.63	243.87	247.09	-153.38	-115.79	-58.48
390.00	665.97	631.30	660.88	26.74	-54.07	-30.16	23.38	67.52	175.72	1375.85	1443.99	-1575.48
390.50	823.06	804.71	825.36	33.90	34.79	51.51	248.62	302.59	291.33	101.16	56.68	39.98
391.00	583.29	616.82	629.31	303.62	306.69	300.70	228.17	200.74	202.78	33.26	32.66	27.20
392.00	332.41	374.90	411.63	326.83	341.73	343.86	53.00	33.20	2.37	-1.72	-15.77	-36.24
393.00	-141.87	-97.64	-55.36	136.75	131.52	109.49	35.07	-20.10	-50.96	-5.97	-3.61	-9.70
394.00	-29.78	2.30	29.32	85.56	77.11	61.03	11.31	-18.62	-23.12	-9.33	-9.35	-7.89

395.00	-40.44	4.35	31.29	60.54	39.60	8.07	6.54	-9.56	-21.47	44.39	32.32	17.98
396.00	16.29	44.17	49.44	-27.94	-28.53	-37.95	41.51	11.64	9.43	37.87	32.66	19.55
397.00	-45.20	-50.84	-73.78	162.76	131.54	84.54	2.79	16.62	-103.66	36.49	12.10	-14.98
398.00	-80.25	-85.26	-89.71	106.67	68.30	57.77	12.33	-34.56	-86.96	-27.90	-27.25	-16.34
399.00	-61.99	-40.71	-10.32	68.40	70.12	70.66	-1.32	-10.46	-37.47	25.27	28.34	22.79
399.50	85.54	126.29	146.28	-96.55	95.68	-119.27	54.38	58.82	47.08	-6.13	2.38	11.82
400.00	-74.73	8.68	38.95	-1049.96	-1034.66	1039.79	-920.78	-900.66	999.66	-418.70	-328.40	-281.02
401.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
403.50	2892.85	190.98	2901.78	1693.30	-1046.04	1655.15	1208.99	-1684.85	984.82	480.87	-193.55	228.60
405.00	2005.55	2048.17	2087.69	813.42	834.79	832.37	334.87	253.80	151.38	297.43	25.42	88.07
406.00	1227.14	1222.58	1230.28	607.42	504.12	415.17	323.03	231.89	90.48	283.43	185.95	97.93
407.00	234.55	712.59	827.82	-212.41	230.90	297.81	-411.27	41.75	145.58	-447.05	-8.87	50.29
407.50	236.54	373.26	532.77	373.46	492.13	656.38	239.54	347.97	422.33	297.15	406.94	560.42
408.00	335.98	407.87	462.92	822.85	873.32	946.79	818.50	841.76	824.22	725.47	659.34	663.64
408.50	-210.26	-161.08	135.06	-1.42	-143.60	-256.58	-408.93	-457.71	-495.21	-146.22	-157.79	-202.89
409.00	-1009.29	-1011.48	-1109.73	-1309.00	-1297.51	-1289.44	-827.91	-833.47	896.72	-1218.64	-1390.96	-1432.31
410.00	-266.00	-190.38	-120.46	-325.06	-463.91	-421.17	-159.56	-126.14	-117.16	102.28	162.30	201.19
411.00	807.79	828.05	845.43	467.98	448.48	422.57	646.52	492.28	385.01	39.14	47.85	59.57
412.00	-846.84	-835.29	-875.75	-184.06	-146.68	-142.57	-293.63	-310.74	-329.02	-17.75	7.60	22.72
414.00	740.10	-910.23	1048.35	153.28	-461.54	695.53	16.14	-280.26	516.28	-692.39	525.02	-407.34
415.00	-511.70	-523.72	-515.67	-430.29	-531.96	-614.27	261.96	243.16	248.56	-678.65	-728.87	-754.11
415.50	-109.83	-259.13	-1696.86	-1010.04	-1051.83	-1143.64	376.84	313.94	247.94	-50.42	-143.75	-268.61
416.00	134.60	275.44	228.55	38.32	-113.15	-328.97	119.46	219.34	156.79	49.14	184.93	137.94
417.00	-37.63	-91.20	-158.19	142.52	128.50	129.75	-231.53	-324.44	-397.56	-19.69	-17.25	-126.81
418.00	-240.83	-245.24	-151.47	-216.07	-407.61	-578.39	-451.53	-464.41	-438.13	-231.22	-239.46	-213.59
419.00	311.59	422.77	527.75	-436.70	-308.29	-202.34	439.92	505.25	563.44	72.29	195.51	299.42
420.00	352.62	379.24	526.98	369.08	388.41	571.55	509.12	411.90	519.68	259.10	313.49	527.71
421.00	-1599.39	-1281.17	-1160.27	-798.14	-543.19	-2346.37	-1080.86	-1138.20	-1122.92	-506.38	-250.04	-184.21
422.00	-1927.58	-1726.10	-1382.98	-1169.56	-1451.86	-2434.16	-1785.70	-1667.44	-1391.01	-235.24	-47.61	298.78

423.00	-984.17	-1011.72	-1047.72	-618.43	0.63	-1541.05	-71.66	-225.14	-526.50	222.53	172.52	129.06
423.50	-1109.68	-1160.05	-1247.57	-2620.49	-2687.41	-2734.46	159.92	99.55	-0.89	-282.91	-299.54	-302.85
424.00	-1170.50	-1885.86	-1615.23	-317.62	-401.89	-822.57	634.57	606.61	811.11	-208.61	-169.14	82.54
425.00	-1041.42	-1134.36	-1173.09	342.98	323.50	-300.27	511.29	529.75	496.59	-266.38	-13.44	200.31
426.00	1011.18	1048.57	1049.27	1384.87	312.07	325.38	573.41	576.71	566.34	-390.41	-376.33	-398.33
427.00	1295.57	1296.34	1323.37	511.04	435.61	433.02	601.15	487.11	417.07	606.99	418.31	349.74
428.00	236.25	311.95	400.86	1019.14	1085.91	1179.44	1235.86	1279.61	1302.72	1418.50	1510.77	1606.41
429.00	1037.02	982.87	873.57	1693.89	1688.22	1674.25	2018.47	2036.55	2025.94	246.29	138.81	87.28
430.00	1311.61	1325.23	1325.29	1081.28	1074.72	1068.26	1736.74	85.71	-103.95	105.43	174.87	76.47
431.00	862.40	918.26	1637.96	-330.73	-167.39	653.90	-136.73	-1070.52	-388.70	152.63	552.21	9.38
432.00	1150.85	1152.74	1159.45	-973.64	-984.70	-939.25	-1233.90	-1289.98	-1296.19	153.28	374.52	705.09
432.50	1728.97	1818.94	1861.08	-512.67	-533.63	-584.51	-842.43	-863.11	-944.94	-258.13	-269.96	-368.87
433.00	87.61	-29.79	-110.74	799.51	801.91	775.91	-26.81	-251.34	-558.41	385.77	355.24	176.05
434.00	-623.06	-715.69	-748.04	286.75	260.73	276.59	324.49	266.16	260.66	279.95	263.30	299.38
435.00	-422.44	-417.28	-419.27	-123.18	-81.25	-53.64	193.75	178.13	115.13	285.57	345.66	357.09
436.00	188.64	233.85	230.76	697.74	739.32	761.51	487.18	484.86	433.75	644.21	698.51	707.80
437.00	-587.86	-654.72	-670.87	-72.71	-344.53	-462.79	-154.34	-218.83	-194.73	-367.50	-438.94	-442.13
438.00	-51.73	-154.62	-285.14	-64.92	-116.62	-175.15	459.60	354.36	233.35	697.18	625.92	567.96
438.50	-657.67	-489.20	-463.71	-497.59	-1401.21	-1376.71	-57.68	-9.69	43.61	356.00	498.10	537.57
439.00	-1091.49	-913.31	-628.67	-737.81	-559.81	-338.15	-713.65	-657.36	-493.10	-181.66	15.34	291.02
440.00	-1679.78	-1679.15	-1687.47	-410.17	-424.13	-463.11	-1494.66	-1617.47	-1707.62	-850.70	-850.82	-843.97
441.00	-1267.51	-1200.50	-1201.30	-654.90	-614.76	-621.26	-1481.87	-1501.75	-1530.30	-615.74	-553.90	-494.60
442.00	-232.49	-237.58	-326.76	-262.23	-219.17	-210.54	-653.43	-714.18	-797.50	33.99	-31.50	186.04
443.00	318.86	424.84	482.42	717.90	788.19	818.76	698.07	734.34	726.16	-131.72	-63.60	-74.48
444.00	906.35	943.76	992.77	17.06	28.00	24.36	897.34	846.85	830.48	233.34	242.54	263.41
445.00	698.79	721.75	737.26	854.59	779.14	716.14	383.06	357.35	343.25	-5.89	13.56	16.88
446.00	485.11	640.65	744.36	487.22	579.75	630.97	272.05	336.83	341.30	-138.89	-29.46	64.17
447.00	1901.24	1935.05	1934.73	80.63	48.15	20.83	811.39	673.05	501.82	-12.42	-75.30	-112.19
448.00	-106.84	-130.95	-196.66	491.50	459.68	418.47	-152.73	-202.40	-315.69	799.35	738.46	695.63

449.00	343.06	436.35	335.08	894.94	894.11	877.44	68.48	111.41	157.39	-237.21	-167.25	-107.60
450.00	2589.56	2644.74	2674.31	935.14	928.76	916.59	709.29	658.45	331.41	227.83	240.85	243.57
451.00	1886.15	2077.98	2301.25	231.75	323.07	441.99	147.12	280.97	467.38	-258.38	-153.61	10.70
452.00	-338.16	-285.75	-150.25	-210.08	-222.21	-129.89	-230.15	-268.00	-282.27	48.79	39.96	104.65
453.00	-694.07	-759.54	-817.44	-144.11	-231.83	-327.23	-332.68	-400.98	-442.17	-68.55	-103.31	-161.99
454.00	-10.63	92.71	184.42	588.89	647.71	671.97	485.54	564.12	618.60	574.11	618.75	587.67
455.00	795.89	826.80	827.93	766.42	610.72	319.05	606.04	579.76	522.47	-10.45	-88.40	-173.42
456.00	-236.12	-189.21	-155.74	-287.59	-330.22	-398.85	241.01	236.38	229.74	-491.96	-558.22	-671.30
457.00	242.07	281.99	301.60	119.37	56.69	-12.45	-747.36	-719.47	-697.32	549.67	539.07	521.89
458.00	172.30	278.88	313.24	29.11	92.20	113.17	744.40	786.73	730.86	793.17	928.02	994.58
459.00	-923.22	-964.85	-927.01	-1037.03	-1094.64	-1042.76	46.08	50.96	90.02	55.63	98.08	144.45
460.50	-2136.19	-2254.63	2234.58	-1578.60	-2235.94	2266.20	-1011.45	-1056.33	1089.59	-500.38	-490.63	499.25
462.00	280.52	-885.38	-694.47	797.98	1137.89	-150.43	-151.27	265.33	458.94	44.47	413.57	556.82
463.00	1254.71	1584.53	252.57	1874.17	2068.08	2549.32	554.66	876.21	1361.83	519.51	804.03	1285.02
464.00	2596.19	2604.93	2608.79	2832.97	2636.80	2383.39	1432.72	1370.66	1291.44	921.08	884.35	832.86
465.00	1376.73	1507.22	2055.51	938.71	847.52	1305.65	433.63	442.55	901.77	-172.83	-136.08	381.87
466.00	417.85	417.31	392.43	-108.75	-96.46	-71.23	-242.51	-257.19	-245.96	-498.04	-539.11	-570.52
467.00	-439.02	-368.20	-125.41	-222.99	-258.99	-112.26	-636.36	-615.62	-426.95	-300.28	-305.73	-110.23
468.00	-242.65	-184.77	308.07	-107.50	-108.72	334.73	-384.76	-384.96	31.52	-444.29	-420.07	51.30
469.00	-12.59	47.14	767.55	199.85	199.51	797.15	8.49	22.46	678.57	-612.18	-585.01	134.32
470.00	-146.44	138.32	742.47	-44.09	175.57	625.29	-6.66	313.49	209.24	-1091.72	-793.46	-190.36
471.00	1431.45	1477.96	1512.10	383.01	388.65	404.08	1.72	-59.17	-101.45	327.37	270.82	204.41
472.00	340.49	201.44	161.46	1086.24	955.39	799.58	787.79	354.57	208.79	418.51	358.88	282.62
473.00	896.86	1009.59	1098.22	633.26	378.68	277.58	1279.52	1369.51	1455.62	-69.36	-190.26	-318.85
474.00	-88.29	-87.20	-146.55	-46.34	-437.99	-450.25	-292.02	-313.94	-310.69	-464.83	-458.57	-451.94
475.00	-86.39	112.84	398.35	1288.62	1508.25	87.58	-194.18	5.28	300.25	-229.82	-79.50	176.14
476.00	1118.09	968.75	988.84	2180.11	2210.19	2221.65	738.08	716.22	720.78	67.11	74.82	83.30
477.00	925.07	938.52	955.36	1637.90	1682.84	1710.75	386.32	392.66	374.39	152.62	137.07	133.71
478.00	157.66	169.87	191.36	862.77	838.30	810.71	-209.21	-247.38	-272.42	-47.23	-167.00	-282.50

479.00	-1643.62	-1665.79	-1792.67	-943.72	-1085.07	-1417.50	86.61	67.77	-13.85	160.02	117.36	58.75
480.00	-1445.57	-1381.07	-1449.94	-244.17	-277.43	-317.61	210.67	180.02	148.71	211.96	172.29	195.41
481.00	-985.41	-946.16	-938.72	-143.71	-141.83	-193.67	-116.25	-394.60	-705.67	-323.17	-388.89	-795.57
482.00	-163.90	-187.06	-347.31	32.47	-281.22	-330.30	-261.19	-387.54	-516.38	-255.32	-399.80	-533.56
483.00	66.97	100.31	165.26	118.17	-15.98	-76.73	26.56	54.85	76.51	-113.27	-104.16	-106.06
484.00	100.39	186.28	689.53	-72.73	-154.52	243.34	66.75	71.72	182.36	14.59	27.75	-45.78
485.00	884.78	993.09	1054.65	203.38	122.82	95.40	148.36	173.04	161.33	-39.37	5.09	9.58
486.00	1070.54	1232.19	1352.53	507.11	605.00	643.09	122.26	92.27	59.53	-16.51	-17.63	-64.99
487.00	941.84	954.07	962.85	648.35	540.63	474.19	324.34	187.76	27.10	443.13	347.44	251.10
488.00	247.49	350.42	487.98	-84.17	-45.29	23.94	94.34	-3.97	-56.70	154.19	227.37	325.30
489.00	-99.10	-37.20	24.05	42.44	0.44	-61.17	-7.57	-40.54	-90.06	-7.53	6.63	24.02
490.00	-604.55	-610.51	-584.43	-50.35	-355.84	-423.28	-92.19	-87.28	-148.43	-264.28	-175.22	-132.61
491.00	-930.77	-684.13	-458.81	-533.63	-399.14	-266.14	-422.70	-321.59	-96.67	-728.33	-524.09	-342.76
492.00	262.78	570.53	703.50	600.37	886.60	809.68	319.09	586.28	600.50	-153.09	234.39	334.35
493.00	1064.02	1159.51	1161.00	1025.70	1034.08	1028.42	737.65	732.68	693.50	112.39	174.45	218.65
494.00	1038.91	1056.95	1086.62	325.52	211.67	148.27	263.91	225.34	189.54	83.06	65.46	53.36
495.00	358.51	436.42	558.83	-52.48	-145.36	-145.58	-124.65	-39.43	67.54	24.97	-37.85	-69.38
496.00	-586.72	-532.85	-534.39	167.70	147.52	79.35	113.60	85.65	-0.40	79.91	45.57	22.04
497.00	-321.22	-233.33	-182.87	537.02	548.63	187.25	430.03	383.10	356.00	111.91	92.25	73.80
498.00	277.35	357.30	429.43	-26.64	-47.57	-47.99	121.33	123.17	127.94	50.27	39.31	27.95
499.00	-5.36	51.29	13.31	-46.75	-85.59	-125.31	72.70	57.60	59.34	-1.04	6.22	18.28
500.00	42.61	106.96	153.28	-76.43	-52.43	-24.79	76.53	108.35	128.46	26.40	24.91	7.27
501.00	315.95	372.94	420.94	73.41	10.17	-77.12	187.46	164.40	104.54	22.16	28.69	25.80
502.00	107.66	177.43	281.74	4.95	-11.20	-5.67	-4.87	-21.58	-18.57	-62.70	-104.47	-133.34
503.00	-937.41	-1100.60	-1006.72	-456.32	-461.38	-449.46	-277.39	-376.87	-530.48	9.22	9.23	-11.44
504.00	-196.94	-57.58	104.24	-499.41	-488.63	-446.01	219.26	271.82	354.09	-386.86	-316.62	-228.98
505.00	-328.24	-114.52	150.62	294.35	313.92	331.98	328.10	311.39	269.55	-36.46	18.03	48.46
506.00	472.86	519.00	558.49	450.81	410.05	365.17	129.61	113.48	109.52	327.35	314.03	298.41
507.00	75.42	348.19	671.11	-549.53	-329.50	-159.94	-125.80	-51.73	103.03	-12.87	236.38	427.34

508.00	-455.27	-420.43	-391.75	-1276.06	-1281.14	-1309.59	-358.57	-501.52	-712.42	-391.68	-336.01	-285.06
509.00	193.64	272.73	402.83	-471.44	-601.88	-657.44	877.46	903.55	925.59	-304.82	-299.73	-274.89
510.00	739.11	592.52	-563.39	423.87	330.32	-320.91	-367.50	-483.73	554.19	-1375.35	-1483.00	1555.34
511.00	264.92	354.54	469.44	247.25	72.07	-41.18	-260.92	-390.10	-492.14	-750.65	-763.84	-781.71
512.00	413.00	700.94	921.30	-181.71	-63.88	-30.86	79.29	390.26	547.24	234.27	325.59	318.97
513.00	1311.94	1313.77	1317.76	212.66	147.90	101.06	1212.45	1147.94	960.21	1252.10	1124.40	993.03
514.00	977.39	1143.69	1271.30	160.71	306.29	405.54	1034.41	961.17	893.32	936.71	935.42	924.43
515.00	-37.59	361.68	782.67	-654.93	-341.71	-6.73	-305.85	-41.50	285.68	-351.36	-68.24	190.90
516.00	-295.39	-295.22	-312.72	-535.65	-599.79	-674.20	-675.68	-771.39	-823.83	-762.39	-792.14	-810.41
517.00	-627.40	-339.30	-156.91	-736.74	-601.64	-578.95	-893.81	-718.04	-639.73	-783.80	-641.99	-578.81
518.00	-293.69	19.13	87.48	-365.21	-122.93	-86.29	-429.80	-98.15	-3.12	-8.74	58.06	-78.30
519.00	38.19	71.66	61.78	125.37	-44.66	-55.48	-35.81	2.56	-26.77	57.55	26.22	-16.51
520.00	-738.80	-628.77	-162.29	-406.93	-535.06	-128.69	-703.69	-604.48	-101.58	-711.81	-690.11	-317.85
521.00	-1478.52	-1445.88	-1459.86	-711.83	-889.91	-1062.50	-1332.73	-1282.73	-1232.23	-1221.77	-1235.23	-1698.25
522.00	-3733.53	-2262.96	-2229.69	-1956.78	-679.71	-1068.17	-3071.60	-1698.61	-1772.73	-2280.38	-1043.45	-1257.39
523.00	-2426.30	-2439.42	-2452.58	341.40	295.65	242.85	-1625.01	-1629.28	-1653.54	-647.37	-725.61	-812.20
524.00	-1545.20	-1609.78	-1542.75	1116.02	1146.82	1178.19	-479.38	-683.13	-745.69	416.55	302.00	242.96
525.00	3.80	110.67	199.80	231.31	200.92	16.24	868.35	727.47	626.28	829.49	868.62	910.51
526.00	119.63	153.87	210.32	297.42	310.04	338.87	991.68	940.27	963.46	829.93	692.52	700.80
527.00	-841.21	-747.71	-674.92	-266.78	-375.51	-474.53	165.38	54.60	-211.37	-126.21	-127.77	-138.12
528.00	-419.15	-653.77	-602.80	-654.30	-717.85	-678.38	-384.87	-505.50	-503.46	-212.13	-185.47	-110.90
529.00	20.51	167.03	290.03	-76.08	-43.19	-9.96	-303.94	-254.50	-195.79	798.47	819.37	865.26
530.00	-1418.79	-1267.95	-1133.61	-561.10	-511.63	-841.86	-664.70	-683.09	-664.83	185.70	298.22	463.56
531.00	-1739.91	-1605.87	-1484.35	-1113.50	-1319.68	-1441.05	-806.58	-703.73	-618.46	-371.31	-512.02	-600.91
532.00	-1648.20	-1262.79	-860.45	-1442.53	-1147.29	-807.94	-806.53	-552.34	-271.16	-1206.98	-960.74	-737.13
533.00	-784.18	-619.10	-503.51	-408.17	-336.37	-399.64	116.20	22.17	-73.13	-689.19	-718.41	-785.20
534.00	-231.95	-202.88	-86.74	817.26	774.62	746.23	496.71	492.60	524.75	-431.99	-406.93	-343.68
535.00	-168.65	-56.10	-52.92	1546.11	1522.93	1451.20	837.24	876.93	849.38	609.05	481.82	200.11
536.00	-1678.98	-901.74	-739.84	-21.80	618.31	653.24	-784.25	-72.19	-54.86	-690.37	73.62	225.01

537.00	-1521.88	-1432.00	-741.14	-456.73	-597.68	-215.14	-1107.51	-1207.17	-687.66	-793.38	-729.19	-103.05
538.00	-1913.41	-1745.41	-1488.13	-1558.62	-1595.06	-1477.86	-1827.08	-1765.40	-1616.54	-1019.77	-994.71	-885.84
539.00	-2219.79	-2185.42	-2180.60	-2250.88	-2302.50	-2364.15	-2181.03	-2099.94	-2318.95	-46.75	-62.57	-140.35
540.00	-2578.01	-2573.85	-2550.21	-2524.20	-2582.74	-2600.92	-2395.54	-2413.63	-2498.94	-112.96	-132.83	-132.32
541.00	-2609.53	-2547.69	-2497.40	-2554.40	-2537.18	-2532.32	-2378.59	-2360.30	-2317.52	-279.68	-382.32	-488.56
542.00	-2238.91	-2182.73	-2231.63	-2171.40	-2233.49	-2376.52	-2061.42	-2015.46	-2125.55	-351.86	-345.28	-392.99

* positive (+) value indicates that the river course was towards right side and negative (-) value indicates it was towards left side with respect to course of the river in year 2010

Figures 7.11 to 7.21 show the shifting of center line of river of year 1970, 1980, 1990 and 2000 with respect to year 2010 while Figs. 7.22a to 7.32a show decadal chnages in the course of river and Figs. 7.22b to 7.32b show change in river course for year 1970 with respect to year 2010 in respect of shifting of centreline, right bank and left bank.

Figures 7.11 to 7.32 reveal that major shifting of the river course in span of year 1970 to 2010 is the reaches 75 -100 km, 300-375 km, 400-485 km and 500-542 km. The river has also high meadering pattern in the above reaches. High meandering and major shift in the upper reaches may be attributed to aggradation of the river bed due to high sediment carried by the river from the hilly areas. Major shifting from left to right has been noticed at Devpura, Jamuha, Keshwapur, Nandnagar and Chitahari while maximum shifting from right to left are at Gujarpurwa, Ikauna, Jyonar and Kanchalpur. No progressive shifting of the course of the river with respect to time has been noticed as evident from Figs. 7.13 to 7.32.

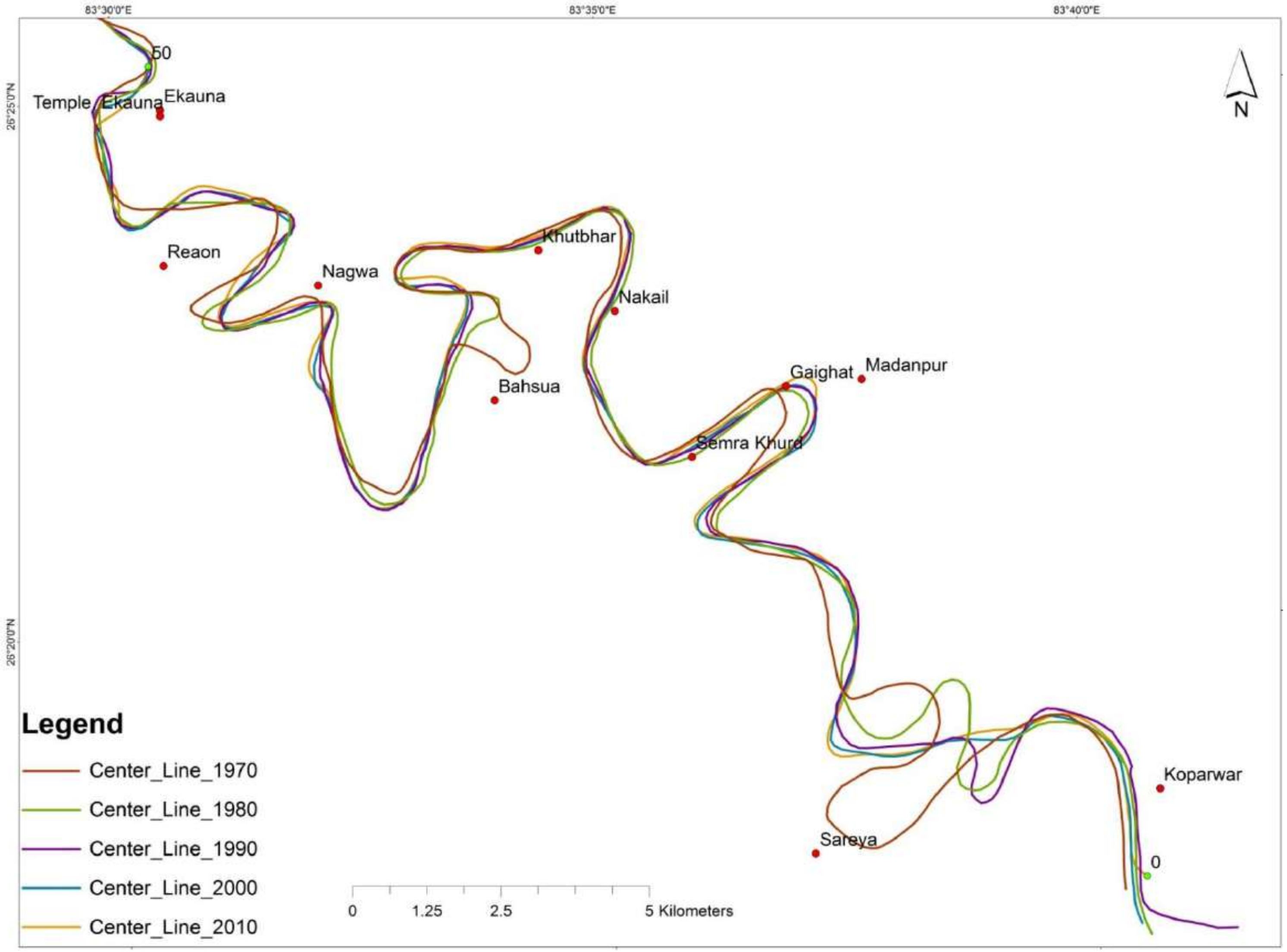


Figure 7.11a Shifting of center line of Rapti river from chainage 0-50 km

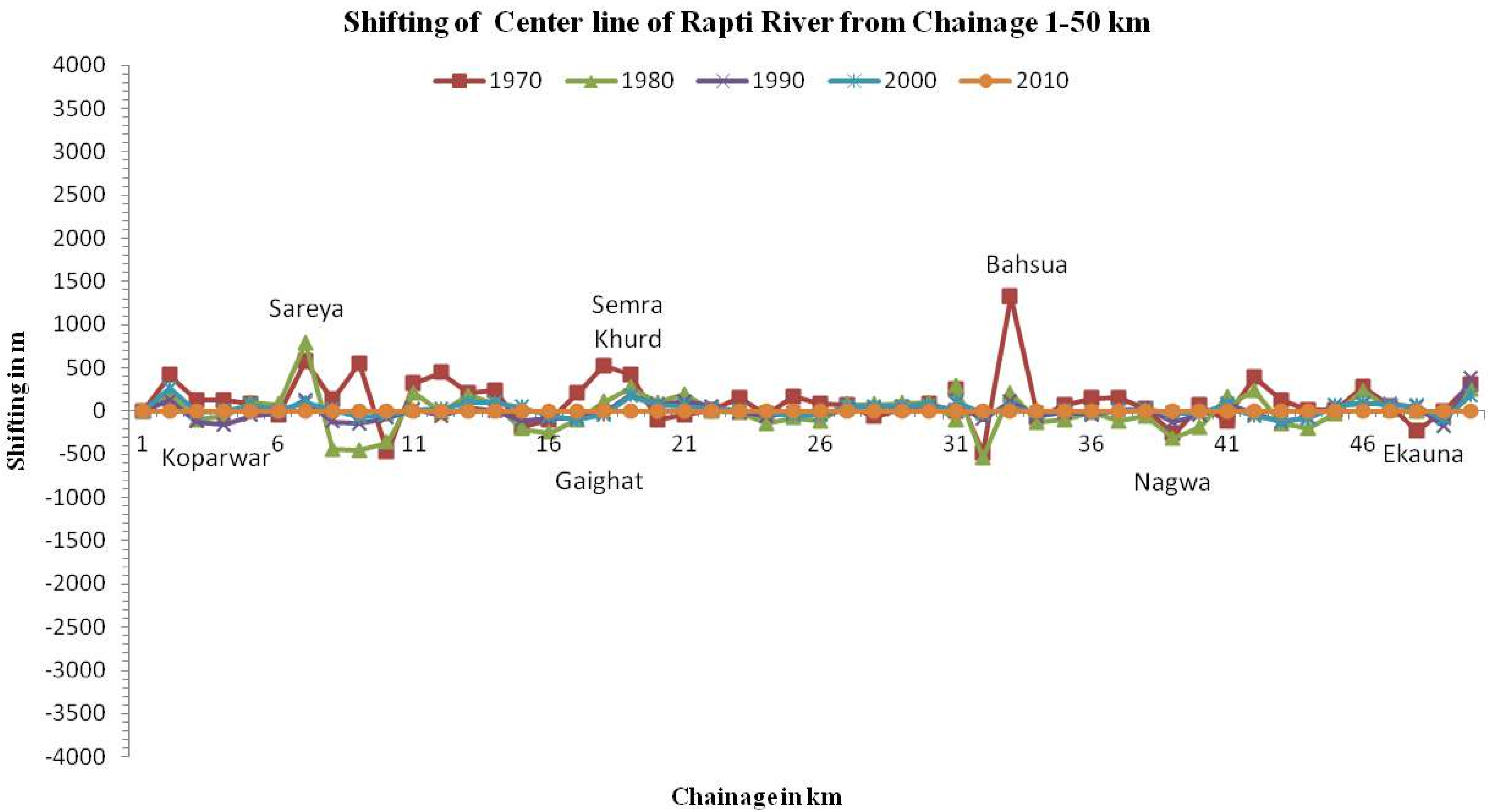


Figure 7.11b Shifting of center line of Rapti river from chainage 0-50 km

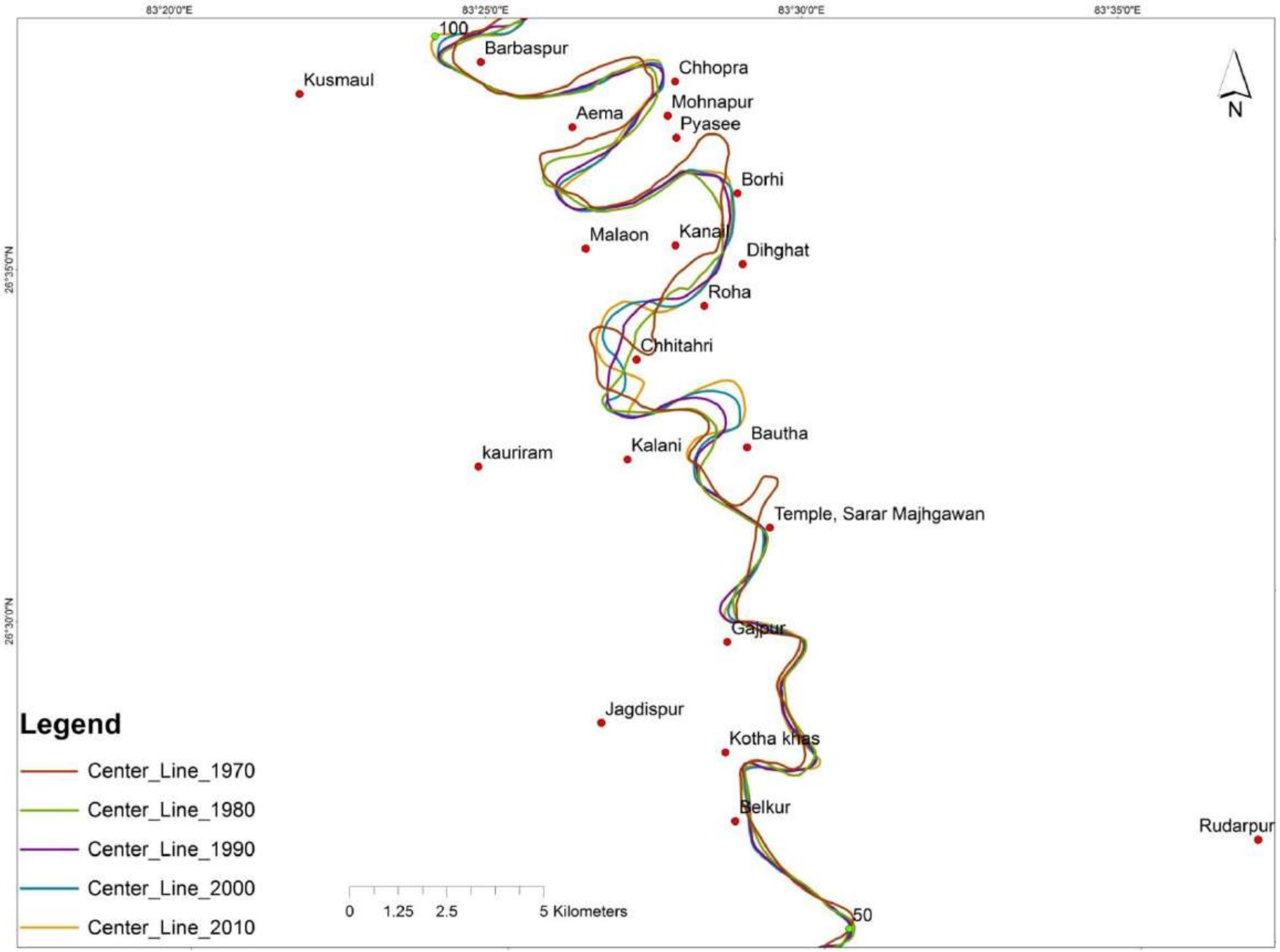


Figure 7.12a Shifting of center line of Rapti river from chainage 50-100 km

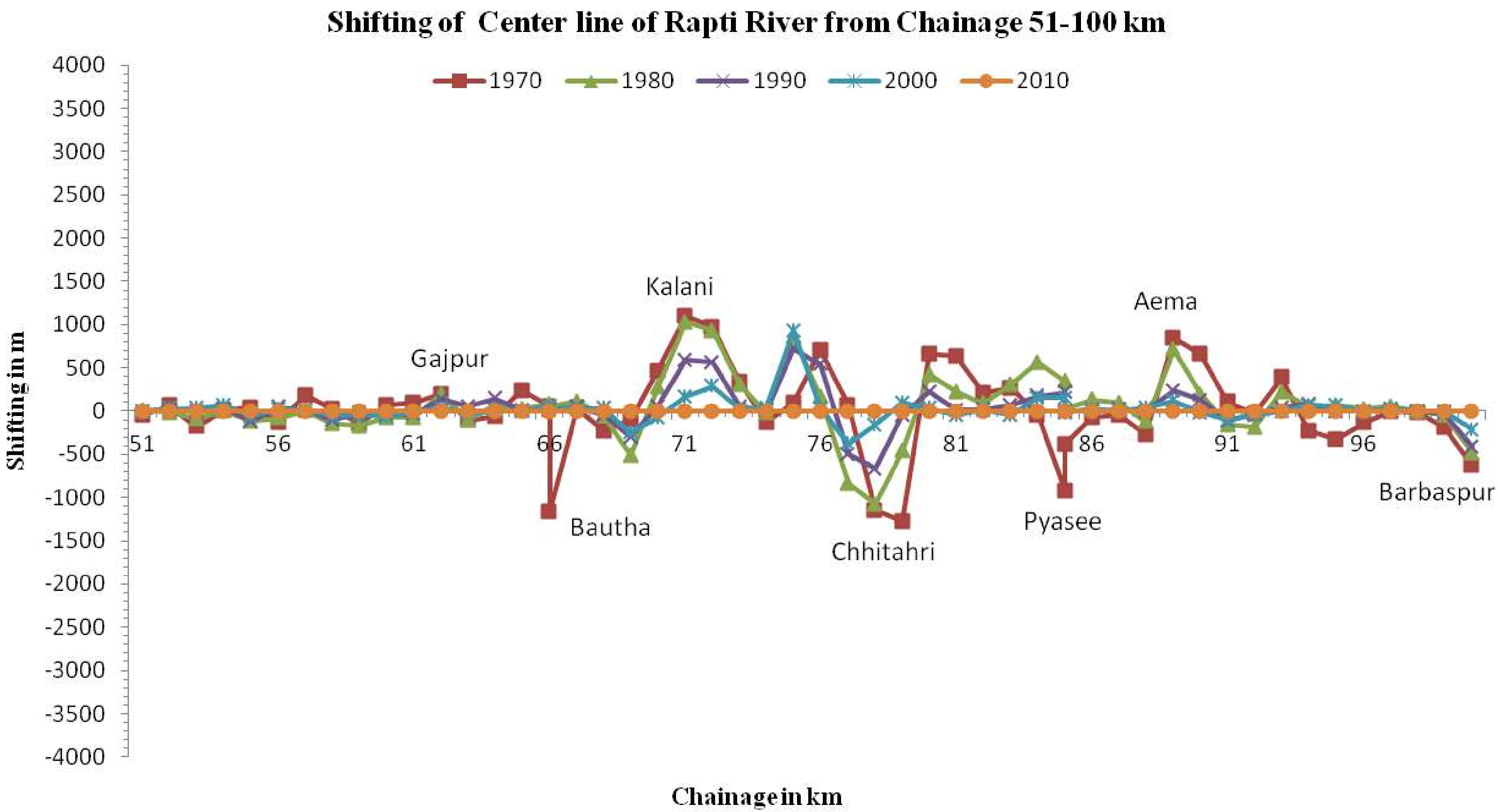


Figure 7.12b Shifting of center line of Rapti river from chainage 50-100 km

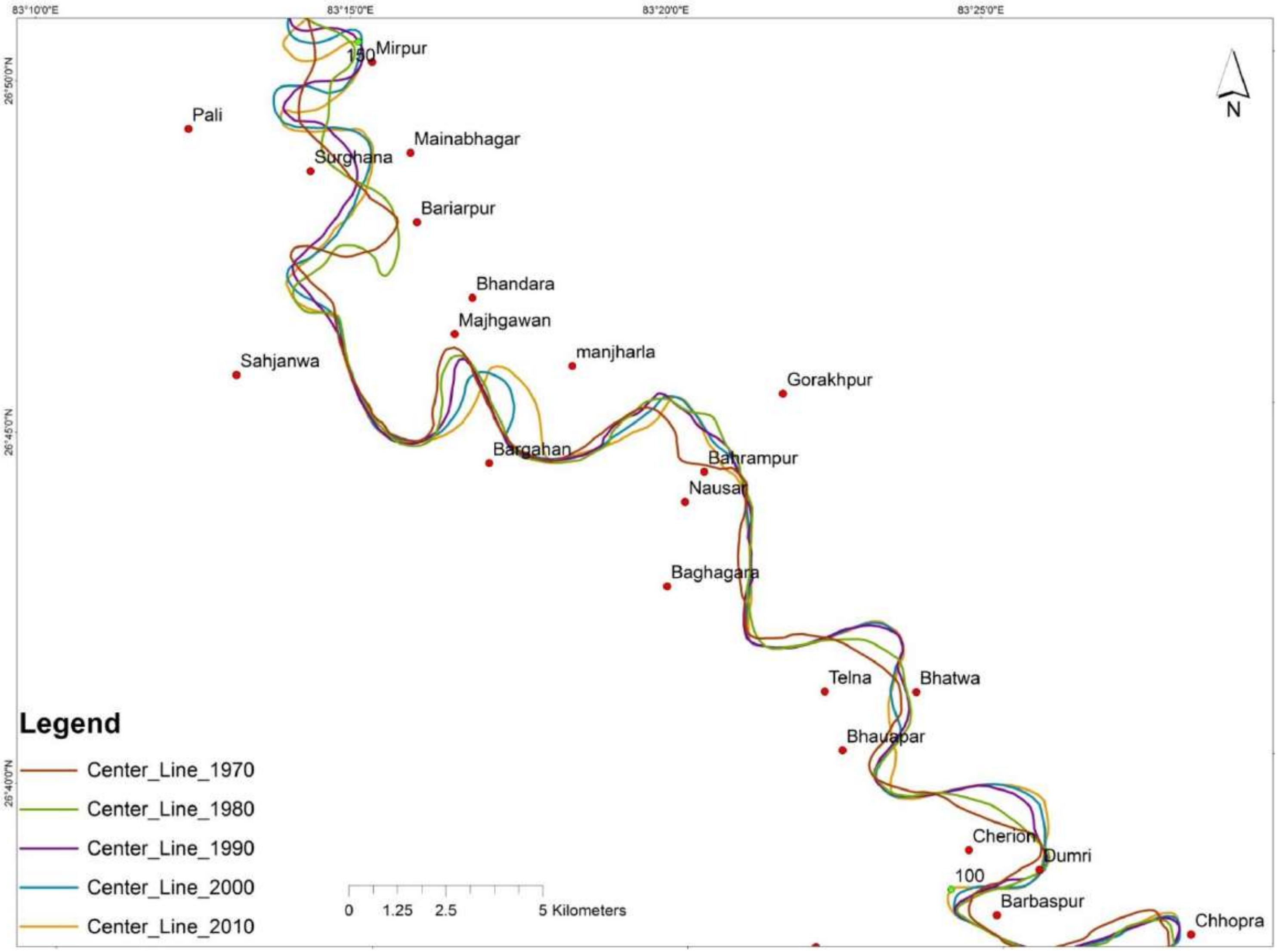


Figure 7.13a Shifting of center line of Rapti river from chainage 100-150 km

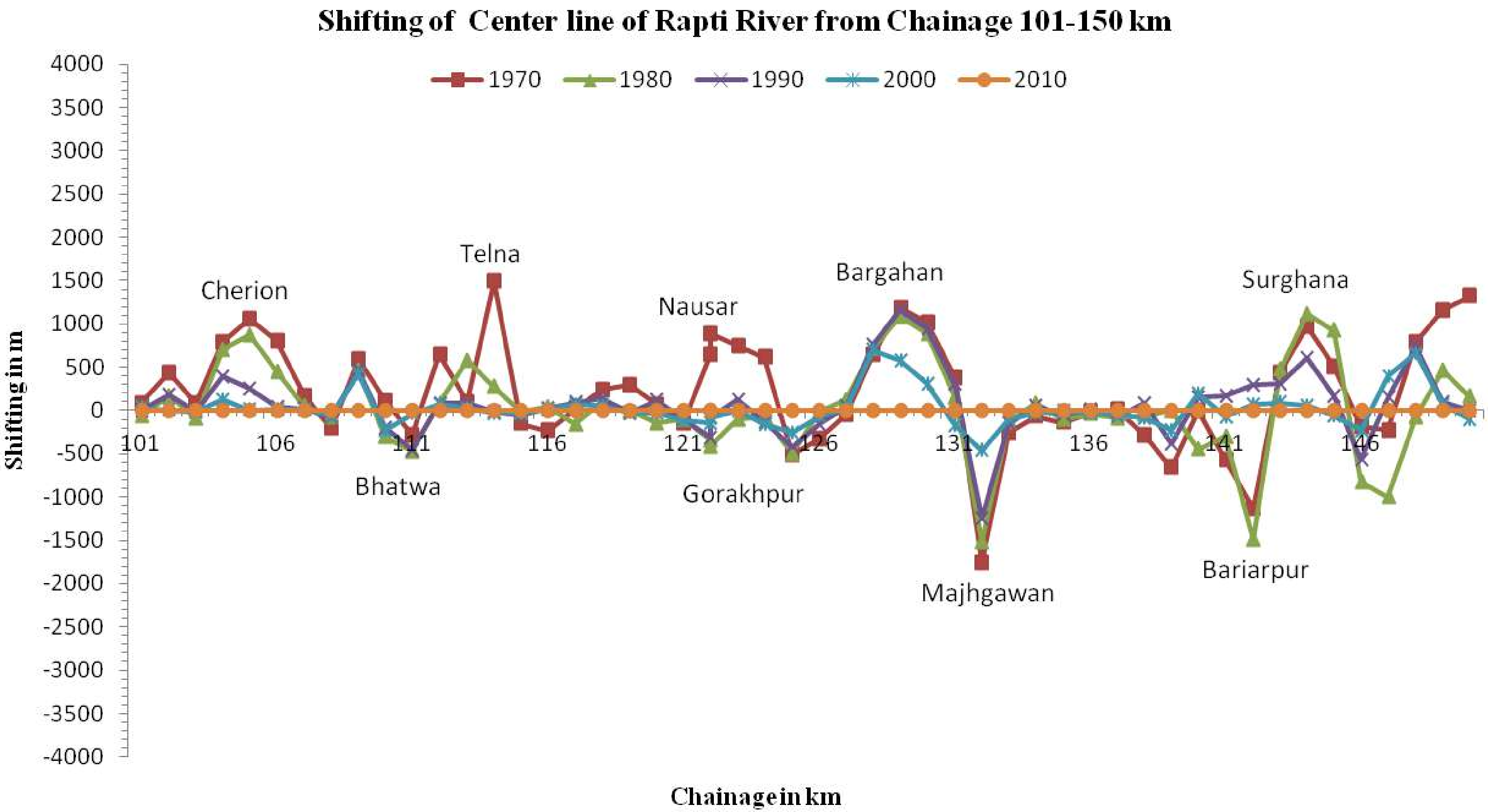


Figure 7.13b Shifting of center line of Rapti river from chainage 100-150 km

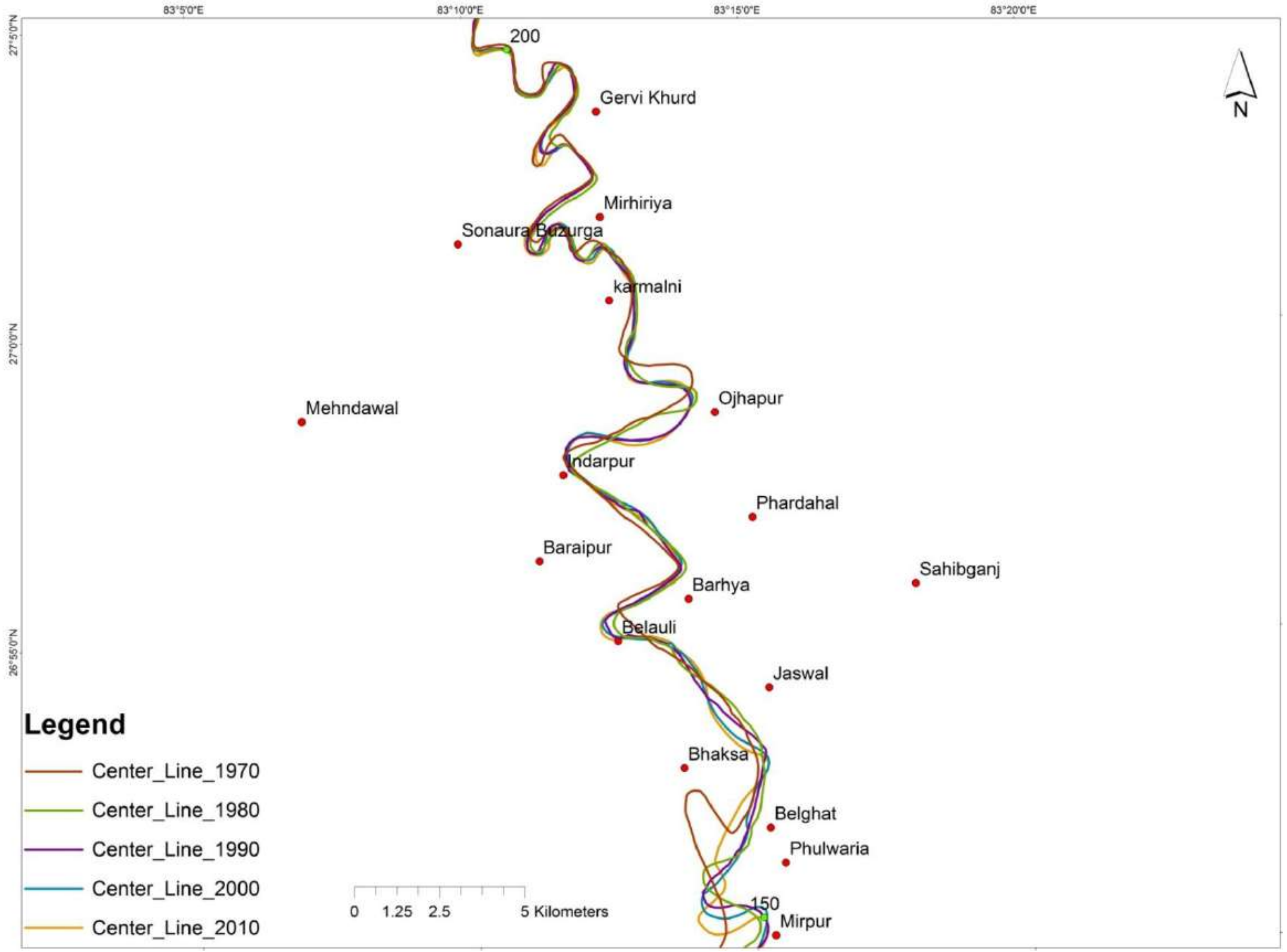


Figure 7.14a Shifting of center line of Rapti river from chainage 150-200 km

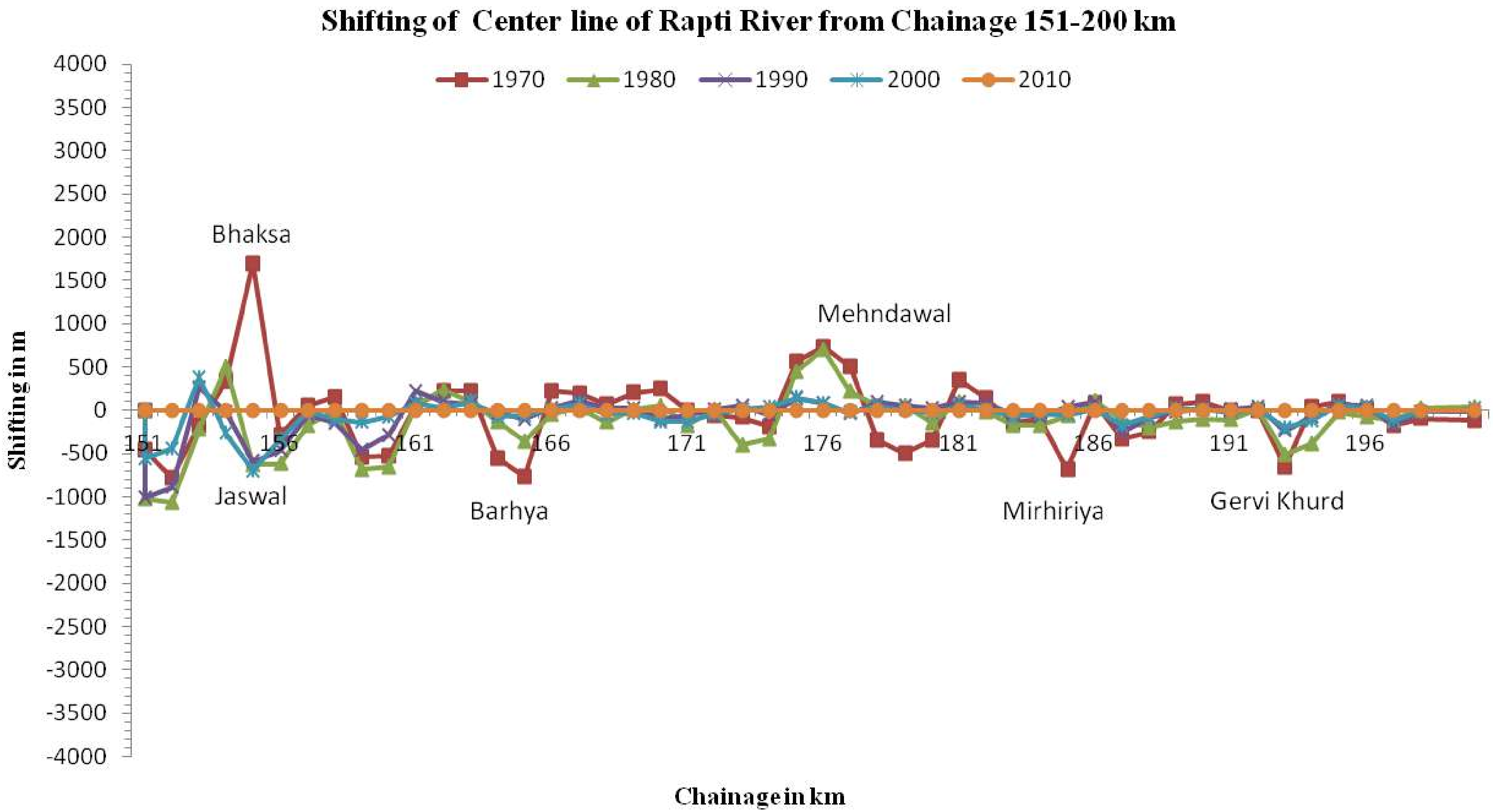


Figure 7.14b Shifting of center line of Rapti river from chainage 150-200 km

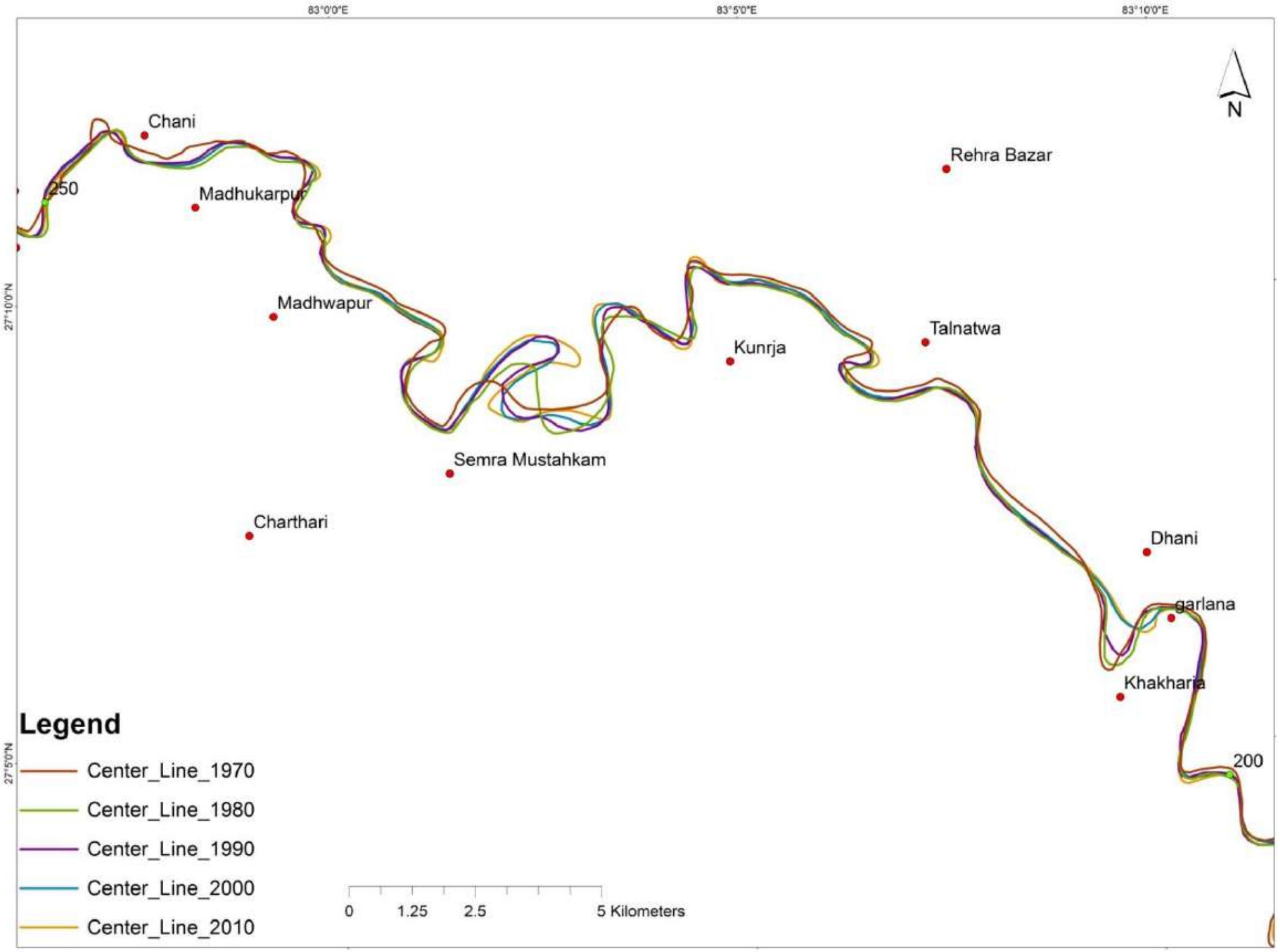


Figure 7.15a Shifting of center line of Rapti river from chainage 200-250 km

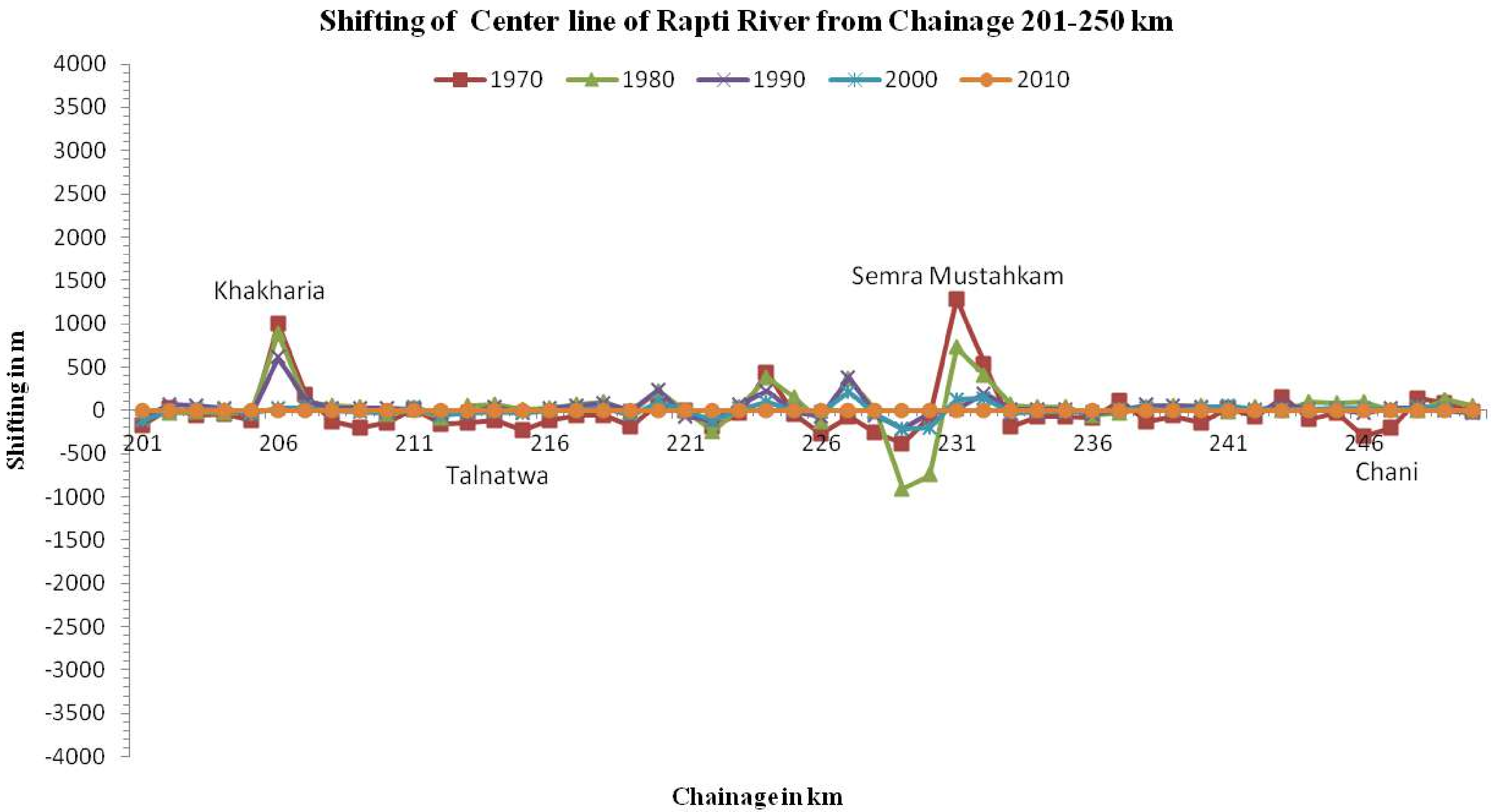


Figure 7.15b Shifting of center line of Rapti river from chainage 200-250 km

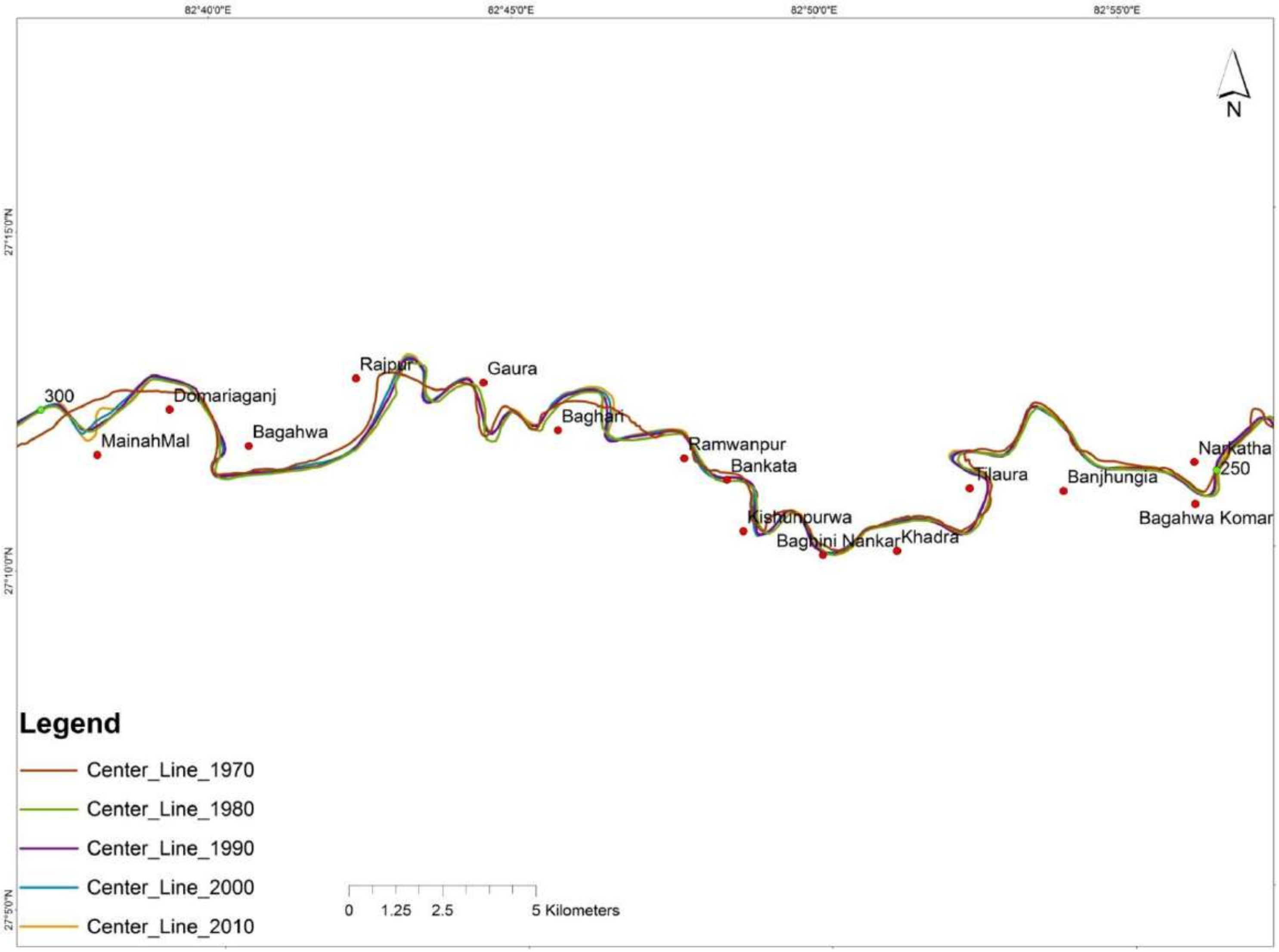


Figure 7.16a Shifting of center line of Rapti river from chainage 250-300 km

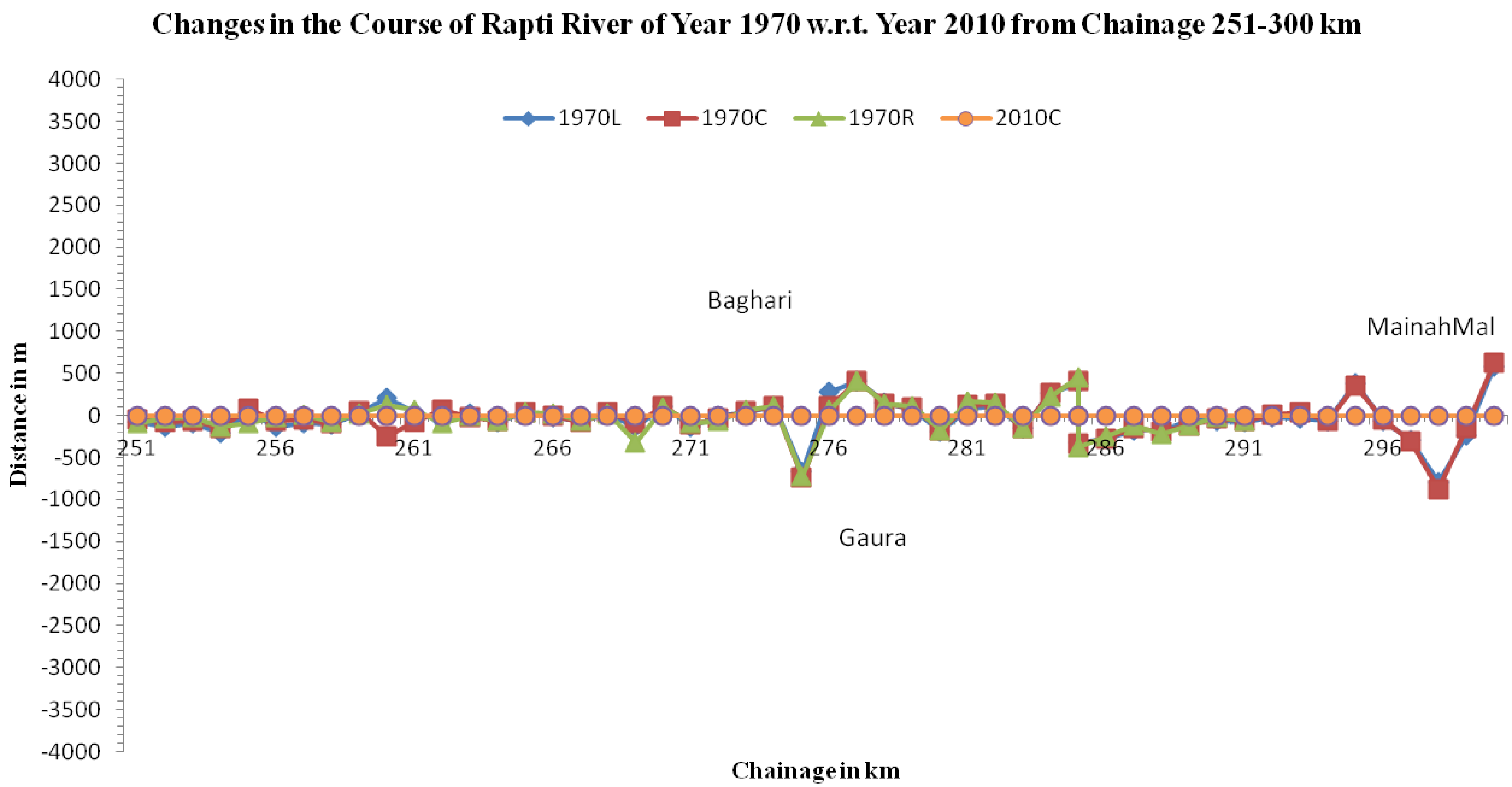


Figure 7.16b Shifting of center line of Rapti river from chainage 250-300 km

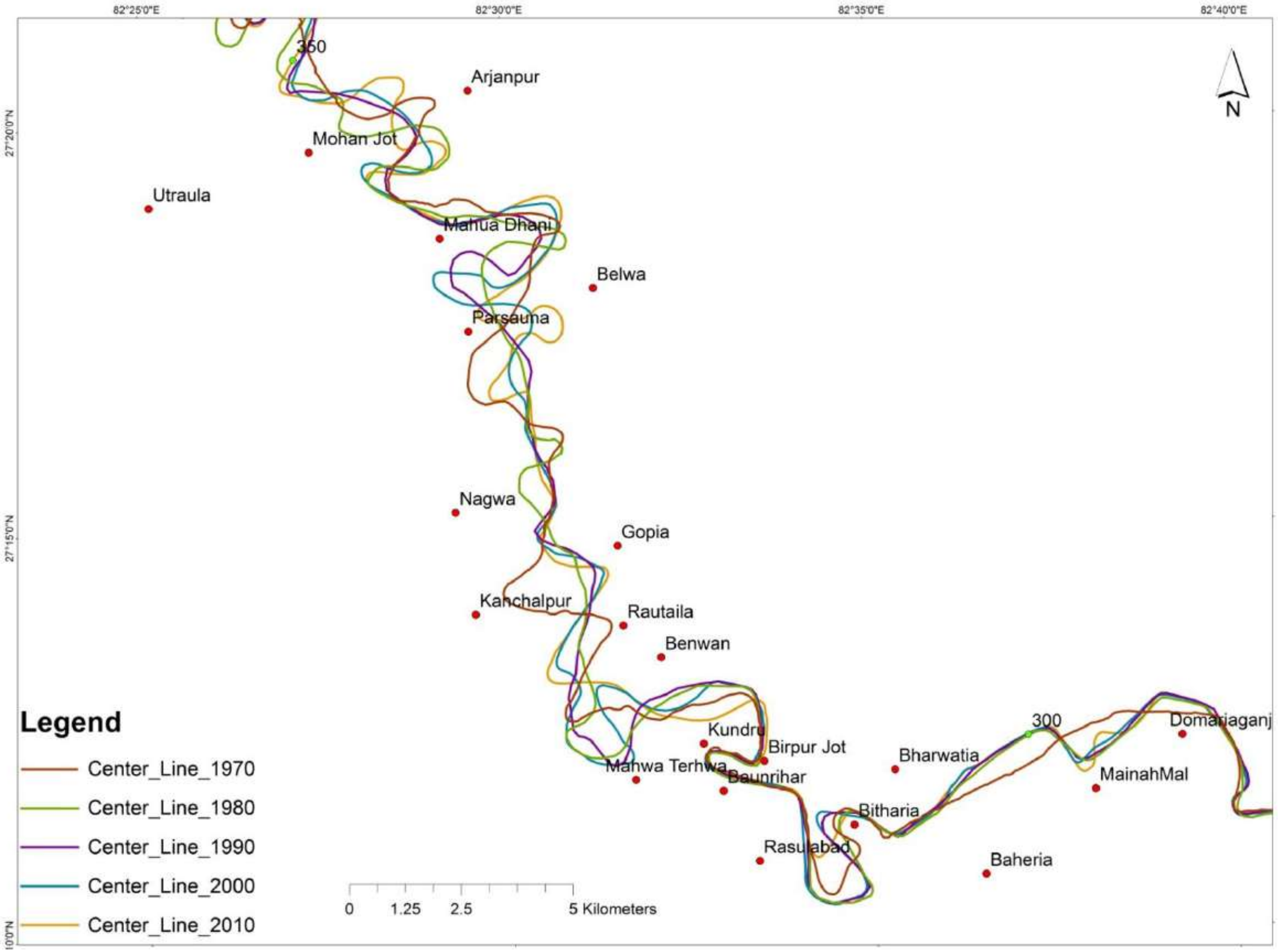


Figure 7.17a Shifting of center line of Rapti river from chainage 300-350 km

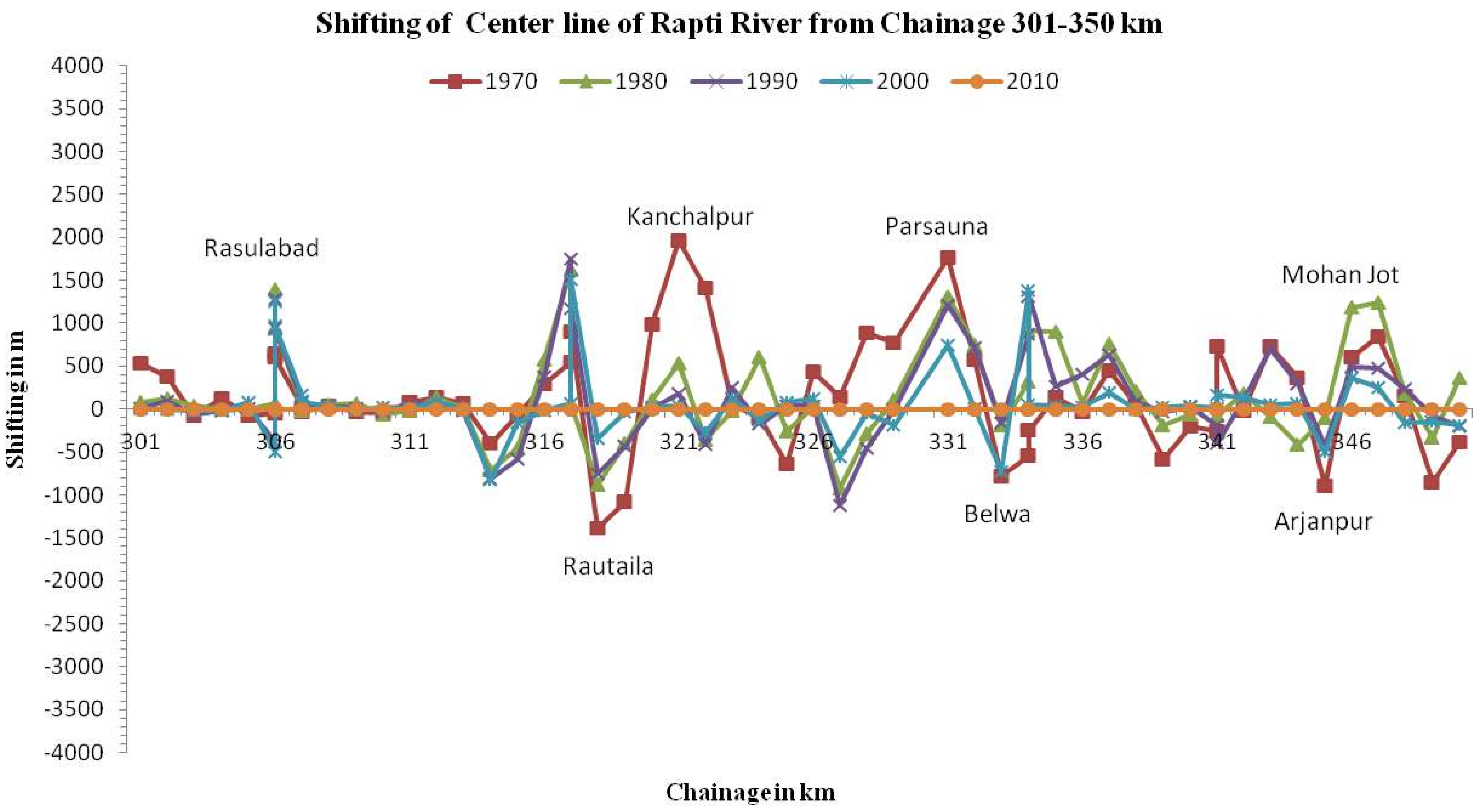


Figure 7.17b Shifting of center line of Rapti river from chainage 300-350 km

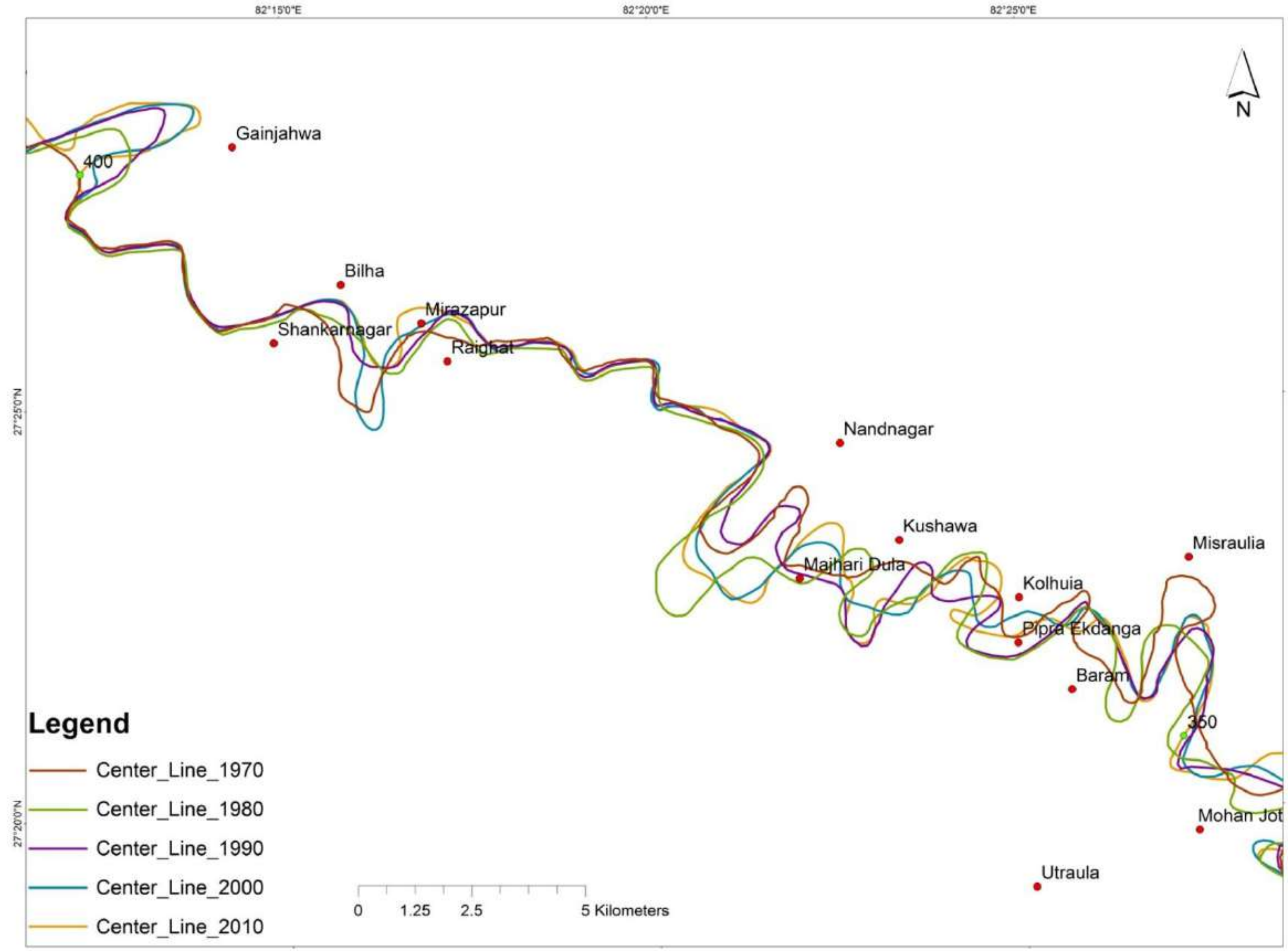


Figure 7.18a Shifting of center line of Rapti river from chainage 350-400 km

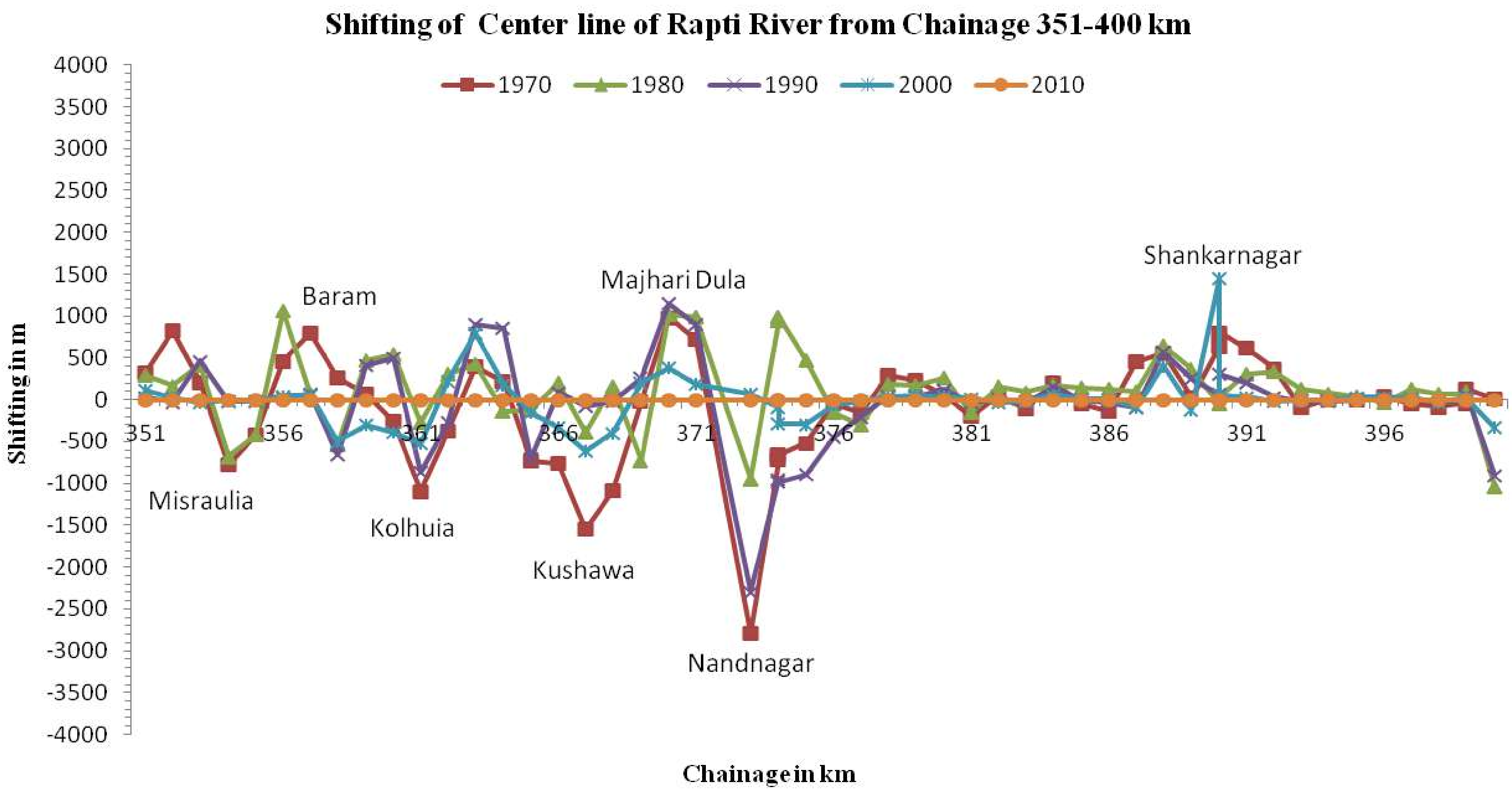


Figure 7.18b Shifting of center line of Rapti river from chainage 350-400 km

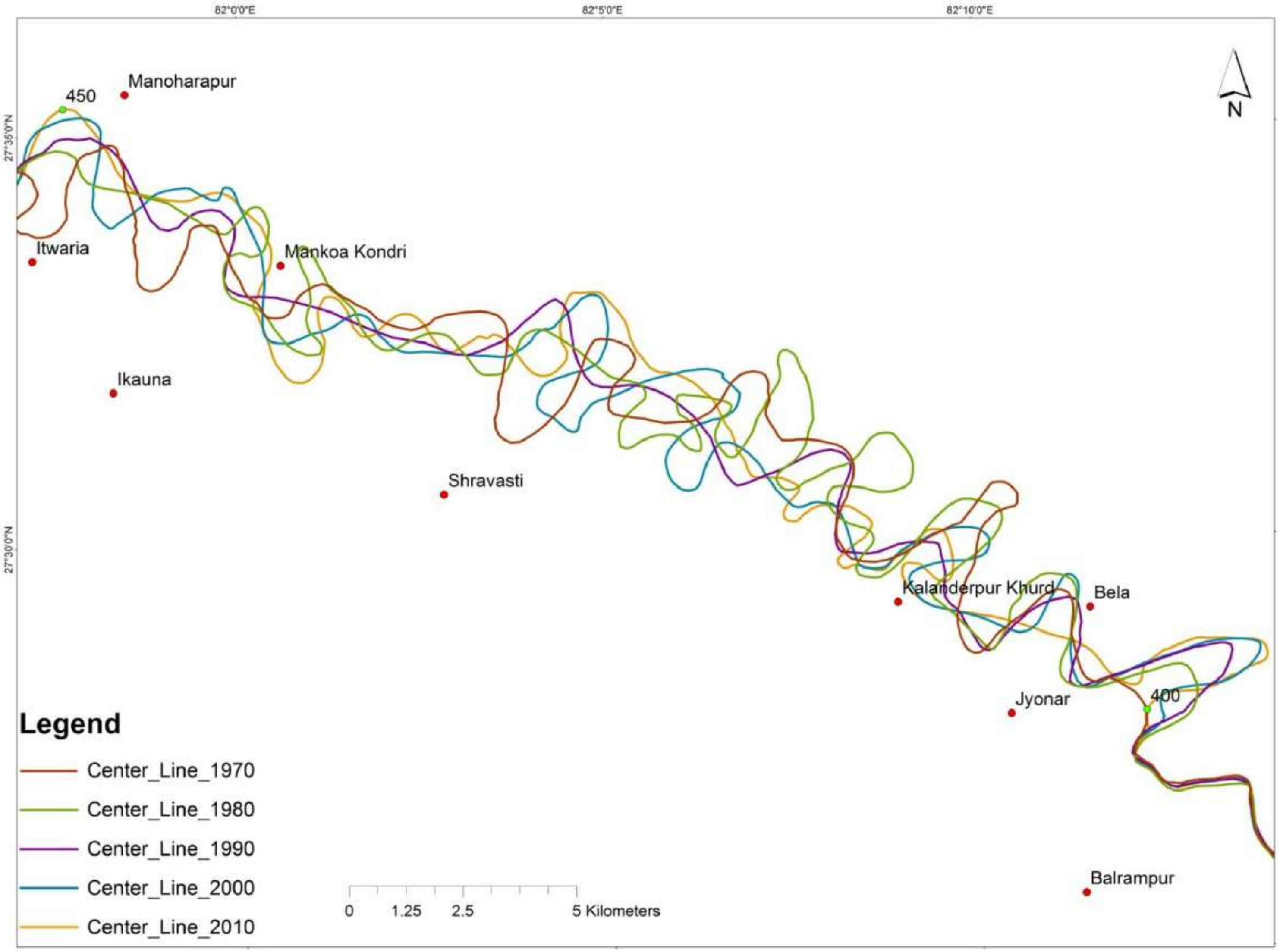


Figure 7.19a Shifting of center line of Rapti river from chainage 400-450 km

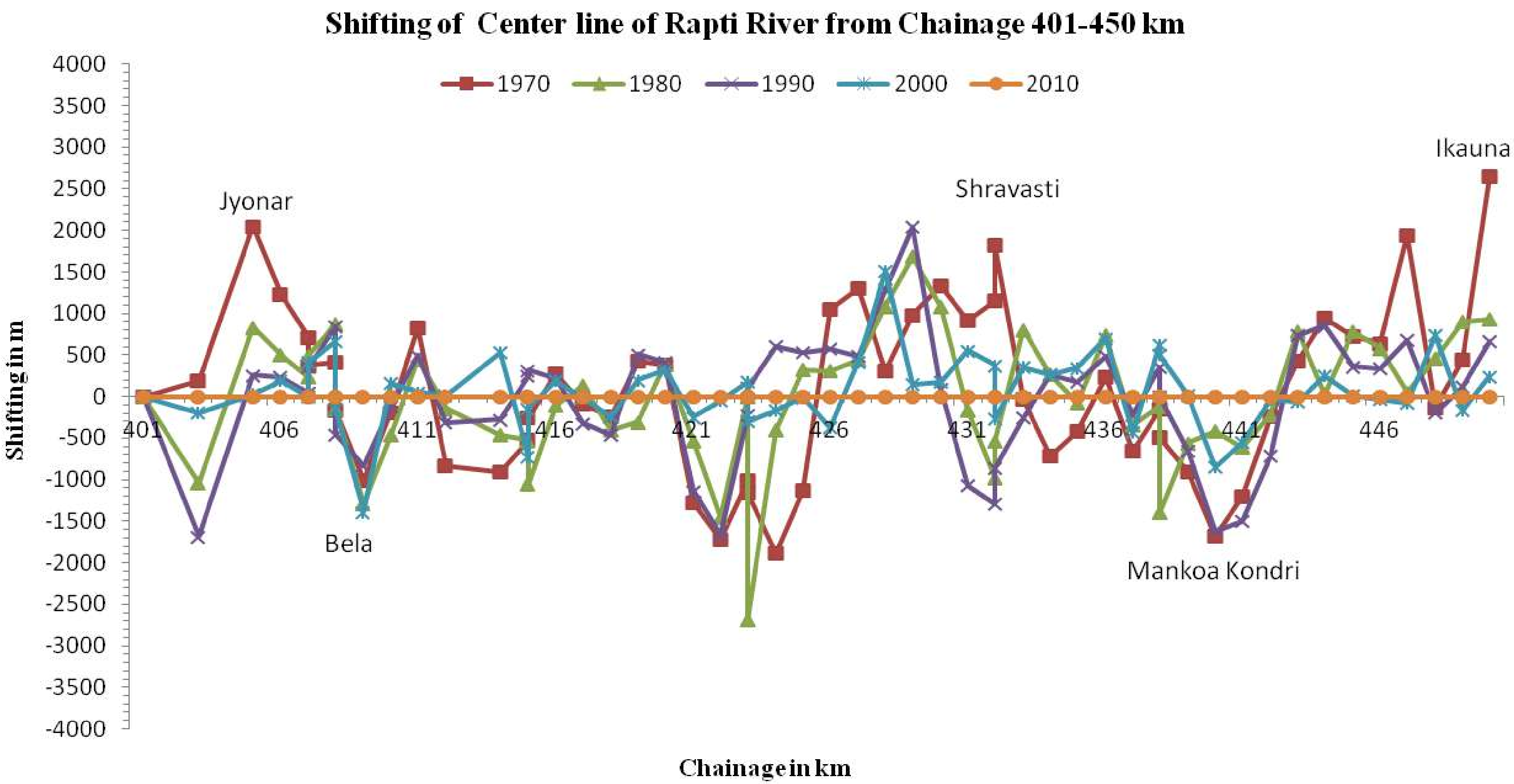


Figure 7.19b Shifting of center line of Rapti river from chainage 400-450 km

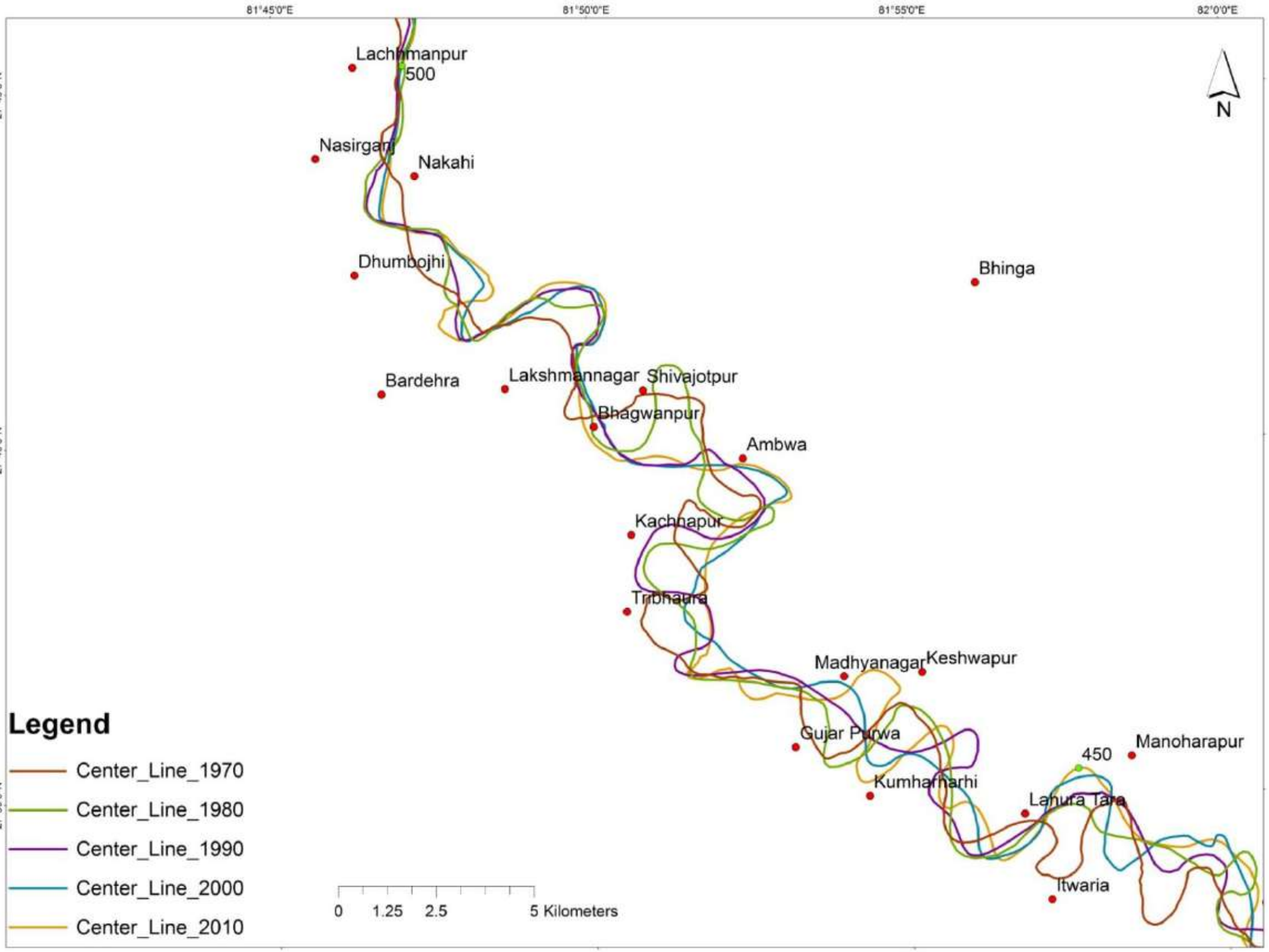


Figure 7.20a Shifting of center line of Rapti river from chainage 450-500 km

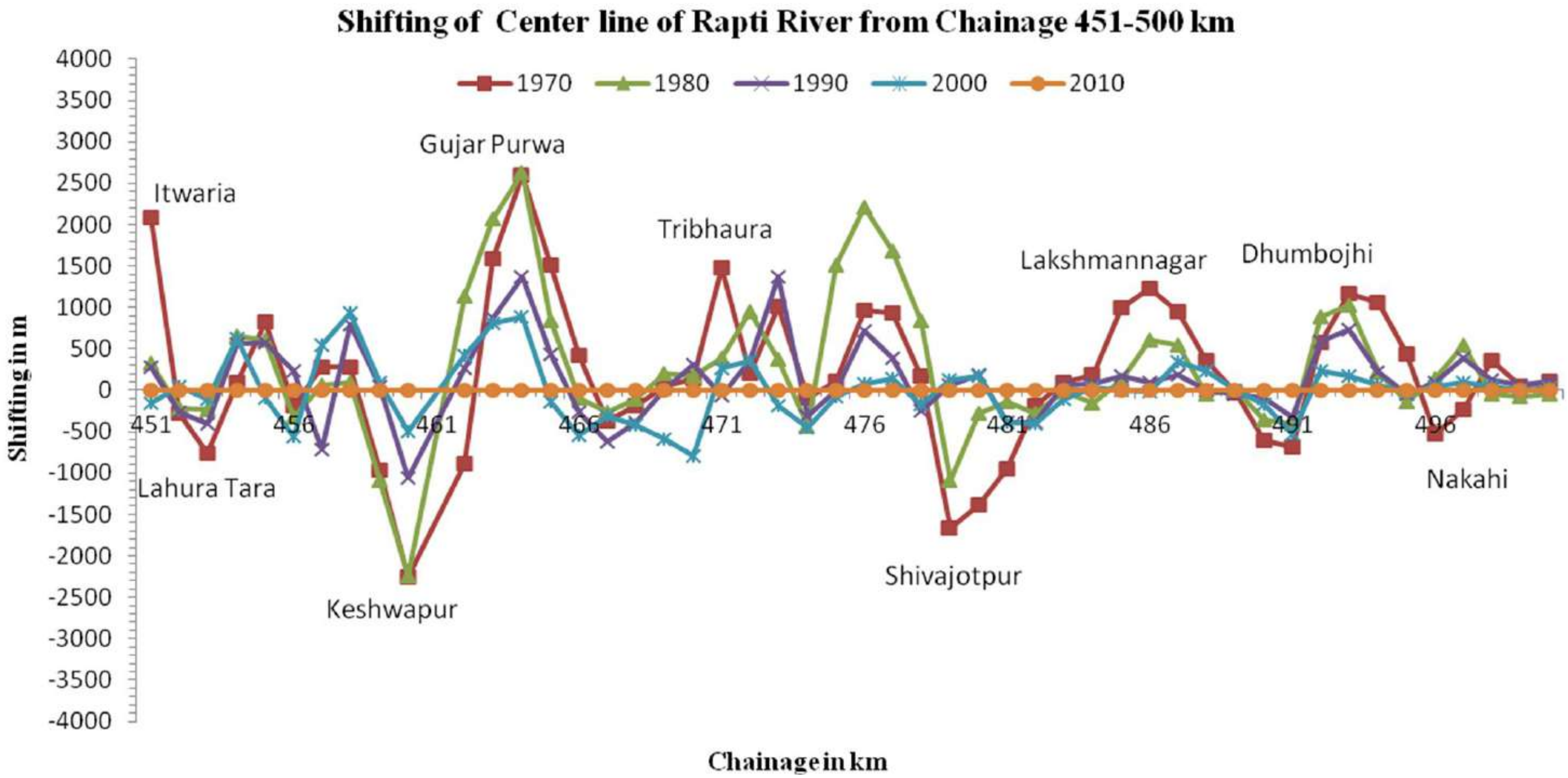


Figure 7.20b Shifting of center line of Rapti river from chainage 450-500 km

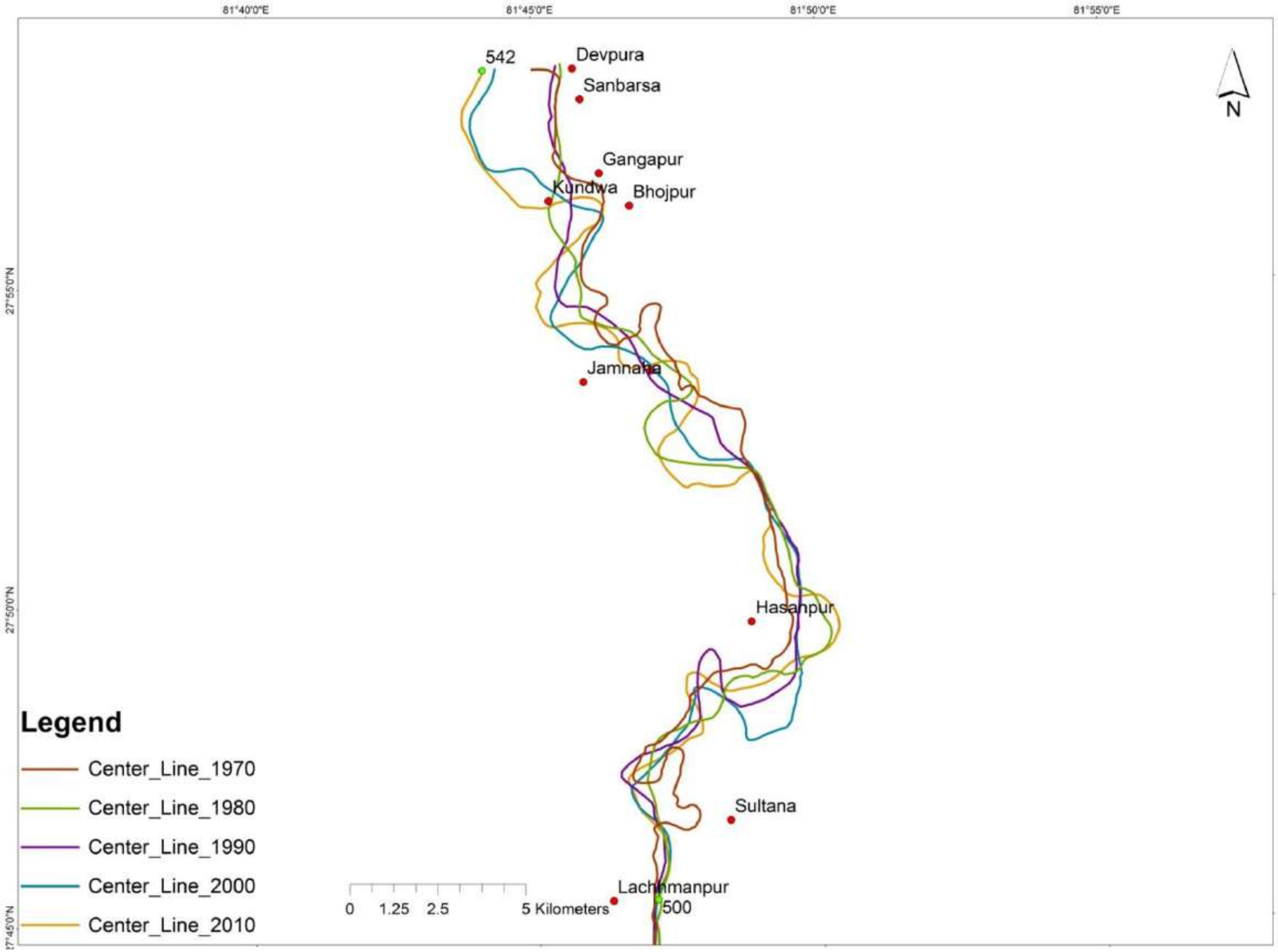


Figure 7.21a Shifting of center line of Rapti river from chainage 500-542 km

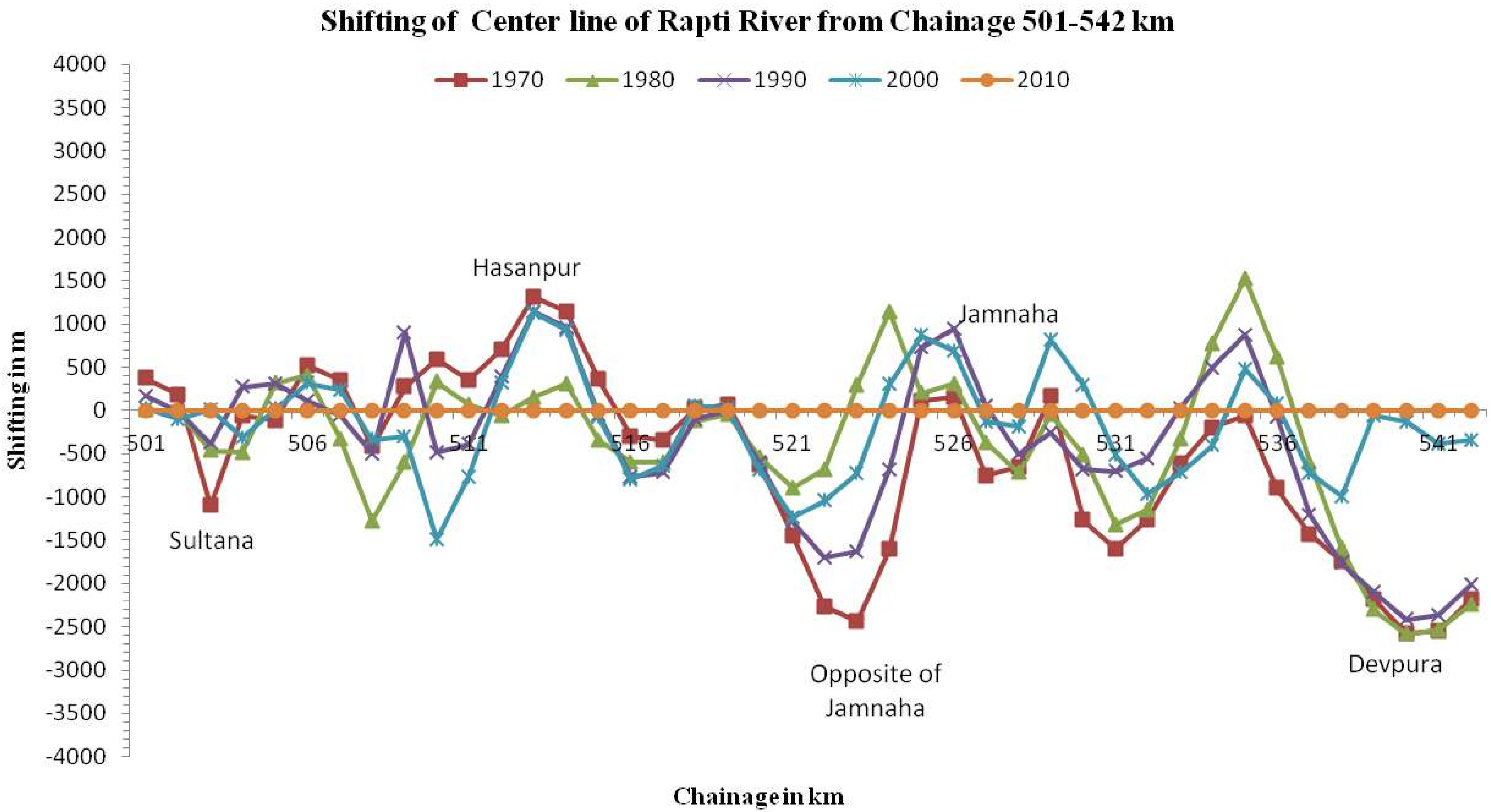


Figure 7.21b Shifting of center line of Rapti river from chainage 500-542 km

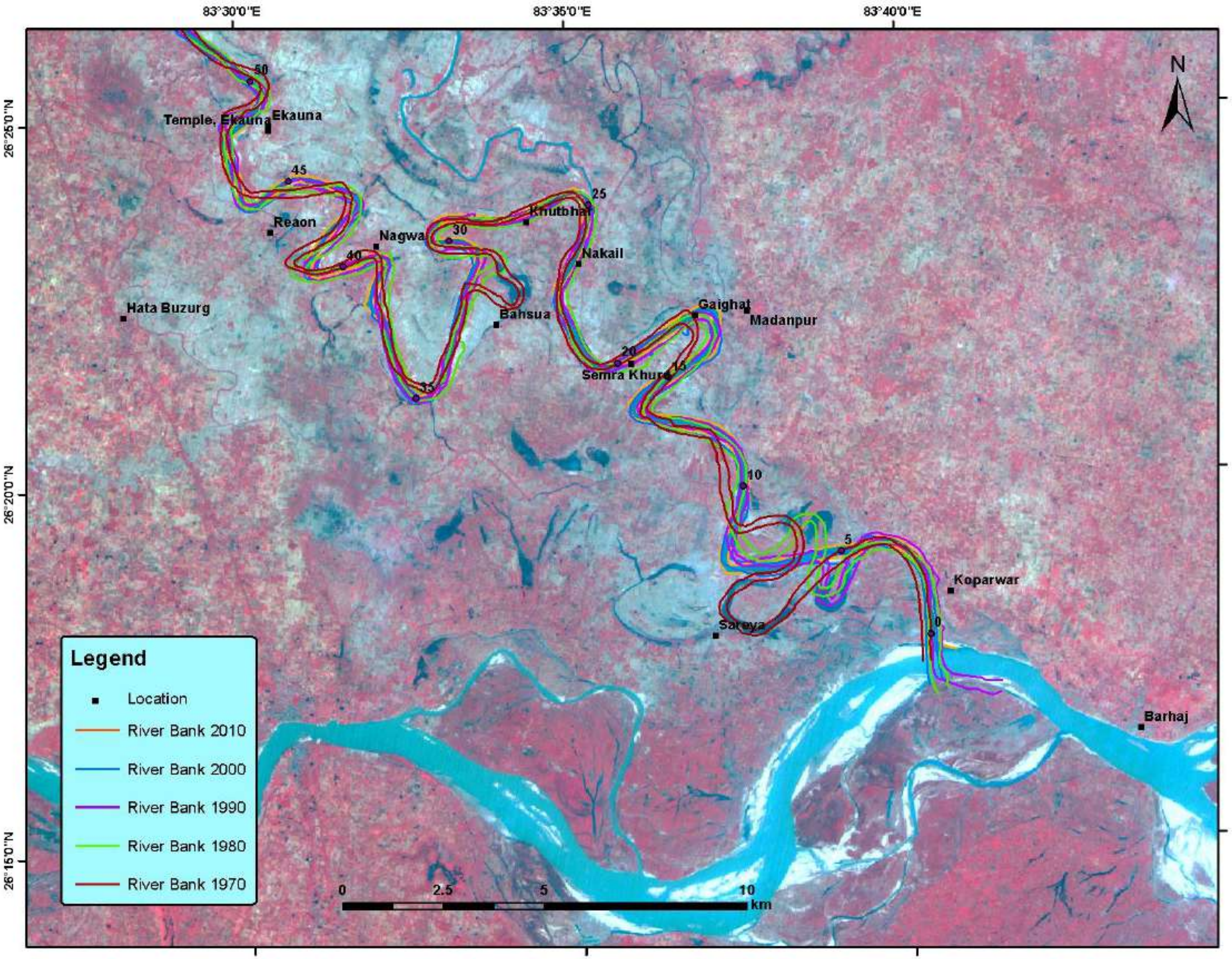


Figure 7.22a Decadal changes in the course of Rapti river from chainage 0-50 km

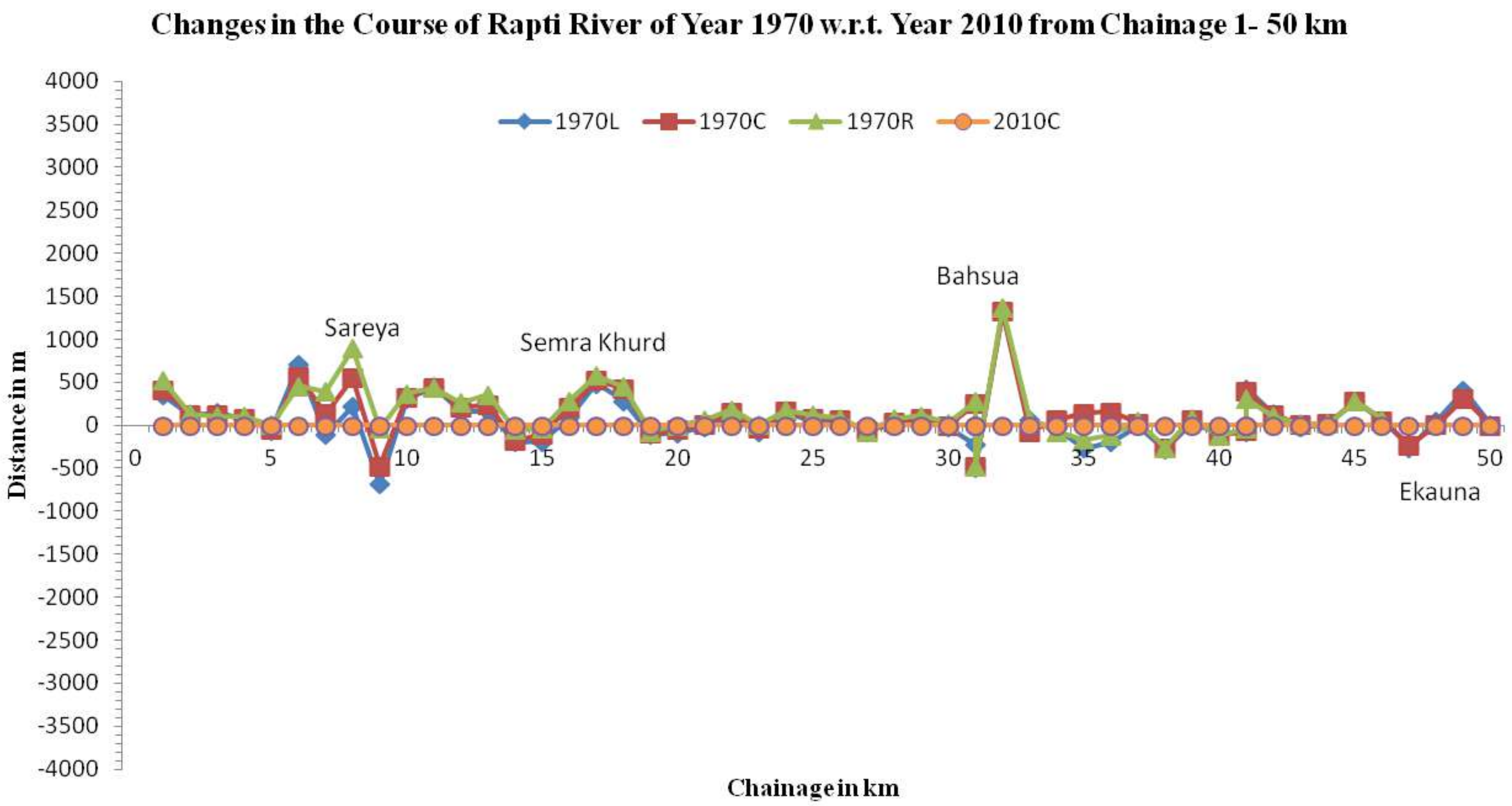


Figure 7.22b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 0-50 km

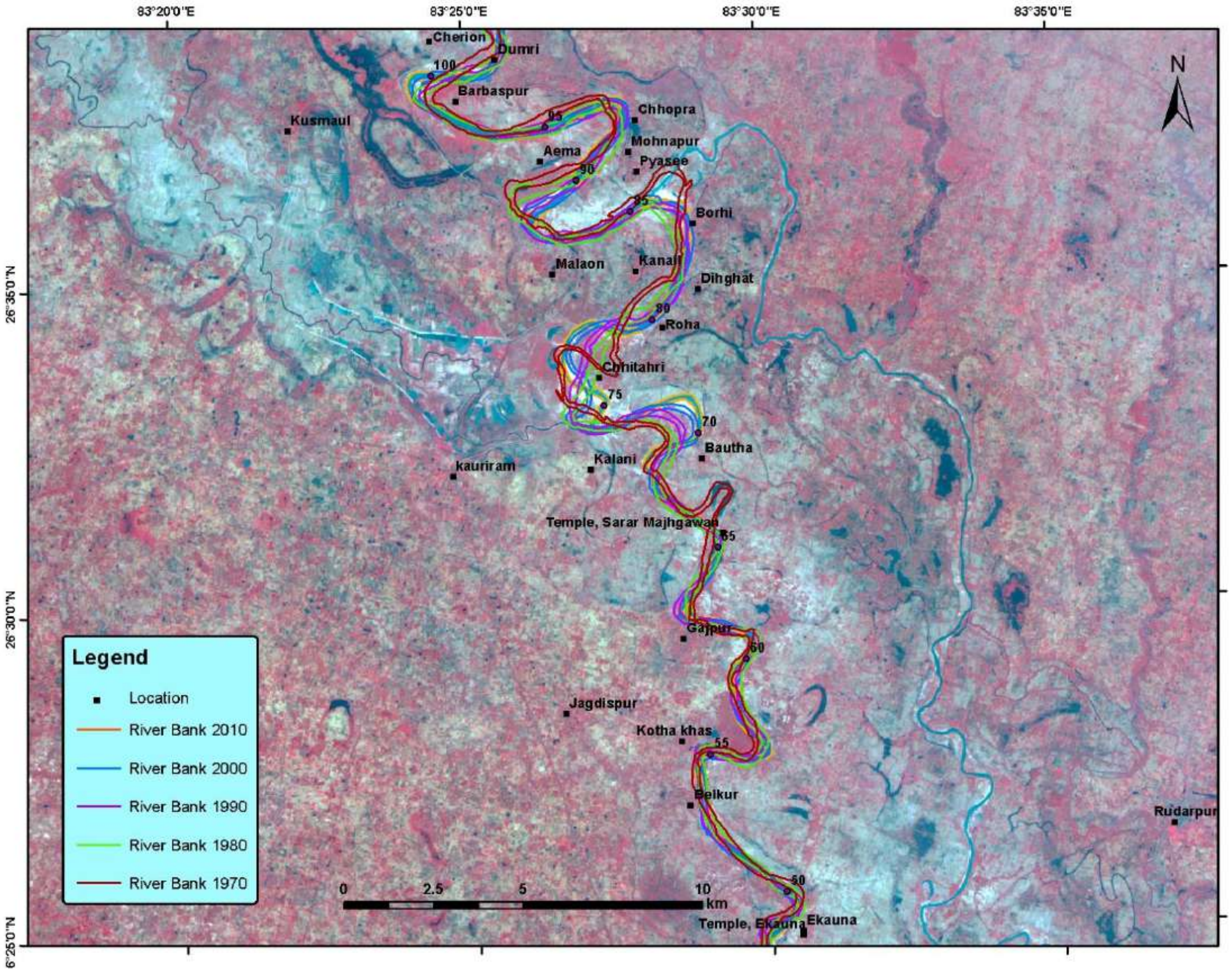


Figure 7.23a Decadal changes in the course of Rapti river from chainage 50-100 km

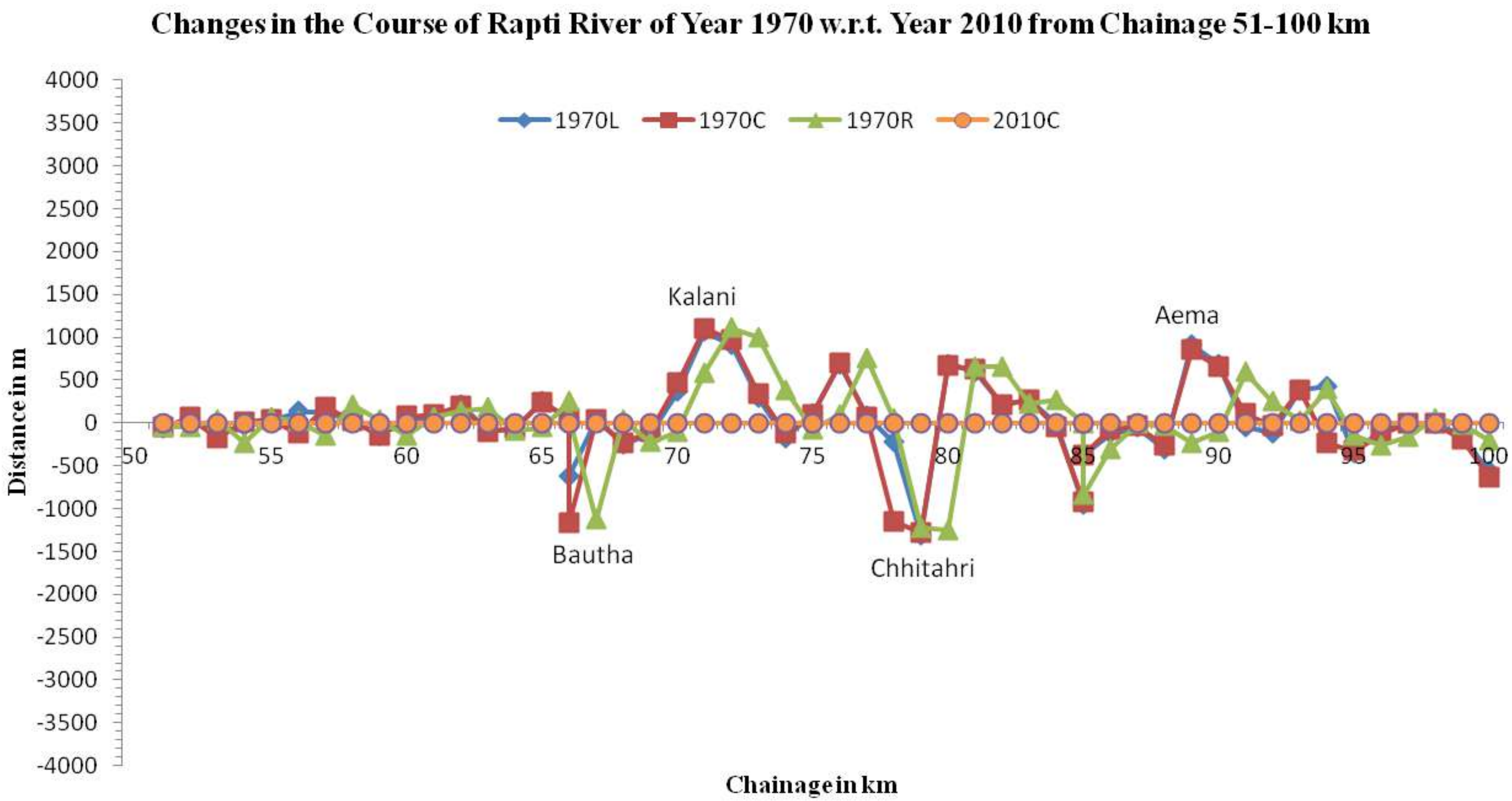


Figure 7.23b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 50-100 km

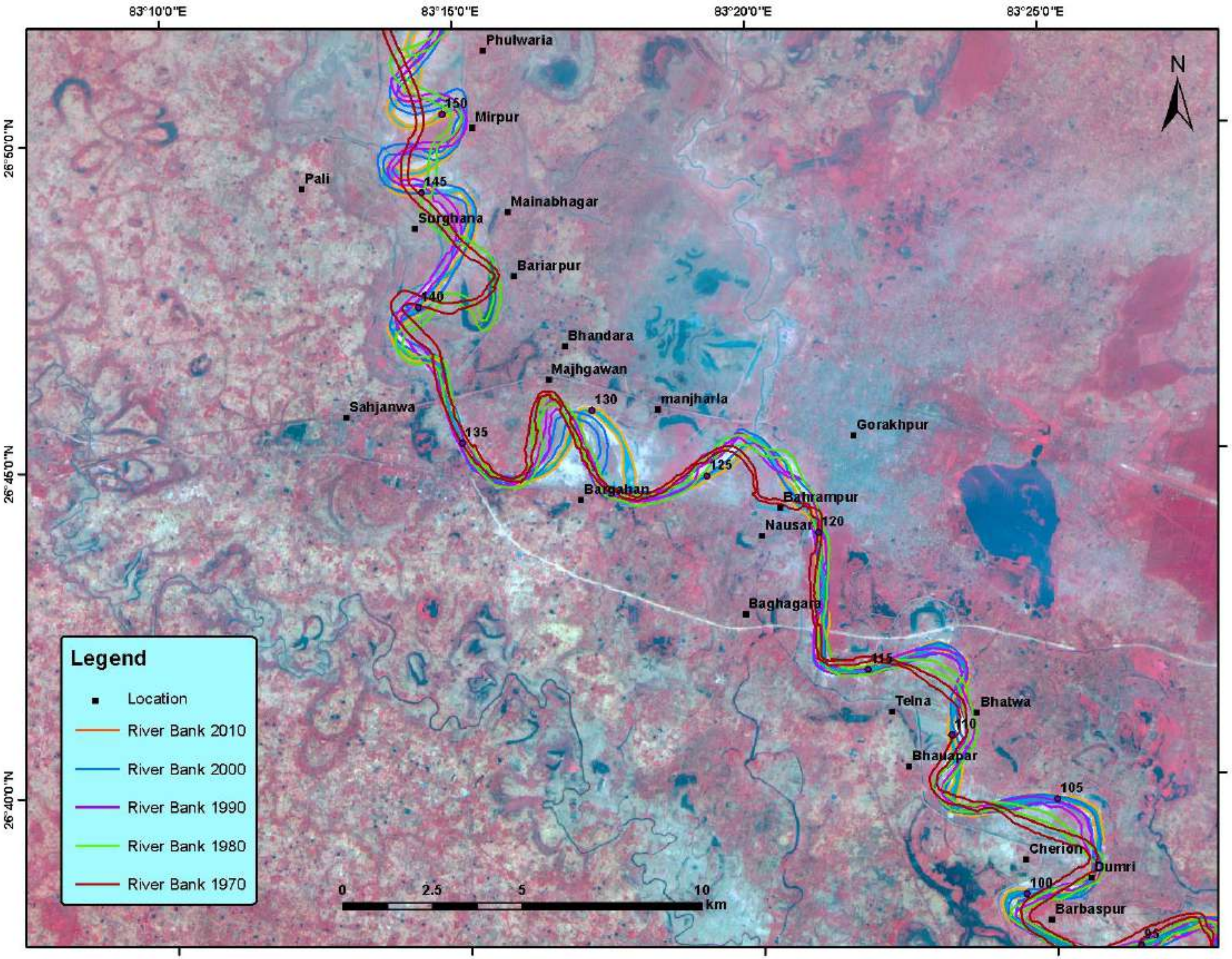


Figure 7.24a Decadal changes in the course of Rapti river from chainage 100-150 km

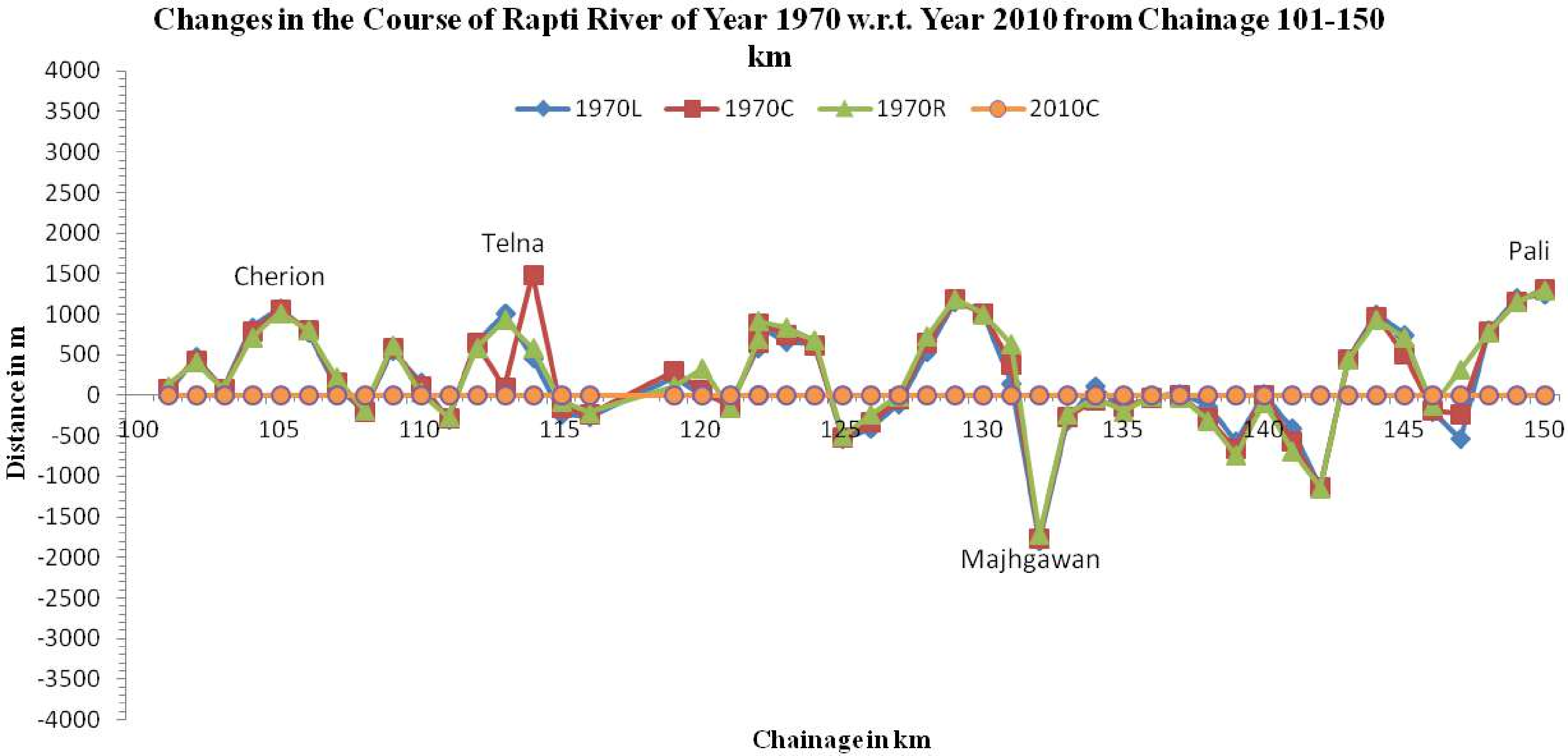


Figure 7.24b Changes in the course of Rapti river of year 1970 w.r.t. year 2010 from chainage 100-150 km

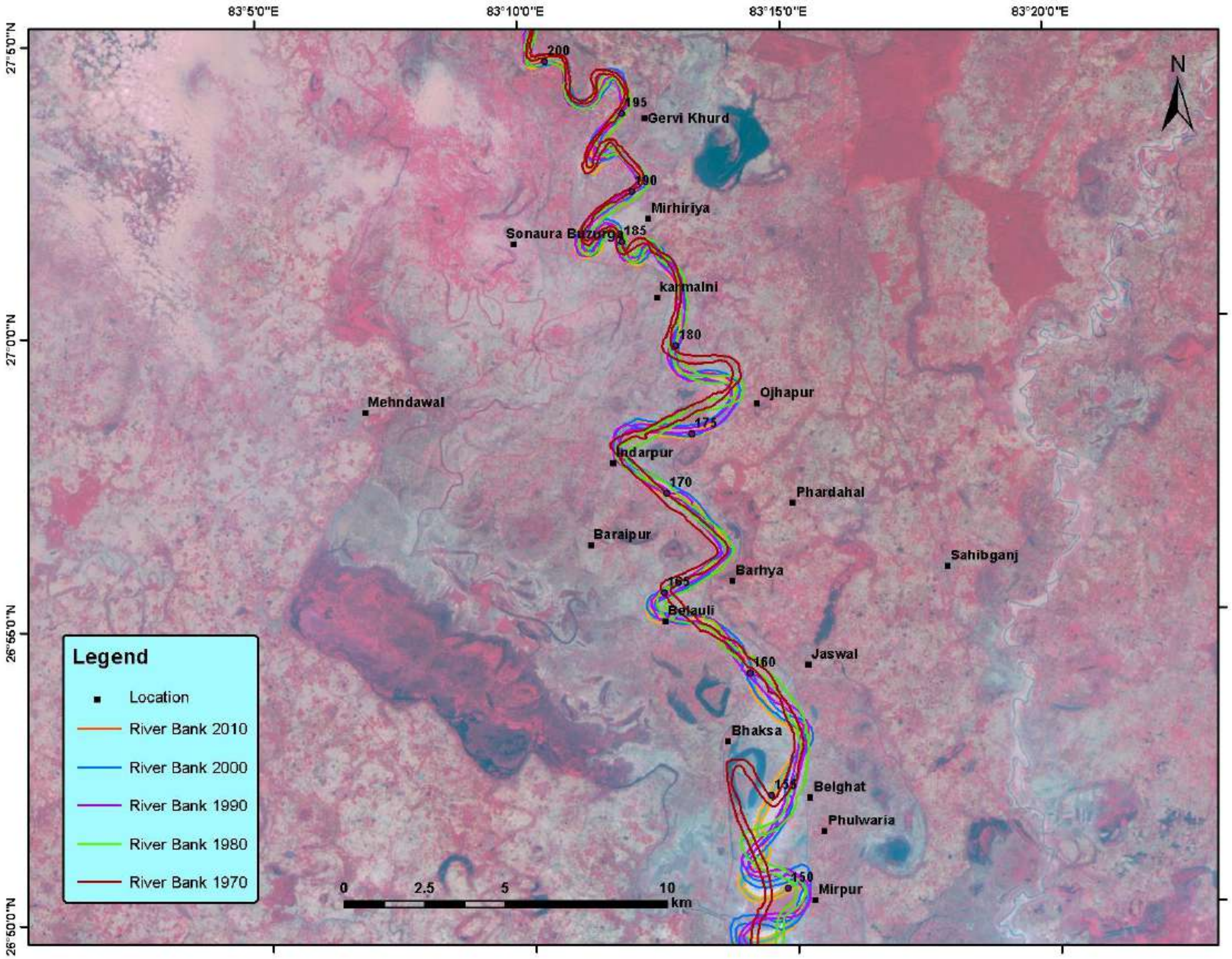


Figure 7.25a Decadal changes in the course of Rapti river from chainage 150-200 km

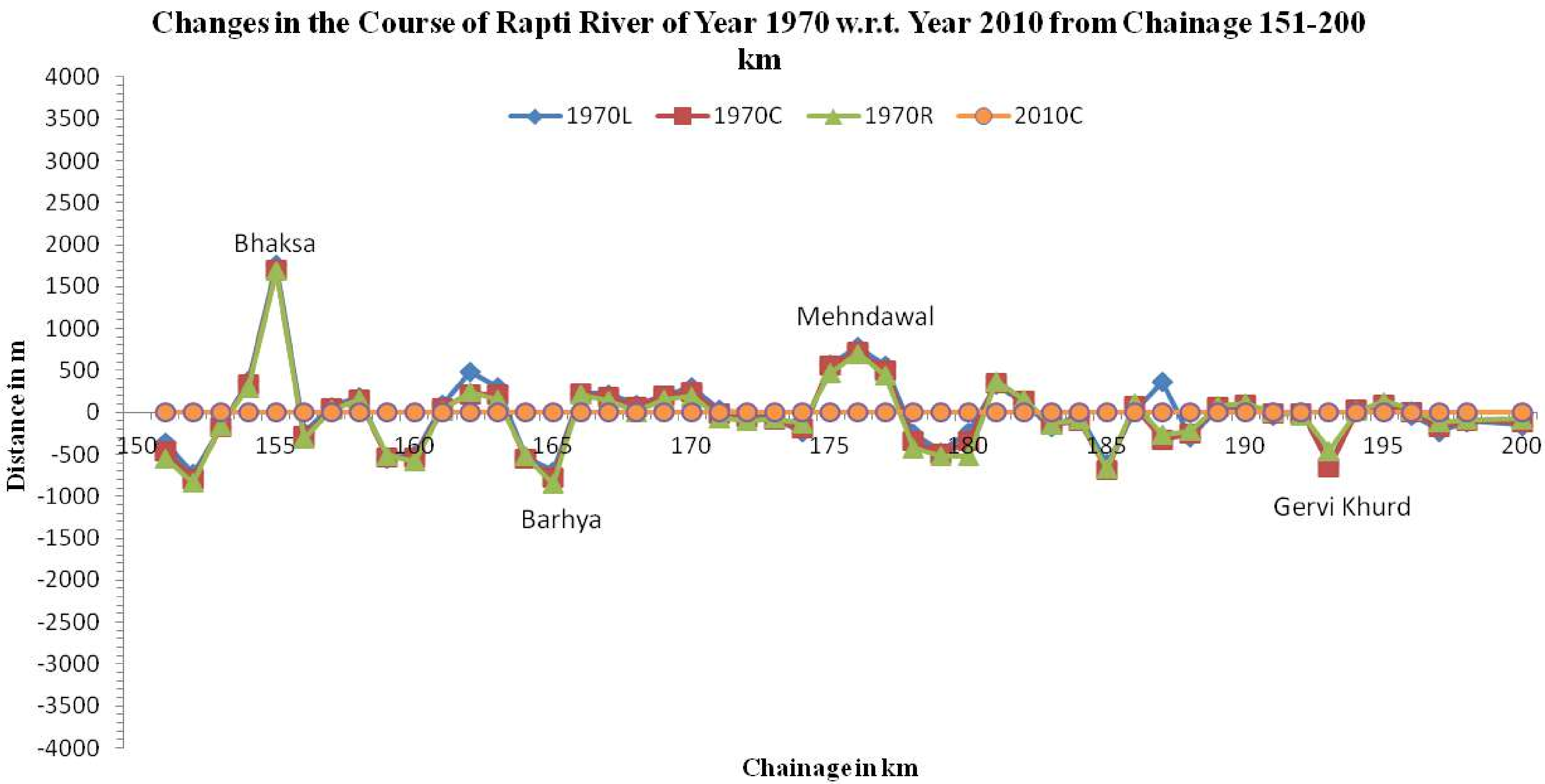


Figure 7.25b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 150-200 km

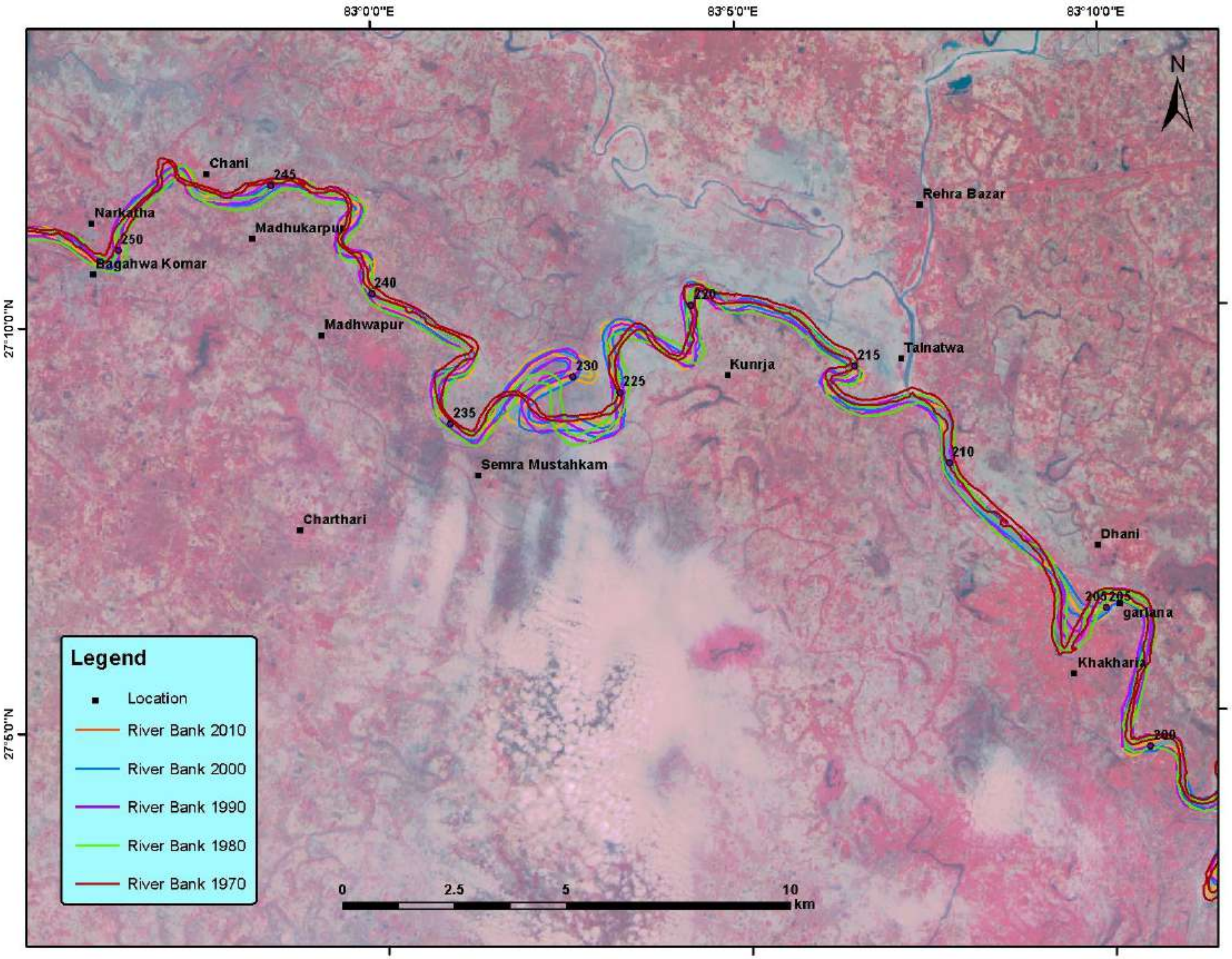


Figure 7.26a Decadal changes in the course of Rapti river from chainage 200-250 km

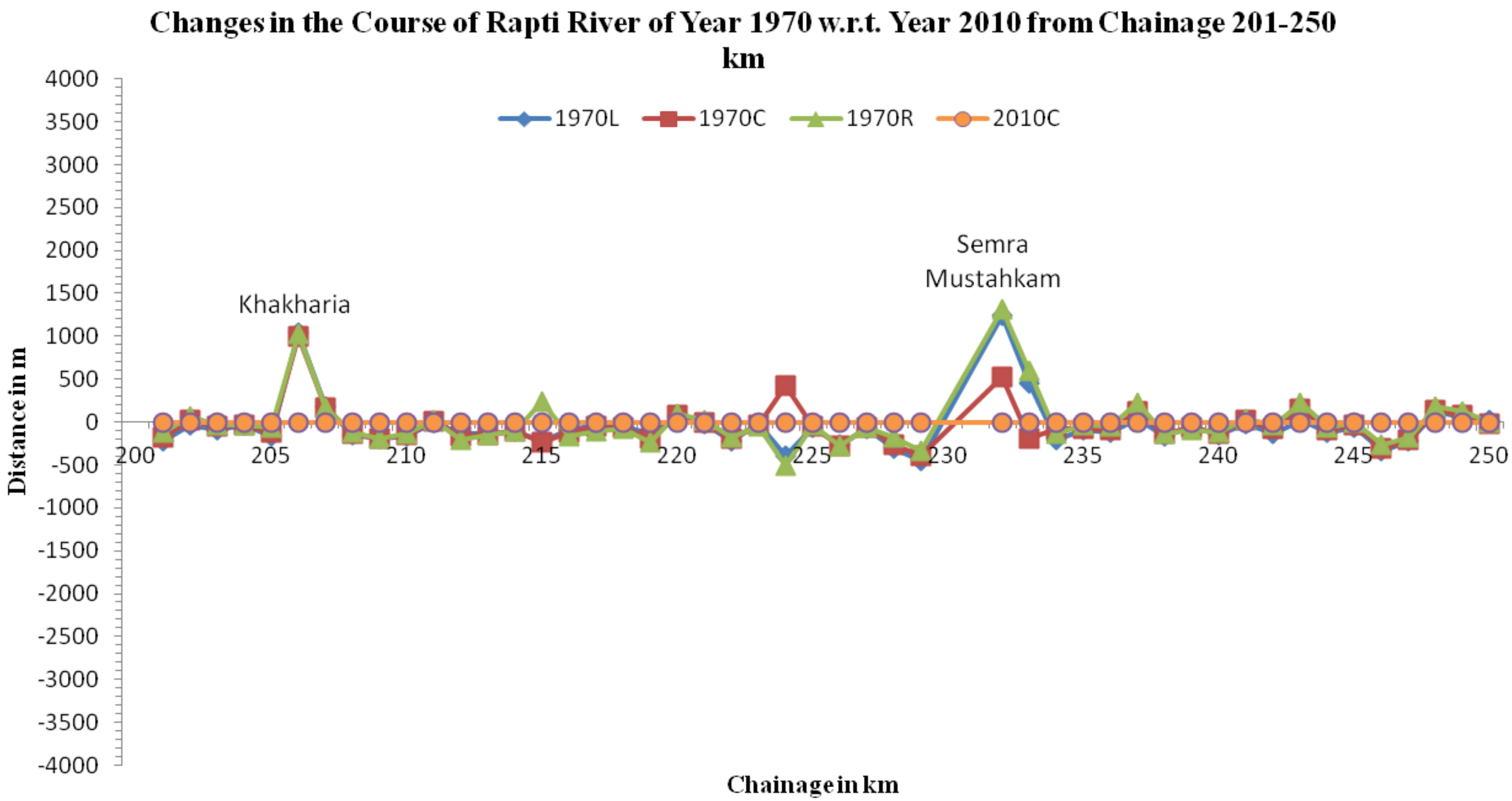


Figure 7.26b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 200-250 km

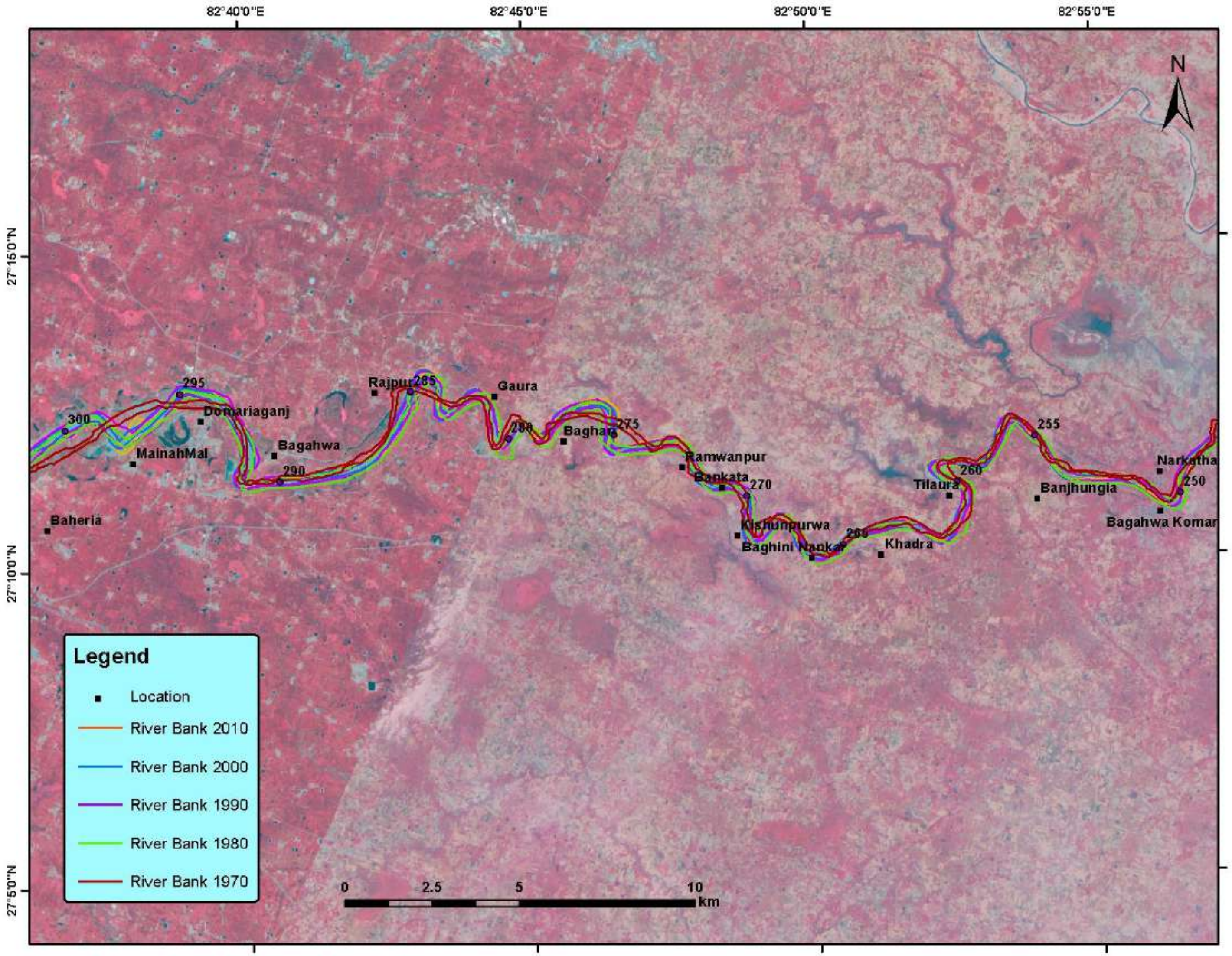


Figure 7.27a Decadal changes in the course of Rapti river from chainage 250-300 km

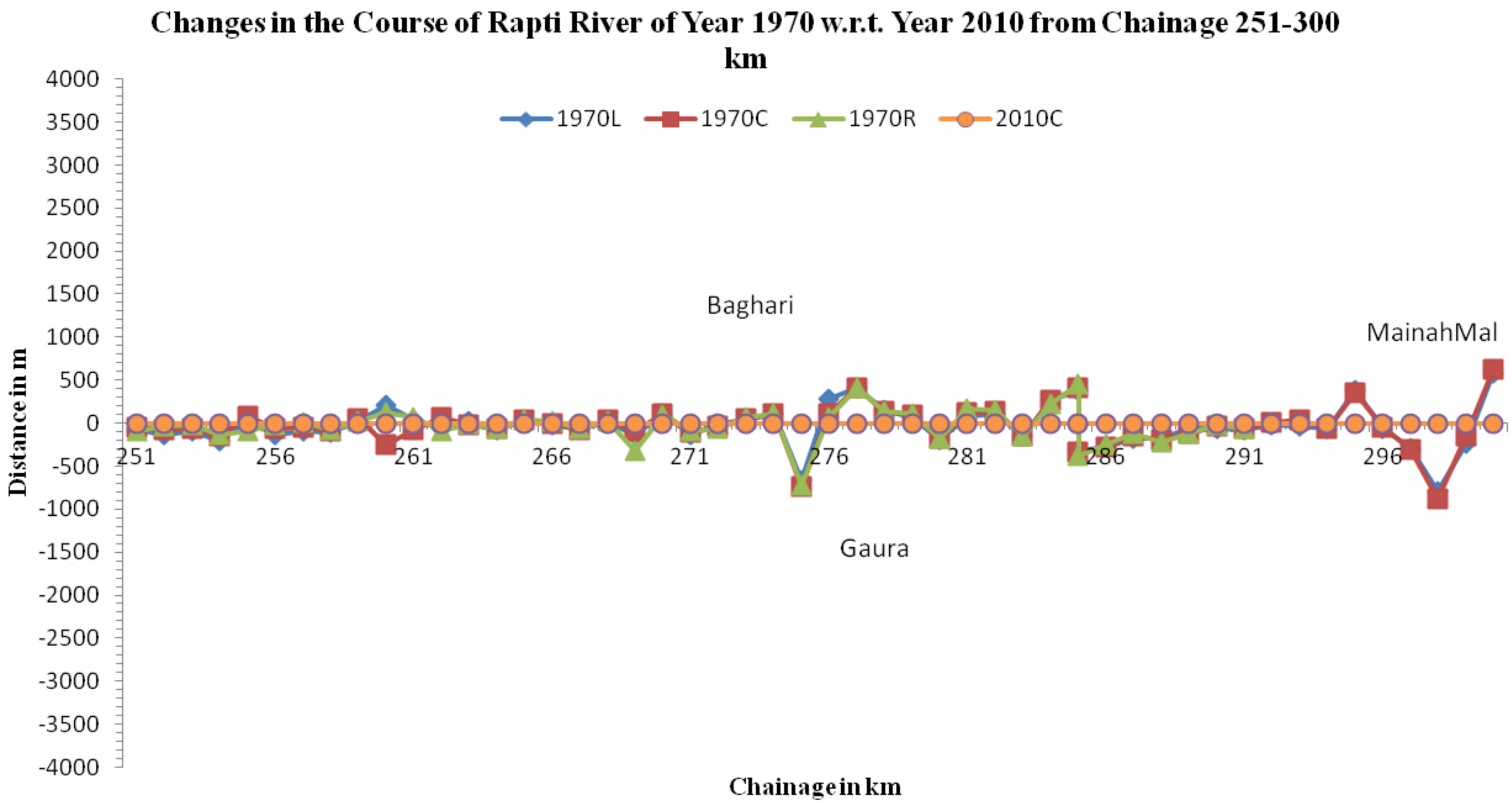


Figure 7.27b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 250-300 km

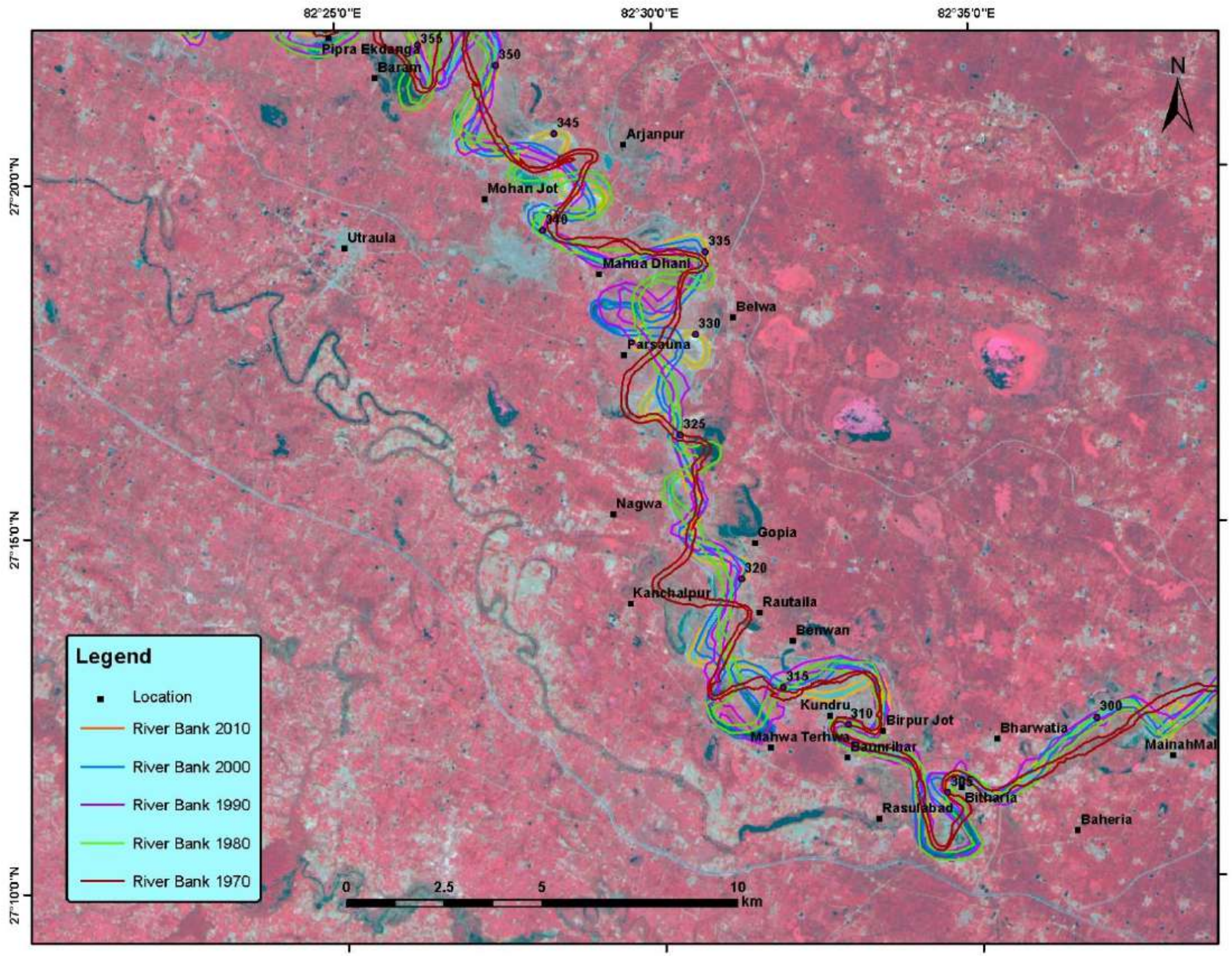


Figure 7.28a Decadal changes in the course of Rapti river from chainage 300-350 km

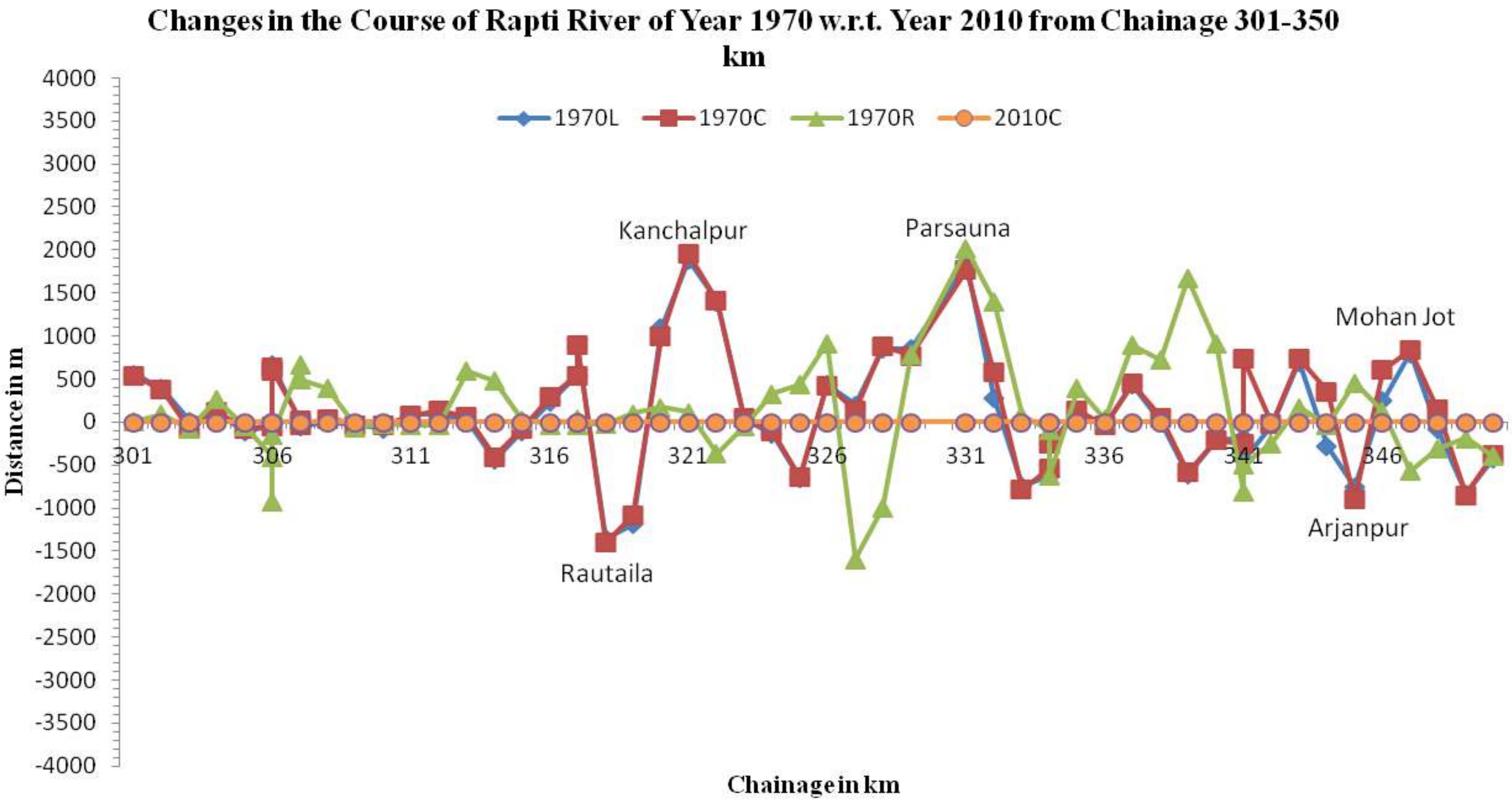


Figure 7.28b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 300-350 km

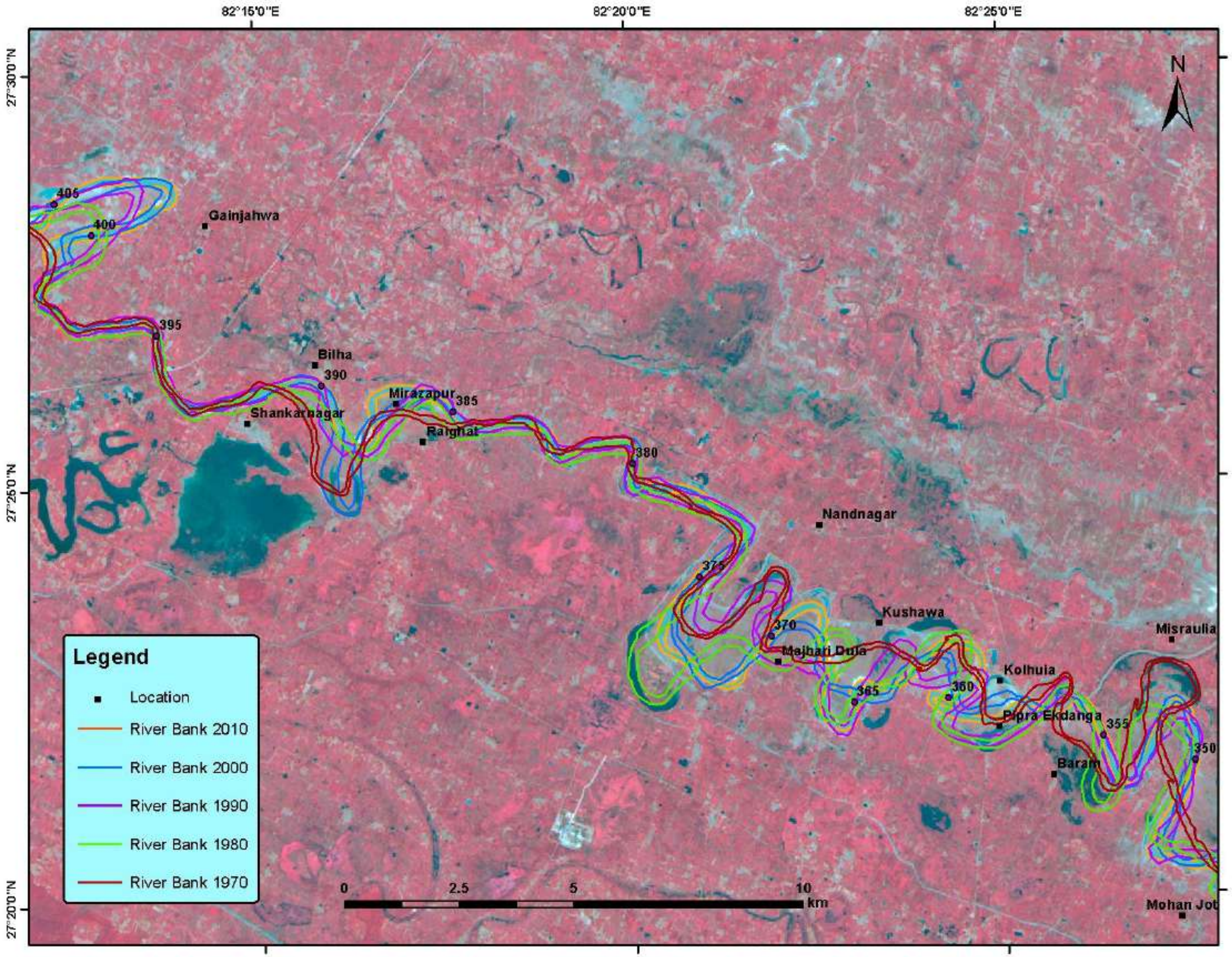


Figure 7.29a Decadal changes in the course of Rapti river from chainage 350-400 km

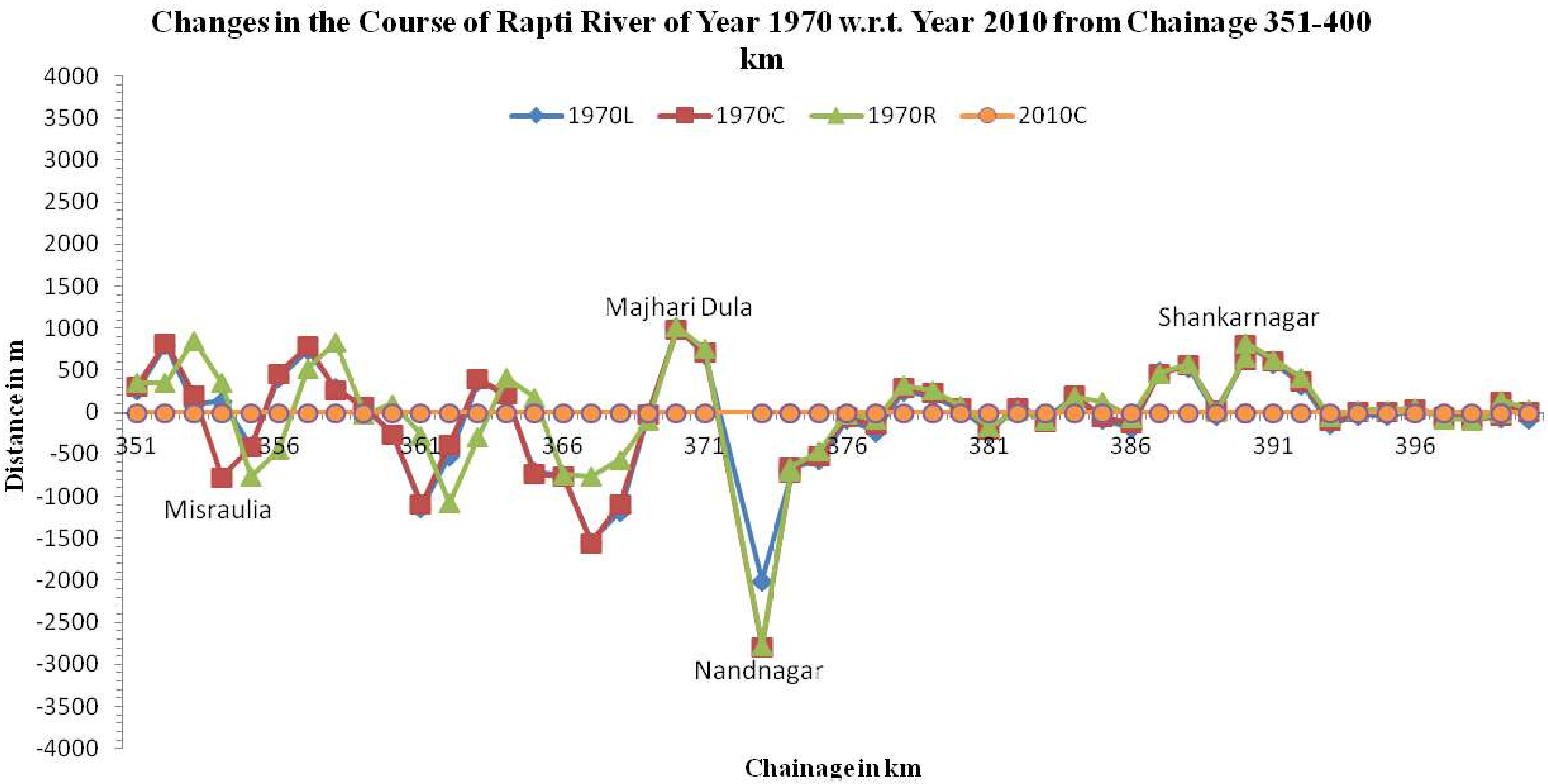


Figure 7.29b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 350-400 km

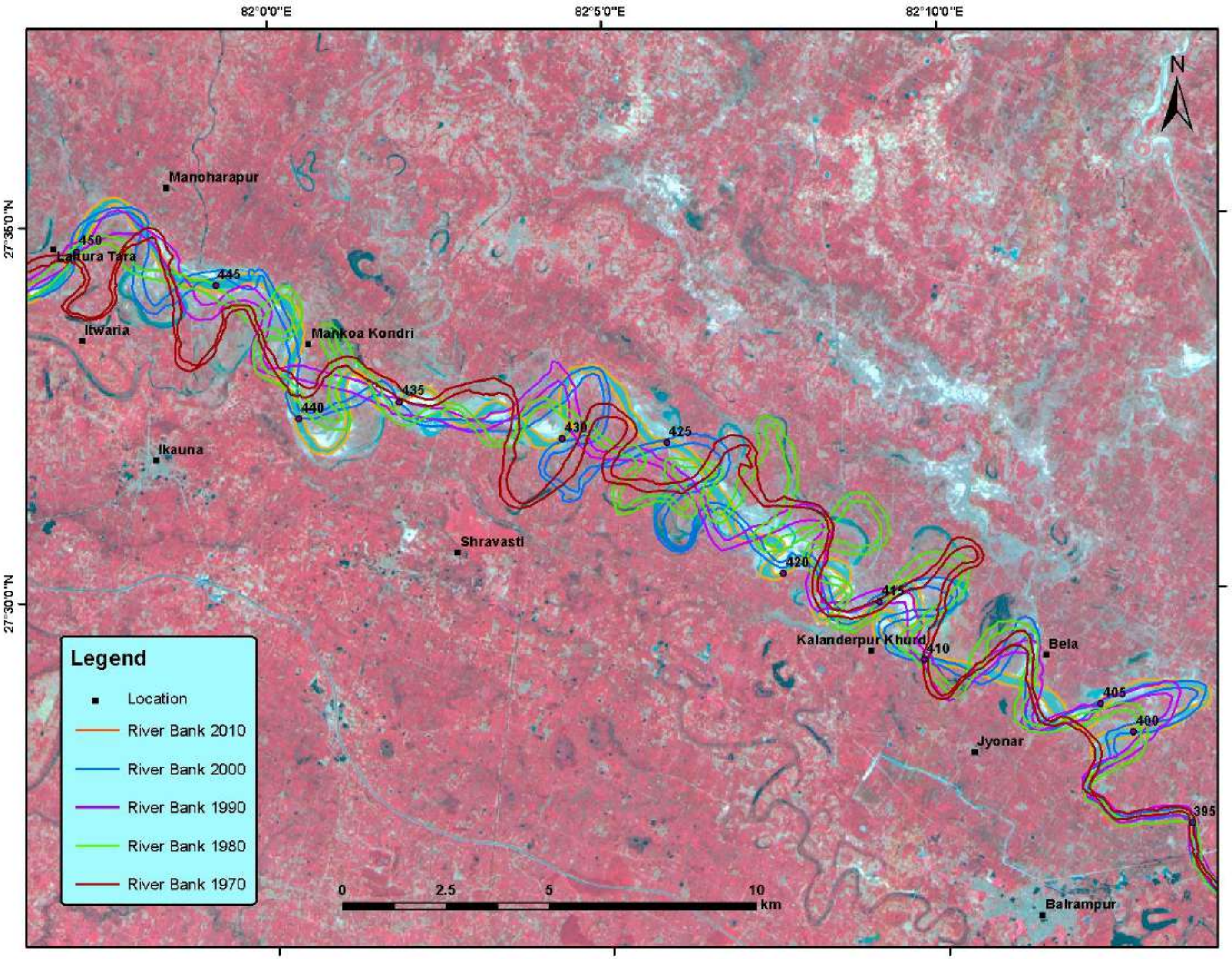


Figure 7.30a Decadal changes in the course of Rapti river from chainage 400-450 km

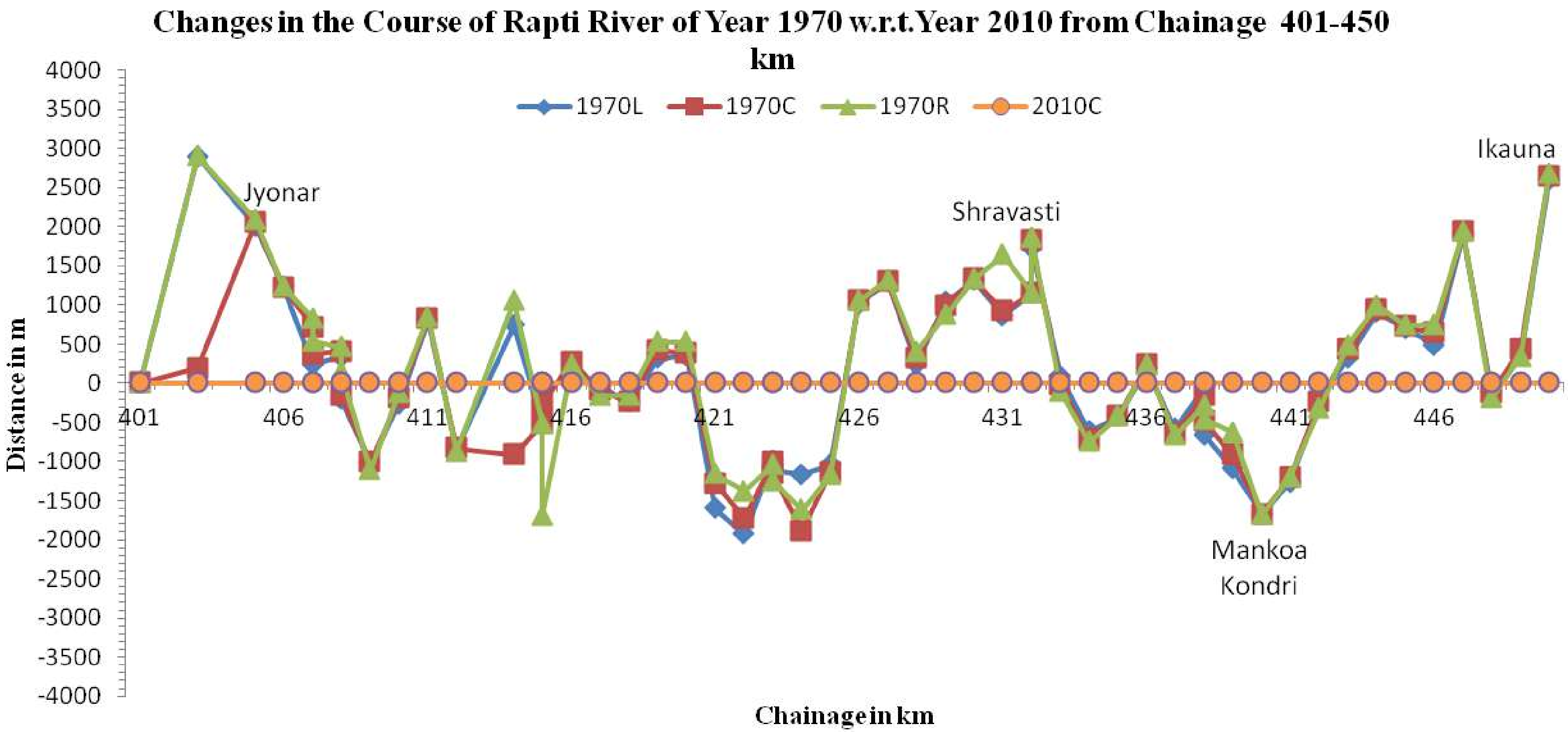


Figure 7.30b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 400-450 km

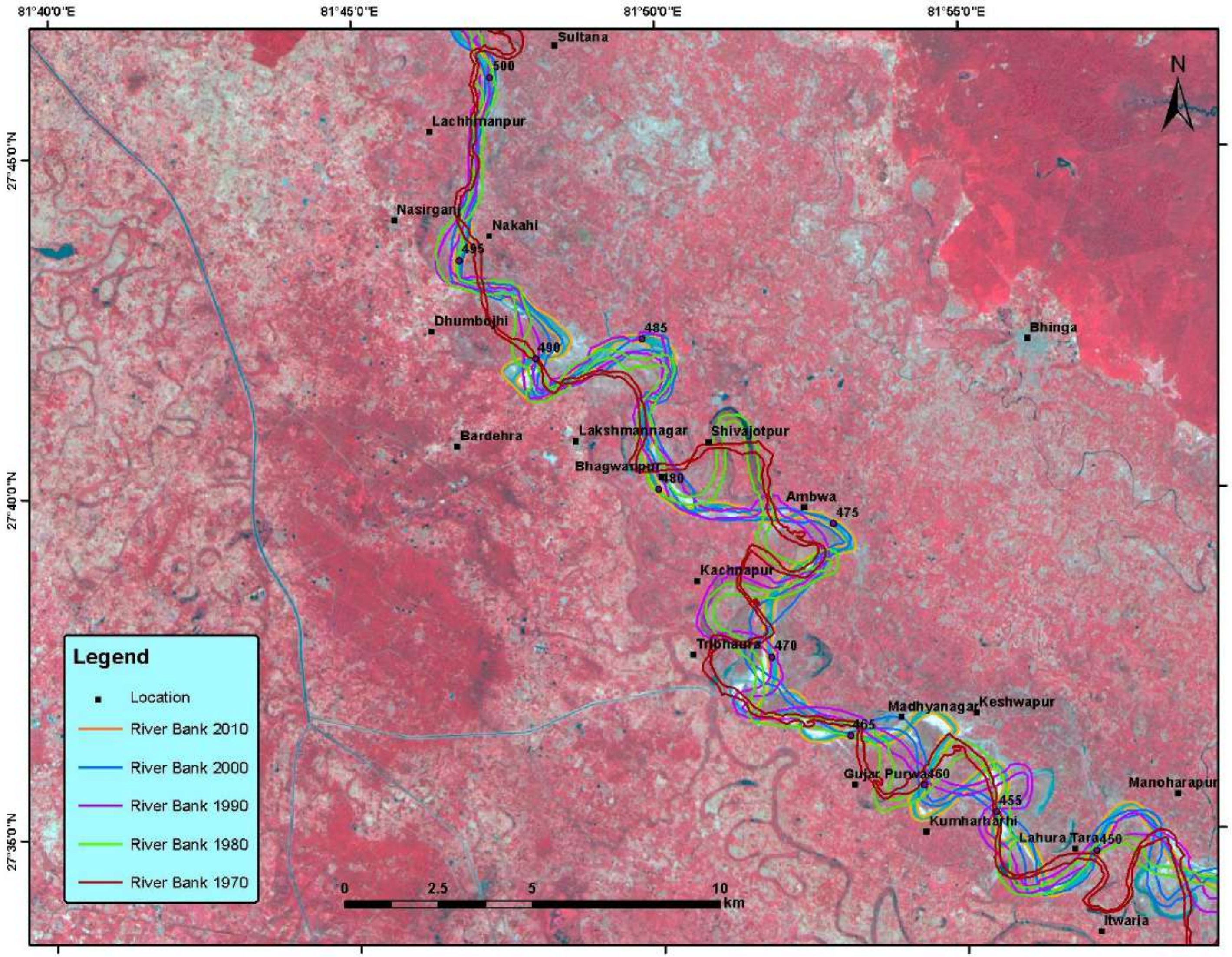


Figure 7.31a Decadal changes in the course of Rapti river from chainage 450-500 km

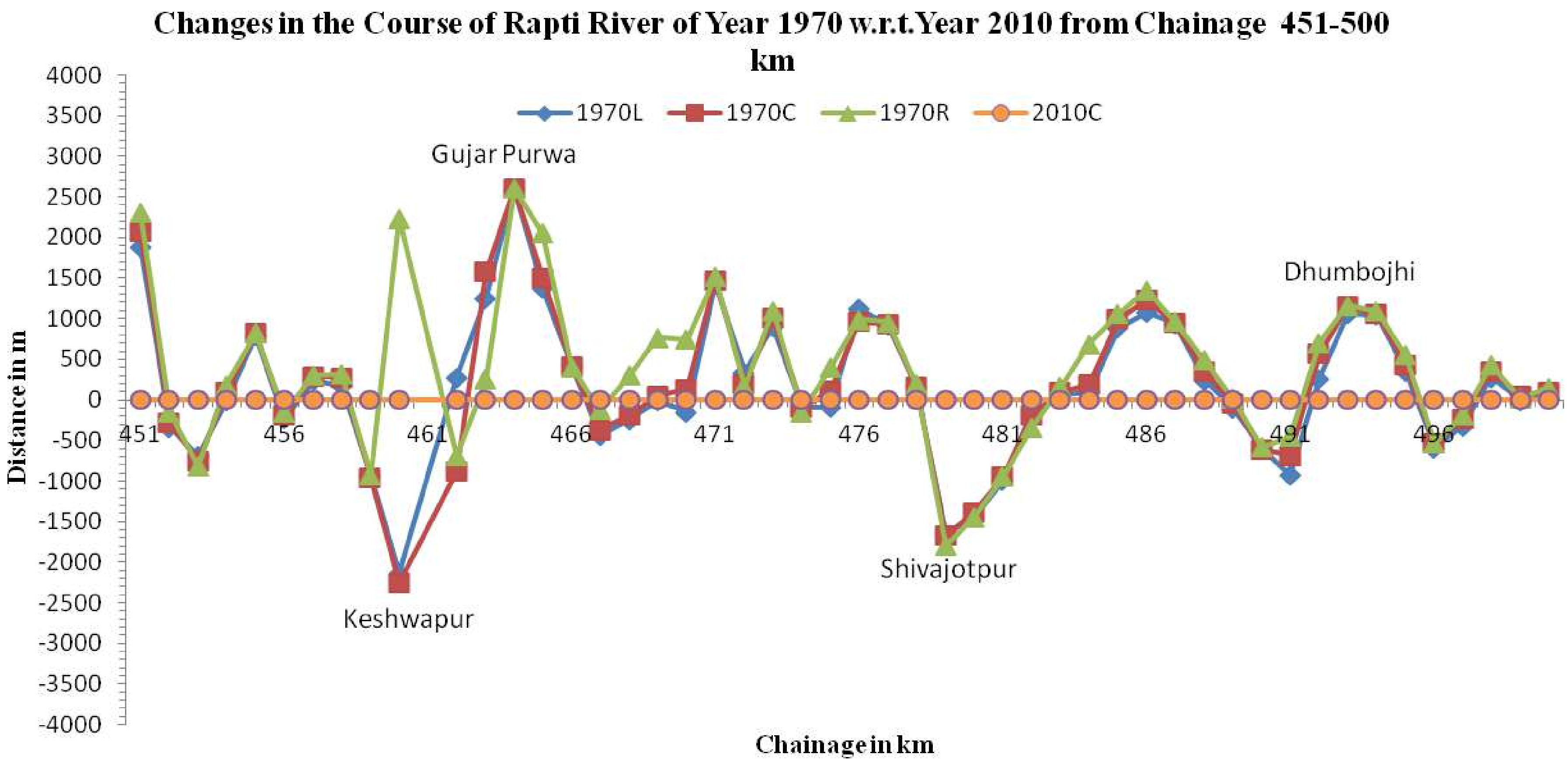


Figure 7.31b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 450-500 km

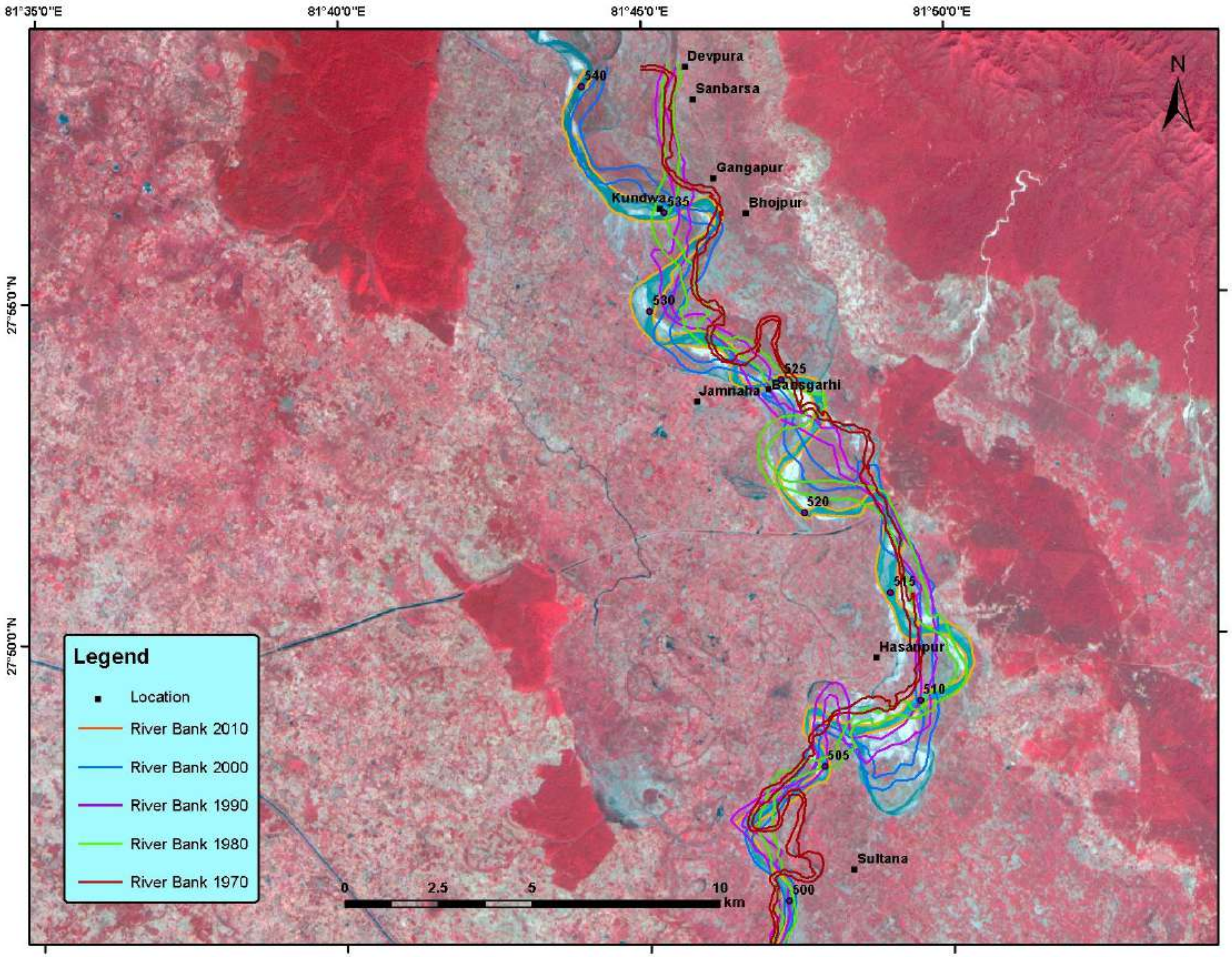


Figure 7.32a Decadal changes in the course of Rapti river from chainage 500-542 km

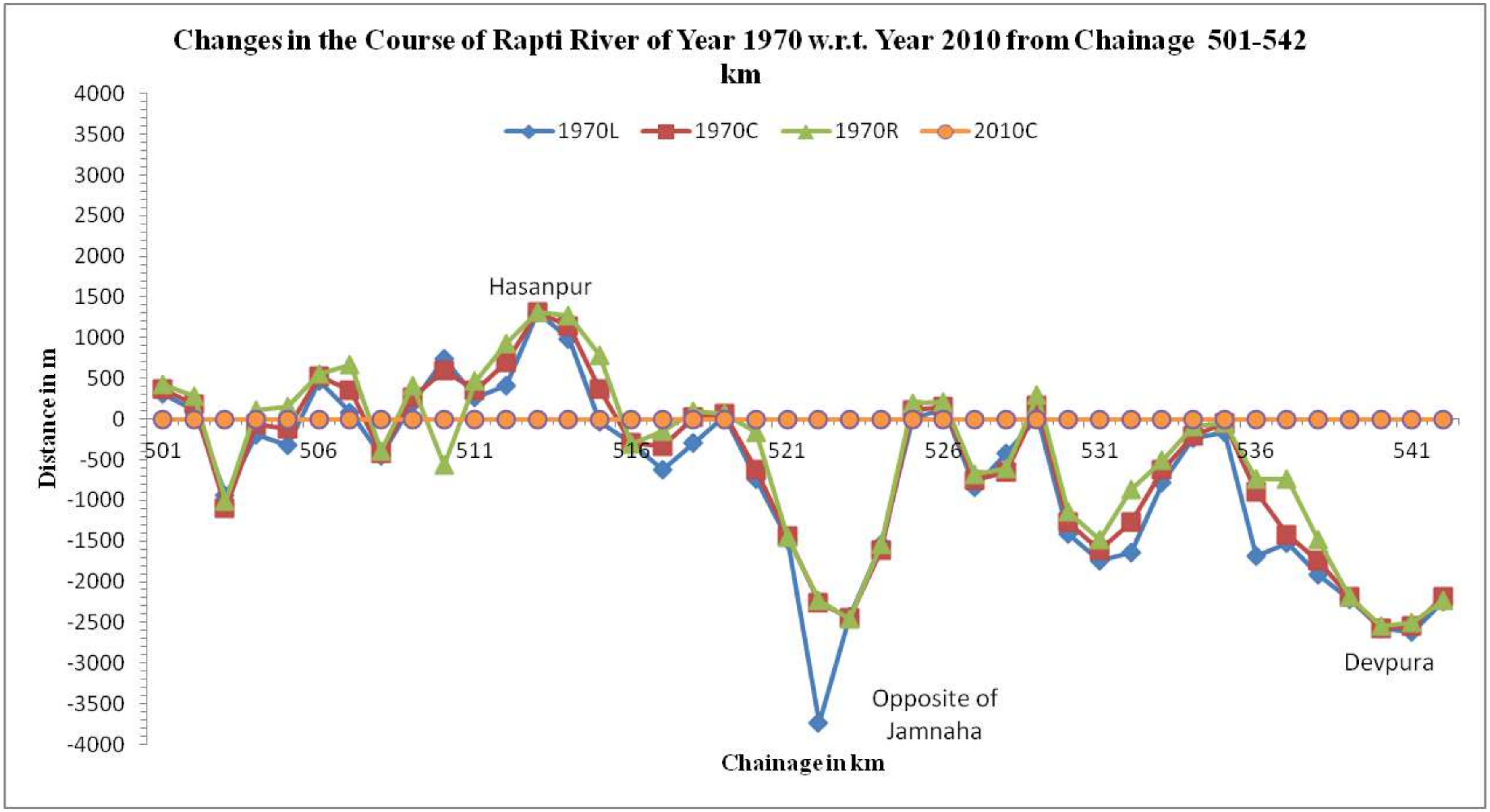


Figure 7.32b Changes in the Course of Rapti river of year 1970 w.r.t. year 2010 from chainage 500-542 km

7.4 RIVER WIDTH

The width of the river has taken equal to width of the active channel. It is estimated using the satellite images of years 1970-2010 by marking the waterlines. The width of the active channel of the Rapti river during the post monsoon is taken perpendicular to the direction of flow of river. Width of river is calculated in GIS software at the intersection of perpendicular bisector of center line of year 1970, 1980, 1990, 2000 and 2010 at a regular interval of 5 km and at an interval of 1 km near the places where river is taking sharp turn. The sample map that depicts the computation of river width is shown in Fig 7.33. Computed width of the river of year 1970, 1980, 1990, 2000 and 2010 are given in Table 7.6 and graphically shown in Figs. 7.34 to 7.44. A comprehensive graph for the width of the river for years 1970, 1980, 1990, 2000 and 2010 for whole the reach of the river is plotted in Fig. 7.45. Figures 7.34 to 7.45 reveal the following:

- There is no definite progressive change in the width of the river over the span of year 1970-2010 in the whole studied reach of the Rapti river.
- From chainage zero to 450 km, the average width of the river is almost constant and is equal to about 206 m, however, in the upper reach i.e., Chainage 450 km to 542 km, the average width is about 290 m - which may be attributed to silting in upper reaches and spreading of flow as the river descends from higher slope to mild slope.

As the active channels are considered in regime condition, it should follow the regime equation and width be related to the discharge. Estimated 25- year return period discharge at gauging stations Balrampur (Chainage 396 km), Rigauli (Chainage 183 km) and Birdghat (Chainage 120 km) are 2836.1 m^3/s, 4386.1 m^3/s and 6324.3 m^3/s, respectively.

Even though 1.5 to 2 year return period discharge is considered as disharge that govern the morphological changes. In the absence of that let consider discharge, Q = 4515.5 m^3/s, i.e., the average value of 25 year discharges at Balrampur, Rigauli and Birdghat. From this, the width equation for the Sharda river in its reach zero to 450 km may be expressed as

$$\text{River width} = 3.1 \times Q^{0.5}$$

Here River width is in m and Q in m^3/s. The multiplying coefficient of the above equation is lower than the Lacey equation.

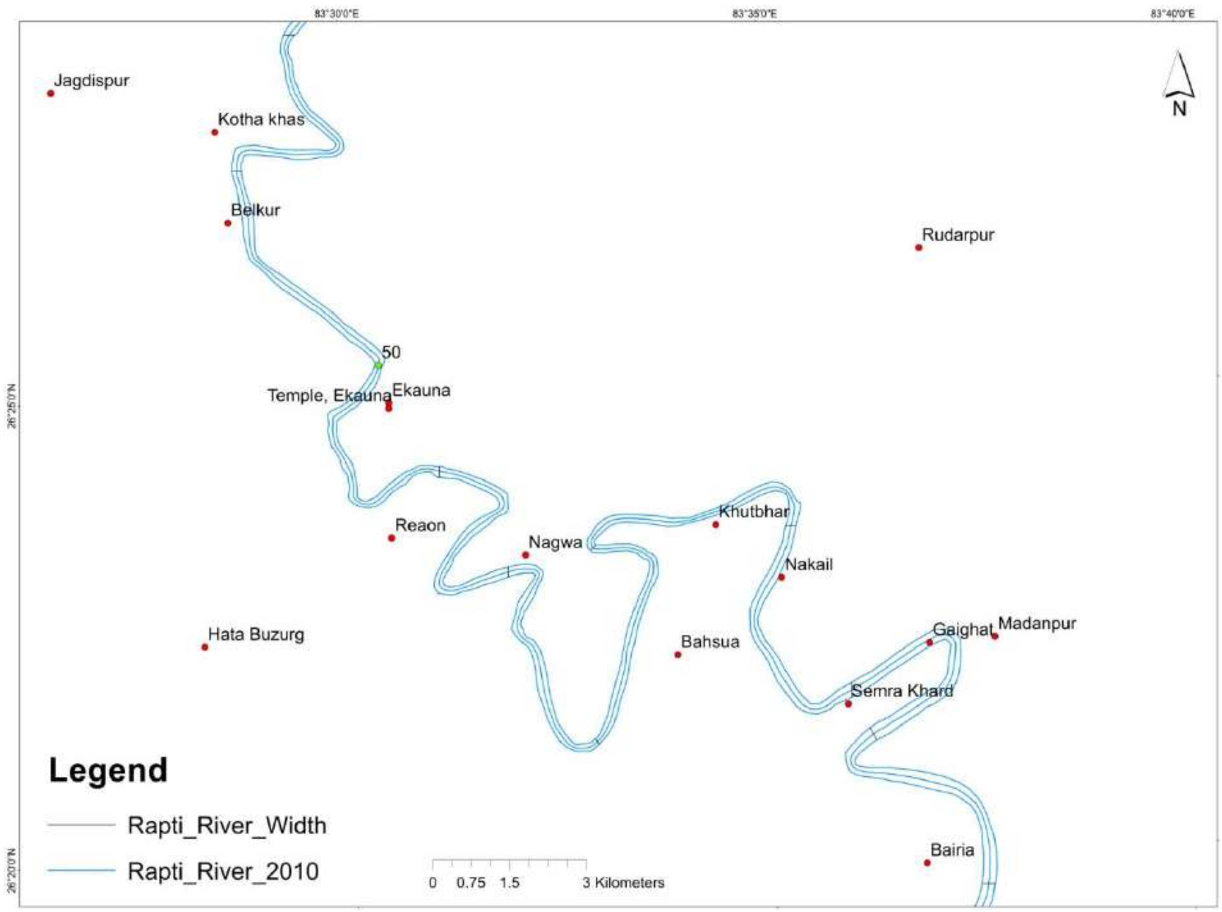


Figure 7.33 Sample map showing width of Rapti river for year 2010

Table 7.6 Width of Rapti river of year 1970, 1980, 1990, 2000 and 2010

Chainage (km)	Width (m)				
	2010	2000	1990	1980	1970
0	357.61	281.95	205.35	251.71	206.63
5	242.36	336.34	261.95	254.13	185.49
10	258.67	284.02	192.68	299.01	206.18
15	276.79	283.42	150.27	278.69	192.94
20	291.49	301.28	261.24	394.16	167.86
25	199.11	173.05	199.79	209.49	140.38
30	139.34	152.62	132.57	195.85	111.09
35	168.86	239.58	134.97	214.33	227.83
40	196.33	265.13	195.85	215.18	231.70
45	209.38	170.79	137.87	127.52	212.34
50	156.02	197.57	217.74	208.13	214.16
55	189.71	152.13	186.74	189.21	196.44
60	220.05	274.02	178.42	294.75	240.09
65	180.09	206.87	195.56	219.61	171.73
70	122.44	186.67	109.08	212.11	92.90
75	168.44	480.68	127.44	280.80	194.56
80	178.26	155.16	86.35	360.47	254.56
85	180.30	190.50	161.62	170.53	86.58
90	281.70	237.18	217.31	204.84	290.22
95	278.36	290.71	274.47	326.64	185.54
100	222.05	236.44	256.99	439.71	290.61
105	238.99	210.09	199.99	207.73	286.15
110	151.27	207.36	192.46	276.33	278.70
115	250.72	278.85	174.61	203.90	88.09
120	251.57	273.92	250.45	248.86	120.06
125	127.64	321.87	165.78	306.75	102.91
130	174.37	222.08	222.56	259.86	173.77
135	207.26	232.37	226.14	194.38	231.83
140	450.99	432.75	151.57	209.99	298.51
145	253.38	277.74	262.60	199.47	214.16
150	277.45	222.20	221.68	251.64	203.82
155	178.33	185.54	156.51	328.58	335.63
160	193.28	215.97	232.74	209.18	262.24
165	214.29	339.89	138.73	311.85	273.69
170	146.59	302.89	225.45	212.55	257.48
175	129.82	290.12	161.20	237.18	260.12
180	140.29	168.36	210.28	196.80	203.77
185	219.79	220.91	201.34	209.56	147.83
190	188.40	171.52	140.67	199.07	157.24
195	138.60	189.79	175.13	273.49	97.12

200	153.84	282.28	288.77	304.76	74.01
205	202.69	334.29	272.86	210.62	108.64
210	140.48	196.53	161.28	228.26	115.52
215	139.99	114.38	99.40	112.55	114.85
220	95.55	170.56	240.87	271.55	86.97
225	165.83	269.35	183.41	208.70	126.00
230	309.55	264.97	140.36	221.52	79.17
235	159.74	198.50	244.04	241.22	102.46
240	126.11	245.08	186.52	185.60	90.10
245	125.28	168.59	161.15	181.49	69.55
250	189.85	240.88	222.43	185.25	234.43
255	190.97	173.39	184.54	201.21	129.27
260	172.07	196.67	147.61	237.19	245.68
265	164.45	151.84	166.32	216.99	173.42
270	121.29	141.08	163.08	184.42	143.23
275	132.34	174.54	150.42	257.91	235.63
280	180.71	205.02	194.94	320.06	161.25
285	160.06	233.21	262.70	262.61	136.95
290	175.27	170.89	192.53	251.70	131.17
295	127.47	158.16	268.39	202.05	285.19
300	176.49	197.71	245.68	233.47	99.84
305	190.83	176.91	415.65	287.54	118.25
310	118.60	112.46	172.91	220.59	76.72
315	127.72	129.76	337.68	201.27	62.96
320	226.46	199.83	223.81	186.66	223.77
325	156.84	154.78	380.24	239.52	153.87
330	188.02	121.03	302.86	263.98	219.58
335	149.51	178.06	222.54	165.69	113.06
340	131.13	159.80	258.52	263.50	242.26
345	144.82	186.03	197.26	212.48	93.55
350	210.51	168.94	220.93	127.30	172.05
355	127.84	178.57	104.58	201.27	147.51
360	123.58	131.76	158.02	197.99	88.13
365	168.73	278.01	209.57	169.30	103.27
370	142.90	145.31	213.52	187.31	189.51
375	185.79	98.57	283.44	359.05	115.52
380	213.06	231.10	296.93	184.34	127.44
385	167.11	193.06	235.65	203.91	94.99
390	342.76	143.80	191.09	399.55	94.19
395	138.10	163.28	165.50	188.69	66.93
400	270.43	136.53	328.88	254.08	160.14
405	156.96	198.90	240.31	198.65	137.78
410	201.57	206.66	314.42	354.28	253.89
415	169.85	171.34	185.95	346.06	174.75

420	381.28	123.86	409.03	185.65	234.85
425	269.14	119.76	263.37	192.56	316.24
430	205.86	470.04	254.19	186.03	253.99
435	175.47	153.77	334.53	164.43	201.50
440	198.77	159.68	328.94	199.65	240.48
445	199.99	193.57	229.38	301.99	175.61
450	181.78	162.51	550.21	199.85	92.16
455	226.73	386.38	308.02	351.67	169.60
460	132.93	157.11	236.23	401.83	139.01
465	142.03	276.10	362.98	305.62	150.51
470	156.55	172.70	122.20	372.45	185.19
475	623.19	269.85	190.04	198.64	198.75
480	236.21	248.78	282.99	351.22	302.85
485	212.95	199.94	220.88	230.13	129.92
490	287.90	126.85	339.48	685.97	253.75
495	364.08	457.68	168.30	461.23	148.24
500	228.64	248.95	179.88	184.65	122.14
505	264.99	179.03	319.92	229.46	213.81
510	206.03	389.09	410.95	289.01	391.56
515	197.02	465.03	403.71	656.54	234.51
520	271.53	371.19	220.81	635.39	179.19
525	301.38	204.21	480.62	442.51	114.32
530	480.54	218.93	508.06	350.58	214.80
535	479.87	358.80	290.40	415.18	181.84
540	271.41	280.50	359.47	321.60	217.68
542	286.67	277.18	307.61	452.17	210.13

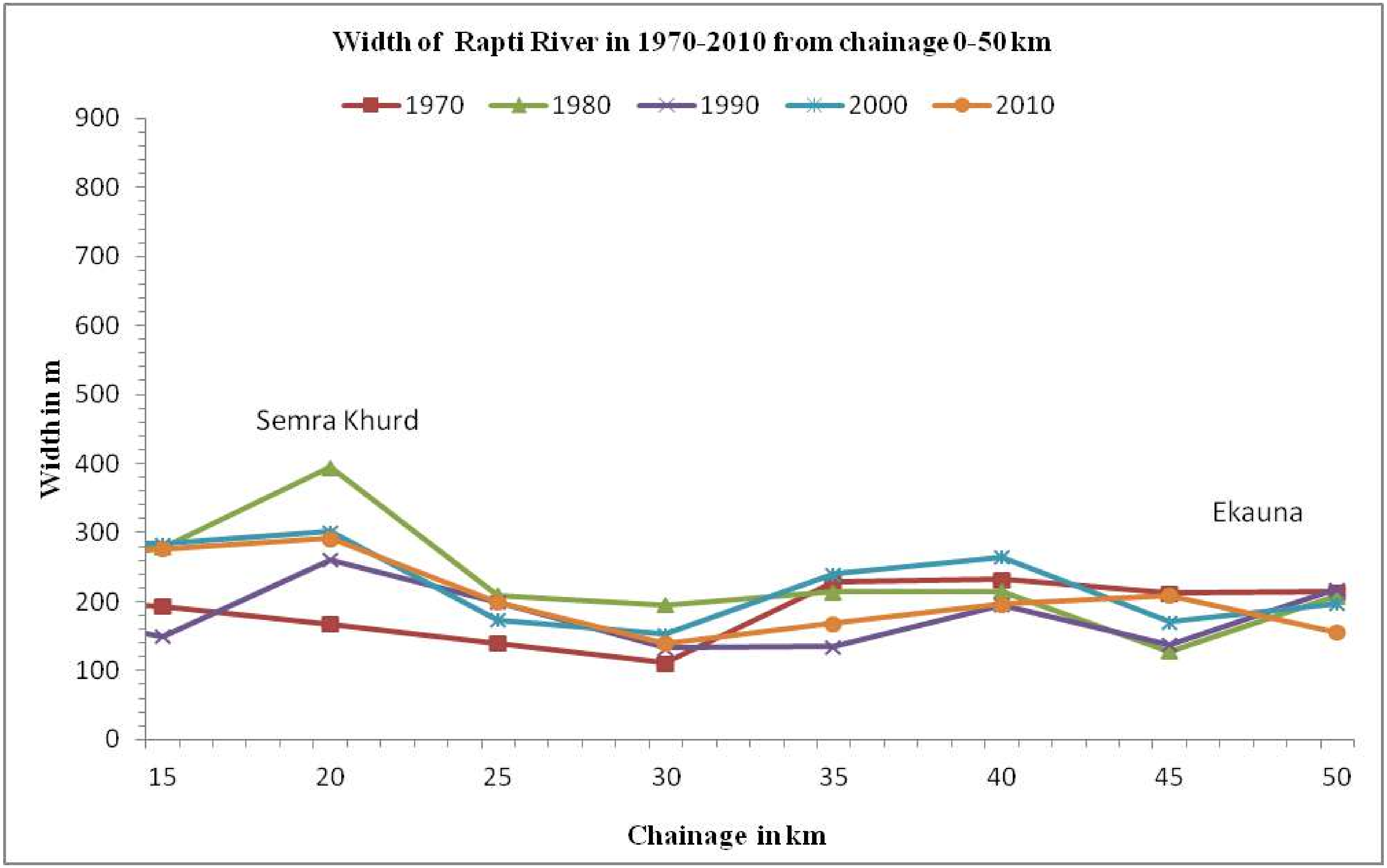


Figure 7.34 Width of Rapti river in years 1970, 1980, 1990, 2000, and 2010 from chainage 0-50 km

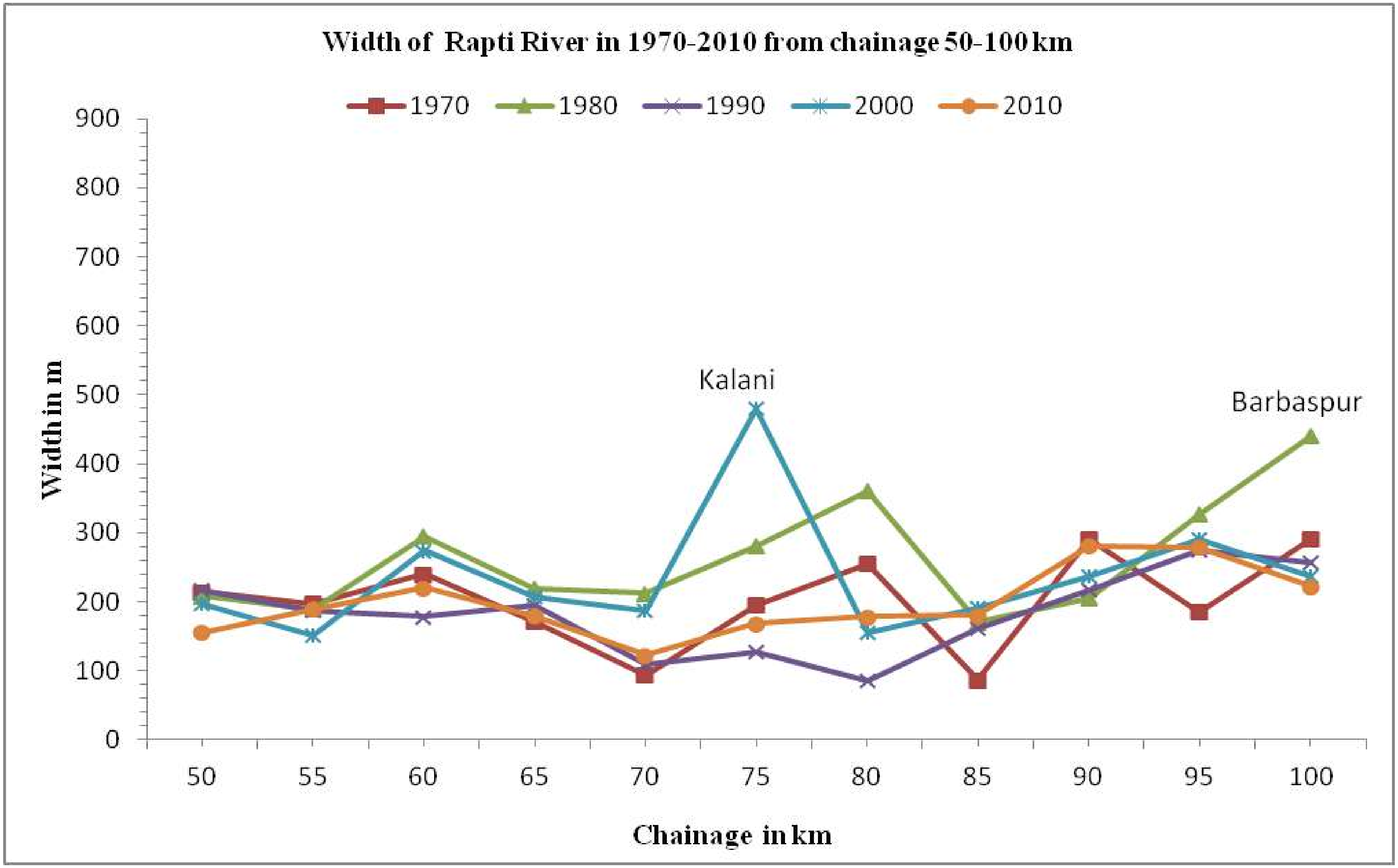


Figure 7.35 Width of Rapti river years 1970, 1980, 1990, 2000, and 2010 from chainage 50-100 km

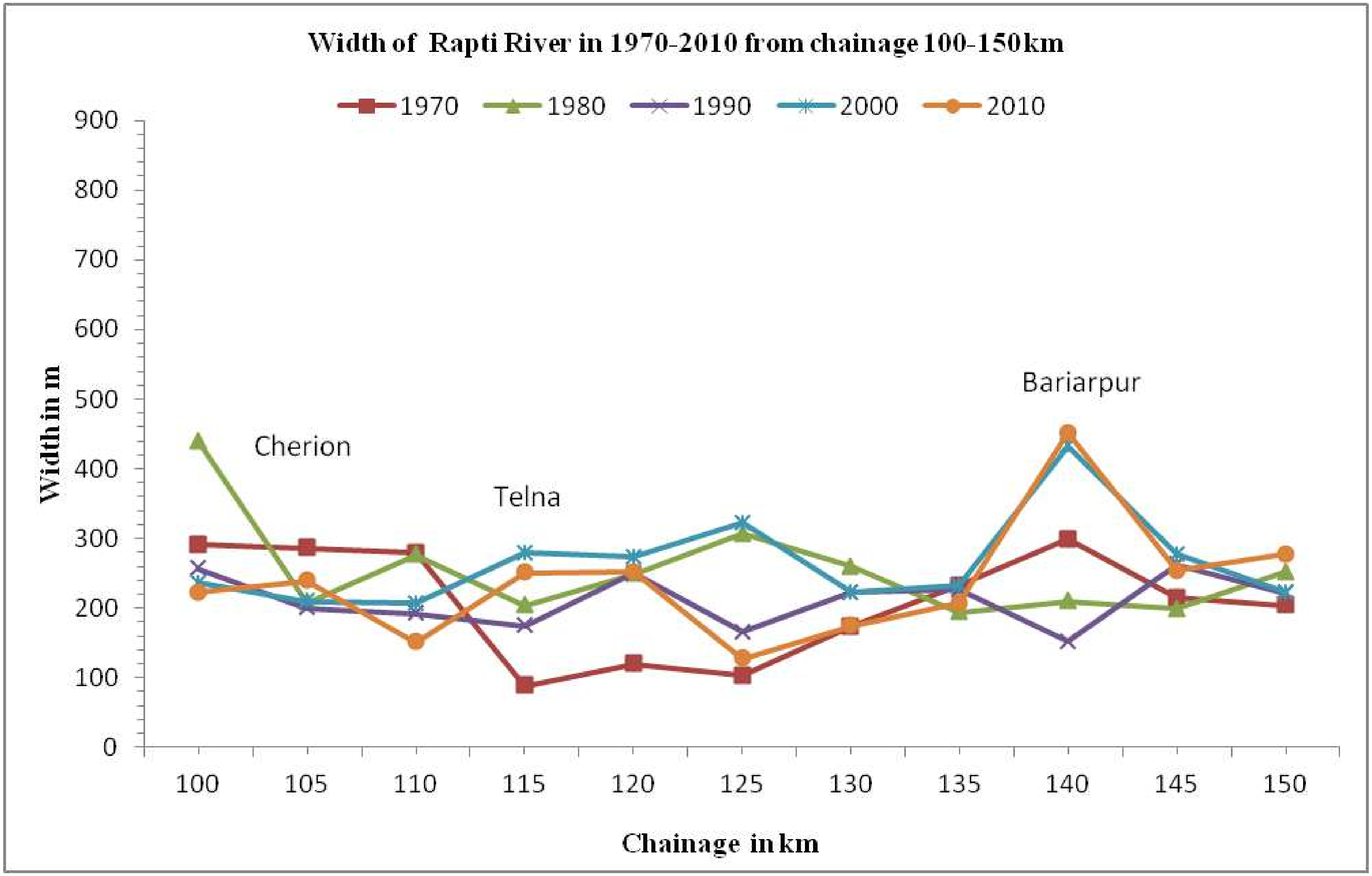


Figure 7.36 Width of Rapti river in years 1970, 1980, 1990, 2000, and 2010 from chainage 100-150 km

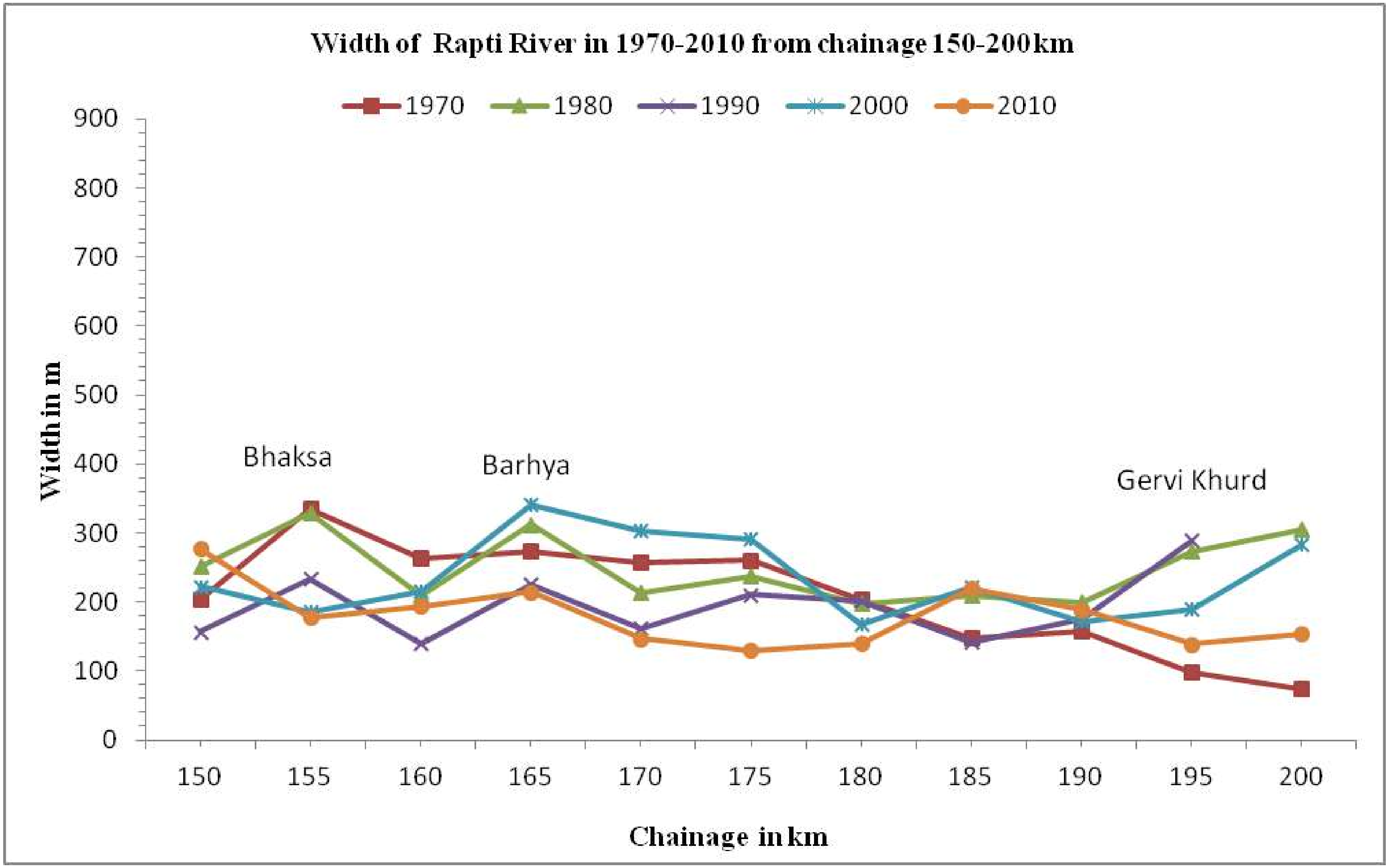


Figure 7.37 Width of Rapti river in years 1970, 1980, 1990, 2000, and 2010 from chainage 150-200 km

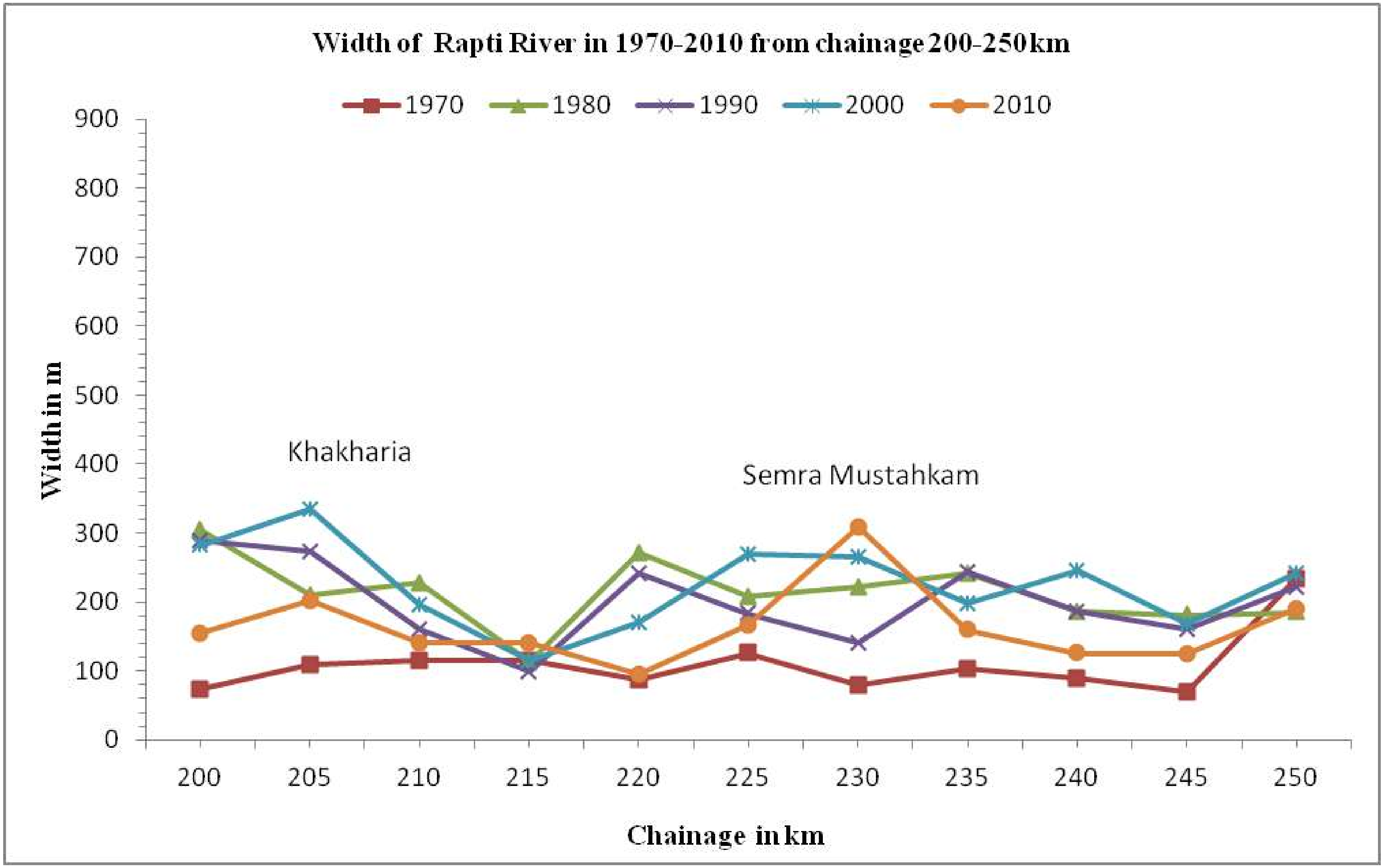


Figure 7.38 Width of Rapti river in years 1970, 1980, 1990, 2000, and 2010 from chainage 200-250 km

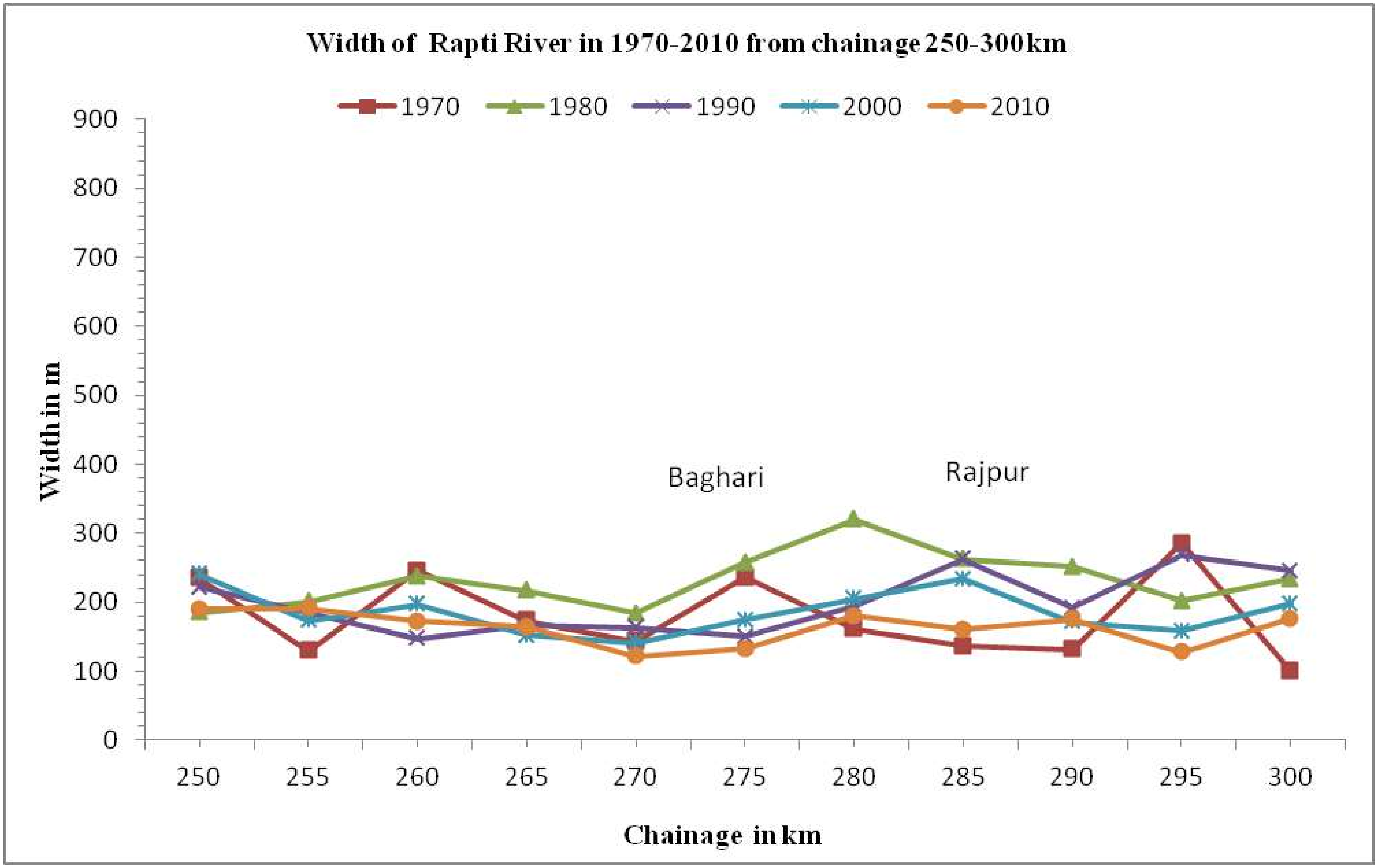


Figure 7.39 Width of Rapti river in years 1970, 1980, 1990, 2000, and 2010 from chainage 250-300 km

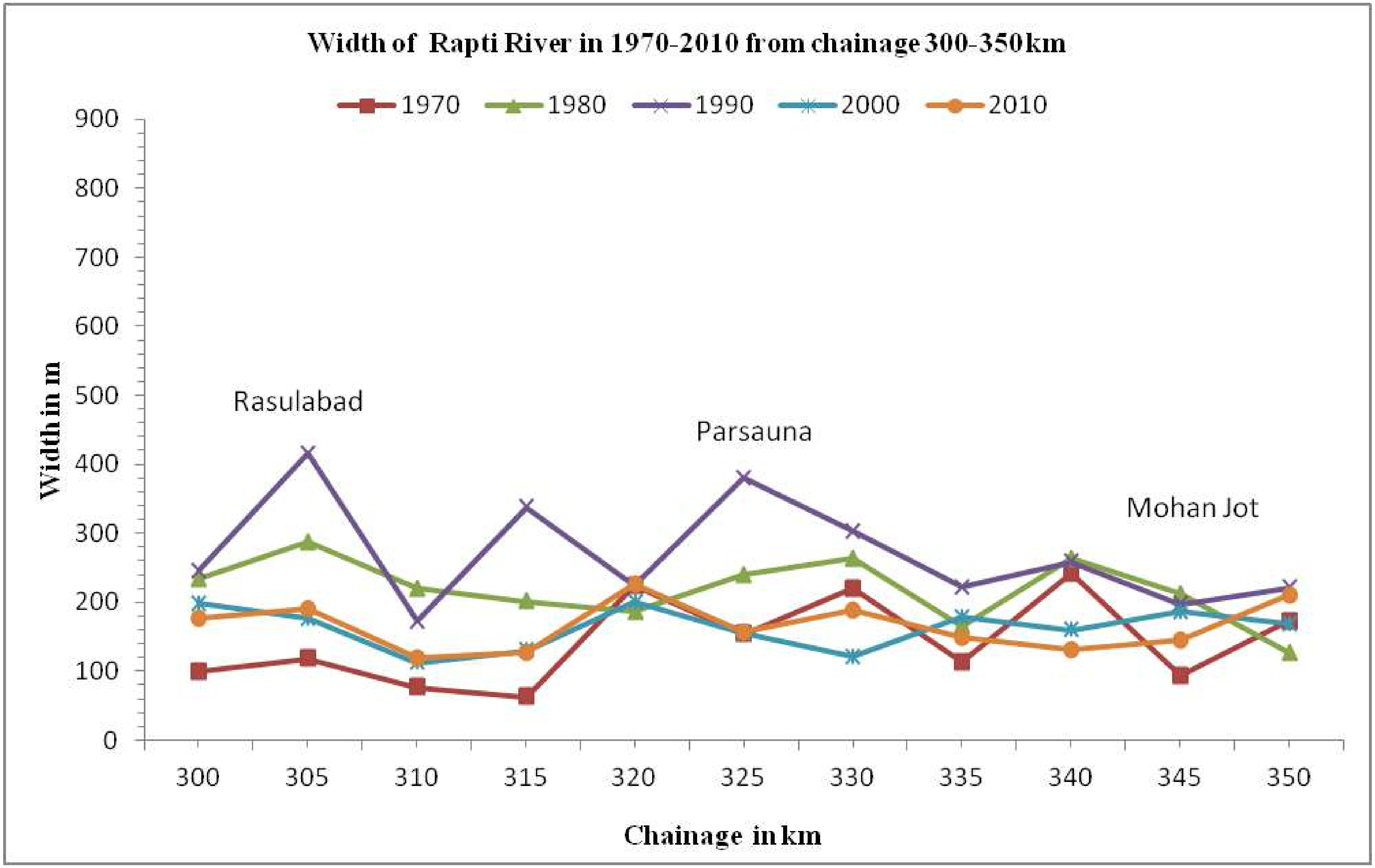


Figure 7.40 Width of Rapti River in years 1970, 1980, 1990, 2000, and 2010 from chainage 300-350 km

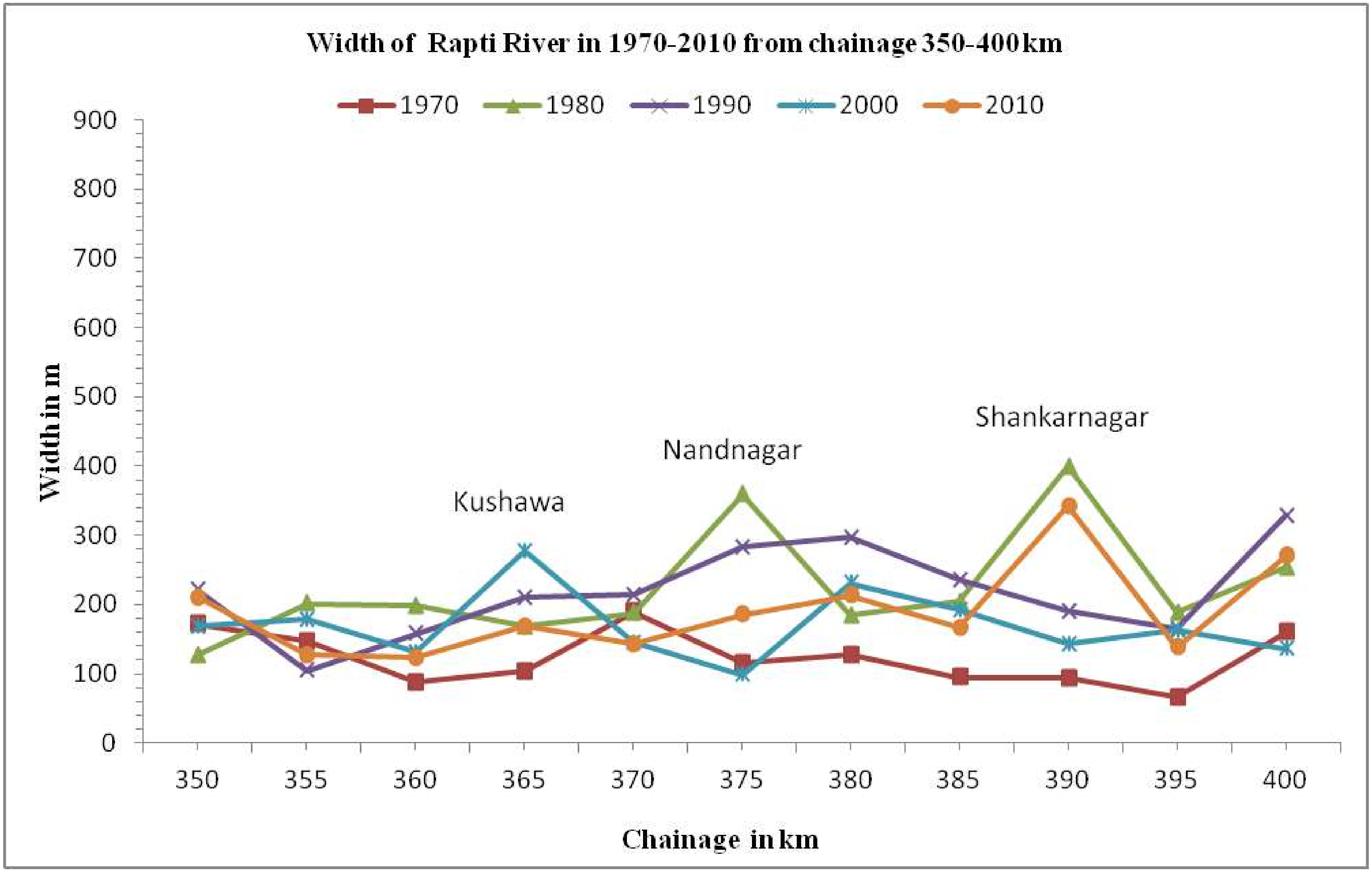


Figure 7.41 Width of Rapti River in years 1970, 1980, 1990, 2000, and 2010 from chainage 350-400 km

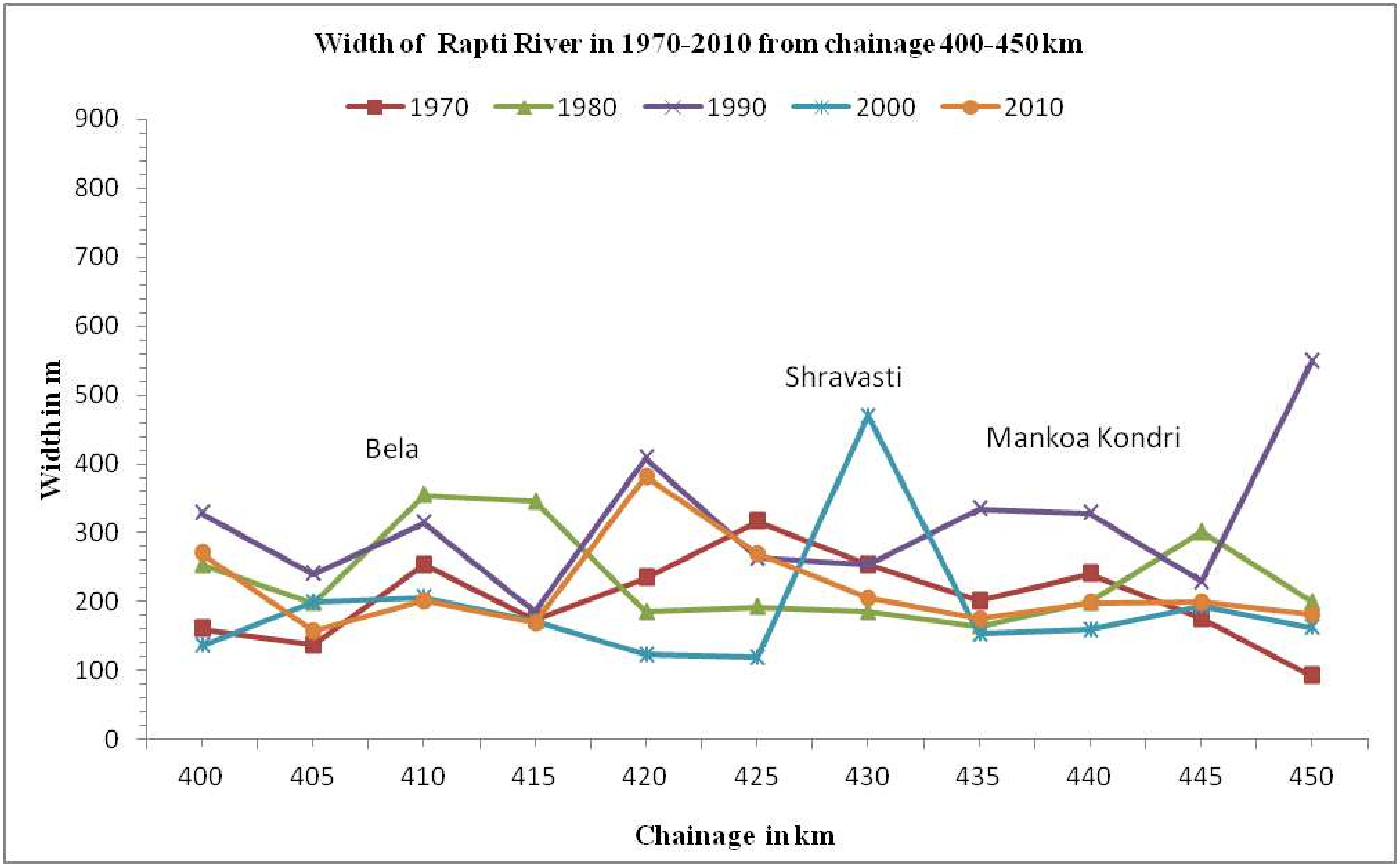


Figure 7.42 Width of Rapti River in years 1970, 1980, 1990, 2000, and 2010 from chainage 400-450 km

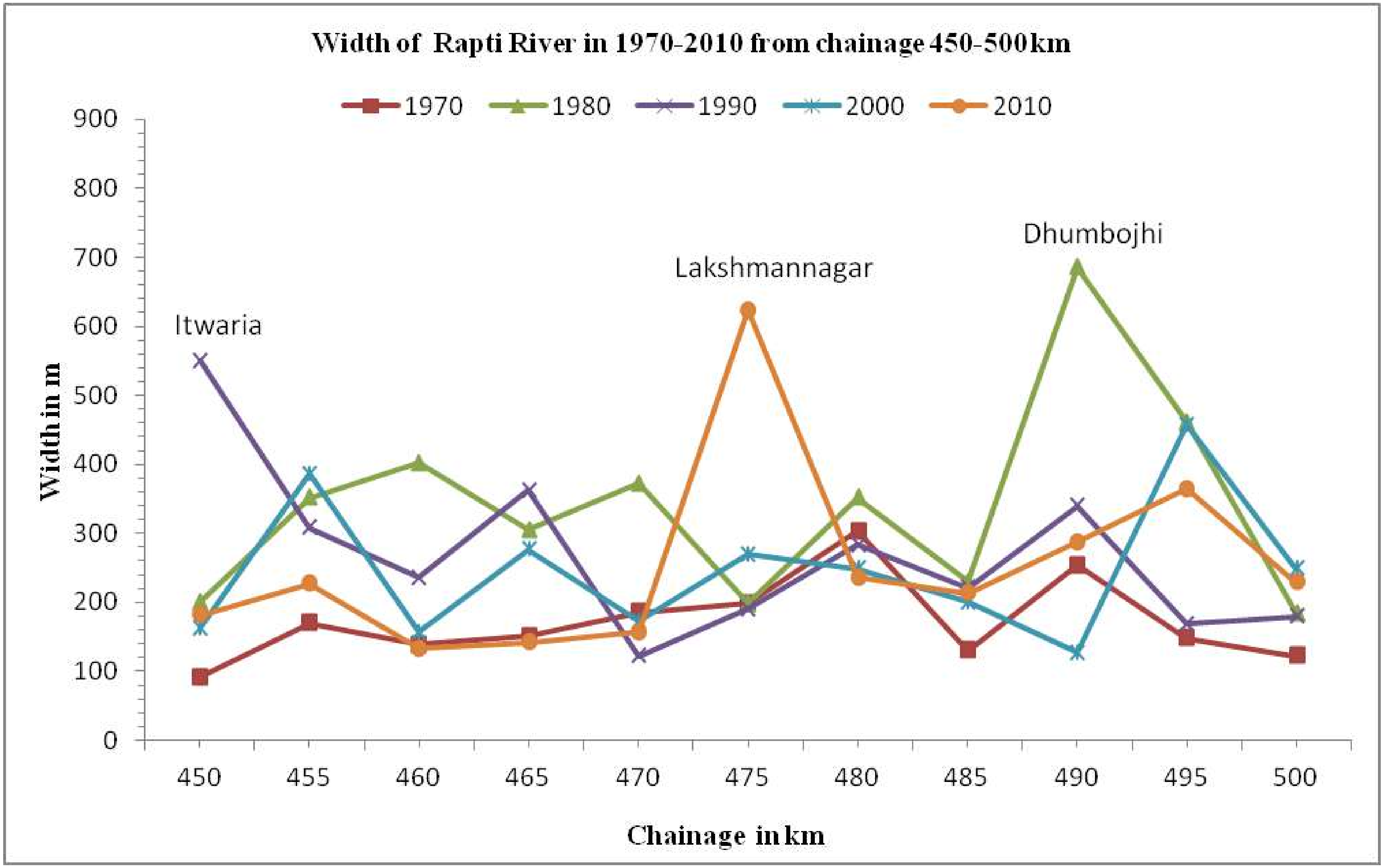


Figure 7.43 Width of Rapti River in years 1970, 1980, 1990, 2000, and 2010 from chainage 450-500 km

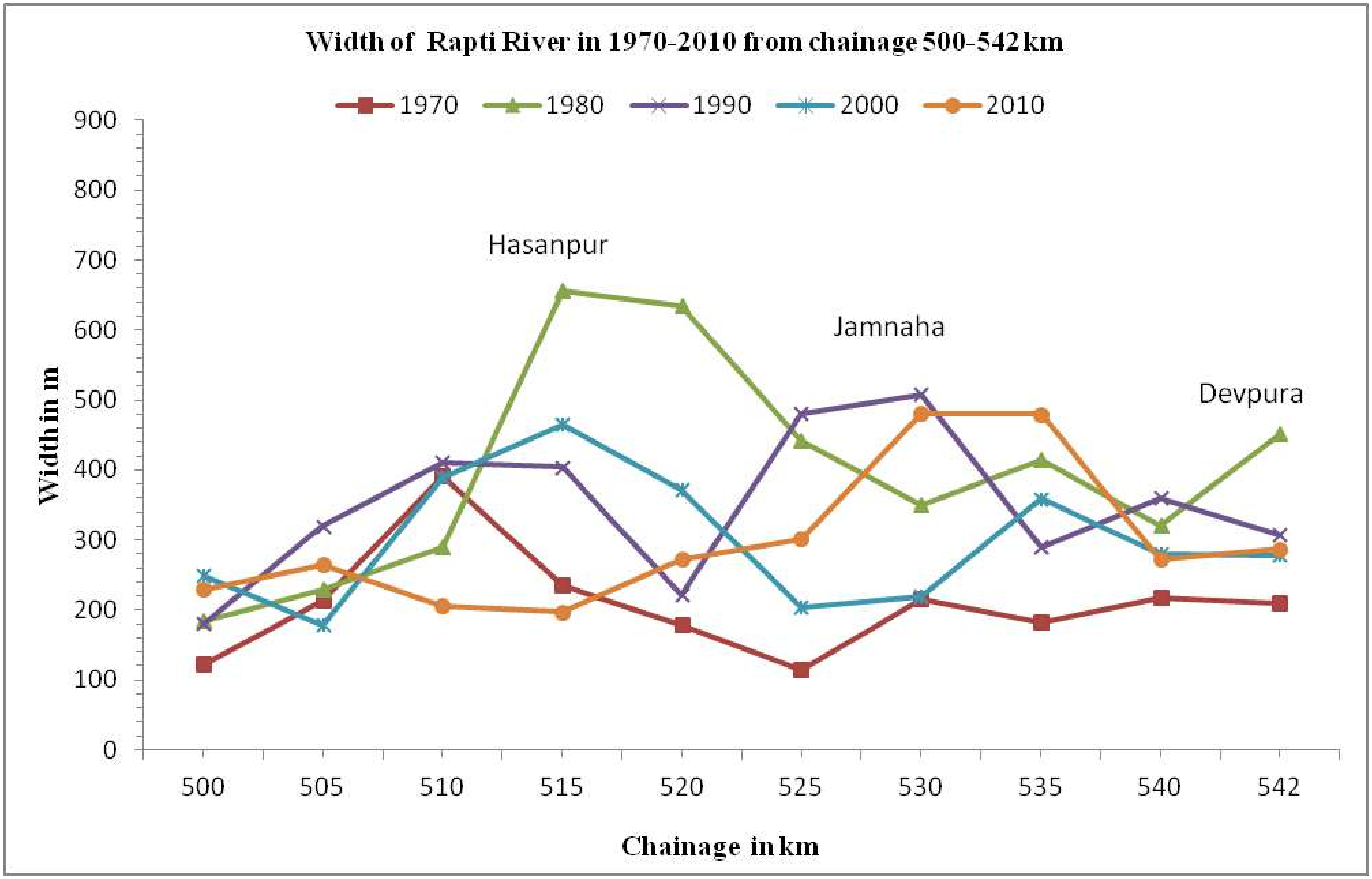


Figure 7.44 Width of Rapti River in years 1970, 1980, 1990, 2000, and 2010 from chainage 500-542 km

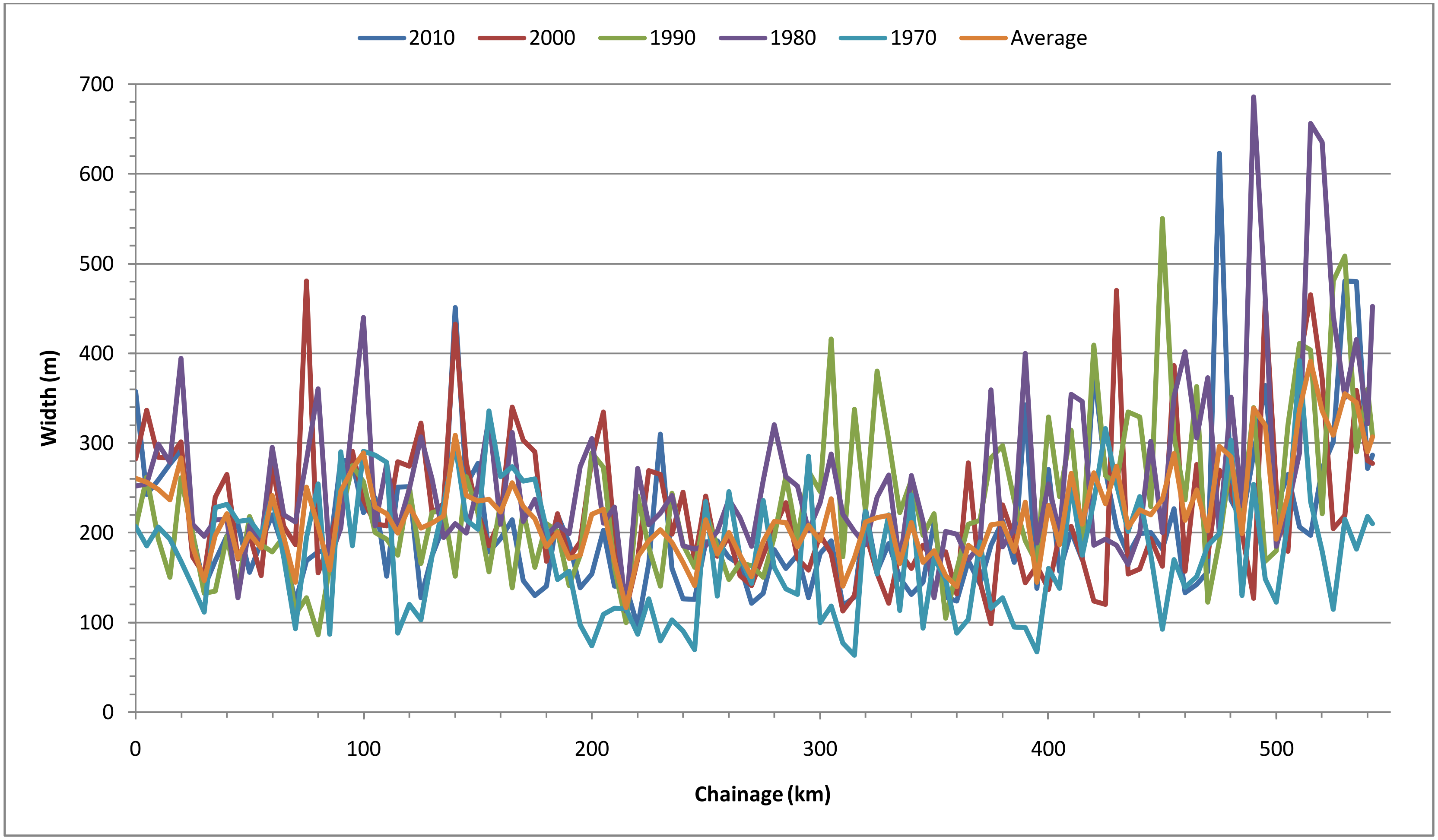


Figure 7.45 Width of Rapti River in years 1970, 1980, 1990, 2000, and 2010 from chainage 0-542 km

7.5 DISCUSSIONS ON RIVER COURSE SHIFTING AND ITS WIDTH

The following points may be noted from the analysis carried out in respect of shifting of course of the river and the river width:

1. Reach 0-50 km: There is no any progressive change in the course of river in this reach in the span of year 1970 to 2010. River is having meandering pattern in this reach. Major changes in the course of river has been noticed near Sareya, Ghaighat and Bahsua. The river has shifted from left to right at Sareya and Bahsua by 3 km and 2 km, respectively.

   Average width of the active channel is about 200 m in this reach. There is no much variation in the width over the years and along the channel except at Semra Khard, the width of the river was 400 m in year 1980.

2. Reach 50-100 km: Major changes in the course of the river have been noticed in the upper part of the reach. It is also meandering in this reach. There is no progressive shift in course of the river in this reach. Major random shifting of the river has been noticed at Chhitarhri. In the upper reaches, the course of river in year 1970 to 2010 was within a buffer of two km.

   The average width of the active channel of Rapti river is about 200 m. The maximum width of the river is about 450 m at Bautha and Chhopra.

3. Reach 100-150 km: There is no any progressive shift of course of river in this reach. Maximum random shift of the order of 2.5 km has been noticed at Bariarpur, Pali and Mirpur. Major shift from left to right of the order of 1 km has been noticed at Surghana. While the river course has shifted from right to left of the order of 1.5 km at Majhgawan and Bariarpur.

   Average width of the active channel in this reach is about 200 m with maximum width of the order of 5 km at Pali. In general, the width of the river in this reach is varying from 100 m to 300 m.

4. Reach 150-200 km: No major shifting in the main course of river has been noticed in this reach except near Phulwaria where the river has followed a straight path from 1980 onwards. There was an acute bend at this location in year 1970. There is no progressive shift in the course of the river in this reach.

   The width of the active channel varies from 150 m to 350 m with an average of 200 m in this reach. There is no any progressive change in the width of the river over the years in this reach.

5. Reach 200-250: In this reach also, no major shifting of the river has been noticed except at Semra Mustakham where river has shifted from left to right of the order of 1 km over the years.

   The width of active channel varies from 100 m to 275 m with an average of 200 m in this reach. The width of the river in 1970 was about 100 m, however, over the years it was increased.

6. Reach 250-300 km: There is no any major change in course of the river in this reach over the years. Critical examination of shifting of center line of Rapti river from year 1970 to 2010 indicates that in the upper part of this reach the tendency of meandering of the river has increased over the years.

   The width of the active channel of the river varies from 125 m to 275 m with an average of 200 m in this reach. There is no any progressive change in the width of river over the years.

7. Reach 300-350 km: Major changes in the course of the river has been noticed in this reach. The river is wandering in a buffer of 2.5 km width. The maximum shift from left to right is of the order of 2 km at Kanchalpur and Parsauna. While maximum shift from right to left of the order of one km has been noticed at Rautaila and Arjanpur. There is no progressive shift in this reach over the years.

   The width of the active channel varies from 100 m to 325 m with an average of 200 m in this reach. The maximum width of the order of 400 m has been noticed at Bagahwa in year 1990. In general, maximum width was noticed in year 1990.

8. Reach 350-400 km: Major changes in the course of the river has been observed in the lower part of this reach. In the upper part major changes in the course of the river has been noticed only at Shankarnagar. River has meandering pattern in the lower part of this reach. The maximum shift of the river course from right to left is of the order of 3 km at Nandnagar from year 1970 to 2010. While river has shifted of the order of 1.5 km from left to right at Shankarnagar.

   Large variation in the width of active channel in this reach has been noticed. River has widen over the years in this reach. In general, minimum width was found in year 1970 and maximum in year 1980. Maximum width of the order of 400 m has been noticed at Mirazapur.

9. Reach 400-450 km: River has remarkable wandering and meandering behavior in this reach. The river course has wandered in a buffer of 3.5 km in this reach in the span of year 1970 to 2010. There is no any progressive change in the course of the river in this reach. The maximum shift from left to right of the order of 2 km is found at Jyonar, Shravasti and Ikauna from 1970 to 2010. However, maximum shift of the river course from right to left of the order of 2 km can be seen at Mankoa Kondri.

   Average width of the active channel in this reach is of the order of 225 m. In general, the width has increased over the years. The maximum width of the order of 500 m was noticed at Shravasti in year 2000 and of the order of 575 m at Itwaria in year 1990.

10. Reach 450-500 km: Major changes in the course of the river has been noticed in this reach. However, no progressive change in the course of river has been noticed over the years. In general, river has been wandering in a width of 3 km. It has acute meandering pattern in this reach. River has maximum shift from left to right at Gujar Purwa and right to left at Keshwapur of the order of 2.5 km in the span of year 1970 to 2010.

    The average width of the active channel in this reach is of the order of 290 m. However, it varies from 150 m to 400 m in this reach. River had maximum width of the order of 650 m at chainage 475 km (Tribhaura) and 490 km (Lakshmannagar). The width of the active channel has increased over the years in this reach.

11. Reach 500-542 km: This reach has also wandering and meandering behaviour of the river. There is no progressive change in the course of river in this reach. However, river has laterally shifted from left to right of the order of 3 km at Devpura and Jamnagar. At Hansapur, river has shifted from right of the order of 1.25 km.

    Average width of the active channel river is of the order of 290 m. The river width has increased from 1970 onwards. The maximum width is found at Jamnaha.

7.6 NODAL POITNS

The nodal points along the reach of the river i.e. wherein minimum morphological changes are seen, have been identified and given in Table 7.7 . This will be helpful in planning of structures like bridge in the future.

Table 7.7 Nodal points of minimum morphological changes

Sl. No.	Chainage (km)	Latitude & Longitude	Location
1.	0-4	83°40'18.92"E 26°17'29.873"N- 83°39'36.565"E 26°19'5.514"N	Koparwar
2.	9-29	83°37'25.54"E 26°19'21.186"N- 83°33'1.142"E 26°23'35.424"N	Madanpur
3.	32-40	83°33'22.75"E 26°22'33.243"N- 83°31'33.763"E 26°23'0.247"N	Nagwa
4.	42	83°31'22.134"E 26°23'29.952"N	Reaon
5.	47-48	83°30'0.387"E 26°24'15.162"N- 83°29'48.992"E 26°24'43.019"N	Ekauna
6.	50-62	83°30'13.772"E 26°25'34.602"N- 83°28'59.886"E 26°29'45.536"N	Gajpur
7.	64	83°28'57.49"E 26°30'22.389"N	Sarar Majhgawan
8.	66-68	83°28'53.166"E 26°31'17.685"N- 83°28'3.749"E 26°32'2.589"N	Bautha
9.	73	83°27'43.138"E 26°32'50.358"N	Kalani
10.	82	83°28'47.148"E 26°35'19.634"N	Dihghat
11.	85-87	83°27'49.889"E 26°36'3.832"N- 83°26'42.979"E 26°35'40.338"N	Malaon
12.	91-98	83°27'16.318"E 26°36'59.329"N- 83°24'38.482"E 26°37'37.829"N	Aema
13.	102	83°25'36.335"E 26°38'26.503"N	Dumri
14.	107	83°23'49.381"E 26°39'31.469"N	Cherion
15.	110	83°23'15.166"E 26°40'40.978"N	Bhatwa
16.	114-120	83°22'27.782"E 26°41'50.767"N-	Nausar

		83°21'3.667"E 26°43'50.584"N	
17.	124-127	83°19'43.443"E 26°44'59.742"N- 83°18'8.338"E 26°44'27.063"N	Bargahan
18.	133-137	83°15'56.096"E 26°44'44.197"N- 83°14'43.814"E 26°46'19.772"N	Sahjanwa
19.	156-163	83°14'51.261"E 26°52'25.693"N- 83°12'55.394"E 26°55'1.519"N	Jaswal
20.	165-172	83°12'34.384"E 26°55'28.222"N- 83°11'43.21"E 26°57'51.927"N	Indarpur
21.	174	83°12'33.302"E 26°58'13.239"N	Indarpur
22.	177	83°14'2.243"E 26°58'51.35"N	Ojhapur
23.	180-186	83°12'54.292"E 26°59'40.558"N- 83°11'32.777"E 27°1'37.024"N	karmalni
24.	188-192	83°11'8.834"E 27°1'41.45"N- 83°11'40.149"E 27°2'59.626"N	Gervi Khurd
25.	194-205	83°11'31.223"E 27°3'17.933"N- 83°9'57.13"E 27°6'16.887"N	Khakharia
26.	206-225	83°9'26.941"E 27°6'30.365"N- 83°3'19.641"E 27°9'3.921"N	Kunrja
27.	233-273	83°1'48.135"E 27°9'8.316"N- 82°47'27.094"E 27°11'54.463"N	Bagahwa Komar
28.	286-293	82°42'42.051"E 27°12'15.724"N- 82°39'52.317"E 27°12'17.832"N	Bagahwa
29.	302-304	82°35'54.086"E 27°11'34.537"N- 82°34'54.204"E 27°11'21.864"N	Bharwatia
30.	306-312	82°34'54.204"E 27°11'21.864"N- 82°33'31.445"E 27°12'37.276"N	Baunrihar
31.	319	82°30'56.393"E 27°13'53.045"N	Rautaila
32.	322	82°30'28.693"E 27°14'47.849"N	Gopia
33.	339	82°28'32.408"E 27°19'5.465"N	Mahua Dhani
34.	377-386	82°21'22.007"E 27°24'35.288"N- 82°17'6.015"E 27°26'10.42"N	Raighat
35.	391-398	82°15'14.841"E 27°26'13.593"N- 82°12'7.213"E 27°27'27.128"N	Balrampur
36.	481.5	81°49'46.762"E 27°40'52.563"N	Lakshmannagar
37.	496-500	81°46'52.445"E 27°43'59.535"N- 81°47'17.137"E 27°46'8.068"N	Nasirganj
38.	517	81°49'1.256"E 27°51'38.618"N	Jamnaha

7.7 CONCLUDING REMARKS

1. The computed sinuosity ratio of the Rapti river in the reach under consideration is higher than 1.5 in the year 1970, 1980, 1990, 2000, and 2010, therefore, the Rapti river is classified as meandering river.
2. Almost whole reach of the river has meandering pattern, however, it is prominent in the reaches 25-50 km, 75-100 km, 300-375 km, 400-425 km and 450-475 km. The meandering is characterized by acute bend with high amplitude, however, they are relatively stable.
3. The plan form index (PFI) of Rapti River is calculated using the formula given by Sharma (2004). It has been observed that the Rapti River always runs bankfull, so no braiding is found in Rapti River.
4. Remarkable shifting of the course of the Rapti river from 1970 to 2010 has been noticed. The maximum shift is of the order of 2.7 km at some locations. The confluence point of Rapti and Gaghara rivers has shifted 500 m towards left in year 2010 w.r.t. year 1970.
5. Major shifting of the river course in span of year 1970 to 2010 is in the reaches 75 -100 km, 300-375 km, 400-485 km and 500-542 km. At Devpura, Jamuha, Keshwapur, Nandnagar and Chitahari shifting is from left to right while at Gujarpurwa, Ikauna, Jyonar and Kanchalpur shifting is from right to left. No progressive shifting of the course of the river with respect to time has been noticed.
6. Width of the active channel of the river and river width based on the extreme banks have been estimated using the satellite images of years 1970-2010. There is no definite progressive change in the width of the river over the span of year 1970-2010 in the whole studied reach of the Rapti river. From chainage zero to 450 km, the average width of the river is almost constant and is equal to about 206 m, however, in the upper reach i.e., Chainage 450 km to 542 km, the average width is about 290 m - which may be attributed to silting in upper reaches and spreading of flow as the river descends from higher slope to mild slope.

Chapter 8 EROSION AND SILTATION

8.1 CHANNEL EVOLUTION ANALYSIS

Channel evolution analysis describes the status of the river channel that includes channel dimension, pattern and longitudinal profile identifying distinct river reaches i.e. channel in upper reaches, channel in flood plain, aggradation and degradation, bank erosion etc. Such study is carried out from a field reconnaissance.

The evolution sequence provides an understanding that reaches of a stream may differ in appearance, but channel form in one reach is associated with other reaches by an evolving process. The channel evolution analysis helps in understanding a stream's response to downstream as well as upstream disturbances in form of morphological changes.

In the present study, the quantification of bank erosion and siltation has been carried out from the satellite images and toposheets. 1970 has been considered as base year and the changes have been plotted graphically.

8.2 EROSION & DEPOSITION

Erosion and siltation studies have been carried out for the Rapti River from Nepalgunj to its confluence point with Ghaghara i.e., near the Barhalganj, UP using the remote sensing techniques. The toposheet and post-monsoon images of years 1970 and 2010 have been used, and the study has been carried out to quantify sediment erosion and deposition for duration from year 1970 to year 2010. The erosion and siltation have been expressed in the terms of area in km^2.

For estimation of erosion and deposition, extreme left and right banks have been identified based on the sand deposit and vegetation. Based on the shifting of extreme left and right banks, the erosion and deposition are determined.

8.3 RESULTS AND ANALYSIS

Estimation of erosion and deposition has been carried out in the view of shifting of extreme left and right bank which are being identified on the basis of sand deposit and vegetation. Details of the computed eroded and sited area and also area that were eroded and subsequently silted or otherwise in the period 1970 to 2010 are given in Table 8.1, and also shown in Fig. 8.1. Net erosion and deposition in each reach of 50 km are shown in Fig 8.2.

Table 8.1 Erosion and deposition in Rapti river based on shifting of extreme right and left banks

Chainage (km)	Erosion (ha)	Deposition (ha)	Erosion+ Deposition (ha)	Net Erosion/ Deposition (ha)
0-50	617.48	549.55	501.37	-67.93
50-100	643.98	522.89	603.94	-121.09
100-150	869.24	663.53	1168.91	-205.71
150-200	625.93	668.49	491.20	42.56
200-250	519.18	343.79	220.31	-175.39
250-300	527.63	344.97	205.41	-182.65
300-350	581.51	463.79	952.34	-117.72
350-400	595.41	426.30	997.27	-169.11
400-450	836.24	770.37	1850.58	-65.87
450-500	996.64	513.39	1801.13	-483.26
500-542	1091.65	457.44	1942.98	-634.20
Total	**7904.89**	**5724.51**	**10735.44**	**-2180.37**

* '-' indicates erosion and '+' indicates deposition
1 ha = 0.01 km^2

From the above table, it can be summarized that total eroded area is 7904.89 ha, total deposited area is 5724.51 ha and total eroded plus deposited area is 10735.44 ha. Net eroded area is 2180.37 ha during the period 1970 to 2010.

Total Drainage area of Rapti River is 23,900 km^2 for Indian part. Thus eroded area per km^2 catchment area is 21.80/23900 (0.09%).

Based on shifting of extreme left and right banks during the period of year 1970-2010, erosion deposition maps for each reach have been prepared and the same are shown in Figs. 8.3-8.13.

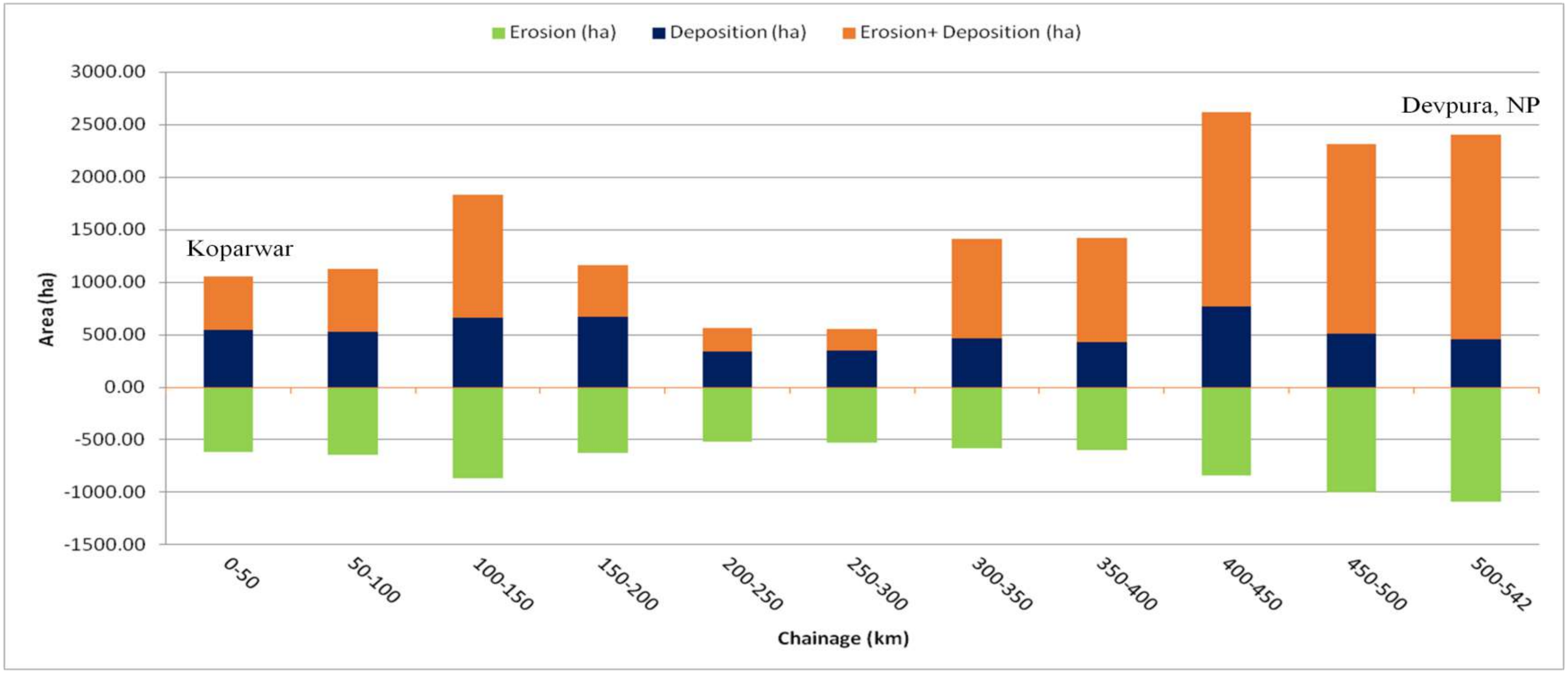


Figure 8.1 Erosion and deposition in Rapti river based on shifting of extreme right and left bank during the period 1970 to 2010

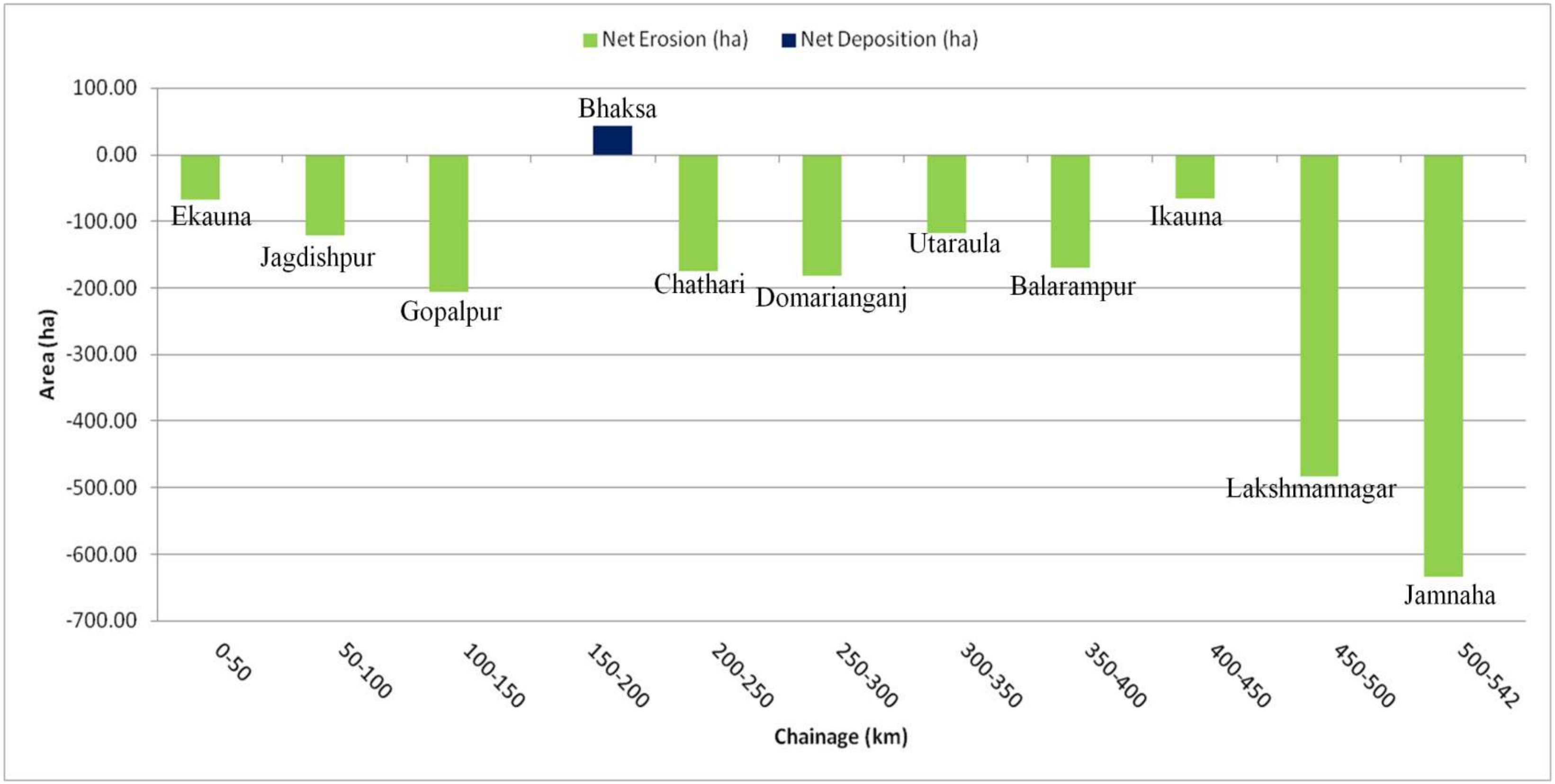
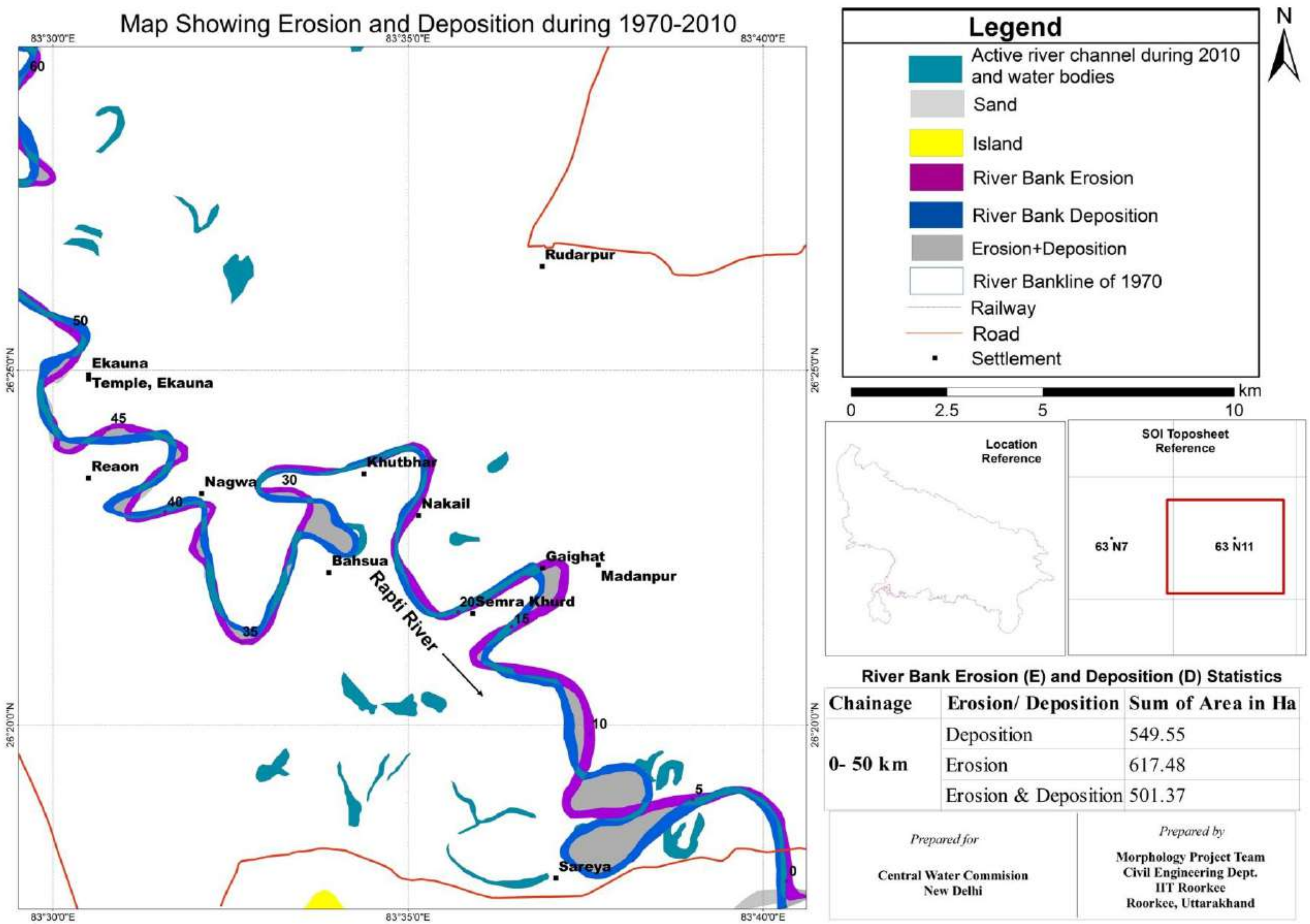


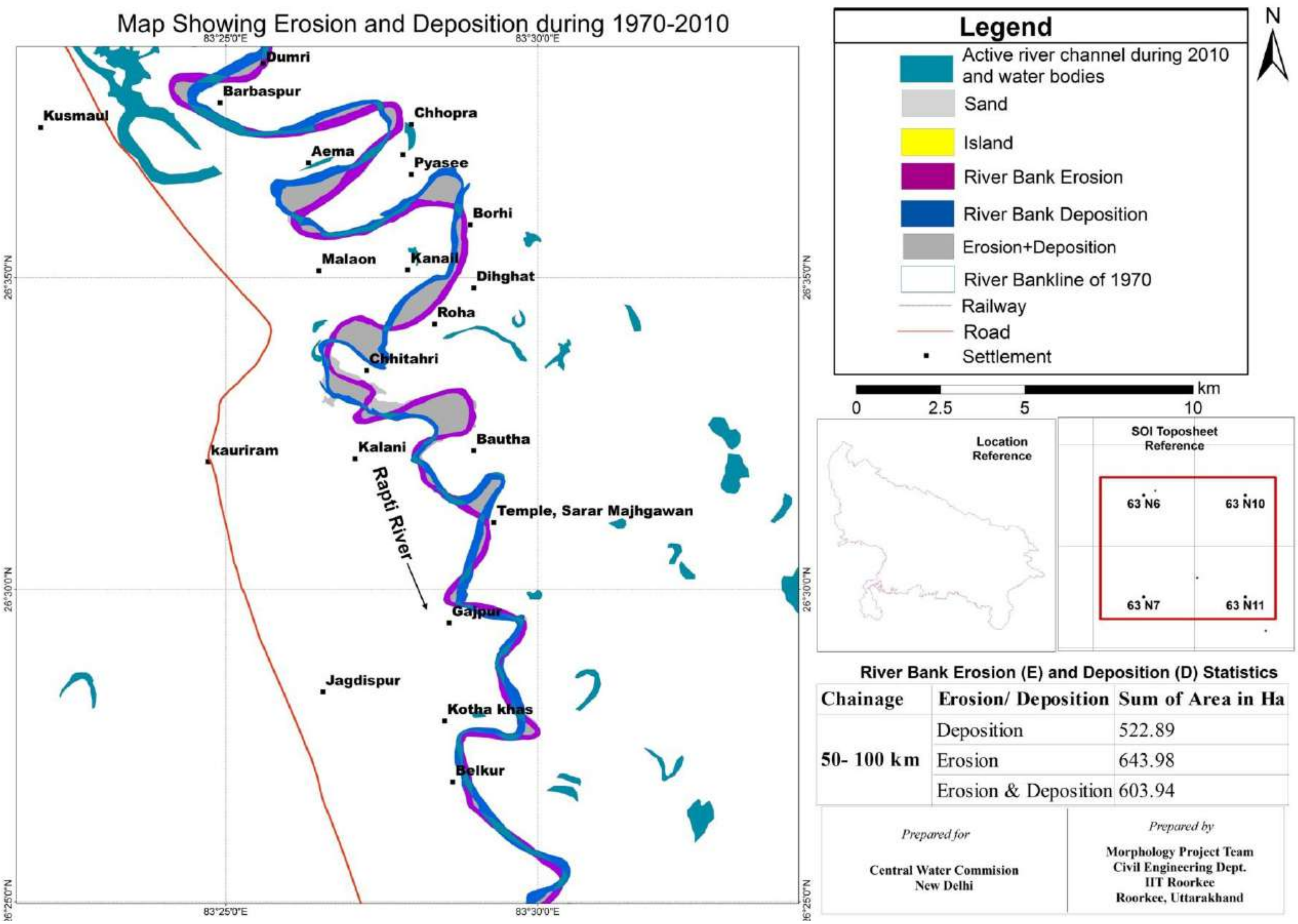
Figure 8.2 Net Erosion and deposition in Rapti River during the period 1970 to 2010 based on shifting of extreme right and left bank during the period 1970 to 2010



River Bank Erosion (E) and Deposition (D) Statistics

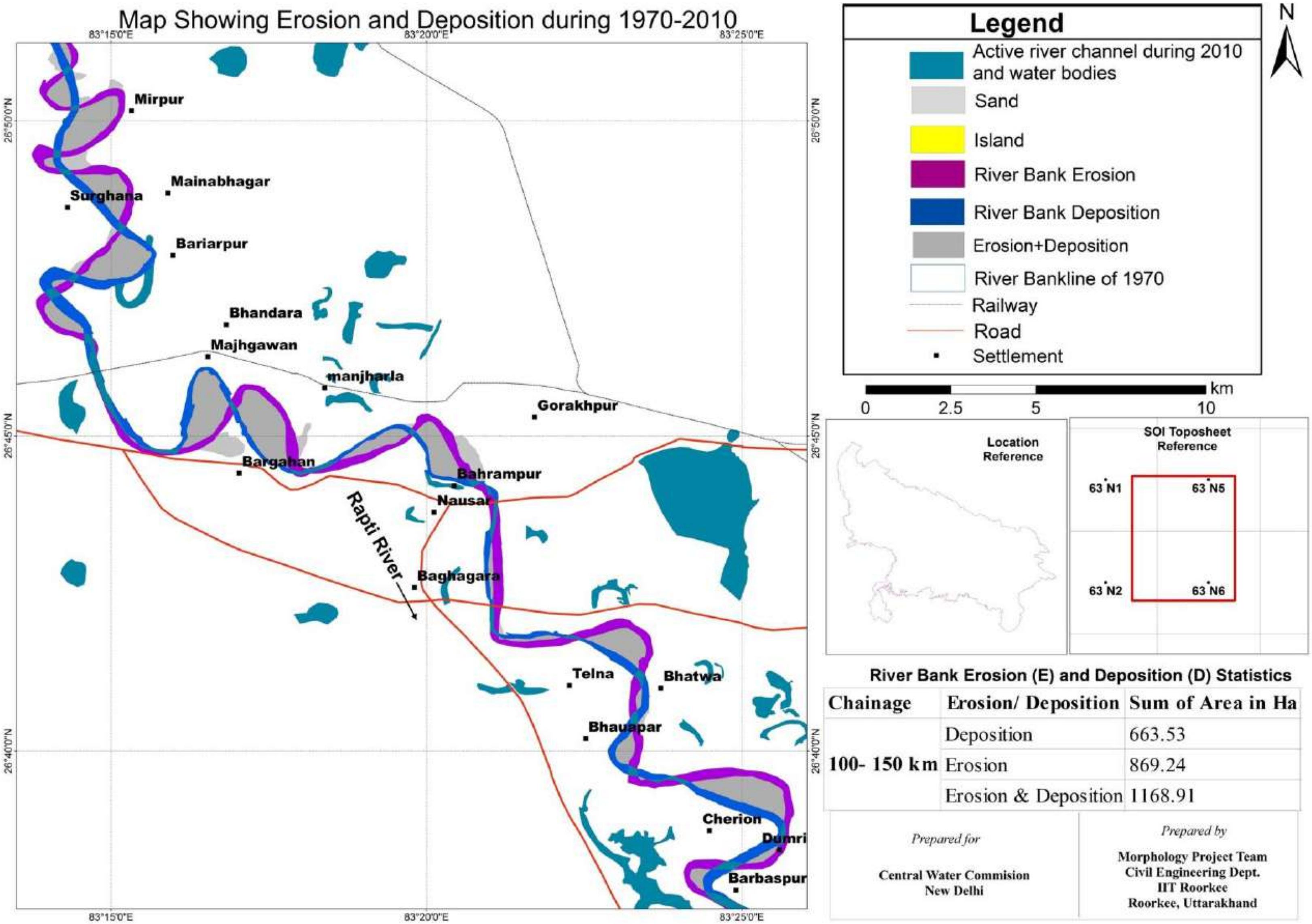
Chainage	Erosion/ Deposition	Sum of Area in Ha
0- 50 km	Deposition	549.55
	Erosion	617.48
	Erosion & Deposition	501.37

Figure 8.3 Erosion and deposition map of Rapti river for period 1970-2010 from chainage 0-50 km



Chainage	Erosion/ Deposition	Sum of Area in Ha
50- 100 km	Deposition	522.89
	Erosion	643.98
	Erosion & Deposition	603.94

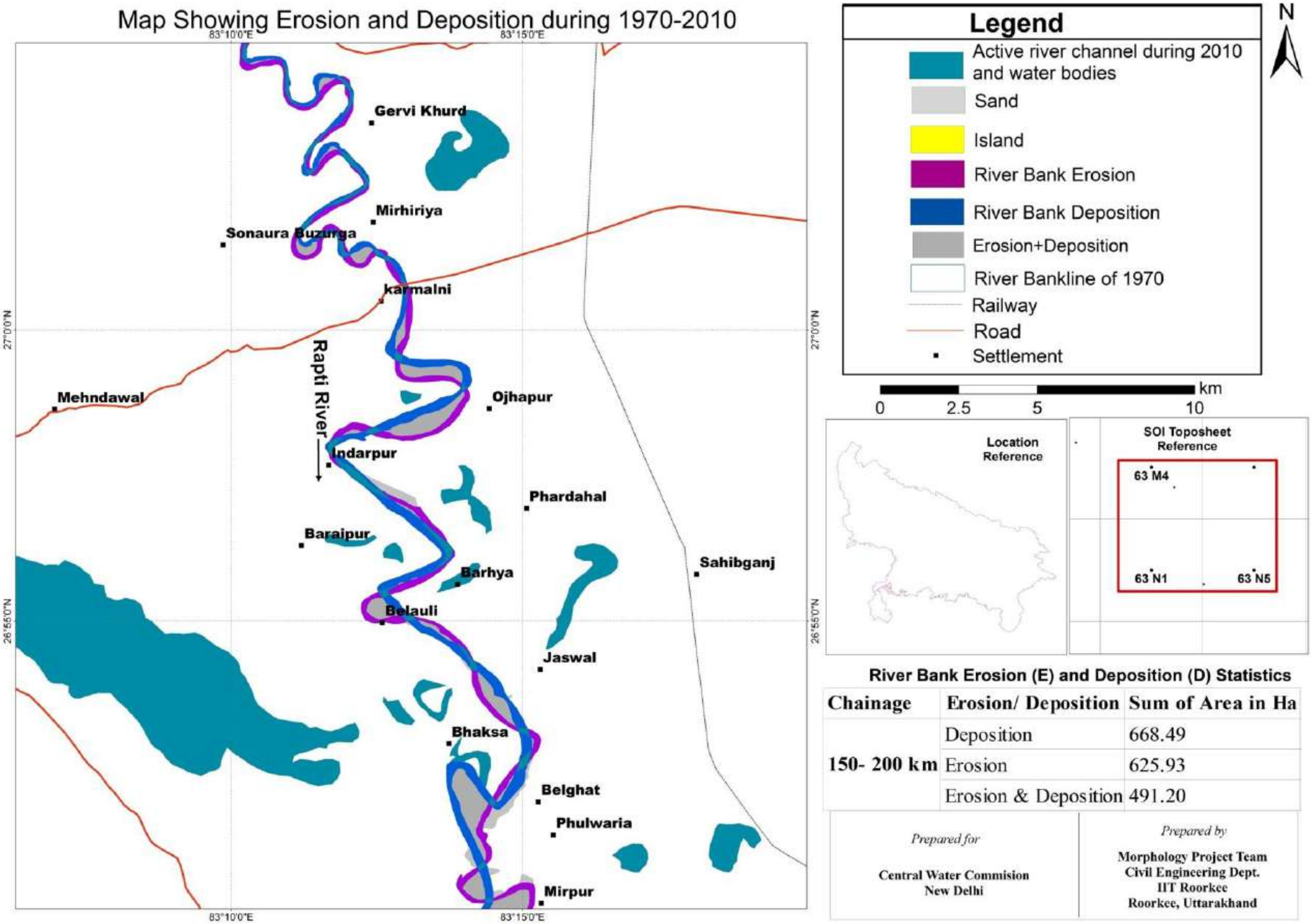
Figure 8.4 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 50-100 km



River Bank Erosion (E) and Deposition (D) Statistics

Chainage	Erosion/ Deposition	Sum of Area in Ha
100- 150 km	Deposition	663.53
	Erosion	869.24
	Erosion & Deposition	1168.91

Figure 8.5 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 100-150 km

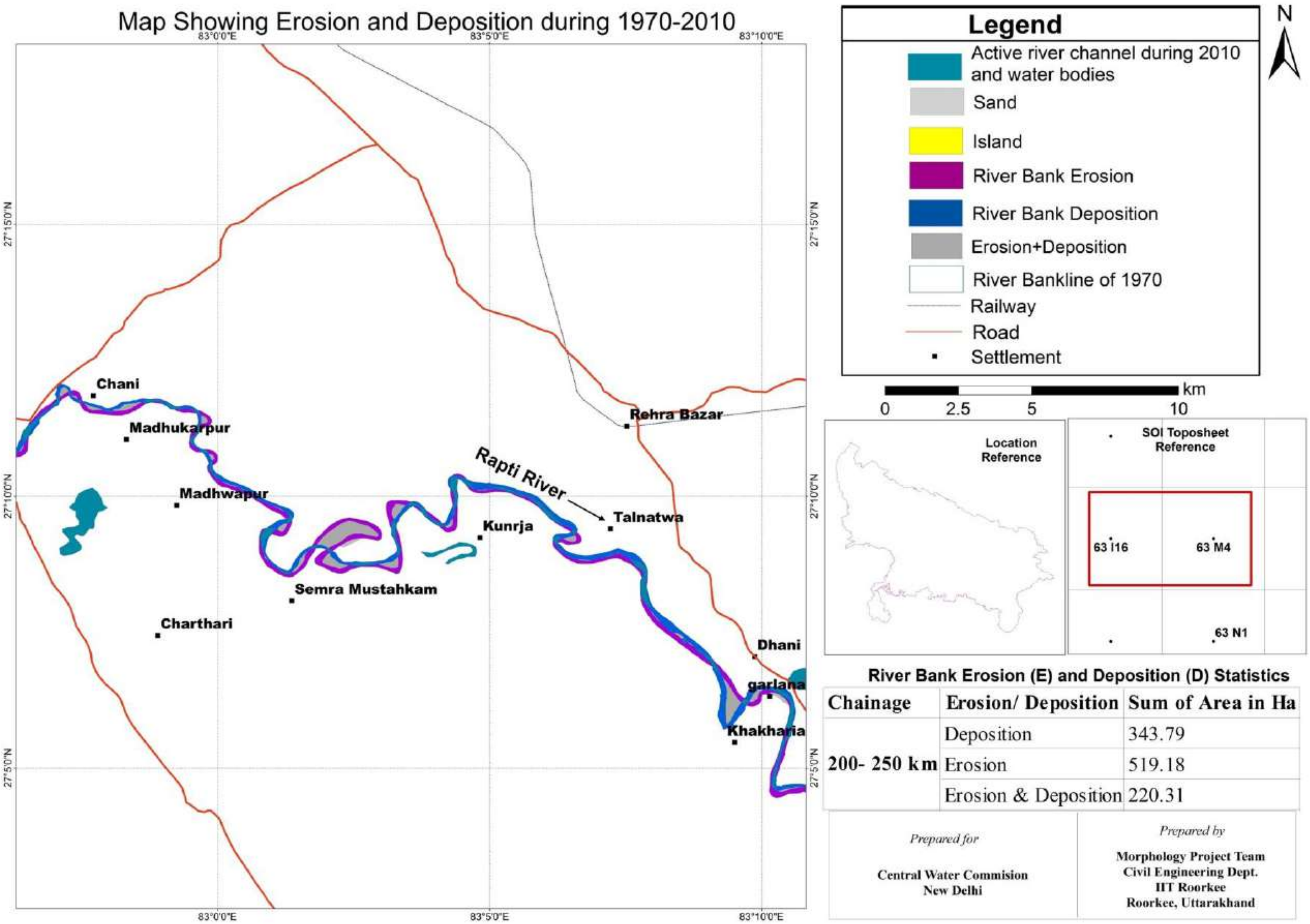


River Bank Erosion (E) and Deposition (D) Statistics

Chainage	Erosion/ Deposition	Sum of Area in Ha
150- 200 km	Deposition	668.49
	Erosion	625.93
	Erosion & Deposition	491.20

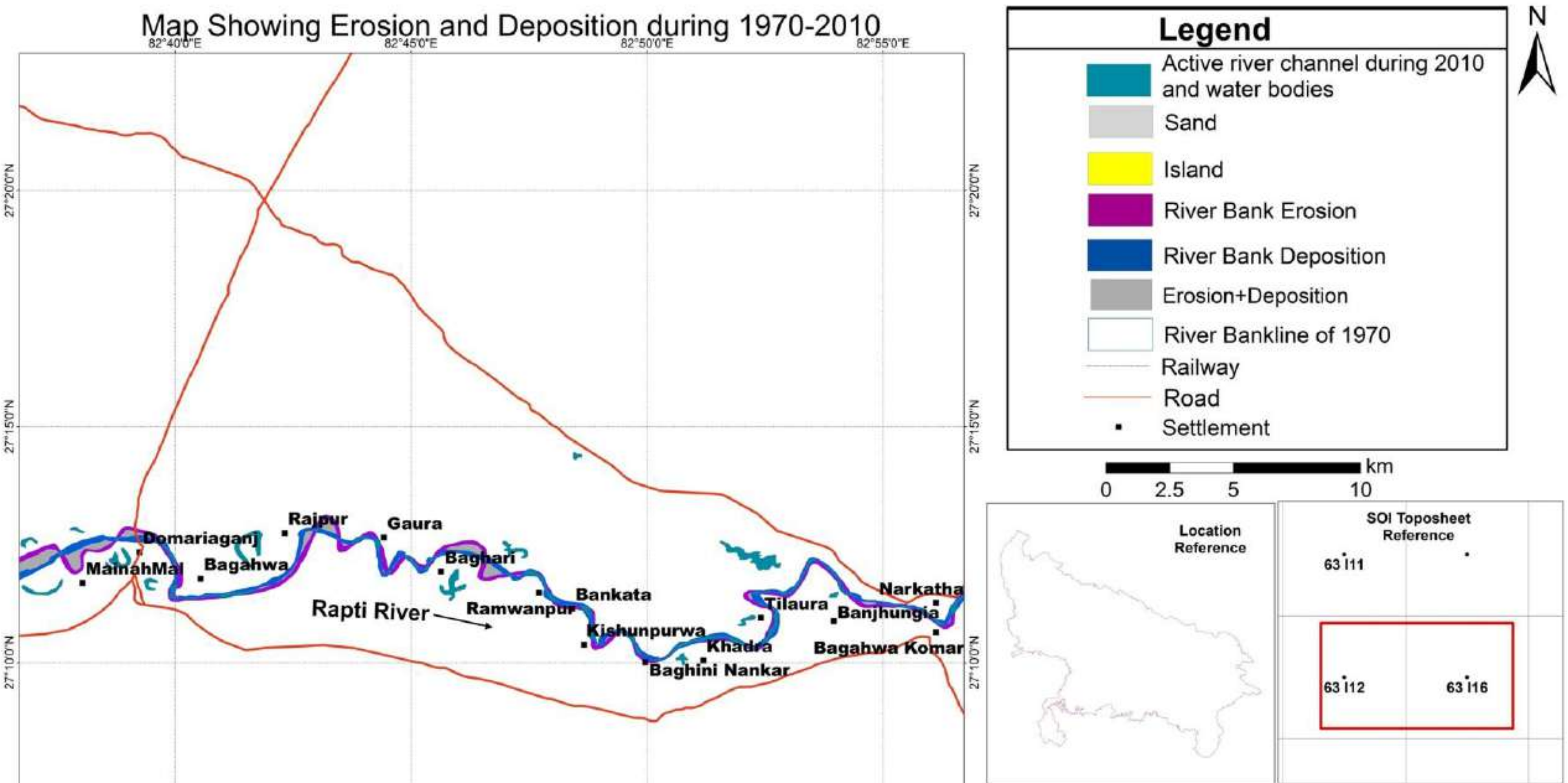
Prepared for	*Prepared by*
Central Water Commision New Delhi	Morphology Project Team Civil Engineering Dept. IIT Roorkee Roorkee, Uttarakhand

Figure 8.6 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 150-200 km



Chainage	Erosion/ Deposition	Sum of Area in Ha
200- 250 km	Deposition	343.79
	Erosion	519.18
	Erosion & Deposition	220.31

Figure 8.7 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 200-250 km

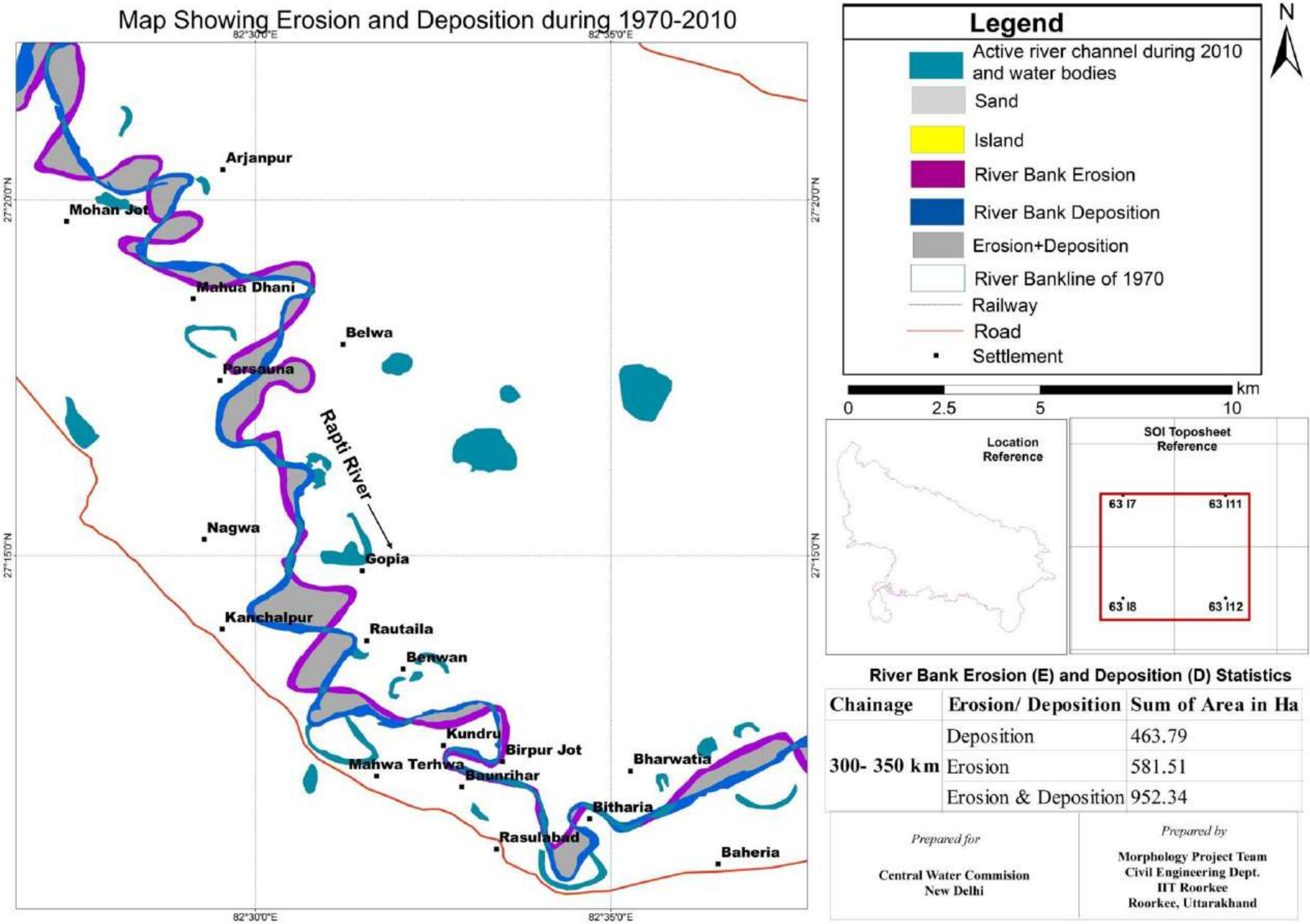


River Bank Erosion (E) and Deposition (D) Statistics

Chainage	Erosion/ Deposition	Sum of Area in Ha
250-300 km	Deposition	344.97
	Erosion	527.63
	Erosion & Deposition	205.41

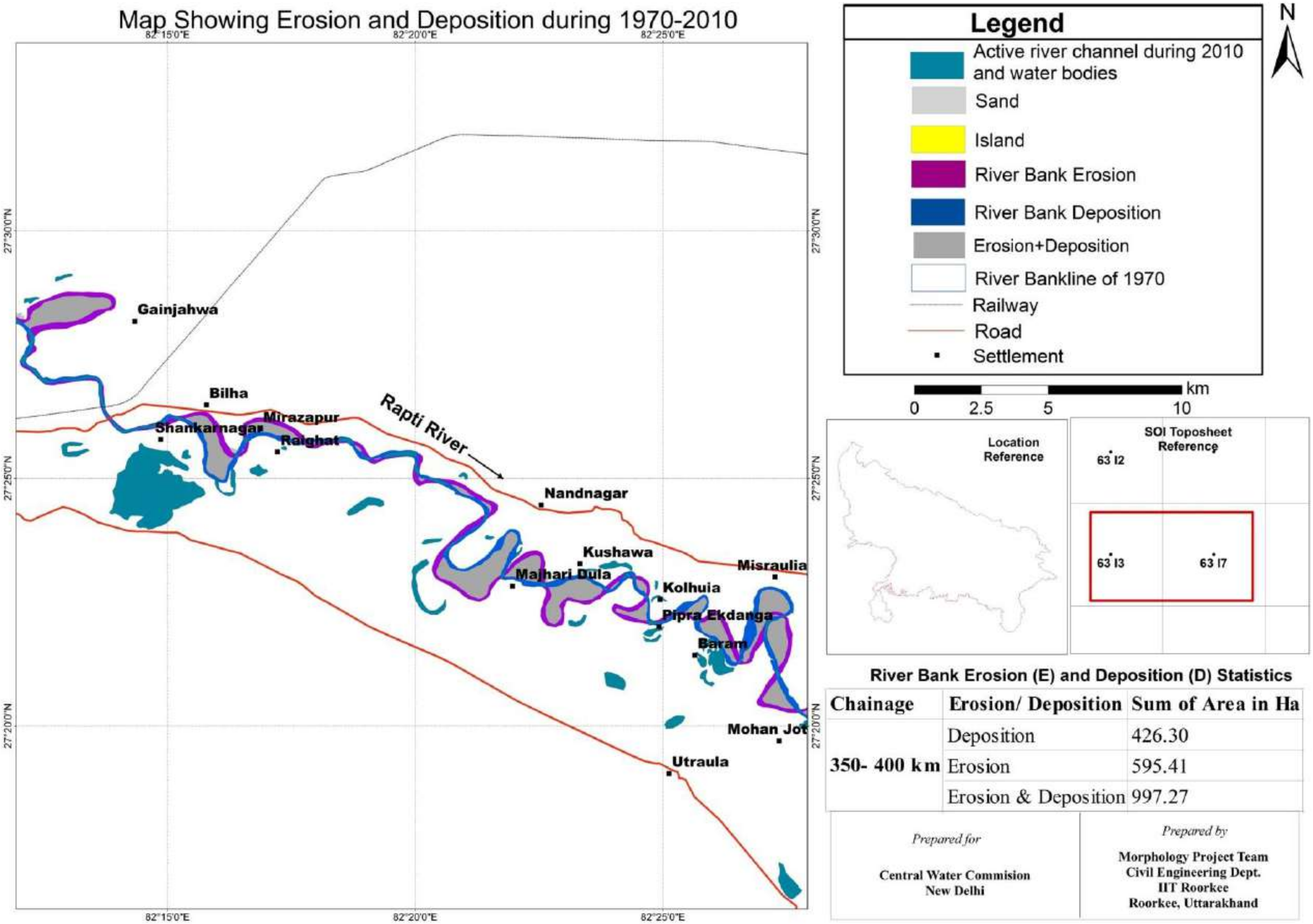
Prepared for	Prepared by
Central Water Commision New Delhi	Morphology Project Team Civil Engineering Dept. IIT Roorkee Roorkee, Uttarakhand

Figure 8.8 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 250-300 km



Chainage	Erosion/ Deposition	Sum of Area in Ha
300- 350 km	Deposition	463.79
	Erosion	581.51
	Erosion & Deposition	952.34

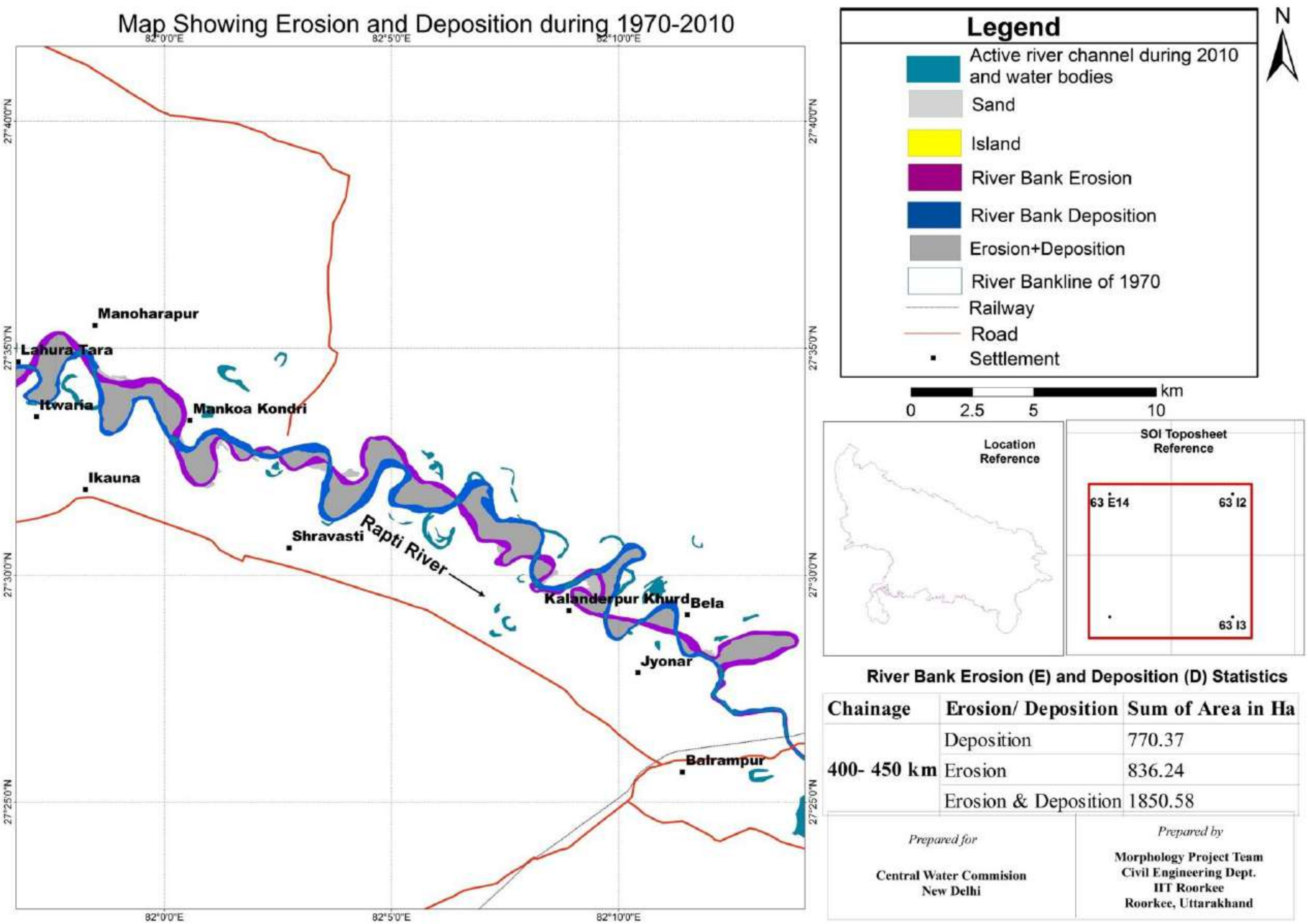
Figure 8.9 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 300-350 km



River Bank Erosion (E) and Deposition (D) Statistics

Chainage	Erosion/ Deposition	Sum of Area in Ha
350- 400 km	Deposition	426.30
	Erosion	595.41
	Erosion & Deposition	997.27

Figure 8.10 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 350-400 km



Chainage	Erosion/ Deposition	Sum of Area in Ha
400- 450 km	Deposition	770.37
	Erosion	836.24
	Erosion & Deposition	1850.58

Figure 8.11 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 400-450 km

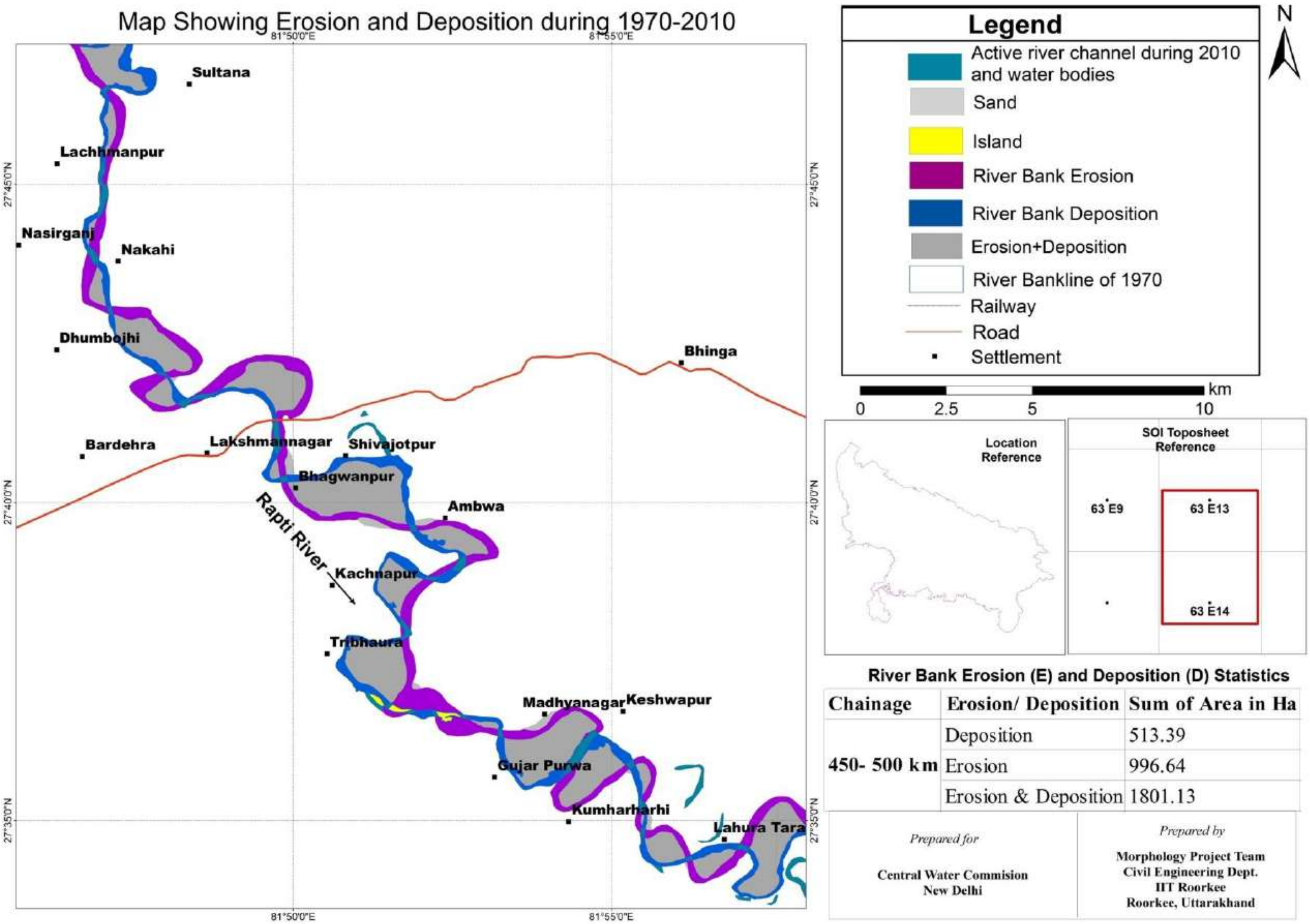
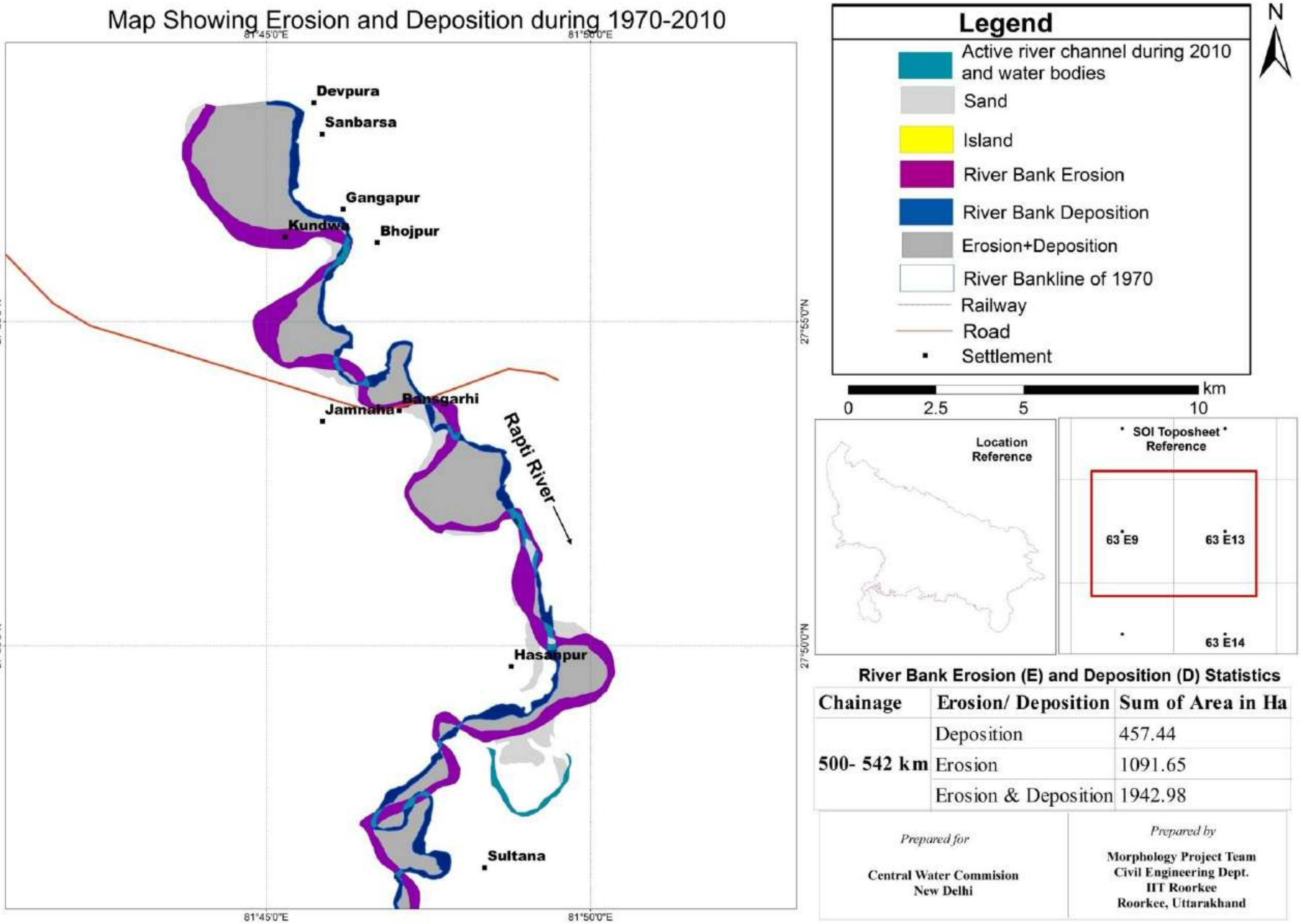


Figure 8.12 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 450-500 km



Chainage	Erosion/ Deposition	Sum of Area in Ha
500- 542 km	Deposition	457.44
	Erosion	1091.65
	Erosion & Deposition	1942.98

Figure 8.13 Erosion and deposition map of Rapti River for period 1970-2010 from chainage 500-542 km

8.5 DISCUSSION ON THE RESULTS

The following points have been noted considering erosion and siltation based on the shifting of extreme left and right banks.

- In the reach 0-50 km, total eroded area, total deposited area and total eroded & deposited area are 617.48 ha, 549.55 ha and 501.37 ha, respectively. Net erosion in this reach is 67.93 ha. Erosion is observed on left bank near Gaighat and Ekauna and deposition near Sareya and Bahssua on the right bank. The possible reason behind this is meandering nature of the river.
- In the reach 50-100 km, total eroded area, total deposited area and total eroded plus deposited area are 643.98 ha, 522.89 ha and 603.94 ha respectively. Net erosion in this reach is 121.09 ha. Erosion is observed on left bank near Chhithari, Dumri, Chhopra and Borhi while deposition has occurred near Malaon & Jagdishpur on the right bank. The possible reason behind this is meandering nature of the river and lateral shifting.
- In the reach 100-150 km, total eroded area, total deposited area and total eroded & deposited area are 869.24 ha, 663.23 ha and 1168.91 ha respectively. Net erosion in this reach is 205.71 ha. Erosion is observed towards left bank near Dumri, Gorakhpur, Mainabhagar and Mirpur, on the other hand deposition was noticed near Bhauapur and Nausar on the right bank. The possible reason behind this is meandering nature of the river and provision of river training works.
- In the reach 150-200 km, total eroded area, total deposited area and total eroded & deposited area are 625.93 ha, 668.49 ha and 491.20 ha respectively. Net deposition in this reach is 42.56 ha. Erosion is observed towards left bank near Mirpur and Ojhapur, and on the other hand deposition was found near Indarpur and Karmalini on the right bank. The possible reason behind this is meandering nature of the river and lateral shifting. There are natural lakes in this reach, and Bakhira taal is the largest among them.
- In the reach 200-250 km, total eroded area, total deposited area and total eroded plus deposited area are 519.18 ha, 343.79 ha and 220.31 ha respectively. Net erosion of this reach is 175.39 ha. No major changes are visible in this reach during the period 1970-2010. Minor erosion on left bank near Madhwapur and deposition near Charthari on the right bank has

been noticed. The possible reason behind this is meandering nature of the river and lateral shifting.

- In the reach 250-300 km, total eroded area, total deposited area and total eroded plus deposited area are 527.63 ha, 344.97 ha and 205.41 ha respectively. Net erosion of this reach is 182.65 ha. No major erosion and deposition are visible in this reach.
- In the reach 300-350 km, total eroded area, total deposited area and total eroded plus deposited area are 581.51 ha, 463.79 ha and 952.34 ha respectively. Net erosion in this reach is 117.72 ha. Erosion is observed on left bank near Gopia, u/s of Arjanpur and Bharwatia on the other hand deposition was found near Raasulabad, Mahua Dhani and Nagwa; on the right bank. The possible reason behind this is meandering nature of the river and lateral shifting.
- In the reach 350-400 km, total eroded area, total deposited area and total eroded plus deposited area are 595.41 ha, 426.30 ha and 997.27 ha respectively. Net erosion in this reach is 169.11 ha. Major changes in the form of erosion and deposition are visible in this reach. There are erosion and deposition on both the banks. The possible reason behind this is meandering nature of the river and existing river training methods.
- In the reach 400-450 km, total eroded area, total deposited area and total eroded plus deposited area are 836.24 ha, 770.37 ha and 1850.58 ha respectively. Net erosion in this reach is 65.87 ha. River has eroded and deposited on both the banks. Erosion is observed on left bank near Manoharpur, on the other hand deposition near Ikauna on the right bank was noticed. Major changes are visible near Jyonar and Balrampur. The possible reason behind this is meandering nature of the river, lateral shifting and constructed structures.
- In the reach 450-500 km, total eroded area, total deposited area and total eroded plus deposited area are 996.64 ha, 513.39 ha and 1801.13 ha respectively. Net erosion in this reach is 483.26 ha. Noticeable amounts of erosion &deposition are visible in this reach, especially on the upstream of the barrage. The possible reason behind this is construction of barrages and braiding & meandering nature of the river due to topographical changes. Other areas are suffered with huge erosion and deposition.
- In the reach 500-542 km, total eroded area, total deposited area and total eroded plus deposited area are 1091.65 ha. 457.44 ha and 1942.98 ha respectively. Net erosion in this

reach is 634.20 ha. Erosion is observed on right bank near Jamnaha and Kundwa. The possible reason behind this is braiding & meandering nature of the river due to topographical change.

8.6 CONCLUSIONS

Following conclusions may be drawn from the study of erosion and siltation in the Rapti river:

a) The total eroded, silted, eroded plus silted, and net eroded area in the Rapti river during the period 1970 to 2010 are 79.04 km^2, 57.24 km^2, 107.35 km^2 and 21.80 km^2, respectively. It may be concluded that over a span of 40 years i.e, 1970 to 2010, about 21.80 km^2 area of Rapti River has been eroded by the flowing water.

b) Erosion has been noticed in the entire reach of Rapti River starting from Nepalgunj to its confluence with Ghaghra River. Major erosion has occurred during the period 1970 to 2010 in the upper reaches (chainage 450-542 km) due to constant shifting of river course. Minor deposition has taken place in the reaches 25 km - 50 km, 150 km - 175 km and 425 km - 450 km that are near Ekauna, Bhaksa and Ikauna, respectively. At other locations, like Gorakhpur, Balrampur, Utraula, and Domrianganj, the erosion is not so severe.

c) There is not much shifting and deposition visible in Rapti river course due to provision of embankments and river training works. There are natural water bodies in the form of ox-bow lakes in vicinity of river due to its meandering nature.

d) Available measured cross sections of the Rapti river for different years at gauging stations of Balrampur, Rigauli and Birdghat have been analysed. No remarkable changes in the historical cross-sections of the Rapti river at Rigauli and Birdghat is noticed, however, river course has shifted towards left side by about 40 m at Balrampur which has resulted in both erosion and siltation at this location. Cross-section of the Rapti river is shallow at Balrampur, however, it is deep at Rigauli and Birdghat.

Chapter 9 MAJOR STRUCTURES & THEIR IMPACT ON THE MORPHOLOGY

9.1 IDENTIFICATION OF MAJOR STRUCTURES

Major structures such as barrages and railway & road bridges located on Rapti River from Nepalgunj to Patana Ghat (confluence point of Rapti and Ghaghra Rivers) have been identified using Google Earth and WRIS website and the same are given in Table 9.1.

Table 9.1 Major structures located on the Rapti River from Nepalgunj to Patana Ghat

ID	Name	Nearby Place	Length (m)	Type	Long.	Lat.
1	Road Bridge (SH-72)	Patana Ghat (Barhalganj)	290	Road	83.671681	26.304840
2	Road Bridge	Sonbah	330.67	Road	83.617588	26.367654
3	Road Bridge	Gheorpar Ahatmali	390	Road	83.522142	26.382252
4	Road Bridge(Panchaldi road)	Banspar	353.73	Road	83.488096	26.482628
5	Road Bridge (Under Construction)	Kaithwalia	357.63	Road	83.453580	26.544960
6	Road Bridge (Gorakhpur bypass road)	Pipari	410	Road	83.350243	26.705609
7	Road Bridge (NH 28)	Gorakhpur	420	Road	83.348608	26.732985
8	Railway Bridge	Mohmadpur Mafi	420	Rail	83.244408	26.767676
9	Road Bridge (Pepeeganj- Sesai Ghar Road)	Peepeganj	294.89	Road	83.237861	26.893515
10	Road Bridge (SH 64)	Karmaini	333	Road	83.214000	27.014072
11	Road Bridge (Bayurbyaas- Dhani	Dhani Bazar	290.01	Road	83.167426	27.108387

	Mag)					
12	Road Bridge (Dhani-Bayurbyaas Marg)	Tal Natawa	232.36	Road	83.126503	27.147096
13	Road Bridge (SH 5)	Bansi	213.54	Road	82.932227	27.183164
14	Road Bridge	Tighra	200	Road	82.796472	27.193603
15	Road Bridge (Dumriyanganj Road)	Domariyaganj	170.81	Road	82.655010	27.213528
16	Road Bridge (Gagapur-Utraula Road)	Kundi,Utraula	150	Road	82.478298	27.317368
17	Road Bridge (SH 1A)	Durgapur	198.55	Road	82.228716	27.437506
18	Railway bridge (Gainjhawa)	Gainjhawa	201.15	Railway	82.226470	27.441303
19	Railway bridge (Gainjhawa)	Gainjhawa	230.09	Railway	82.226489	27.441152
20	Road Bridge	Kodri Ghat	280	Road	82.138970	27.496591
21	Road Bridge (Under Construction)	Andher Purwa	287	Road	81.952020	27.583987
22	Road Bridge(SH 96 A)	Mankapur	160	Road	81.827075	27.688620
23	Road Bridge (Barrage)	Dayali	285.04	Barrage/ Road	81.813558	27.864529

9.2 BARRAGES ON THE RAPTI RIVER

There is only one barrage namely Rapti Barrage on Rapti river near Baharaich at Chainage 519 km. The construction of the Rapti Barrage was started in the year 1977-78 and completed in year 2008. This barrage is part of Sarayu Nahar Pariyojana. Uttar Pradesh Govt. took initiative to provide irrigation to 12.0 Lacs h.a. area (C.C.A) of Baharaich, Shravasti, Gonda, Balrampur, Basti, Siddharthnagar, Sant Kabir Nagar & Gorakhpur through this project. Location of Rapti barrage on Goolge earth image is shown in Fig. 9.1a while a photograph of the Barrage is shown in Fig. 9.1b.

Salient features of the barrage are as follows:

Salient Features	
Name of the Structure	Rapti Barrage
Nearest city	Baharaich
District	Shrawasti
State	Uttar Pradesh
Name of the River	Rapti
Basin	Ganga
Purpose	Irrigation
Design flood (cumecs)	4990
Length of Barrage and Anicut (m)	284.5
No. of bays (i.e. number of openings)	15
Width of Bay (m)	18
Type of spillway gate	Others
Thickness of Intermediate Plot (m)	2.5
Crest Level (m)	125
Pond level (m)	127.7
Under sluice bay- Number	4
Gates for under sluice- Size (m)	14 m×18 m×3 m
Means for dissipating energy (Hydraulic)	DENTATED SILL DEVICE
Status of BWA Construction	Completed

Figure 9.1a Location of Rapti barrage

Figure 9.1b A photogragh of the Rapti barrage

9.2.1 Impact of the Rapti barrage on the morphology of the river

To study the impact of the barrage on the river morphology, decadal satellite images and geospatial datasets are examined. Fig 9.2a shows the major course of the Rapti River of the year 1970, 1980, 1990, 2000 and 2010 on the satellite image of the year 2015 while Figs 9.2 b-g show images of the year 1970, 1980, 1990, 2000, 2010 and 2015, respectively.

From the Fig. 9.2a, one can conclude that the river course has wandering behavior upstream of the barrage. However, no shifting has been observed downstream of the barrage over the years.

The barrage was commissioned in year 2008. Since then no noticeable silting upstream of the barrage has been observed. Nevertheless, river in year 2015 was flowing in two channels upstream of the barrage.

A site visit was undertaken on 23rd October 2016, to have the comprehensive idea of the morphology of the river at the barrage site. The river has severe wandering behavior upstream of the barrage. In the past, the river had come very close to the right approach road, however, with the provision of series of spurs along the right approach road, it was protected against the erosion - subsequnetly river shifted away from the right approach road.

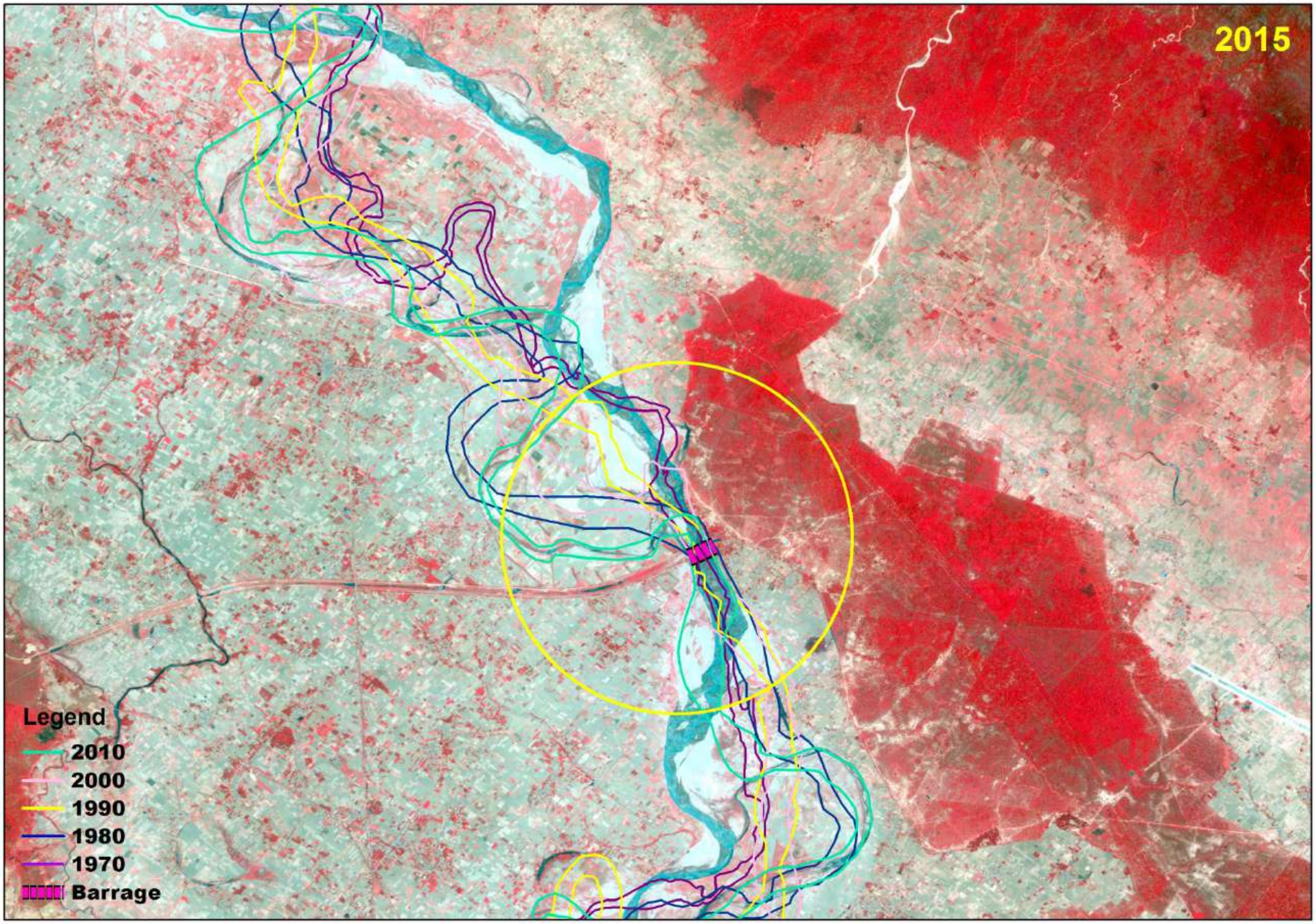
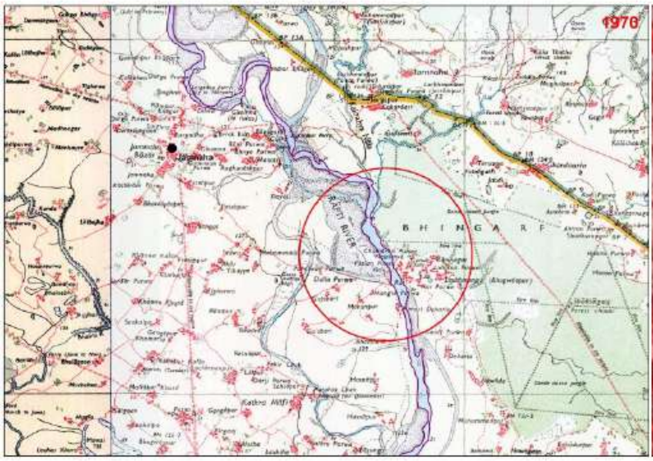
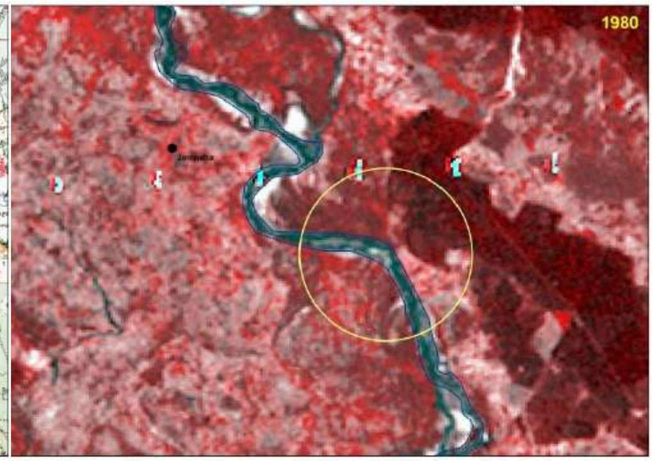


Figure 9.2a GIS layer of the Rapti river of the year 1970, 1980, 1990, 2000 and 2010 on the satellite image of 2015





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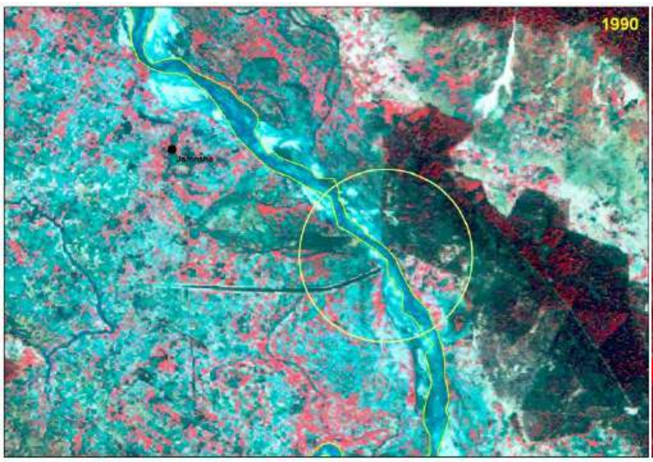

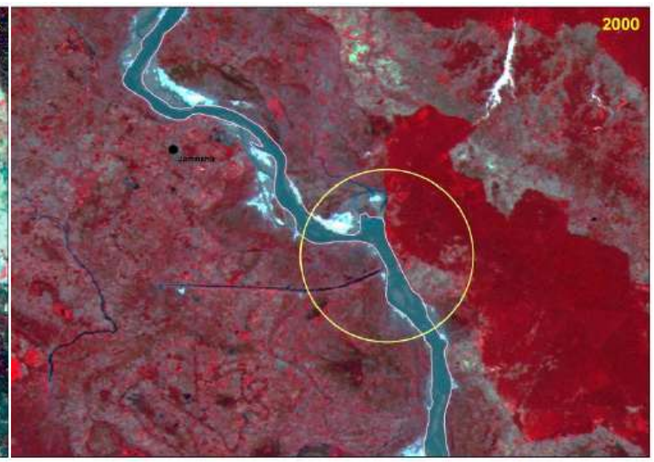

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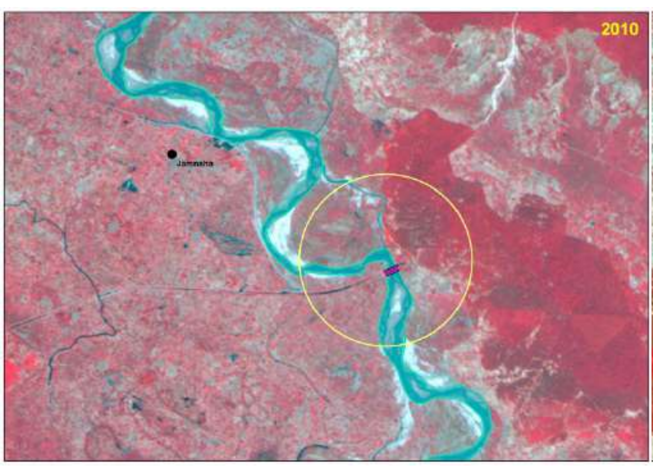

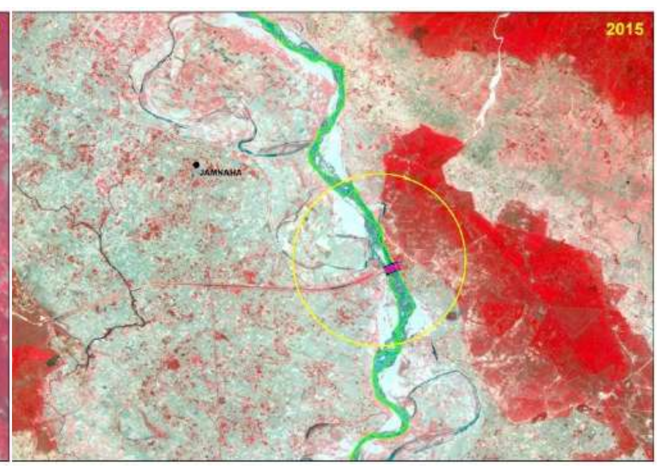

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Figure 9.2b-g Images of Rapti river for the year 1970, 1980, 1990, 2000, 2010 and 2015

9.3 BRIDGES ON THE RAPTI RIVER

Details of the bridges located on the Rapti River and morphology of the river near such bridges are given in Table 9.2.

Table 9.2 Details of the bridges on Rapti river and morphology of the river near such bridges

ID	Name of the Bridge/ Road	Chainage	Length (m)	Type of Bridge	River Width (m)	Nearby Place	Remarks
1	**Road Bridge**	**2**	**290**	**Road**	**230**	**Patana Ghat**	* Located in relatively straight and stable reach of the river. * No protection works have been provided. * In past, river had come close to the right approach road of the bridge - spurs were provided to protect the approach road. * As such no measures are required for training the river at the bridge site. *Provision of embankment towards right side, upstream of the bridge (SH 72 Bridge) to control the spread of flood water is recommended. (see Fig. 9.3)
2	Road Bridge	17.5	330.67	Road	150	Sonbah	* No protection works are provided near the bridge, however, river has a 90^{o} bend at about 450 m upstream of the bridge - the outer bank of the river is protected using series of spurs against erosion. *A pilot channel is excavated towards left side near the bend.

							* In year 1970, the river was away from the bridge towards the right side. * As such not measures are required for training the river at the bridge site.
3	Road Bridge	41	390	Road	200	Gheorpar Ahatmali	* No protection works are provided near the bridge. * Located in a straight reach, however, in a meandering zone. * There is an acute bend at about 720 m upstream of the bridge -outer bank protected using series of spurs. * No measures are required for training the river at the bridge site.
4	Road Bridge (Panchaldi road)	60	353.73	Road	200	Banspar	* No protection works are provided. * Located in relatively straight and stable reach of the river. * No measures are required for training the river at the bridge site.
5	Road Bridge (Under Construction**)**	**74**	**357.63**	**Road**	**140**	**Kaithwalia**	*Located just downstream of an acute bend and major shifting of river towards its left side has been noticed upstream of the bend. *Recommended to provide series of spurs towards left side upstream of the bend to arrest such shifting so that out flanking of the bridge can be avoided. (see Fig. 9.4)
6	Road Bridge (Gorakhpur bypass road)	117.5	410	Road	250	Pipari	*Located in a relatively straight and stable reach of the river. *No protection works are provided. *No measures are required for training the river at the bridge site.
7	Road Bridge	121	420	Road	240	Gorakhpur	*Currently located skewed in the respect of

	(NH 28)						direction of flow of the river. * Elliptical guide bund is provided towards right side which performance is satisfactory. * No damage to the guide bund has been noticed. * River is relatively stable near the bridge and requires no protection works.
8	Railway Bridge	137	420	Railway	210	Mohmadpur Mafi	* Jacketing of the river upto about 1 km upstream of the bridge using embankment and spurs. Performances of such structures are satisfactory. * Located in a straight and stable reach of the river. * No any other protection works are required.
9	Road Bridge (Peepeganj-Sesai Ghar Road)	**160**	**294.89**	**Road**	**230**	**Peepeganj**	* Relatively in a straight and stable reach from year 2000 onwards, however, right bank over a length of 700 m upstream of the bridge is under erosion and the same is to be protected using boulder revetment/ porcupine/series of spurs. (see Fig. 9.5) * In the years 1970 to 2000, the river was away from the bridge towards the left side.
10	Road Bridge (SH 64)	183	333	Road	230	Karmaini	* Slightly skewed in the respect of direction of flow. * Series of short spurs are provided towards right side upstream of the bridge to control the erosion. * Except for erosion of right bank upstream of the bridge, the river is stable and no any other river raining or protection work is

							required.
11	Road Bridge (Bayurbyaas-Dhani Mag)	**205**	**290.01**	**Road**	**200**	**Dhani**	* Located on meandering path of the river. * There is an acute bend upstream of the bridge and the river has come very close to the right side approach road upstream of the bridge. * Even though few spurs have been provided to deflect the course of river away from the road, however, it is strongly recommended to provide river training works in the vicinity of the bridge to guide the flow. (see Fig. 9.6)
12	Road Bridge (Dhani-Bayurbyaas Marg)	**212**	**232.36**	**Road**	**235**	**Dhani**	Located in relatively stable reach of the river, however, it is recommended to protect the both banks near the bridge with boulder revetment to the existing both sides embankments. (see Fig. 9.7)
13	Road Bridge (SH 5)	**251.5**	**213.54**	**Road**	**123**	**Rajendra Nagar**	*Located in straight and stable reach of the river. * Embankments are provided towards both the sides of the river at spacing of about 250 m near the bridge. * As river is flowing abutting the left embankment upstream of the bridge, it is recommended to provide protection to the left embankment upstream of the bridge in the form of boulder revetment/short spurs. (see Fig. 9.8)
14	Road Bridge	**272.5**	**200**	**Road**	**160**	**Tighra**	*Located in a straight and stable reach of the river. *As such, no river training/ protection works

							are required, however, it is suggested to provide boulder revetment to the both approach roads of the bridge. (see Fig. 9.9)
15	Road Bridge (Dumriyanganj Road)	295	170.81	Road	170	Domariyaganj	*Located in a relatively straight and stable reach of the river from year 1980 onwards. In the year 1970, the river was away from the bridge towards right side. * Embankments are provided towards both sides and near the bridge. * As such, no river training/protection measures are required.
16	Road Bridge (Gagapur-Utraula Road)	340	150	Road	160	Kundi,Utraula	*Located in a relatively straight and stable reach, however there is an acute meandering of the river upstream of the bridge and remarkable changes in the morphology of the river have been noticed. * Embankments are provided towards both sides of the river. * As such no river training/protection works are required, however, the behavior of the river shall be watched in future and depending on its behavior, suitable measures be provided.
17	Road Bridge (SH 1A)	395	198.55	Road	145	Balrampur	* Located in a relatively straight and stable reach of the river. * As such no river trainings /protection works are required.
18	Railway bridge (Gainjhawa)	395.5	201.15	Railway	160	Gainjhawa	*Located in a relatively straight and stable reach. * Right guide bund along with

19	Railway bridge (Gainjhawa)	395.5	230.09				embankments are provided towards right side upstream of the bridge. * The performances of such structures are satisfactory and no any other structures are required near the bridge side for training of the river and protection of the banks.
20	Road Bridge	**418**	**280**	**Road**	**250**	**Kodri Ghat**	* The river is highly unstable near the bridge as major planform changes have been noticed. *Currently provided truncated right guide bund and right embankment upstream of the bridge are in order, like wise provided left embankment upstream of the bridge is also working satisfactory. *It is recommended to extend the existing left guide bund of about 90 m downstream so that right approach road can be protected against the erosion. (see Fig. 9.10)
21	Road Bridge (Under Construction)	451	287	Road	260	Andher Purwa	*Guide bund is provided towards left side while an embankment is provided towards right side. Their performances are satisfactory. * Presently the river is in a straight reach however, historical images indicate major changes in the morphology of the river near the bridge site. In 1970, the river was about 2 km away from the bridge towards right side. * Adequate river training /protection works have provided. No further are required.
22	Road Bridge	484	160	Road	225	Mankapur	*Located just downstream of an acute bend

	(SH 96 A)						in the river. From 1970 onwards, the river has shifted towards left side upstream of the bridge. * River is widespread downstream of the bridge. * Two elliptical guide bunds each of length 160 m are provided towards both the sides. * Left bank of the river beyond the guide bund is protected with series of the spurs & boulder revetment and such arrangements are successfully protecting the bank against erosion. * Even though river near the bridge is having acute bends, however, adequate measures have been taken for training the river. No additional measures are required near the bridge.

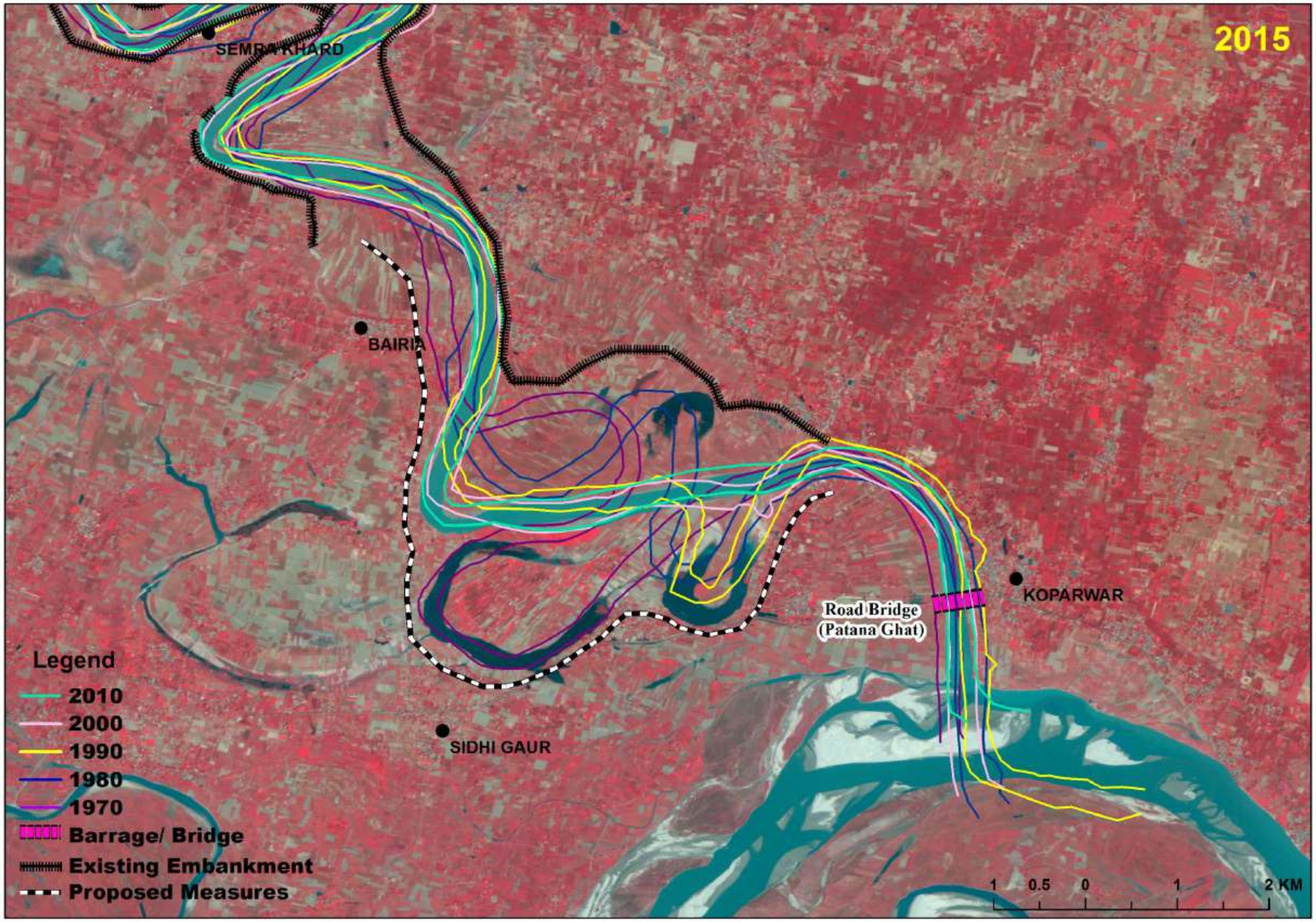

Figure 9.3 Courses of the Rapti river of year 1970, 1980, 1990, 2000, and 2010 on the image of year 2015 near road bridge at Patana ghat

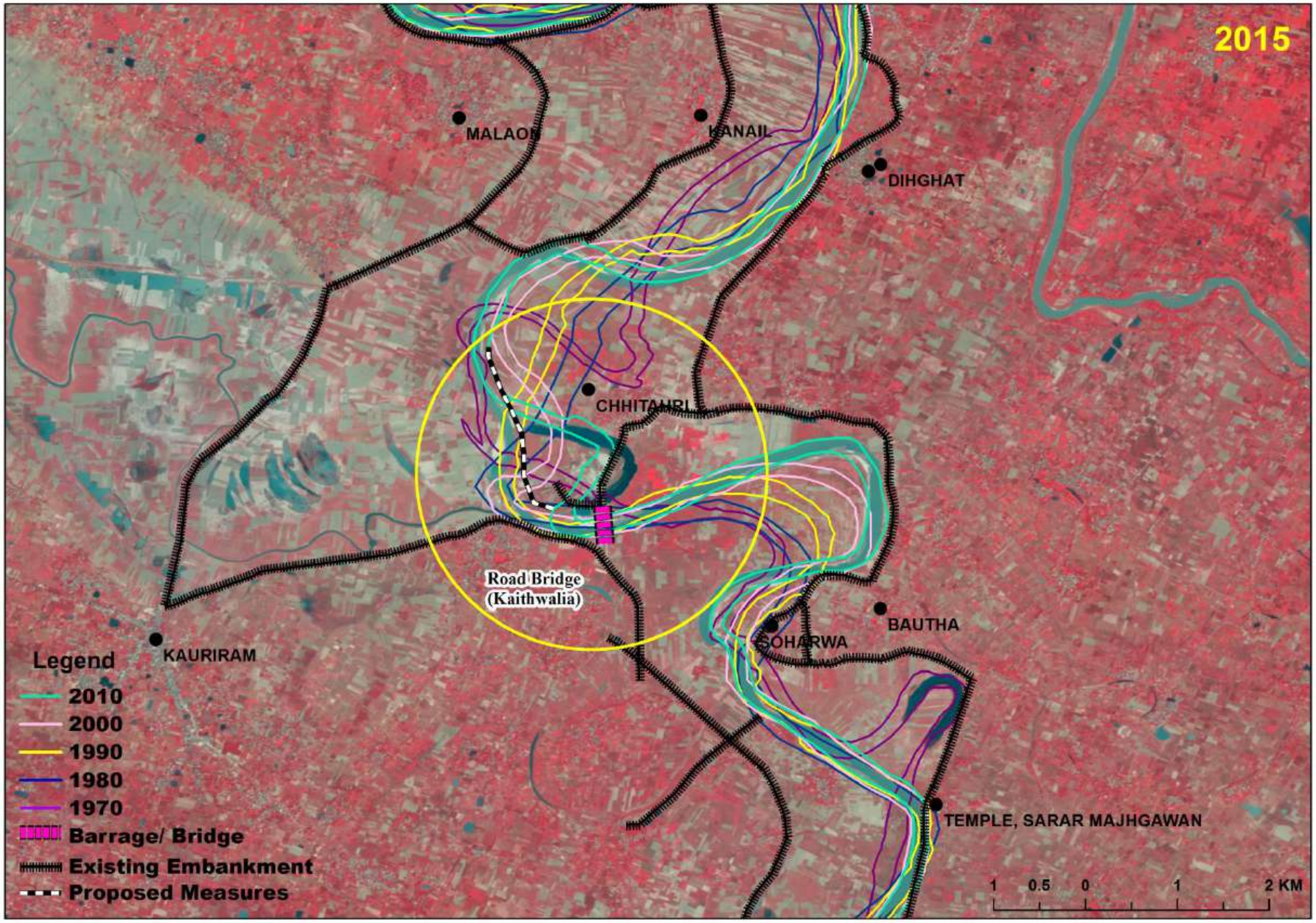

Figure 9.4 Courses of the Rapti river of year 1970, 1980, 1990, 2000, and 2010 on the image of year 2015 near road bridge at Kaithwalia

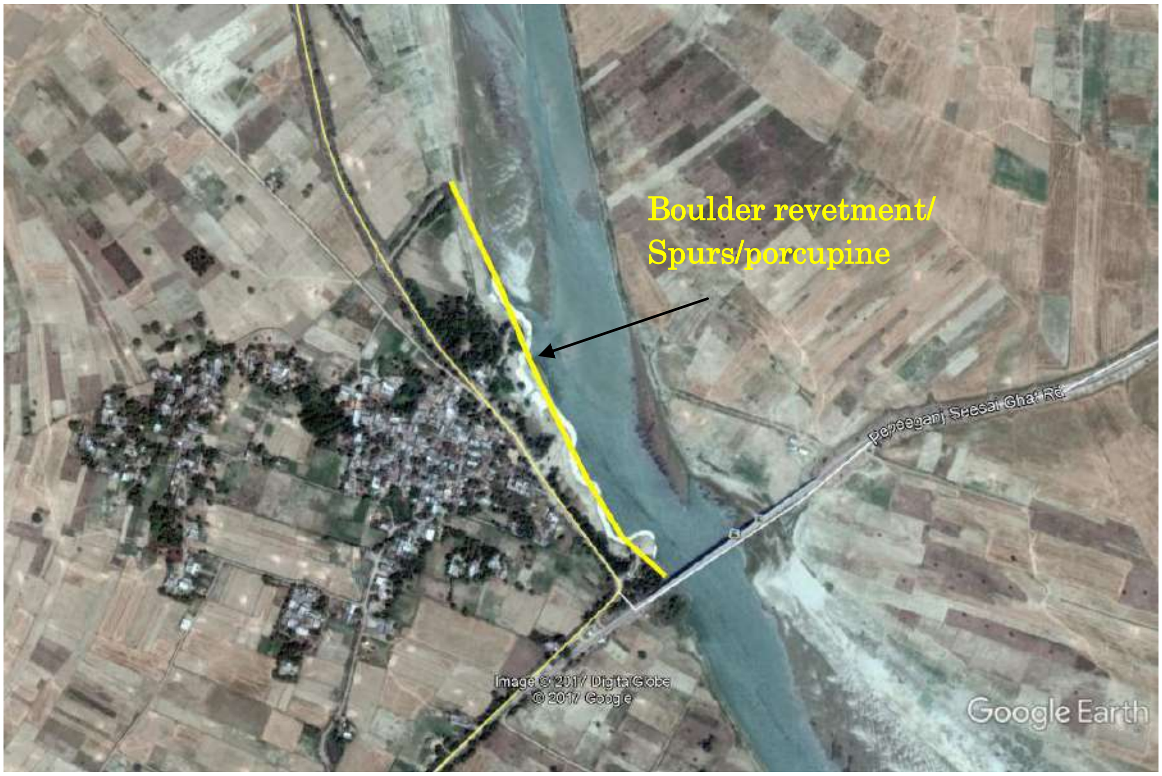

Figure 9.5 Boulder revetment/porcupine/series of spurs on right bank over a length of 700 m upstream of the bridge at Peepeganj (Chainage = 160 km)

Figure 9.6 Provision of series of spurs towards left side at Dhani (Chainage = 205 km)

Figure 9.7 Boulder revetment to the existing both sides embankments at Dhani (Chainage = 212 km)

Figure 9.8 Provision of protection to the left embankment upstream of the bridge (SH5) in the form of boulder revetment/short spurs at Rajendra Nagar (Chainage = 251.5 km)

Figure 9.9 Provision of boulder revetment to both the approach roads at Tighra (Chainage 272.5 km)

Figure 9.10 Extension of the existing left guide bund of about 90 m downstream at Kodri ghat (chainage 418 km)

9.4 CONCLUDING REMARKS

Following conclusions may be drawn:

1. The river course has wandering behavior upstream of the barrage. However, no shifting has been observed downstream of the barrage over the years. The Rapti barrage was commissioned in year 2008. Since then no noticeable silting upstream of the barrage has been observed. Nevertheless, river in year 2015 was flowing in two channels upstream of the barrage.
2. There are about 22 bridges on the Rapti river from Nepalgunj to its confluence with Ghaghra river at Patana ghat. Morphological changes have noticed near the major bridges, however, proper river training works have been provided which are working satisfactorily.
3. Road bridge (SH 72, Patana Ghat) is located in relatively straight and stable reach of the Rapti river. In past, river had come close to the right approach road of the bridge - spurs were provided to protect the approach road. As such no measures are required for training the river at the bridge site. However, it is suggested to provide embankment towards right side, upstream of the bridge (SH 72 Bridge) to control the spread of flood water.
4. Road bridge (Kaithwalia) is located just downstream of an acute bend and major shifting of river towards its left side has been noticed upstream of the bend. It is suggested to provide series of spurs towards left side upstream of the bend to arrest such shifting so that out flanking of the bridge be avoided.
5. Protection works are suggested in the vicinity of the bridges at Chainages 160 km, 205 km, 212 km, 251.5 km, 272.5 km and 418 km to train the Rapti river as per detail below:
   a) Boulder revetment/porcupine/series of spurs on right bank over a length of 700 m upstream of the bridge at Peepeganj (Chainage = 160 km, Fig. 9.5)
   b) Provision of series of spurs towards left side at Dhani (Chainage = 205 km, Fig. 9.6)
   c) Boulder revetment to the existing both sides embankments at Dhani (Chainage = 212 km, Fig. 9.7)
   d) Provision of protection to the left embankment upstream of the bridge (SH5) in the form of boulder revetment/short spurs at Rajendra Nagar (Chainage = 251.5 km, Fig. 9.8)
   e) Provision of boulder revetment to both the approach roads at Tighra **(**Chainage 272.5 km, Fig. 9.9)
   f) Extension of the existing left guide bund of about 90 m downstream at Kodri ghat (Chainage 418 km, 9.10)

Chapter 10 GROUND VALIDATION

10.1 INTRODUCTION

This chapter deals with details of the site visit undertaken to various locations of the Rapti river by the team of IIT Roorkee. The observations made during the site visits have been examined in the perspective of the outcomes of the morphological study carried out in this study.

10.2 VISIT TO RAPTI BARRAGE ON 23 OCTOBER, 2016

A team of IIT Roorkee visited the Rapti barrage on 23rd October 2016 also had discussion with the barrage authority. Two canals off-take from each side of the river upstream of the barrage. The left canal terminates just after it's off-take from the barrage. However, the right canal is functional and on the day of visit repair work of the canal was in progress. Guide bunds are provided towards both sides of the river both upstream and downstream of the barrage. Such bunds were intact and no major damage to the bunds was noticed during the visit.

The length of barrage is 284.5 m and is designed for peak discharge of 4990 m^3/s. Lacey perimeter corresponding to this peak discharge is estimated as 335.5 m against the provided length of barrage of 284.5 m. Thus the looseness factor of the barrage is 1.18.

Major changes in the course of Rapti River upstream of barrage have been noticed. The river has wandering behavior at the barrage. On the day of visit, the river was flowing relatively towards its left side.

No major silting was noticed in upstream and downstream of the barrage during the site visit. Some of the photographs taken during the site visit are shown in Figs. 10.1 to 10.5.

	**Figure 10.1** View of the Rapti river upstream of the barrage
	**Figure 10.2** Head regulator of the right channel
	**Figure 10.3** Upstream view of the Rapti Barrage

Figure 10.4 View of the Rapti river downstream of the Rapti barrage

Figure 10.5 Termination of the left canal system

10.3 VISIT TO BANSI BRIDGE SITE ON 29/07/2016

Rapti River flows through Bansi town and on the day of visit it was flowing almost at danger level. Flood water was spread over the right side and a breach in the bund had occurred that was repaired with sand bags. Villagers on enquiry told that marginal embankments have been constructed on both banks of the river and these are beneficial to them. There is no threat to any embankment as told by villagers. The provided embankments successfully contained the flood water and do not allow to spread beyond those.

10.4 VISIT TO BIRDGHAT (GORAKHPUR) AND PATANA GHAT (BARHALGANJ) ON 30/07/2016

Rapti River at Birdghat was flowing at danger level on the day of visit. The flood water was spread over both the banks of the river. Some low lying areas and a primary school located on the right bank and upstream of the bridge were submerged. After this, the visiting team moved to Patana Ghat bridge on River Rapti located close to its influence with the Ghaghra River near Barhalganj. In downstream of bridge, water was found to spread on both sides of the river. There were no embankments on upstream and downstream sides of the bridge. The left bank was higher and right bank was submerged with a vast area. In the meeting held with the Officers of U.P. Irrigation Department, it was told that 6.1 km long bund is proposed to be constructed towards right side on upstream of bridge.

In the afternoon, a meeting was held with Chief Engineer (Gandak) concerning Superintendent Engineer and Executive Engineers of U.P. Irrigation Department. It was requested to provide a map showing the existing bunds on either banks of Rapti river starting from Nepal Boarder to Patana Ghat Bridge. It was also requested to provide details of the protection works that were provided over and above the embankments. It was also requested to provide threatening reaches and new works recently proposed to protect the bunds, so that possible measures may be considered for the provision of protection works in the near future. Department officers told that the existing bunds are constructed taking about two times the Lacey's perimeter. The river has a tendency of attacking either of the embankments and eroding them depending on flow condition and protection works provided. The Department officers told that in the place of boulders revetments, provision of geobags and porcupines have been found to be quite encouraging. This type of protection works have been executed this year in river Rapti, and few years back in river Sharda. They were requested to provide feedback in this respect after the monsoon, so that it may also be included in the report. Use of geobag and porcupine has given better performance in lower discharge, like in Rapti and Sharda. In Ghaghra River, these works have not been found to be successful. Some relevant photographs taken during the site visits are shown in Figs. 10.6 to 10.11.

Figure 10.12 shows location of the sites of the Rapti river that were visited by the IIT Roorkee team.

	**Figure 10.6** Rapti river just upstream of its confluence with Ghaghra river (26.304926N, 83.668530E) and downstream of the bridge over it
	**Figure 10.7** Rapti river just upstream of its confluence with Ghaghra river (26.304926 N, 83.668530 E) and upstream of the bridge over it
	**Figure 10.8** Rapti river just upstream of its confluence with Ghaghra river (26.304926 N, 83.668530 E) and upstream of the bridge over it - left bank of the river is on higher elevation

	**Figure 10.9** Rapti river just upstream of its confluence with Ghaghra river (26.304926 N, 83.668530 E) and upstream of the bridge over it - right bank is flat and spurs are provided to protect the road SH-72
	**Figure 10.10** Rapti river downstream of NH29 (26.732984 N, 83.348470 E) - Left bank is elevated and right bank is flat, a bund is provided along right bank
	**Figure 10.11** Rapti river downstream of NH-29 (26.732984 N, 83.348470 E) - a bund is provided along right bank

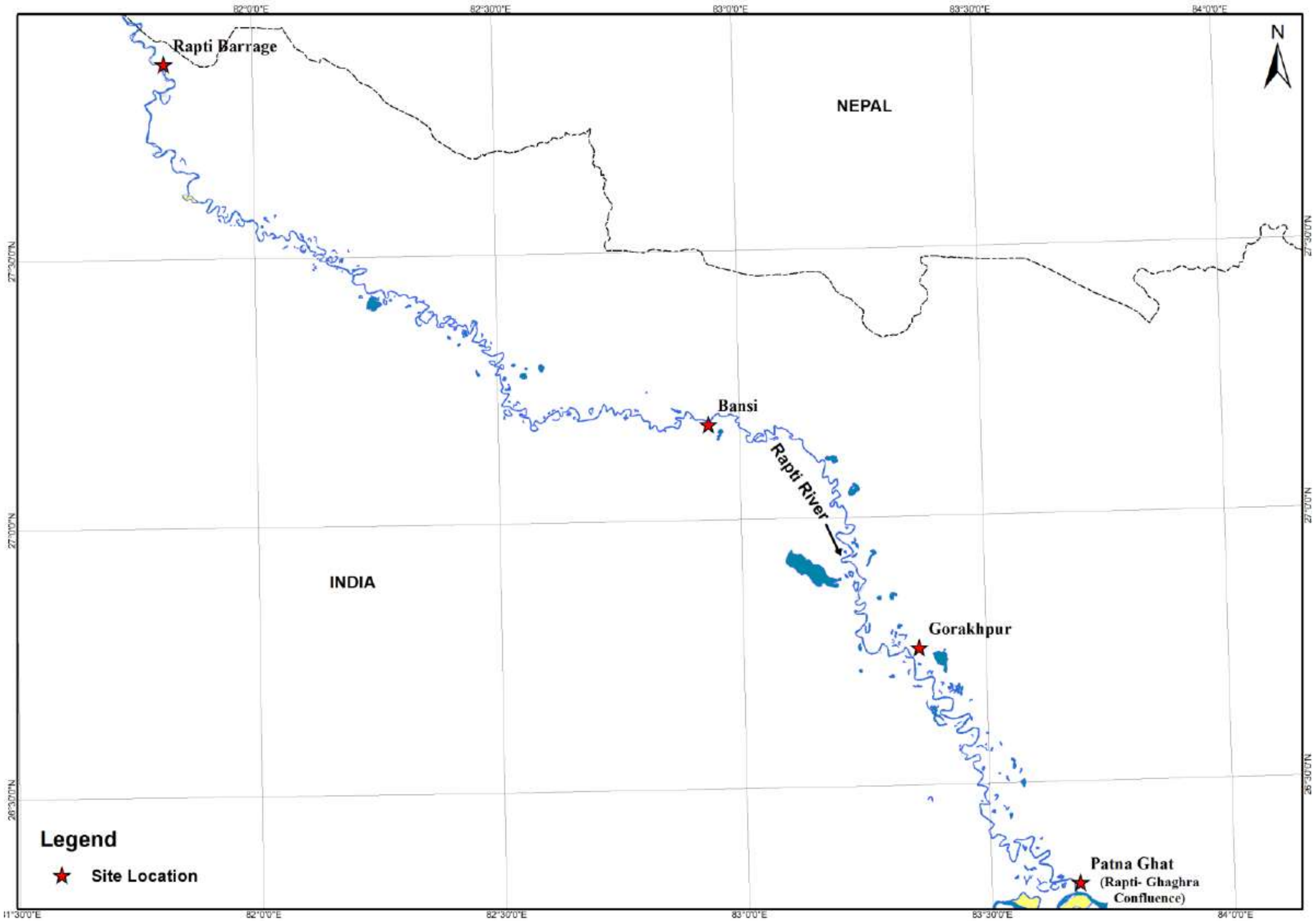

Figure 10.12 Location of the sites of the Rapti River visited by the IIT Roorkee team

Chapter 11 IDENTIFICATION OF CRITICAL REACHES & RIVER TRAINING WORKS

11.1 IDENTIFICATION OF THE CRITICAL REACHES

Discussion on the plan form changes of the river in the terms of bank line shifting, sinuosity, plan form index etc. has been mentioned in the previous chapters. For fulfilling the objective of the study regarding identification of the critical reaches and provision of river training works thereof, suitable basis has been discussed here.

The proposed basis for the identification of the critical reaches is as follows:

a) The reach of the river that has been progressively shifting towards either sides from the base year 1970 shall be considered as critical reaches. This is due to the fact that such progressive shifting of the course of river causes severe erosion of the agricultural areas, which results in loss of the agricultural land.

b) Localized erosion of the either banks in the habitated/ settlement areas, as such erosion causes displacement of the houses to the new locations, inundation of pricey areas etc.

(c) In agricultural land, where the river is wide and the width is much higher than regime width of the channel even though there is no progressive shifting of river course in either directions. Such frequent shifting of the river in wide width of the land causes loss of the crops and agricultural land. Thus there is a need to confine the width of the river so that spread of the flood water which is causing huge inundation can be controlled.

The above basis has been adopted in this study for identification of critical reaches of the Rapti river.

As per the IS code 12094:2000, the spacing between the embankments/levees for the containment of the river should not be less than 3 times Lacey's wetted perimeter for the design flood discharge. In no case, should an embankment be placed at distance less than Lacey's wetted perimeter from the river bank or one and a half times.

In the present study for the relatively straight reach, width of the river is kept 3 times of the Lacey perimeter. However, at locations where sinuosity ratio of the river is higher, it is proposed to place the embankments at 4 times the Lacey perimeter apart.

Lacey's perimeter for the alluvial river may be obtained by

$$P = 4.75\sqrt{Q} \qquad (11.1)$$

Where P is in m and Q is discharge in cumecs.

Invoking the methodology/criteria discussed in the above section, the identified critical reaches of the Rapti river are given in the Table 11.1 with justification. Nine reaches of the Rapti river have been identified as critical.

In the reaches from 68-80 km, 138-156 km, 304-322.5 km, 326.5- 378 km, 387-392 km, 399-433 km, 438-466 km, 470-492 km and 506-515 km, the historical images of the river indicate its random wandering in wide width. These reaches are located near Chhithari, Mirpur, Rasulabad, Utraula, Jyonar, Ikauna, Lakshmannagar and Jamnaha in Uttar Pradesh. The left and right banks of the river of the year 1970, 1980, 1990, 2000 and 2010 are marked on the LISS IV image of year 2015 and shown in the Figs. 11.1a to i. The land in this area is mostly agricultural.

Table 11.1 Critical reaches of the Rapti River

Chainage (km)	Location	Justification	Figure No.
506-515	**Jamnaha, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1a
470-492	**Lakshmannagar, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide	11.1b

		width. No progressive shifting in either directions.	
438-466	**Ikauna, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1c
399-433	**Jyonar, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1d
387-392	**Shankarnagar, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1e
326.5-378	**Utraula, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1f
304-322.5	**Rasulabad, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1g
138-156	**Mirpur, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1h
68-80	**Chhitahri, UP**	Agricultural land on either sides of the river. Random wandering of the river in wide width. No progressive shifting in either directions.	11.1i

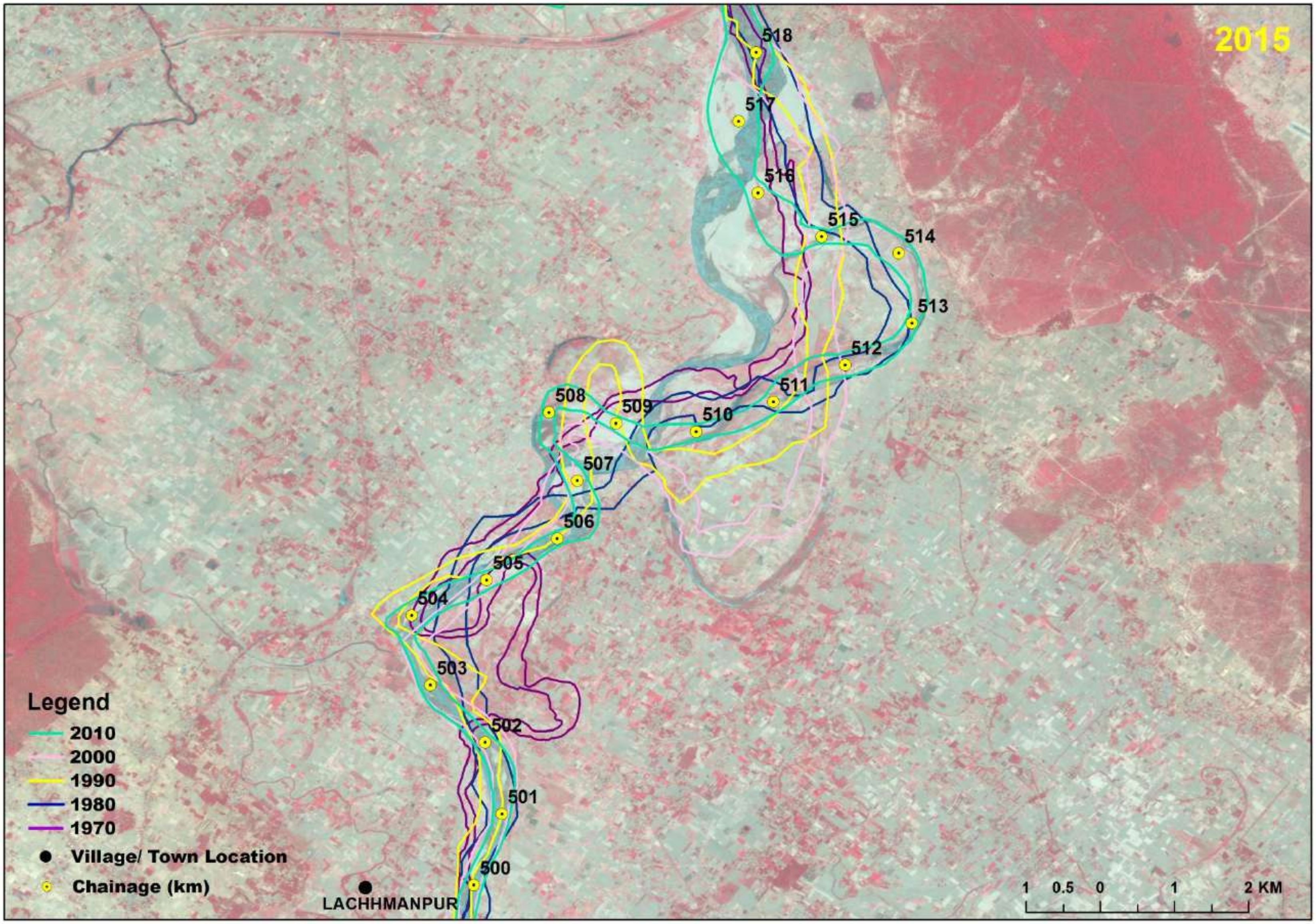

Figure 11.1a Critical reach of Rapti river from chainage 506- 515 km

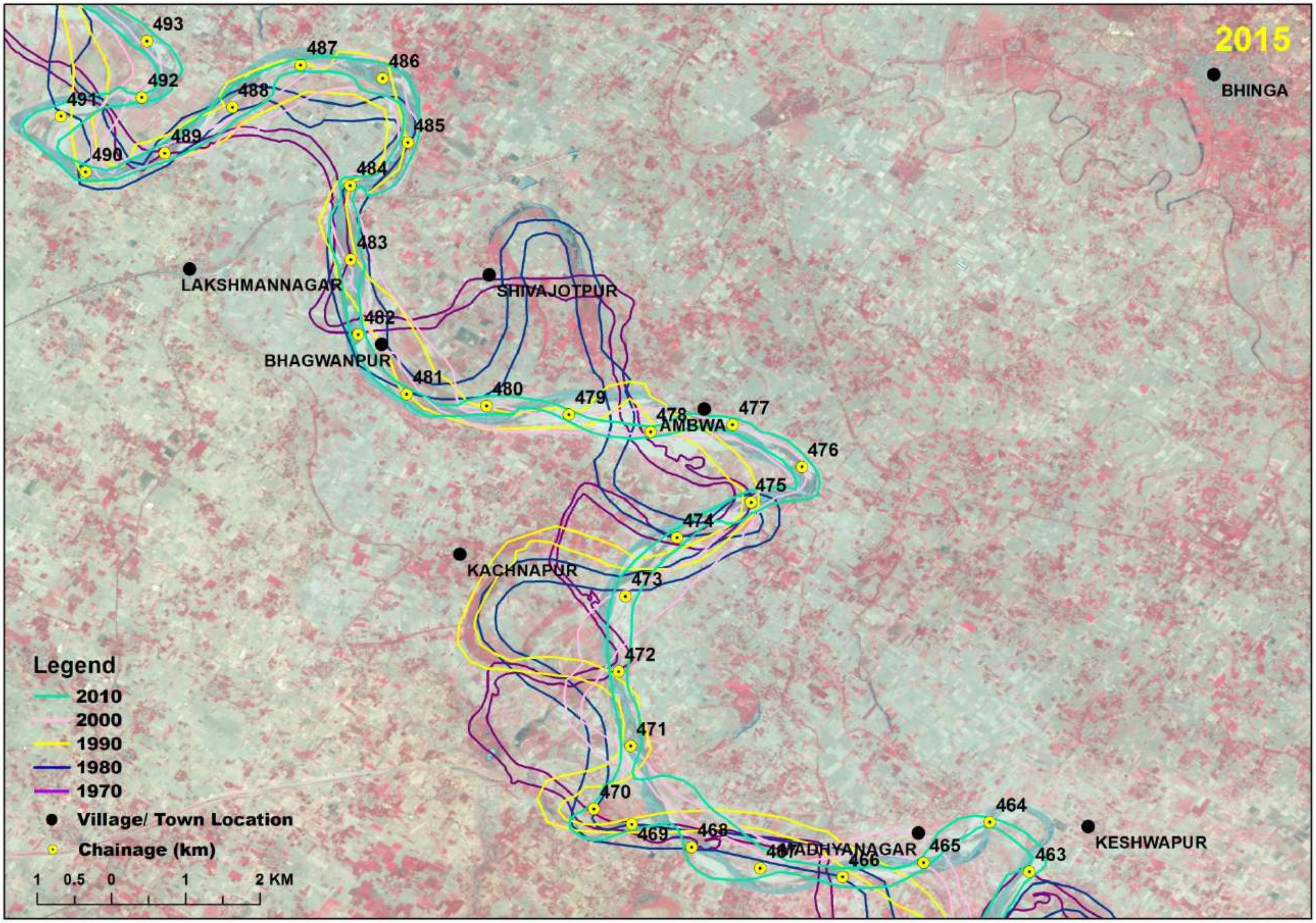

Figure 11.1b Critical reach of Rapti river from chainage 470- 492 km

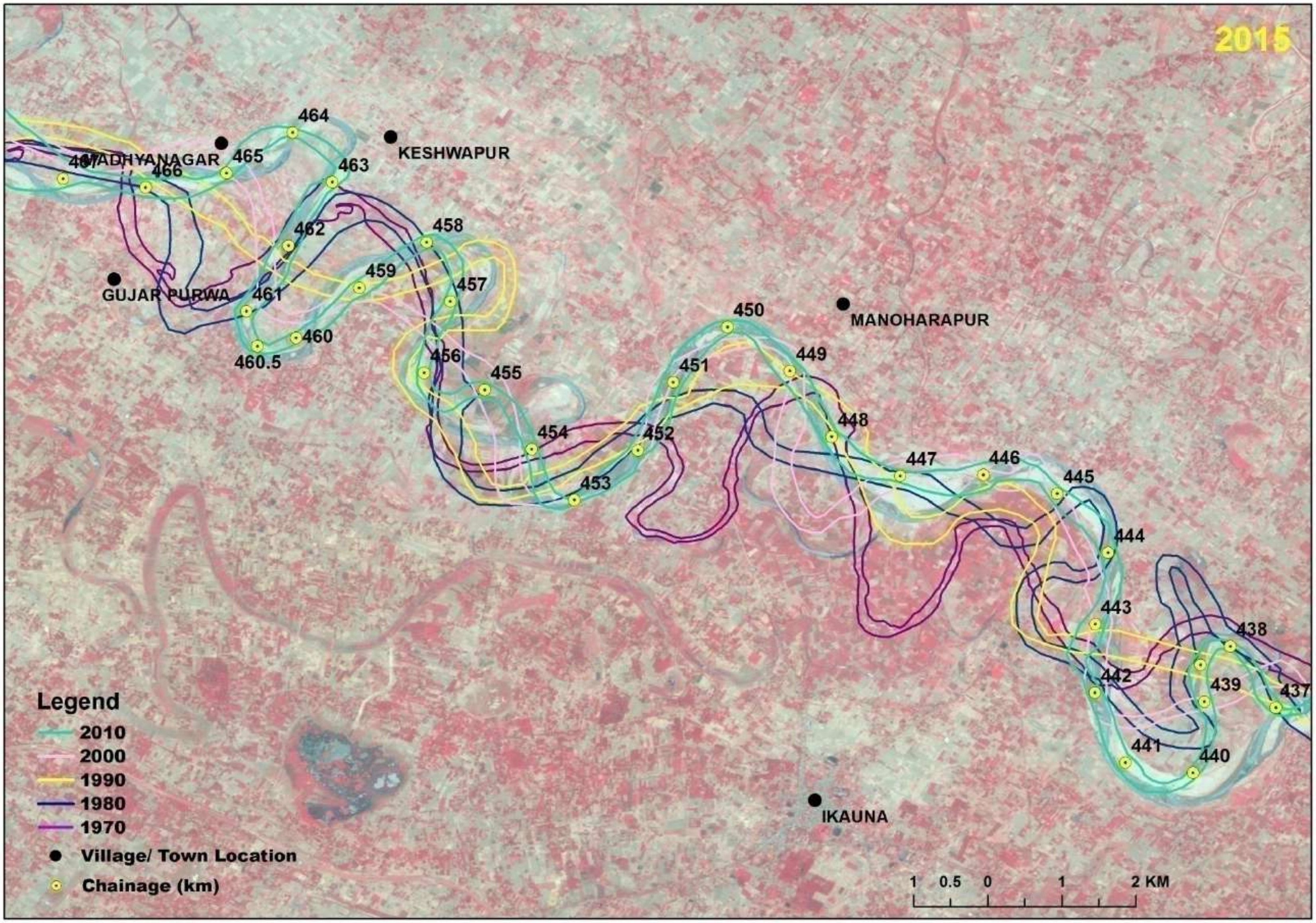

Figure 11.1c Critical reach of Rapti river from chainage 438-466 km

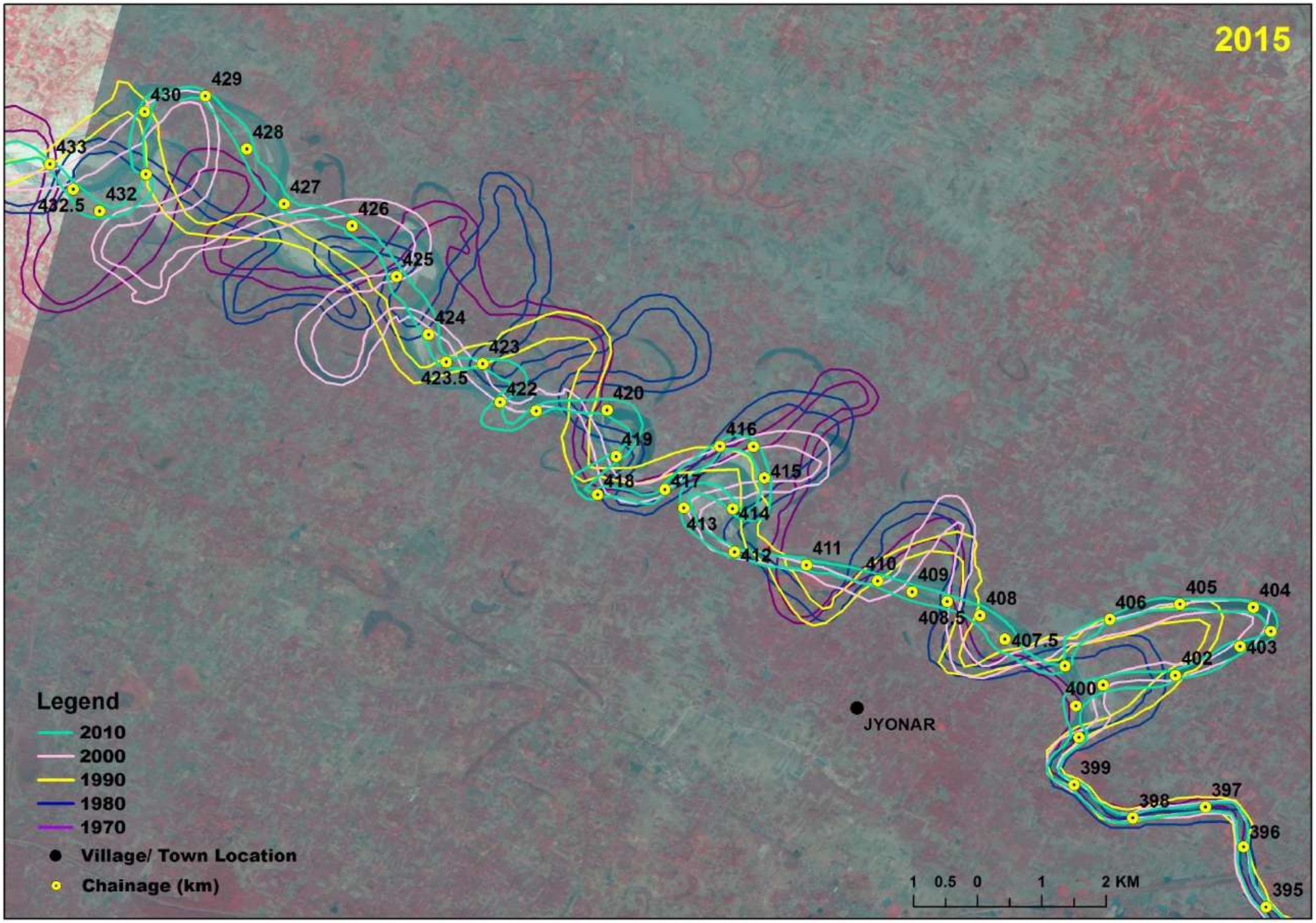

Figure 11.1d Critical reach of Rapti river from chainage 399- 433 km

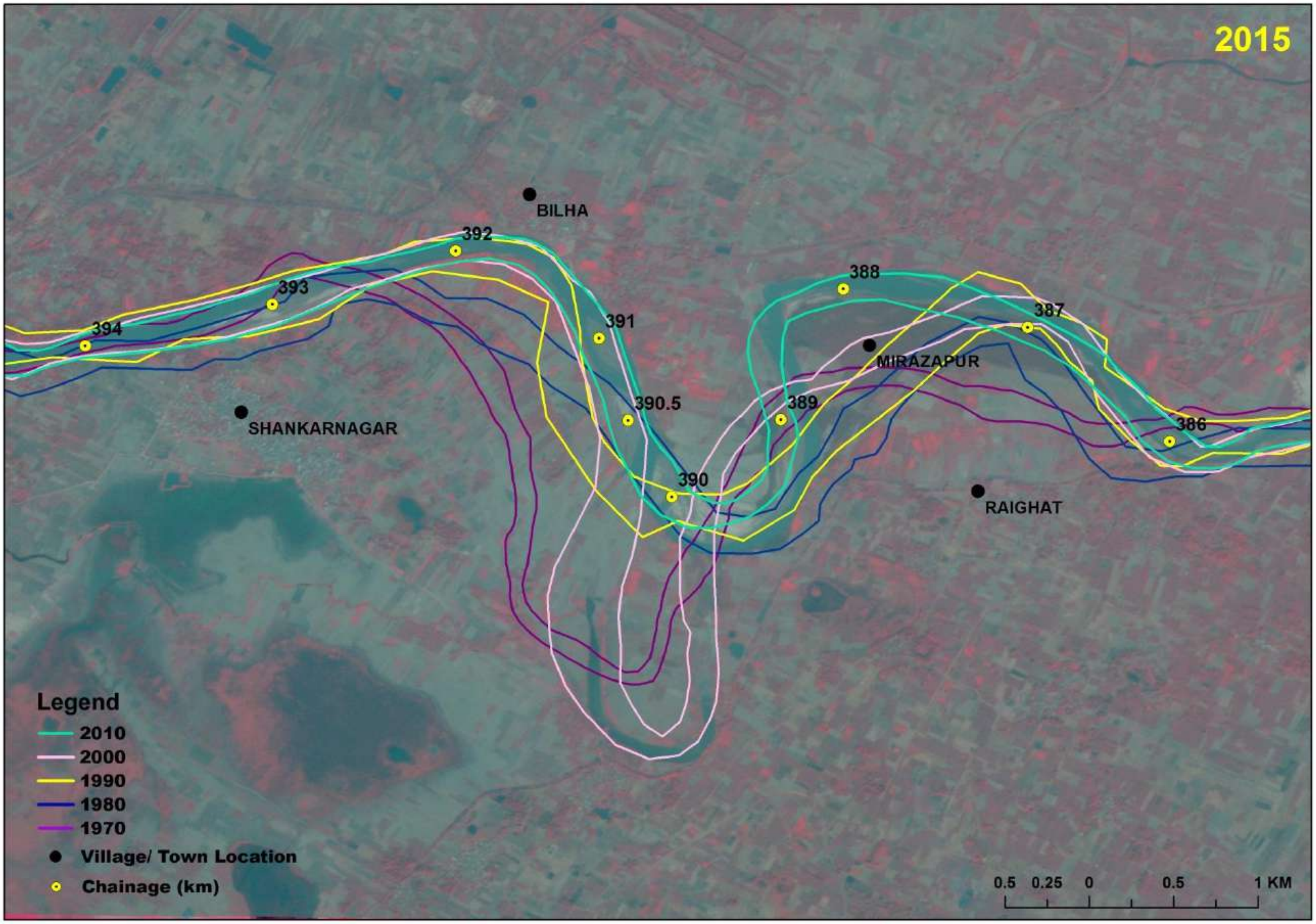

Figure 11.1e Critical reach of Rapti river from chainage 387-392 km

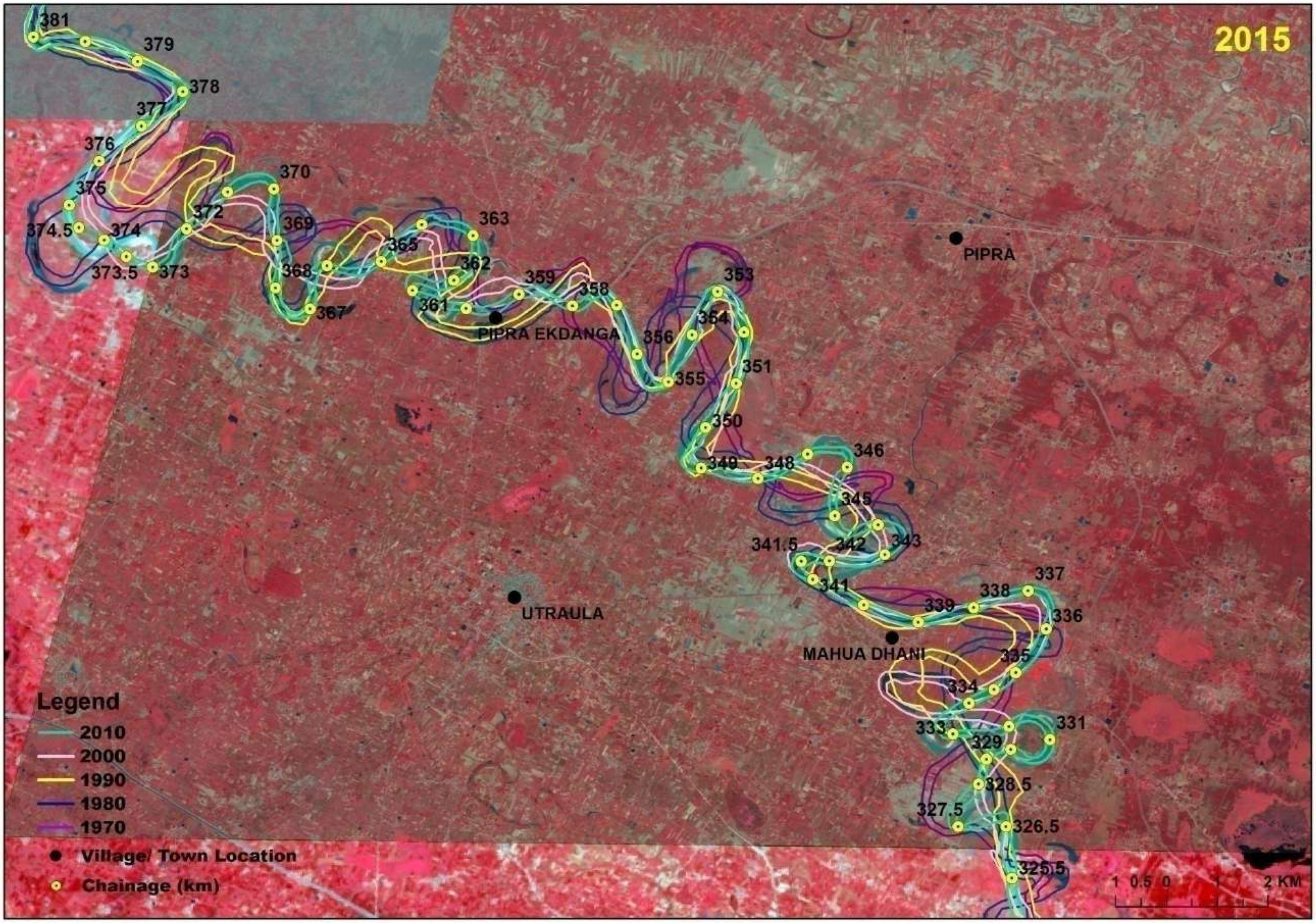

Figure 11.1f Critical reach of Rapti river from chainage 326.5- 378 km

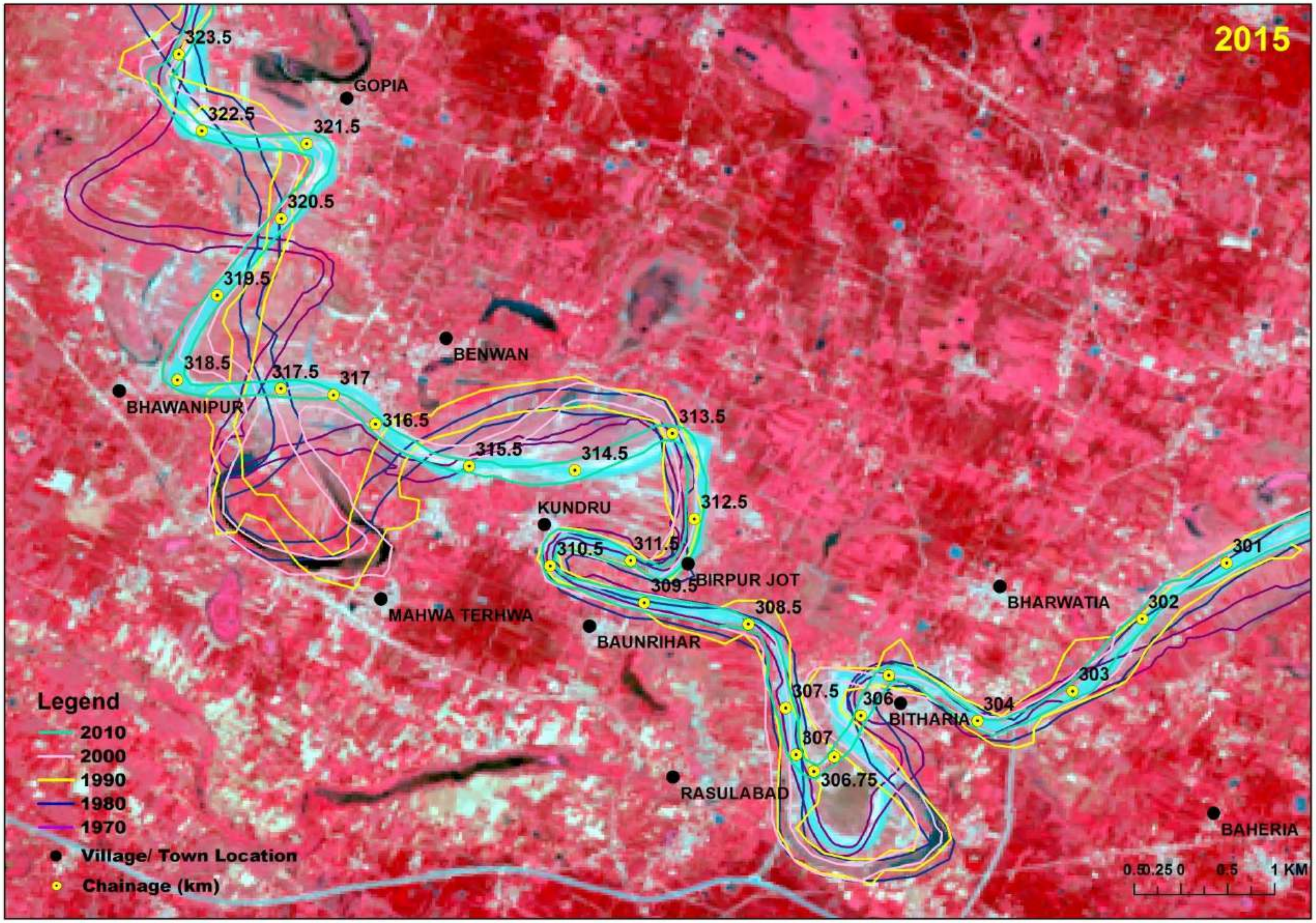

Figure 11.1g Critical reach of Rapti river from chainage 304- 322.5 km

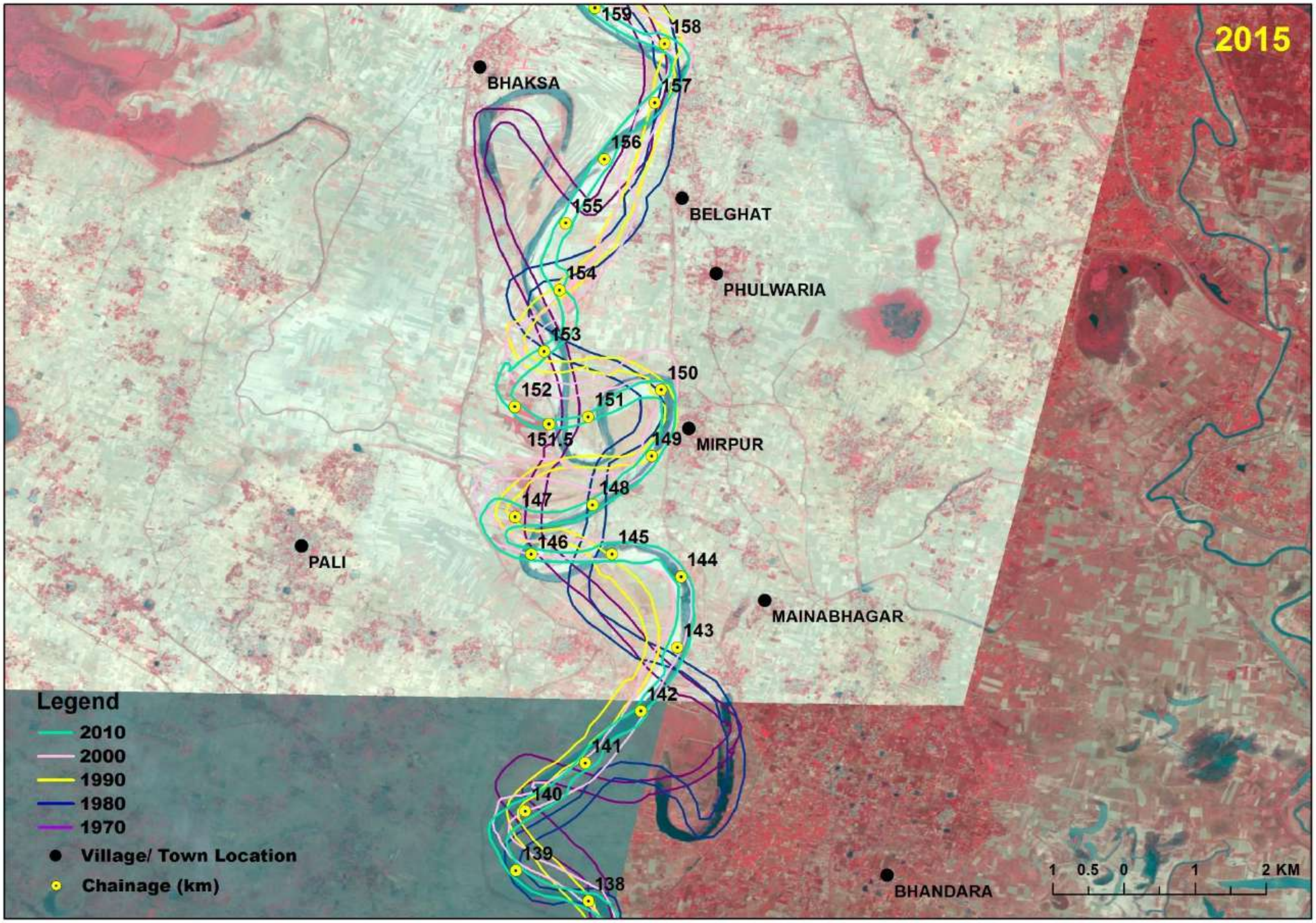

Figure 11.1h Critical reach of Rapti river from chainage 138- 156 km

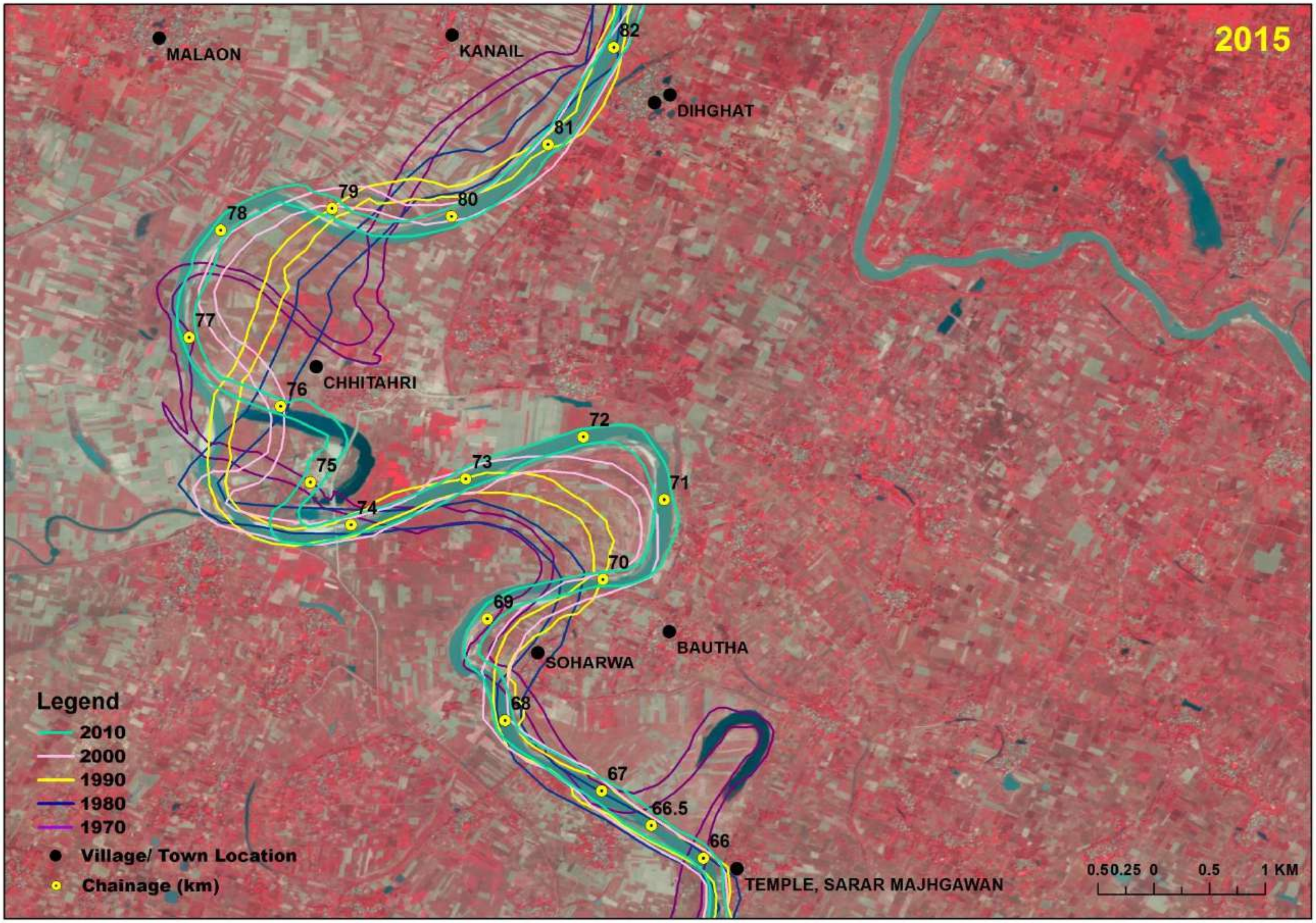

Figure 11.1i Critical reach of Rapti river from chainage 68- 80 km

11.2 PROPOSED RIVER TRAINING WORKS FOR RESTORATION OF CRITICAL AND IMPORTANT RIVER REACHES

Design methodologies of various river training works like guide banks, spurs, pilot channels etc., are given in Annexure - A. Such methodologies have been compiled from the relevant IS and IRC codes and also from relevant literature.

For the containment of the flood water at the critical reaches, Lacey waterway has been estimated using Eq. (11.1) and lines of the 4 times the Lacey waterway have been drawn and shown in the Figs. 11.2a to 11.2d for the selected critical reaches for the illustrations. The computed Lacey waterway corresponding to the design discharge of Rapti bararge and 100 year return period estimated discharge at various gauging sites are given in Table 11.2.

Table 11.2 Design discharge of Rapti barage and 100 year return period estimated discharge at various gauging sites

Barrage	Chainage (km)	Discharge (m^3/s)	$P=4.75\sqrt{Q}$ (m)
Rapti Barrage	519	4990.00	335.54
Balrampur	396	3455.9	279.24
Rigauli	183	5288.9	345.44
Birdghat	120	7934.9	423.12
		Average value	345.8

Proposed river training works for the various critical reaches are mentioned in the Table 11.3 with justification. For the positioning the levees/embankment, the extreme left and right banks of the Rapti river attained during the period 1970-2010 have been marked along with buffer of four times Lacey perimeter (P) on the satellite images of 2015 for different critical reaches. The alignment of the levee has been marked such that it should be close to extreme banks and 4P lines. As the variation in estimated Lacey perimeter in Table 11.2 from Chainage 120 km to 519 km is not large, an average perimeter P=345.8 m is adopted in this study. Figs. 11.2a-d show extreme banks and 4P lines in the four critical reaches for illustrations, while suggested river training works at four locations i.e., Utrauli, Rasulabad Chhitahri and Patana ghat are shown in Figs. 11.3a-d.

In the critical reaches as shown in Figs. 11.1a to 11.1i, wherever river is striking to the existing embankments, porcupine/ boulder revetment shall be provided to control breach in the embankment.

Table 11.3 River training works for the critical reaches of the Rapti River

Critical Reaches (Chainage / Location)	Type of River Training Works	Justification
506-515 (**Jamnaha, UP)**	NIL	River course is wandering in wide width with maximum shift of 2.5 km. No measures required. No major habitation.
470-492 (**Lakshmannagar, UP**)	NIL	River course is wandering in wide width with maximum shift of 2.8 km. No Measures required. No major habitation.
438-466 (**Ikauna, UP)**	NIL	River course is wandering in wide width with maximum shift of 2.9 km. No measures required. No major habitation.
399-433 (**Jyonar, UP)**	NIL	River course is wandering in wide width with maximum shift of 3.4 km. No Measures required. No major habitation.
387-392 (**Shankarnagar, UP)**	NIL	River course is wandering in wide width with maximum shift of 1.7 km. No measures required. No major habitation. Embankments are provided towards both sides of the reach.
326.5-378 (**Utraula, UP)**	Embankment with boulder revetment	River course is wandering in wide width with maximum shift of 1.5 km. Partially provided embankments should be fully provided in this reach, preferrably at 4P. **Boulder revetment is to be provided where the deeper part of the river is close to the proposed embankments.**
304-322.5 (**Rasulabad, UP)**	Embankment/ Levees	River course is wandering in wide width with maximum shift of 2.5 km. **Recommended to provide embankment towards both sides at a spacing of 4 times Lacey perimeter to control the spread of flood water**. It may be noted

		that embankments are provided in this reach partially.
138-156 **(Mirpur, UP)**	NIL	River course is wandering in wide width with maximum shift of 2.3 km. Wandering between the existing embankments. No Measures Required.
68-80 **(Chhitahri, UP)**	Series of spurs upstream of Road bridge (Kaithwalia, Chainage 74 km)	River course is wandering in wide width with maximum shift of 1.7 km. **Road bridge is located just downstream of an acute bend. Suggested to provide series of spurs towards left side upstream of the bend to arrest such shifting so that out flanking of the bridge be avoided.**
2-12.5 **(Patana Ghat, UP)**	Embankment/ Levees	**Provision of embankment towards right side, upstream of the bridge (SH 72 Bridge) to control the spread of flood water**.

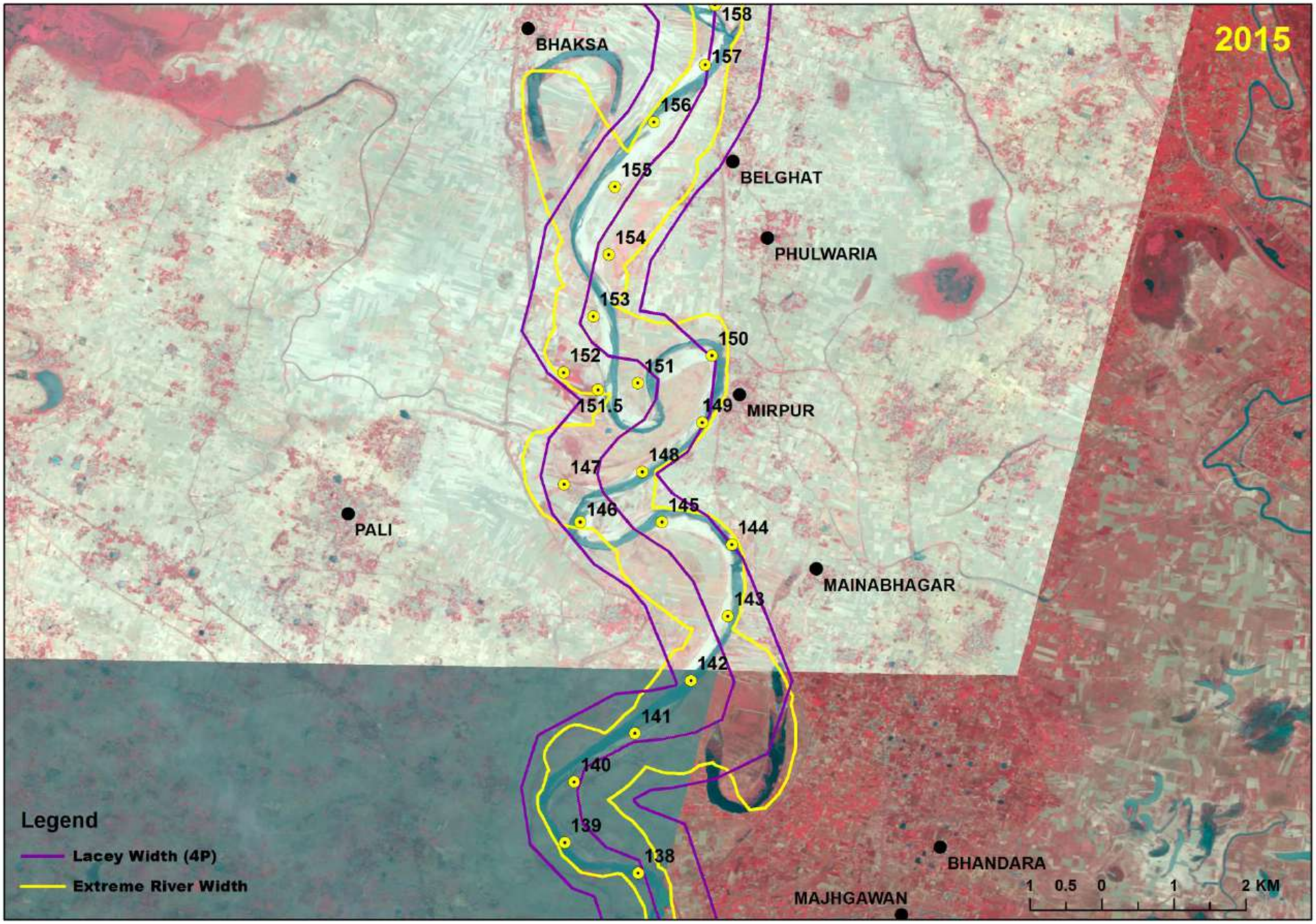

Figure 11.2a Extreme banks and 4P lines from chainage 138- 156 km

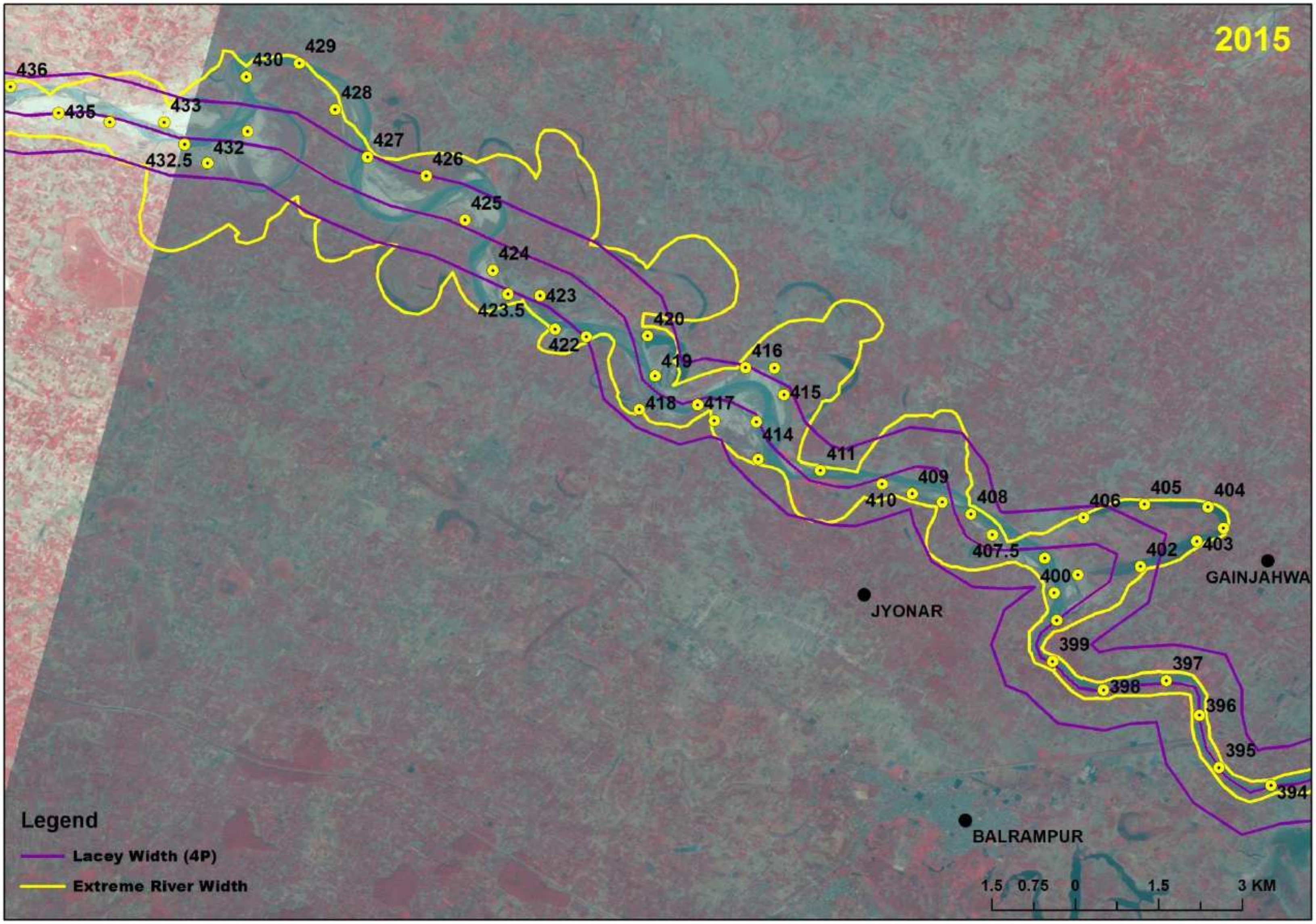

Figure 11.2b Extreme banks and 4P lines from chainage 399- 433 km

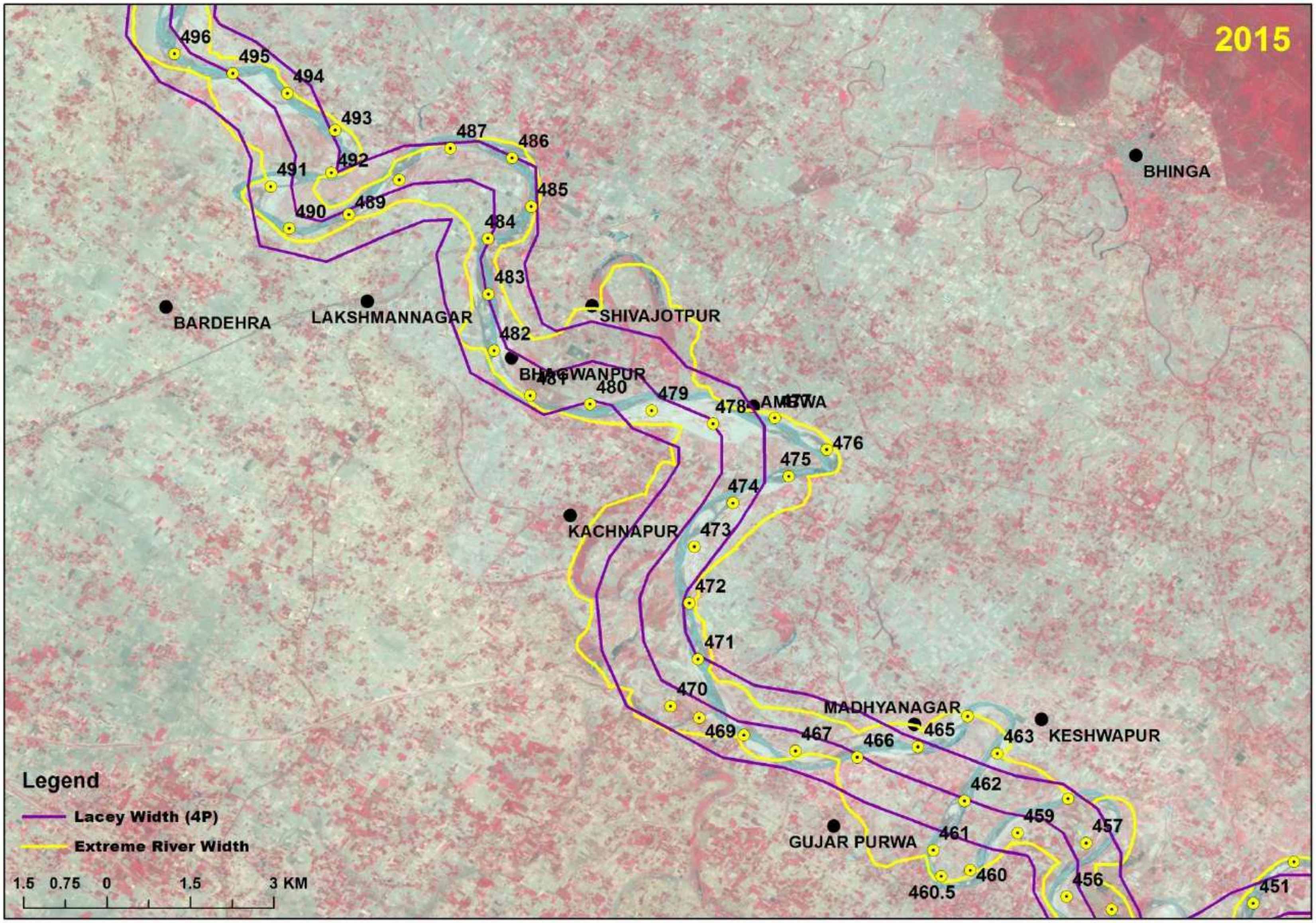

Figure 11.2c Extreme banks and 4P lines from chainage 470 - 492 km

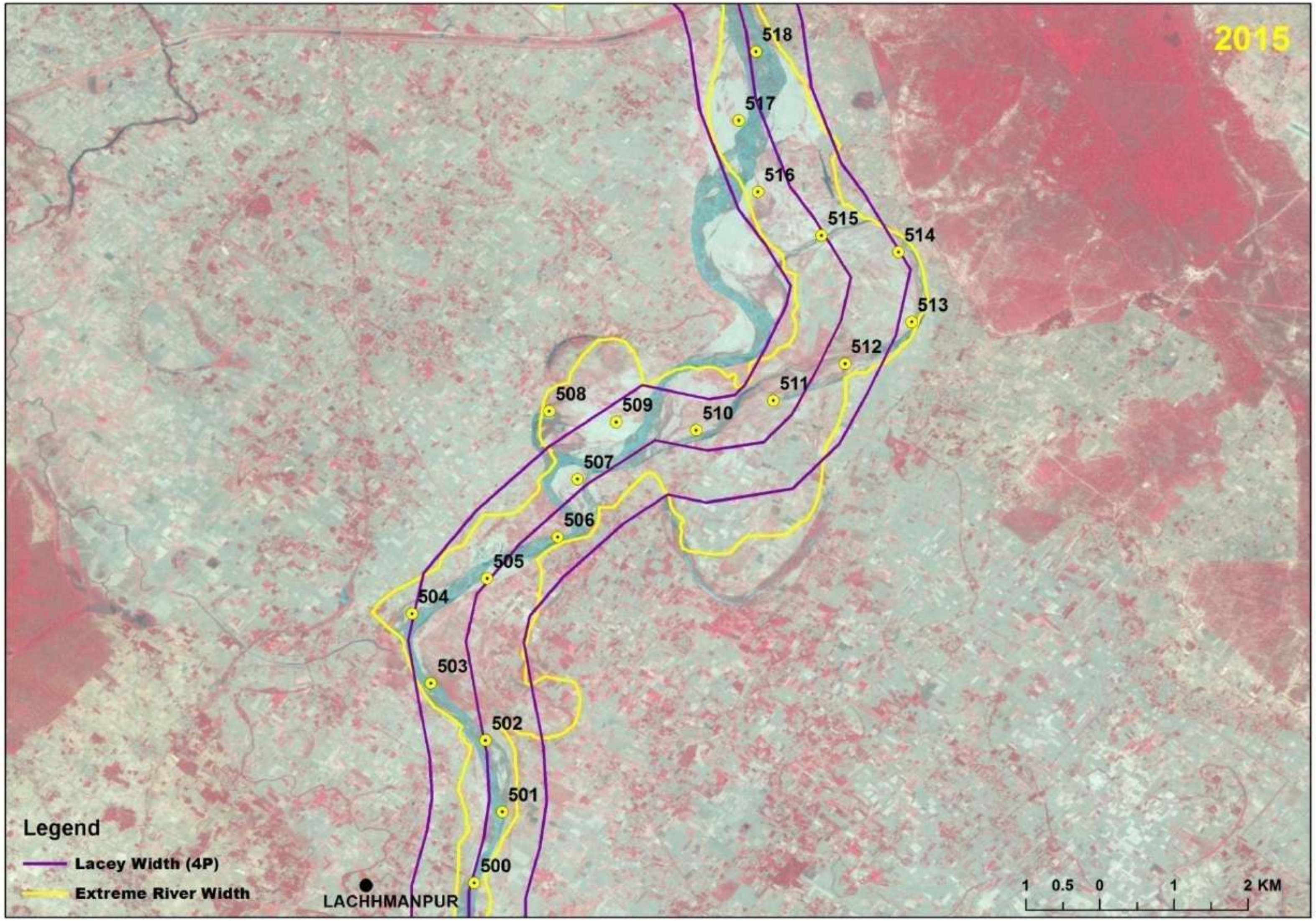

Figure 11.2d Extreme banks and 4P lines from chainage 506 - 515 km

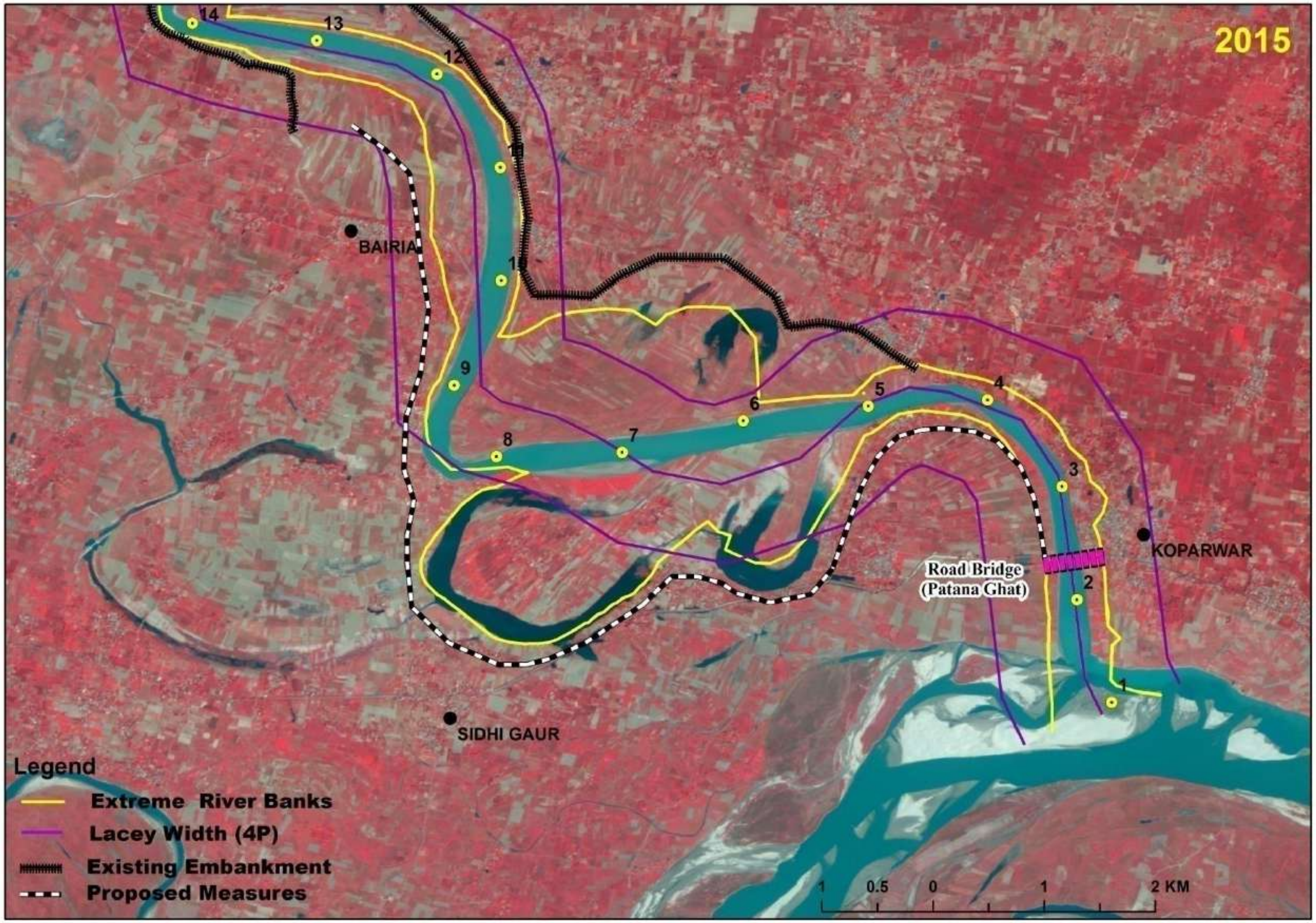

Figure 11.3a Extreme banks, 4P lines and location/alignment of the suggested works from chainage 2-12.5 km

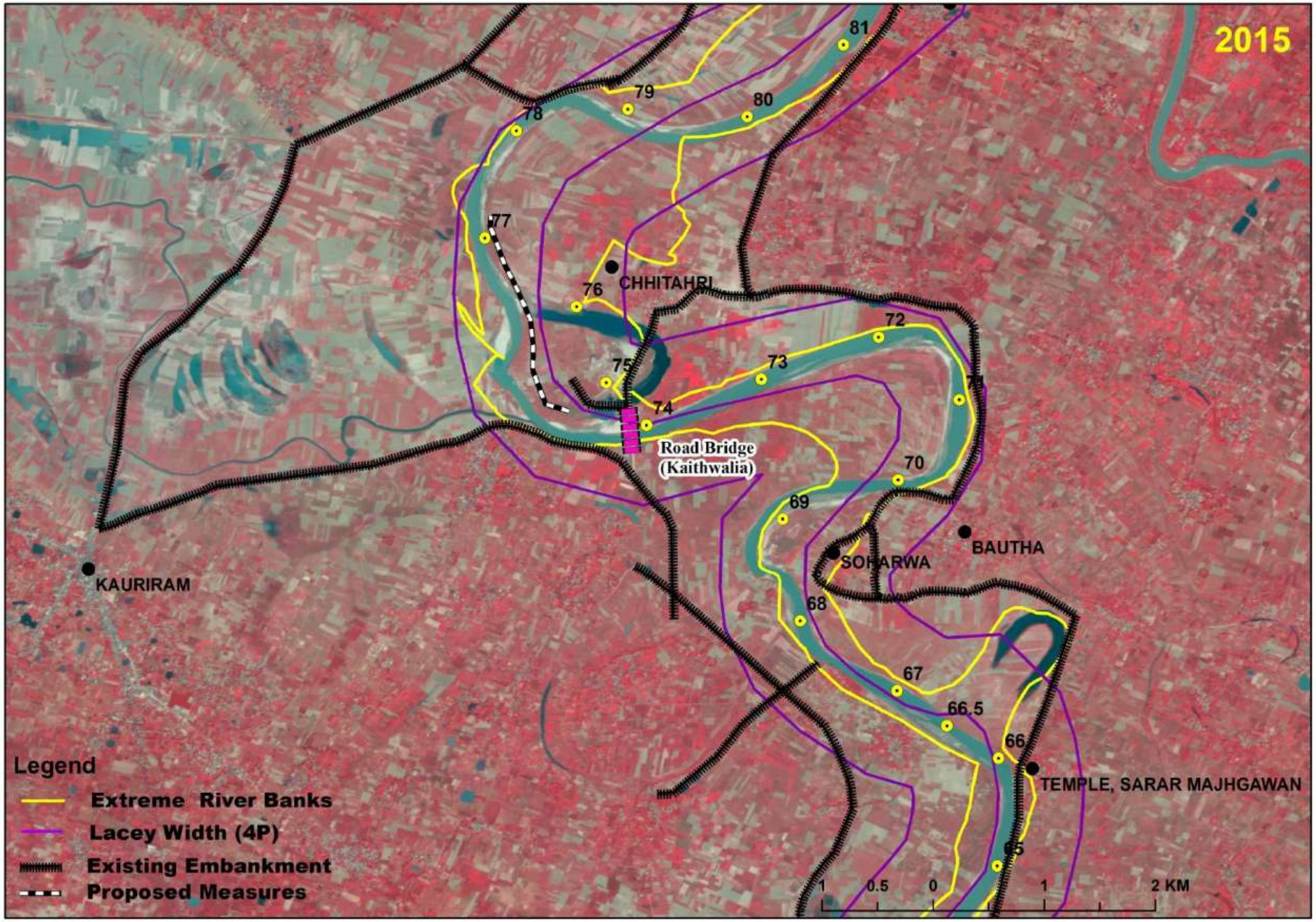

Figure 11.3b Extreme banks, 4P lines and location/alignment of the suggested works from chainage 75-77 km

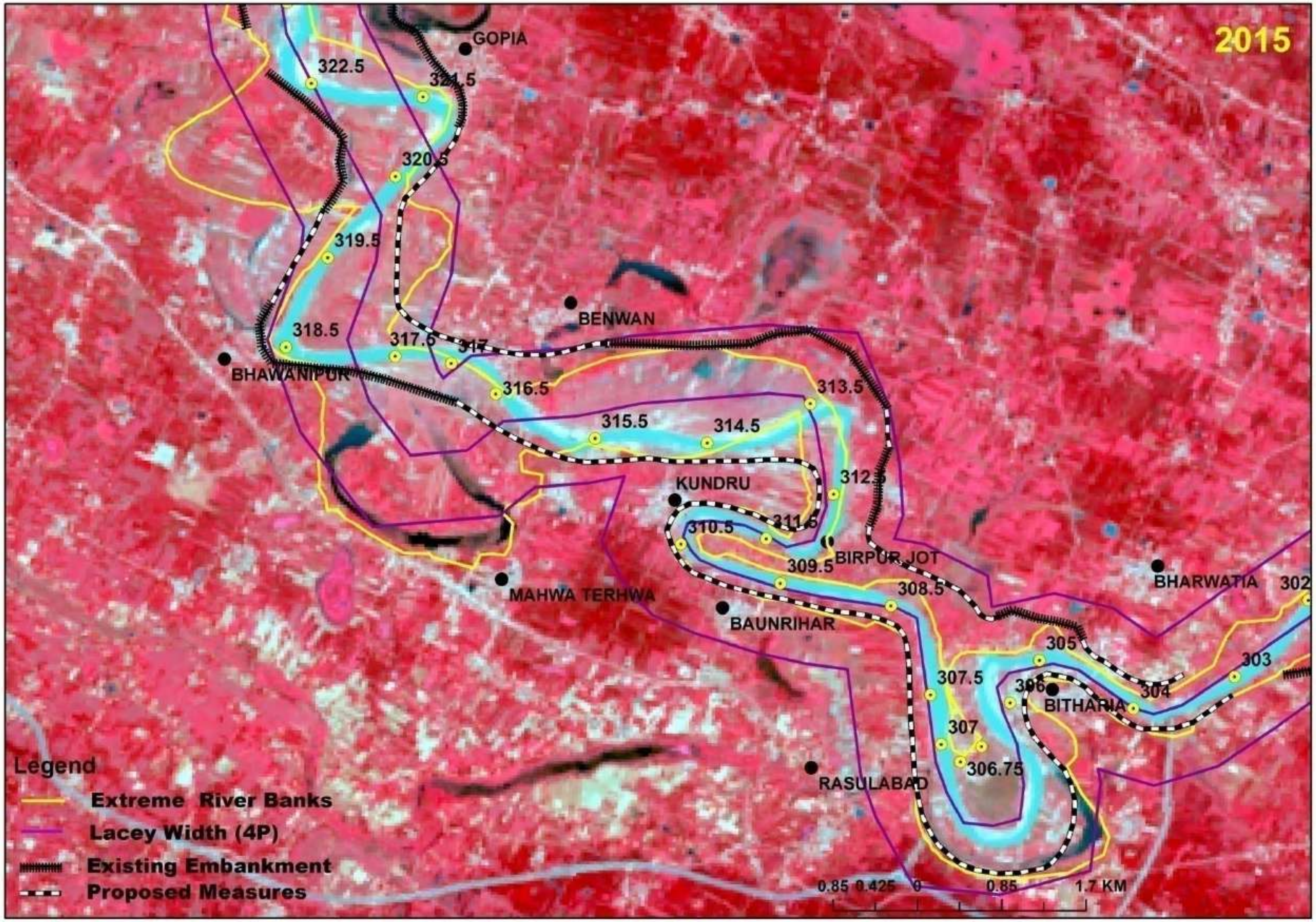

Figure 11.3c Extreme banks, 4P lines and location/alignment of the suggested works from chainage 304-322.5 km

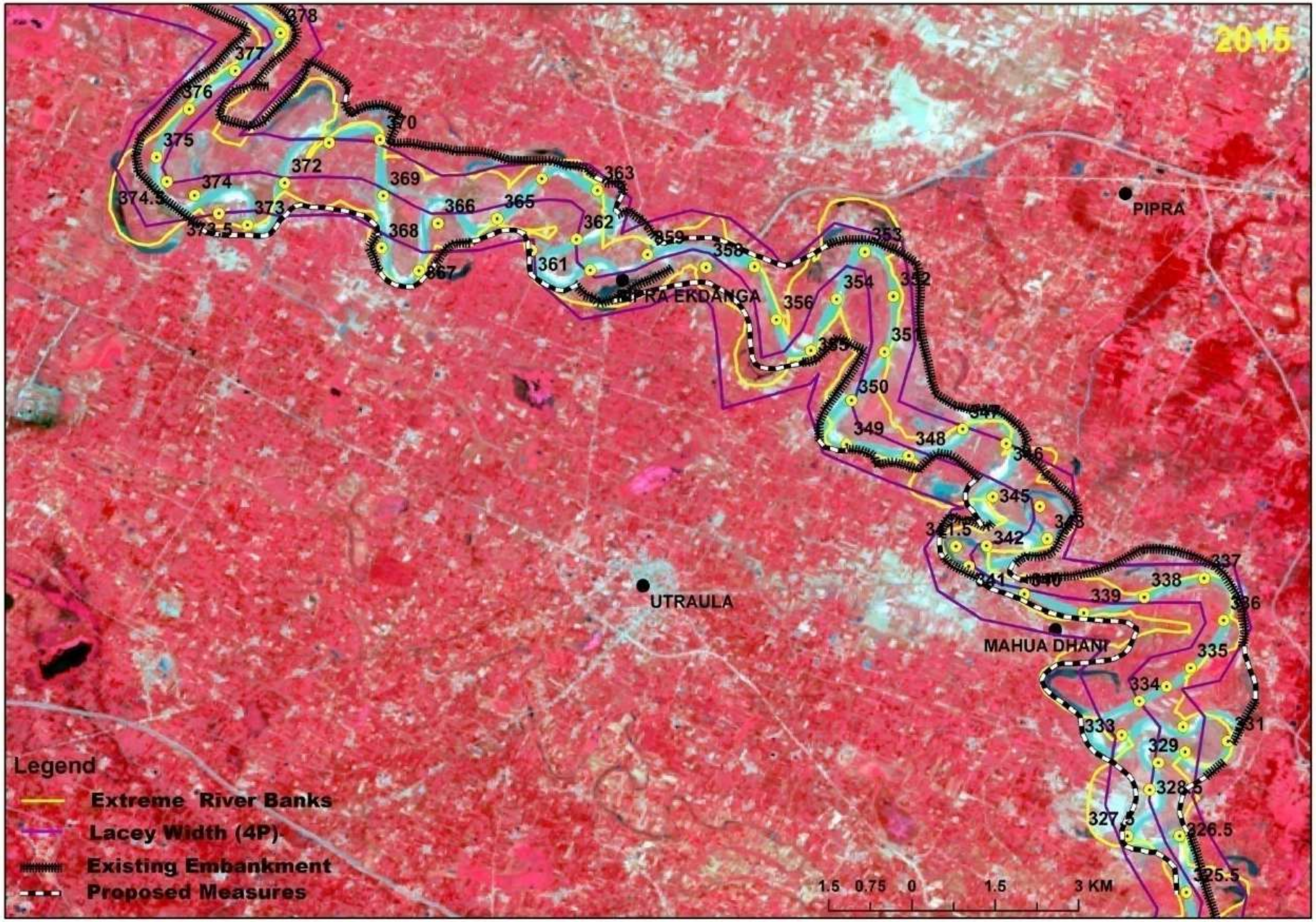

Figure 11.3d Extreme banks, 4P lines and location/alignment of the suggested works from chainage 326.5-378 km

11.3 EXISTING EMBANKMENTS

Embankments are provided towards both sides of the river in its most of the length in particular in the lower reaches. Location of such embankments are shown in the Figs. 11.4a to 11.4k. It may be noted that embankments are partially provided in the upper reaches. Distances of the embankment at different chainages from the centreline of the river as in year 2015 are given in the Table 11.4 and also shown graphically in Fig. 11.5.

It may be noted that the proposed embankments, as mentioned in the section 11.2, are suggested to be provided in the upper reach of the Rapti river on its both sides.

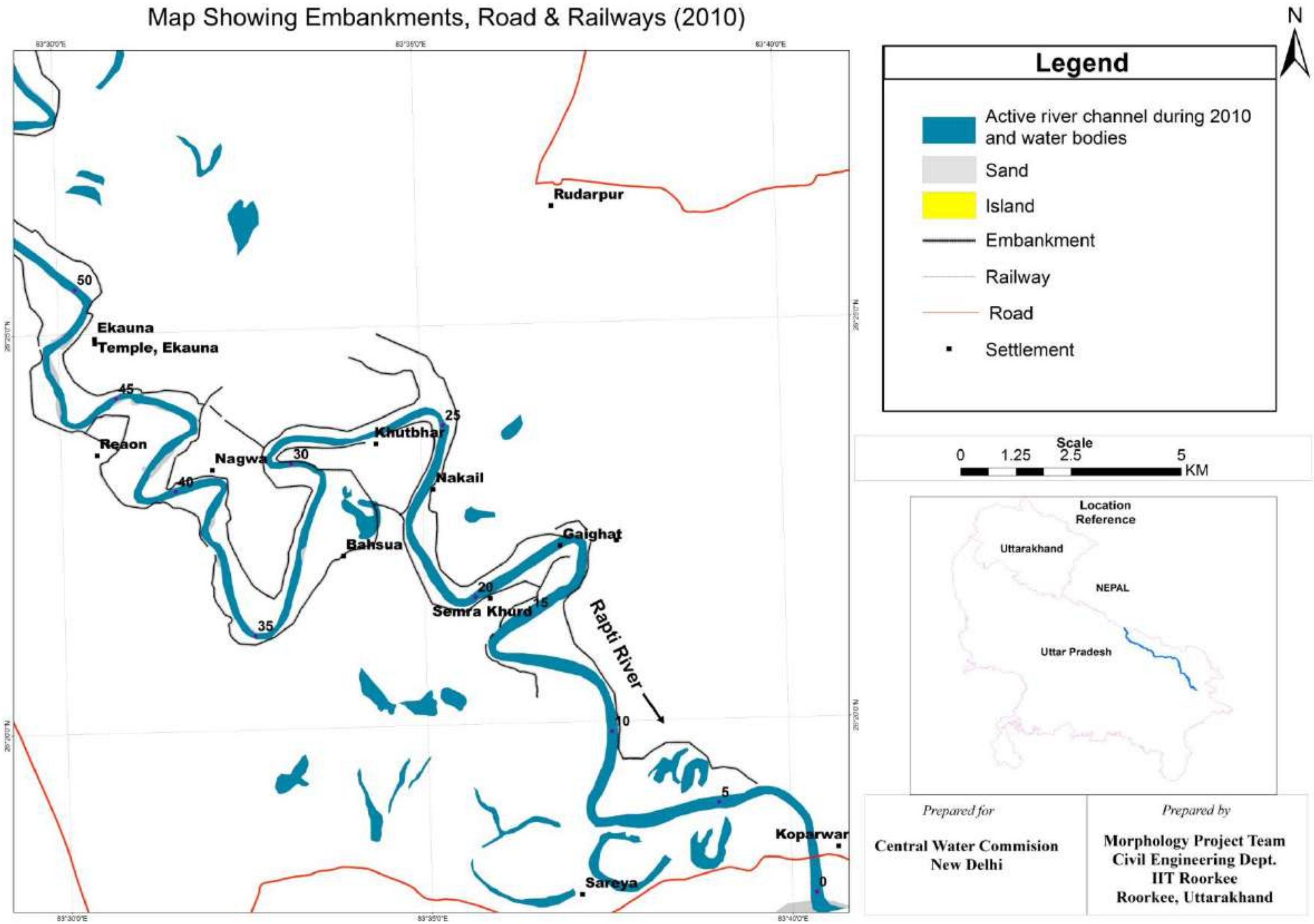

Figure 11.4a Existing embankments on Rapti river from chainage 0-50 km

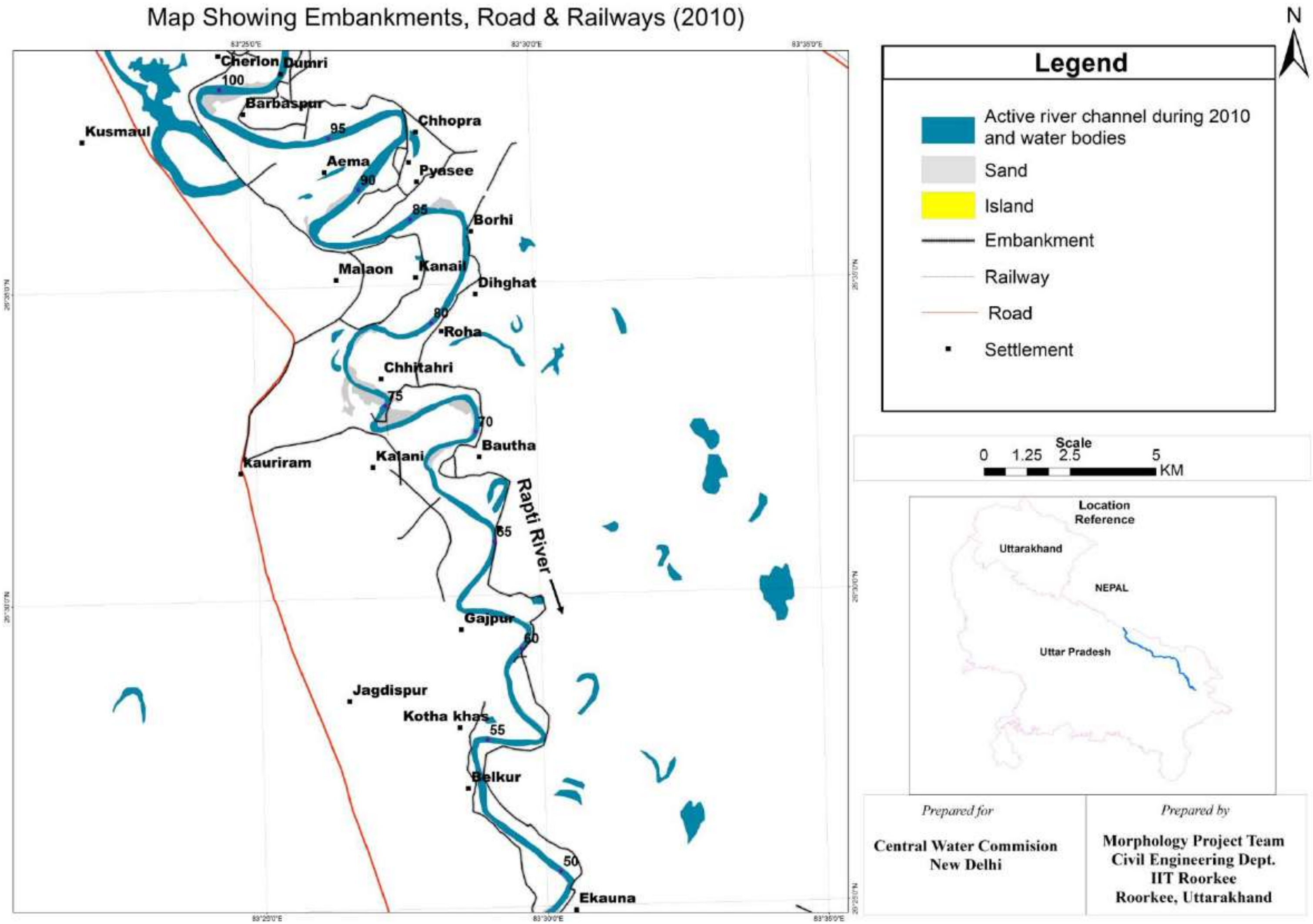

Figure 11.4b Existing embankments on Rapti river from chainage 50-100 km

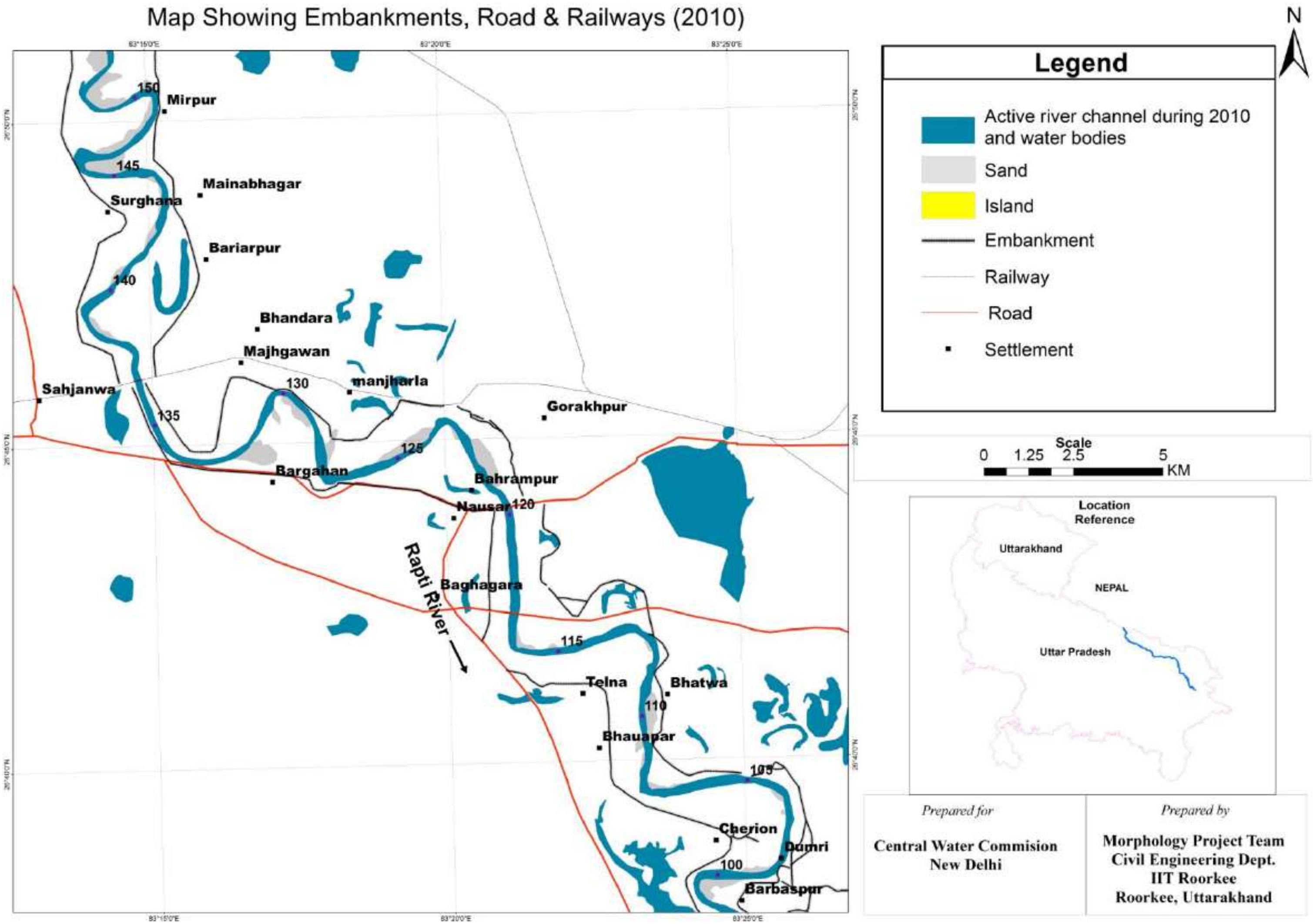

Figure 11.4c Existing embankments on Rapti river from chainage 100-150 km

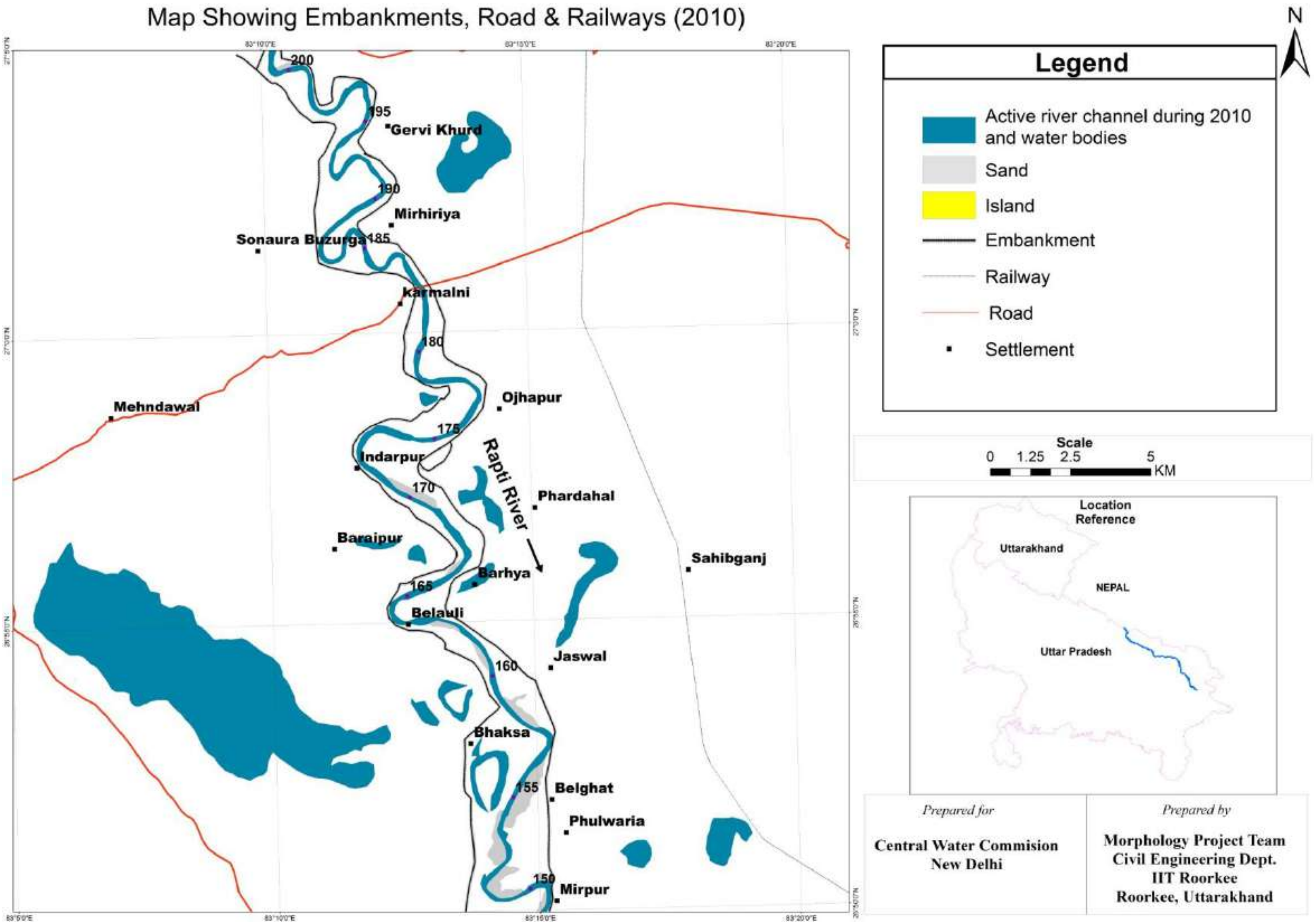

Figure 11.4d Existing embankments on Rapti river from chainage 150-200 km

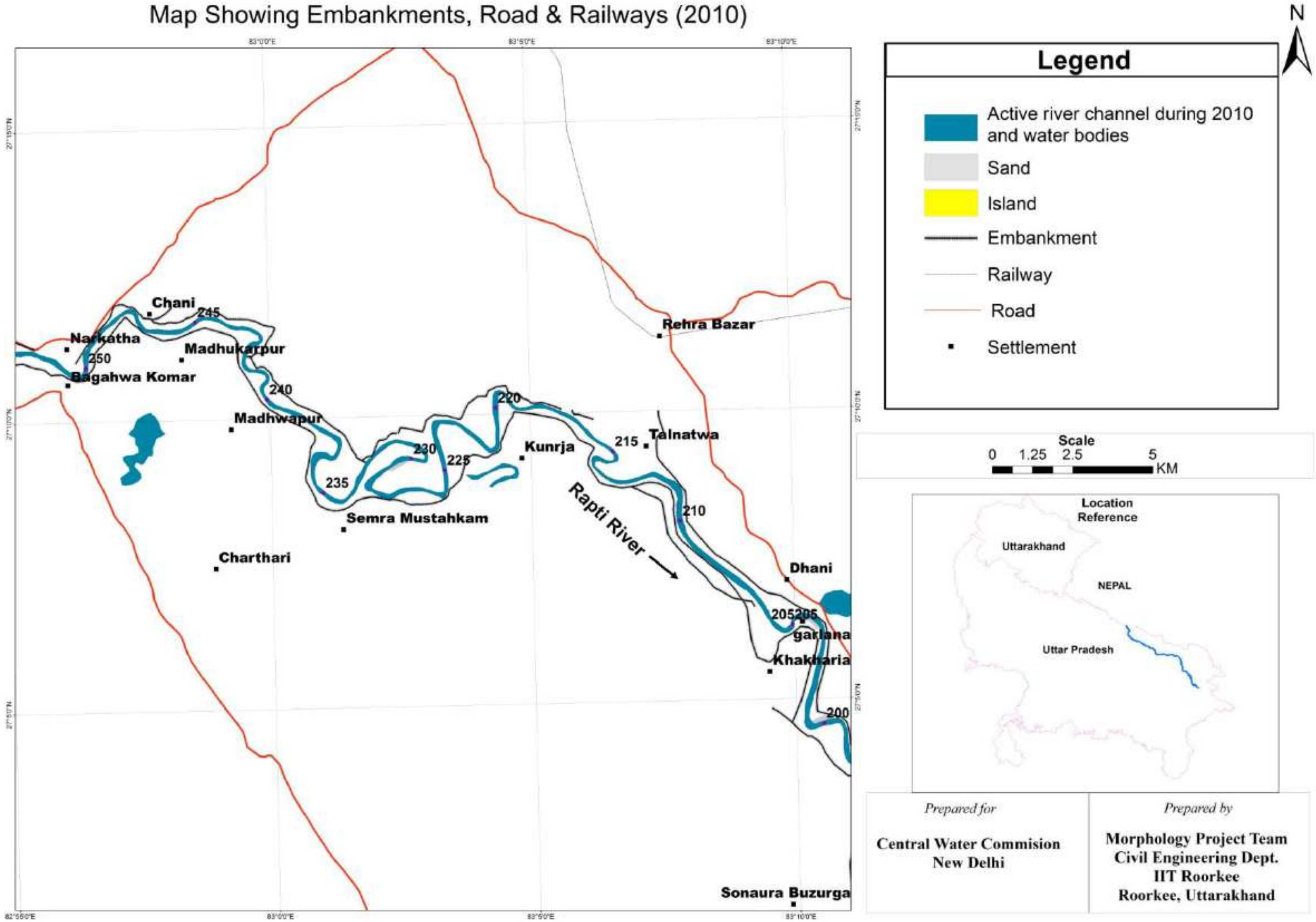

Figure 11.4e Existing embankments on Rapti river from chainage 200-250 km

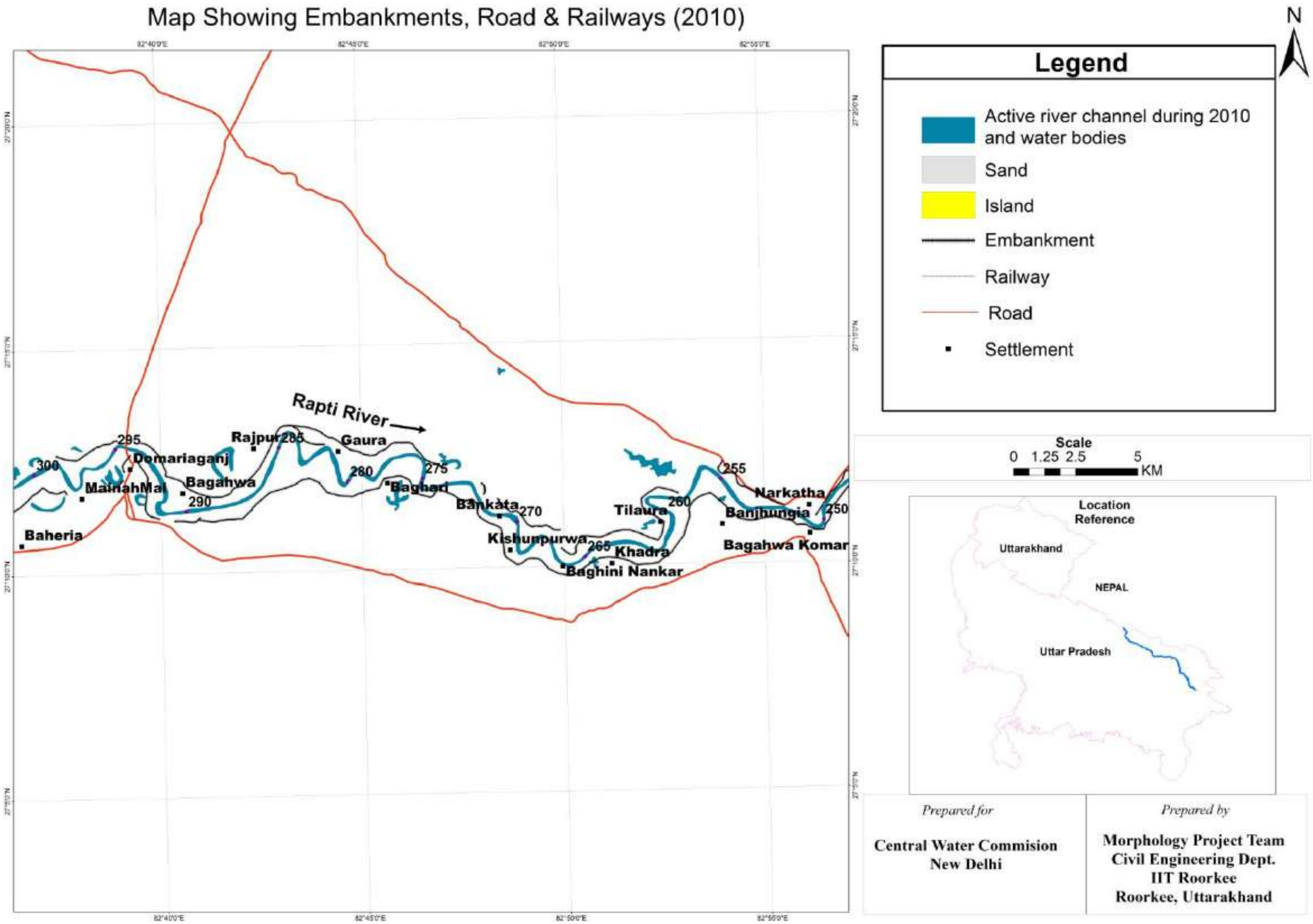

Figure 11.4f Existing embankments on Rapti river from chainage 250-300 km

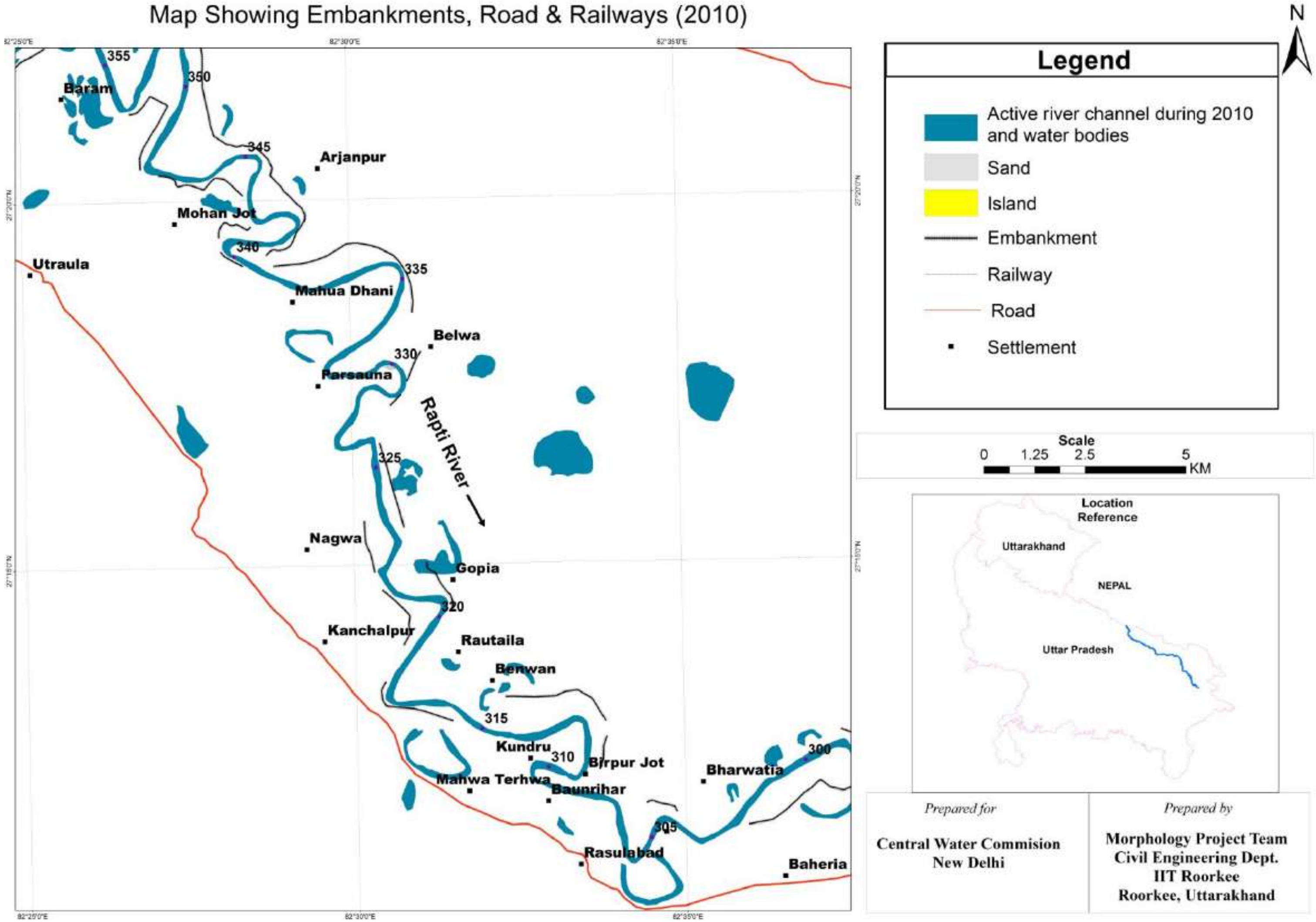

Figure 11.4g Existing embankments on Rapti river from chainage 300-350 km

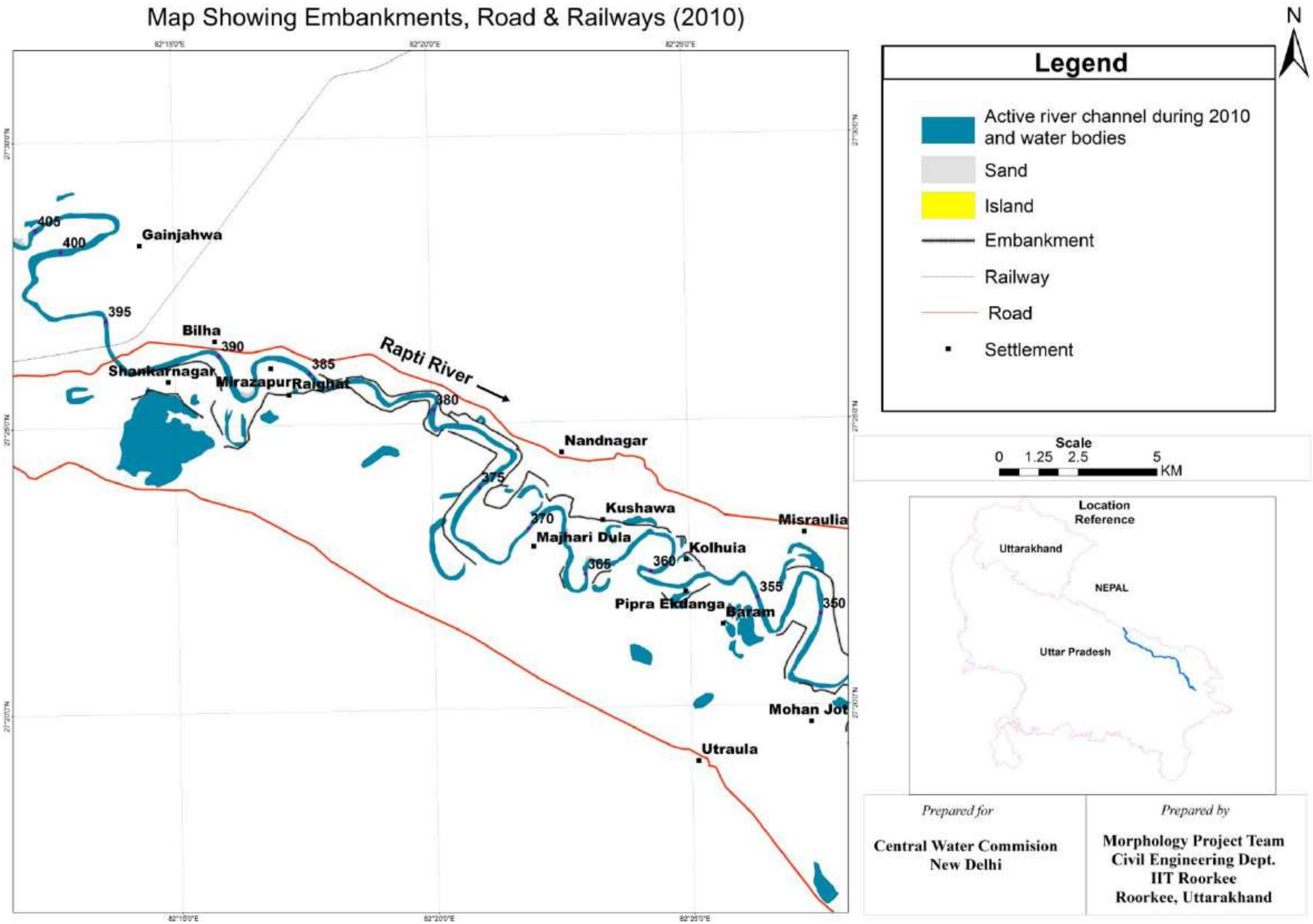

Figure 11.4h Existing embankments on Rapti river from chainage 350-400 km

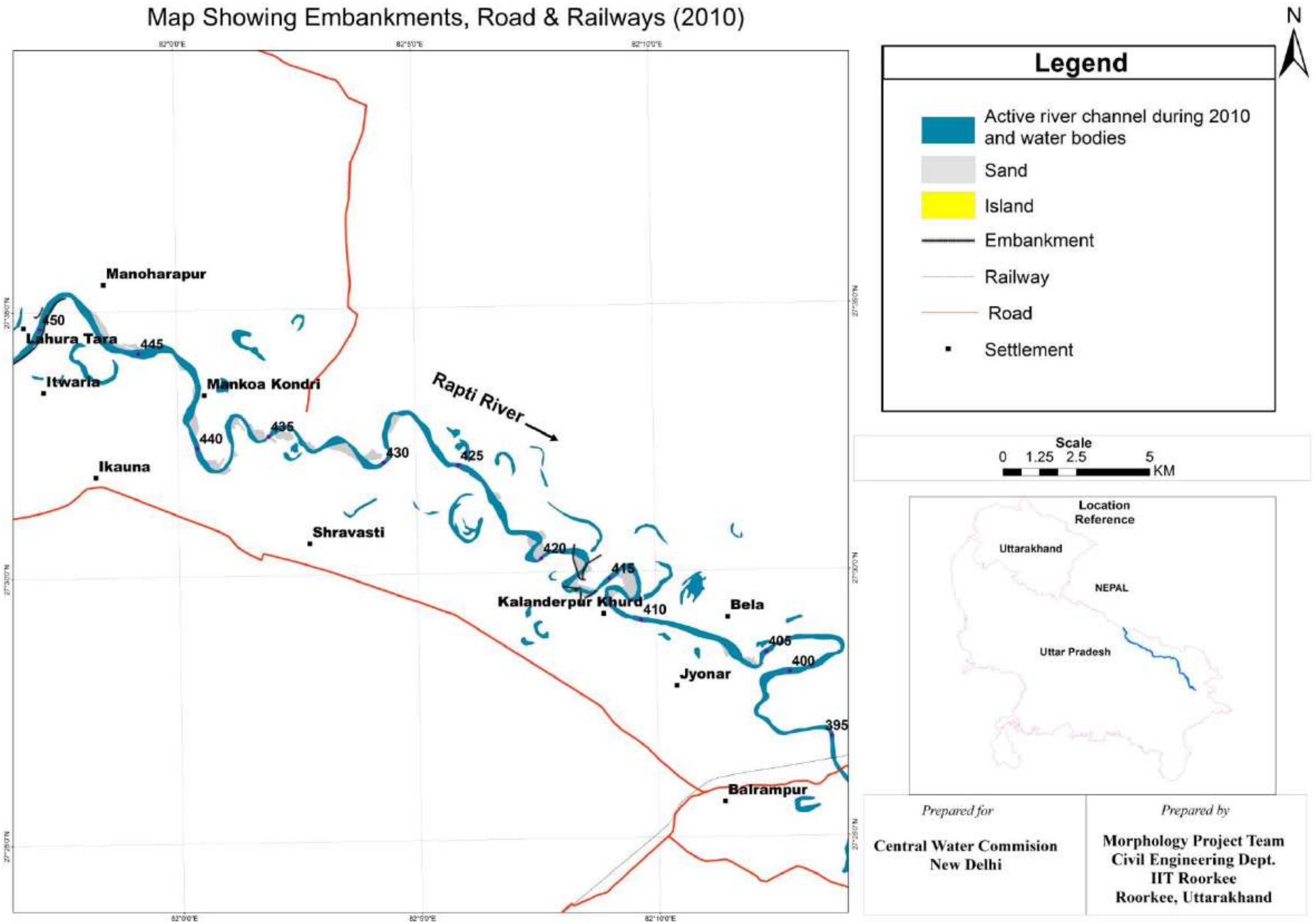

Figure 11.4i Existing embankments on Rapti river from chainage 400-450 km

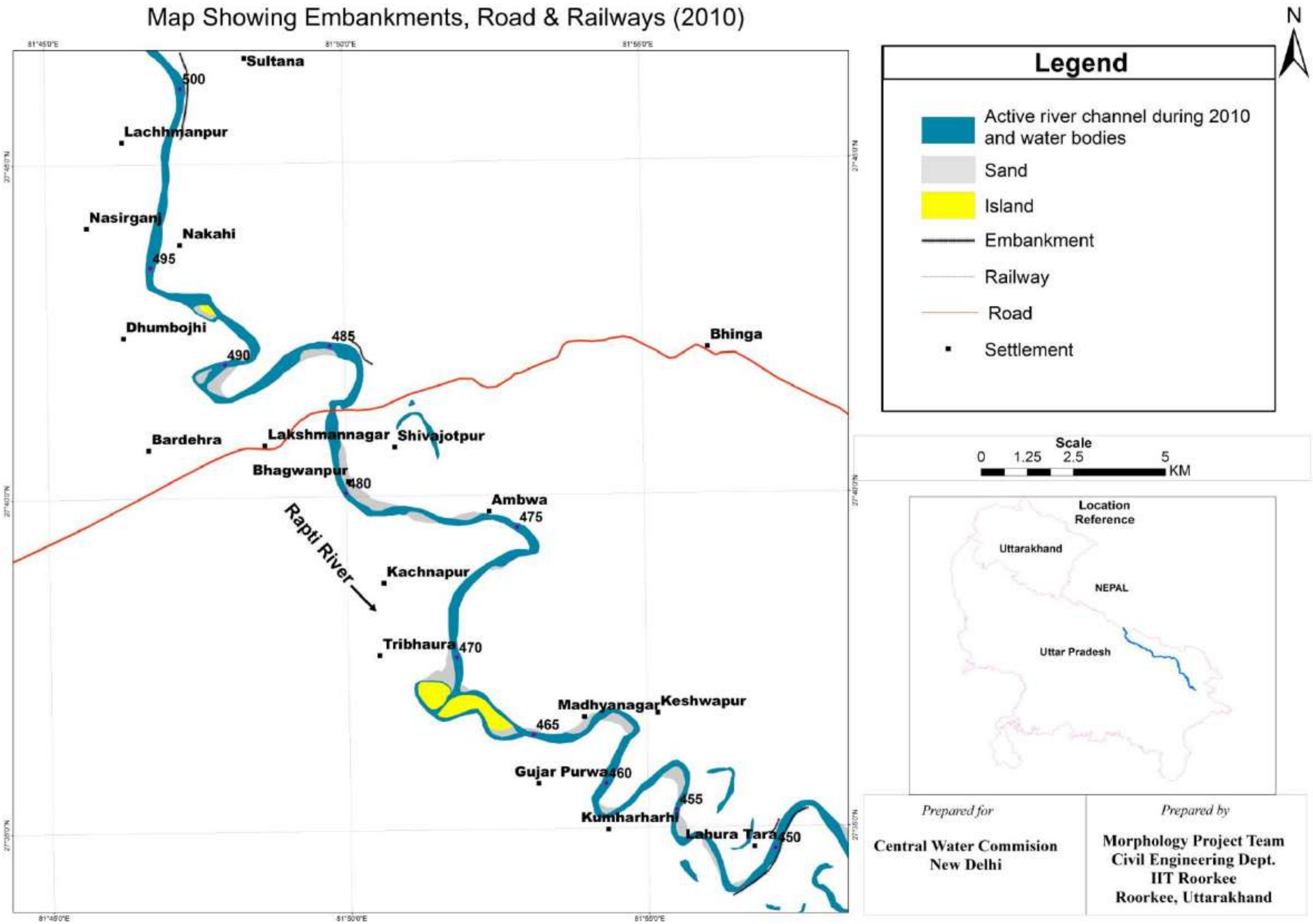

Figure 11.4j Existing embankments on Rapti river from chainage 450-500 km

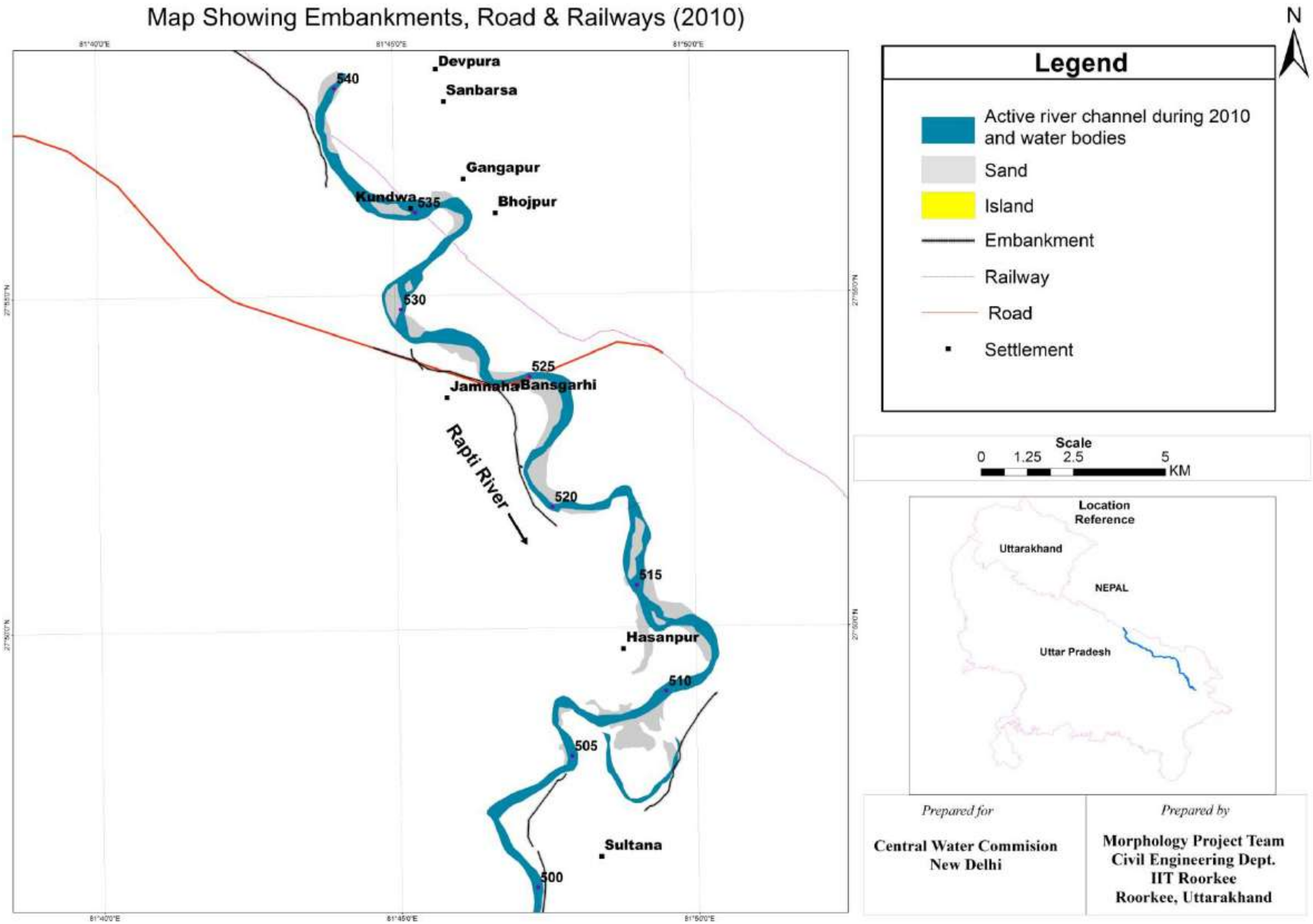

Figure 11.4k Existing embankments on Rapti river from chainage 500-542 km

Table 11.3 Distance of embankments from centerline of the Rapti River as in year 2015

Chainage (Km)	Distance from Center line of river as in year 2015 (m)		Nearby Location
	Right Embankment	Left Embankment	
10	279.78		Bairia
20	211.36	249.52	Seema Khurd
30	99.06	243.73	Nagwa
40	663.29	146.12	Nagwa
50	1123.03	79.24	Ekauna
60		410.92	Road Bridge (Pachaldi Rd)
70		71.32	Bautha
80	962.44	395.92	Dihghat
90	2478.60	1016.35	Mohnapur
100	133.76	1392.52	Barbaspur
110	572.30	819.00	Bhauapur
120	947.01	533.73	Nausar
130	2249.17	143.60	Manjharia
140	266.15	2406.49	Mainabhagar
150	2916.96	137.19	Mirpur
160	237.17	1173.01	Pepeeganj Road Bridge
170	417.79	803.46	Baraipur
180	339.32	1021.99	Karmalni
190	1523.50	318.71	Sonaura Buzurga
200	1282.16	87.52	Gartana
210	455.00	296.63	
220	700.78	392.01	Kunrja
230	1282.72	850.33	
240	195.02	472.96	Madhwapur
250	296.12	113.31	Bansi
260		413.89	Banjhugnia
270	699.08	488.90	Kishanpurwa
280	748.42	1132.77	Gaura
290	476.48	613.13	Bagahwa
300	705.58		Domariaganj
310			
320	596.80		Gopia
330		513.83	Mahua dhani
340		250.83	Gagapur Utraula rd bridge
350	146.53		Utraula
360	772.57	946.32	Pipra Ekdanga
370		144.87	
380	329.40	384.68	

390	1418.71		Raighat
400			
410			
420		298.23	Road Bridge
430			
440			
450	224.06		Manoharapur
460			
470			
480			
490			
500		320.70	Lachhmanpur
510		2499.67	
520	2302.40		Rapti Barrage
530	4240.79		
540	146.05		Nepalganj

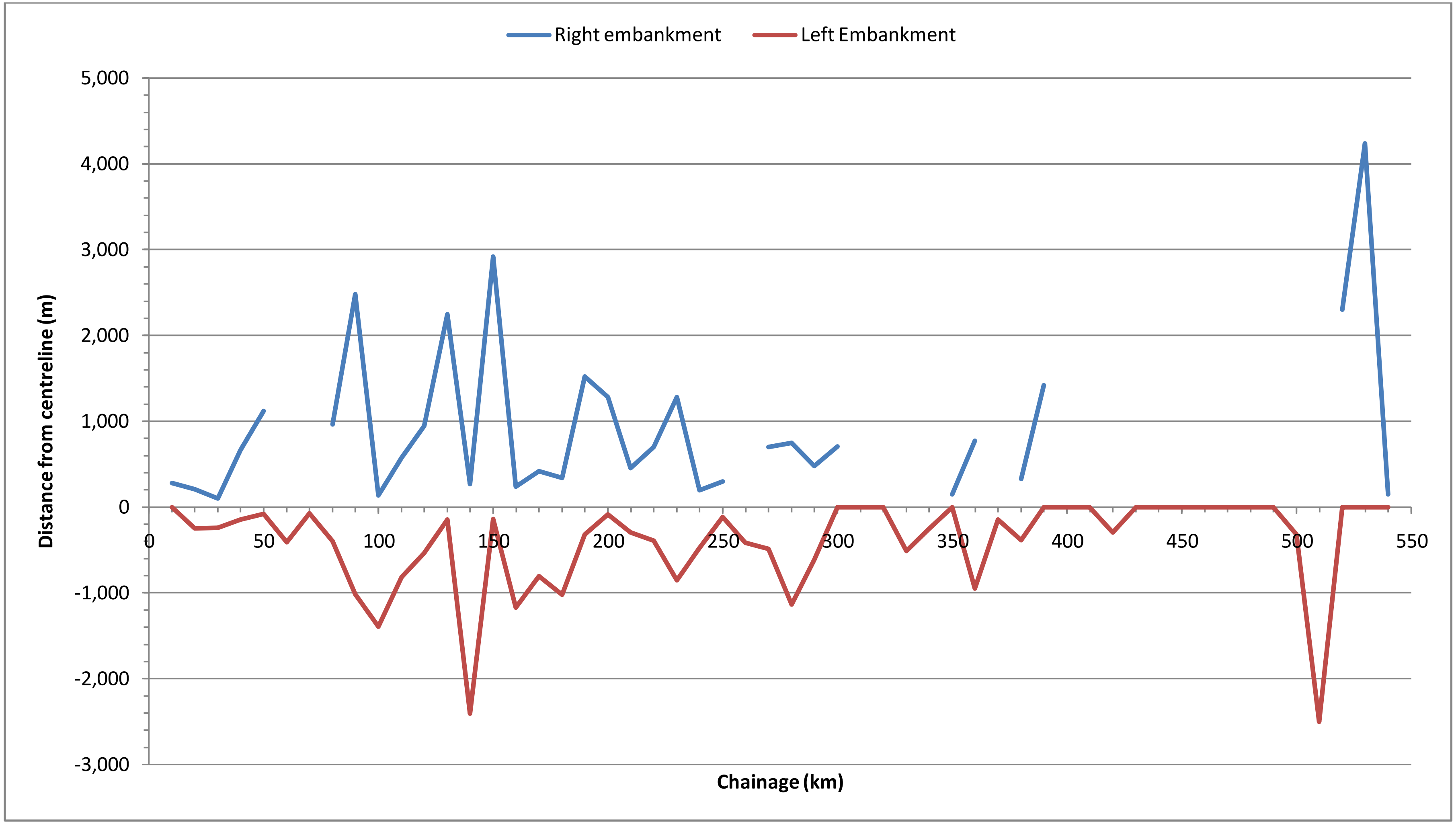

Fig 11.5 Distance of the embankment from centreline of the river as in year 20

11.4 TENTATIVE DESIGN OF RIVER TRAINING WORKS

A sample design of Levees/embankment has been carried out in this section on the basis of some assumed data. It is recommended that other suggested measures shall be designed after acquiring required data and invoking the methodology described in the Annexures-A and B.

A sample design of Levees/Embankment in the reach Chainage 326.5 - 378 km

It is proposed to keep the top width of the embankment of 3 m and side slope 1V: 2H. The top level of the embankment shall be 1.5 m higher than the highest flood level. Further, it is proposed to provide Biomac blankets which are also known as Rolled Erosion Control Protection (RECPs) mats and are used for surface erosion protection (Fig. 11.6). Placed onto top soiled and seeded slopes, Biomac supports the establishment of vegetation. As the mat biodegrades over time, the protection function is maintained by the vegetation. The Biomac are made with a mixture of fully biodegradable fibres properly integrated during manufacturing. The fibre mat is reinforced with a fine polypropylene scrim netting securely stitched on both sides during manufacturing.

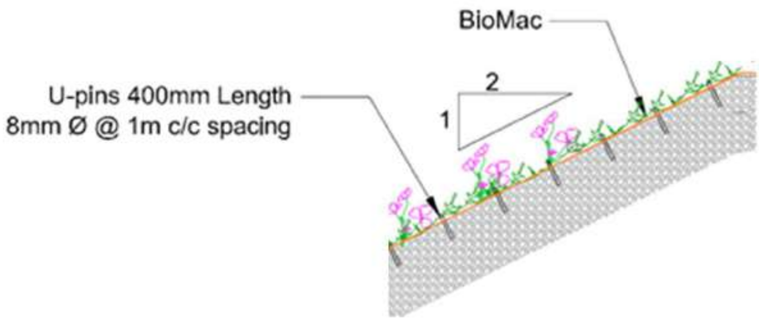

Figure 11.6 Details of BioMac

Nearest hydrological station to the reach 326.5 km-378 km is Balrampur (Chainage 396 km). Peak discharge for 25 years return period at Balrampur is estimated as 2836.1 m^3/s and ever maximum recorded water level at this station is 105.47 m. Let adopt these data for the design of the embankment in the reach 326.5 km-378 km.

As such, no revetment on the sloping surface of the levees and launching apron are required, however, it is suggested that river behaviour shall be watched and if river has tendency to come close to levees, slope protection and launching apron be provided as per detail below:

Slop protection

It is proposed to provide geo-bags for the control of erosion of the slope. Annexure-B may be seen for the details of flexible system including geo-bags.

Size of Bags: Weight of bags shall be calculated by

$$W = \frac{0.0232\ 3\ S_s}{K\ (S_s - 1)^3} V^6 \quad (1)$$

$$K = \left[1 - \frac{\sin^2\theta}{\sin^2\phi} \right]^{\frac{1}{2}} \quad (2)$$

where, W - weight in kg

V – velocity in m/s

Ss - Specific Gravity of protection material (adopted between 1.5 to 1.8)

θ - Angle of sloping bank

φ - Angle of repose of protection material

The average velocity U during flood is given by Lacey equation

$$U = \left(\frac{Qf^2}{140} \right)^{1/6} \quad (3)$$

For Q = 2836.1 m^3/s and f = 1, the above equation yields V = 1.65 m/s

let assume $\varphi = 30^0$

$\theta = \tan^{-1}(1/2) = 26.565^0$

K = 0.45

Let take $S_s = 1.7$

From Eq. (1), W = 5.16 kg, let provide bags of size 1.1m x 0.7m x 0.15m (weight around 126 kg) as per Nomograph given in IS-14262.

Thickness of Pitching: Thickness should be more than that calculated as under:

$$T = \frac{V^2}{2\,g\,(S_s - 1)} \quad (4)$$

T - thickness in m

V – velocity in m/s

Ss - Specific Gravity of protection material (adopted between 1.5 to 1.8)

g - Acceleration due to gravity (9.81 m/s^2)

For the data in the present case, Eq. (4) yields T =0.20 m

Pitching may be provided in double layers of geo-bags (in loose).

Launching Apron

Figure 11.7 shows a general arrangement of a launching apron that is generally provided at the toe of the embankment. It is assumed that the launching apron placed on the river bed would launch into the scour hole to take a slope of 1V: 2H. This launching apron is placed on the river bed over a length equal to 1.5 times D, where D is the scour depth measured below the river bed.

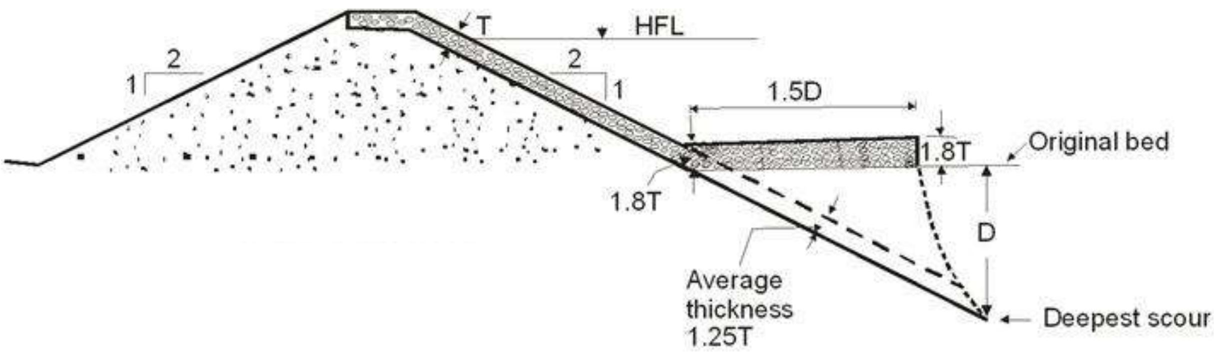

Figure 11.7 A typical sketch of embankment & launching apron (conventional)

According to IS Code: 10751:1994, the maximum scour depth D_{se} measured from the high flood level at the toe of straight part of the embankment 1.5R, in which R is Lacey's normal scour depth also measured from high flood level. The value of R is given by

$$R = 0.48(Q/f)^{1/3} \quad \text{in SI units} \qquad (5)$$

where f is Lacey's silt factor, let assume f = 1.

For Q = 2836.10 m^3/s i.e. discharge adopted for the scour computations as per IRC: 78-2000 and f = 1.0, Eq. (5) gives

$$R = 0.48(2836.1 /1.0)^{1/3}$$

$$= 6.8 \text{ m}$$

Maximum scour depths D_{se} at the toe of the embankment measured from HFL at different locations = 1.5R = 10.20 m

High flood level (HFL) =105.47 m

Deepest scour level = 105.47-10.20 = 95.27 m

Bed level of the river = 105 m (assumed)

Scour below bed level D = 105-95.27 = 9.73 m

Length of the launching apron = 1.5D = 14.60 m , provide 14 m

Thickness of launching apron = 1.8T = 1.8×0.20 = 0.36 m, let provide 0.40 m thick geo-bags in 2-3 layers.

Disclaimer: ***The above is a sample design and based on the gross assumed data. Thus this should not executed in the present form. It is suggested to collect detailed data and design shall be carried out as per the above procedure.***

11.5 CONCLUSIONS

Following conclusions have been drawn from the study carried out in this report:

a) Nine reaches of the Rapti river have been identified as critical. These reaches are Chainages 68-80 km (Chhithari), 138-156 km (Mirpur), 304-322.5 km (Rasulabad), 326.5- 378 km (Utraula), 387-392 km (Shankarnagar), 399-433 km (Jyonar), 438-466 km (Ikauna), 470-492 km (Lakshmannagar) and 506-515 km (Jamnaha). In these reaches, river has wandering behaviour in wide width. No progressive shifting in either directions has been noticed over the years.

b) Methodology for the design of various river training works has been discussed and based on the morphological changes of the river, it is suggested to provide embankment or levees in critical reaches of the river.

Chainages 2-12.5 km	Embankment on right side
Chainages 75-77 km	Series of spurs on left side
Chainages 304-322.5 km	Embankments on both sides
Chaianges 326.5-378 km	Embankments on both sides

In the identified critical reaches, wherever river is striking to the existing embankments, porcupine/ boulder revetment shall be provided to avoid breach in the embankment.

c) Embankments are provided towards both sides of the river in its most of the length, in particular in the lower reaches. In some reaches, embankments are not continuous and that requires to be plugged by construction new embankment as suggested in this study.

Chapter 12 CONCLUSIONS & RECOMMENDATIONS

12.1 CONCLUSIONS

Following conclusions have been drawn from the study carried out in this report:

a) Hydrological Analysis

1. Analysis of maximum observed discharge and maximum observed water level at different gauging sites on Rapti river using the available data indicates that there is no remarkable trend of temporal variation of maximum discharge and maximum water level at the gauging sites Kakardhari, Balrampur, Bansi, Rigauli and Birdghat over a long period of time.
2. The, maximum discharge at Balrampur has shown a decreasing trend, however, no trend has been found at Rigauli and Birdghat gauging sites. The maximum water level has an increasing trend at Kakardhari and Balrampur and decreasing trend at Bansi, however, no trend was found at gauging sites of Rigauli and Birdghat.
3. Estimated peak discharge at different gauging sites for 25, 50 and 100 years return periods has been estimated using various flood frequency methods. The estimated values indicate that peak discharge increases continuously in the downstream of the river.

b) Morphological Changes

1. Reach 0-50 km: There is no any progressive change in the course of river in this reach in the span 1970 to 2010. River is having meandering pattern in this reach. Major changes in the course of river have been noticed near Sareya, Ghaighat and Bahsua. The river has shifted from left to right at Sareya and Bahsua by 3 km and 2 km, respectively.

   Average width of the active channel is about 200 m in this reach. There is no much variation in the width over the years and along the channel except at Semra Khard, where the width of the river was 400 m in year 1980.

2. Reach 50-100 km: Major changes in the course of the river have been noticed in the upper part of the reach. It is also meandering in this reach. There is no progressive shift in course of the river in this reach. Major random shifting of the river has been noticed at Chhitarhri. In the upper reaches, the course of river in year 1970 to 2010 was within a buffer of 2.0 km.

   The average width of the active channel of Rapti river is about 200 m. The maximum width of the river is about 450 m at Bautha and Chhopra.

3. Reach 100-150 km: There is no any progressive shift of course of river in this reach. Maximum random shift of the order of 2.5 km has been noticed at Bariarpur, Pali and Mirpur. Major shift from left to right of the order of 1 km has been noticed at Surghana. While the river course has shifted from right to left of the order of 1.5 km at Majhgawan and Bariarpur.

   Average width of the active channel in this reach is about 200 m with maximum width of the order of 5 km at Pali. In general, the width of the river in this reach is varying from 100 m to 300 m.

4. Reach 150-200 km: No major shifting in the main course of river has been noticed in this reach, except near Phulwaria where the river has followed a straight path from 1980 onwards. There was an acute bend at this location in year 1970. There is no progressive shift in the course of the river in this reach.

   The width of the active channel varies from 150 m to 350 m with an average of 200 m in this reach. There is no any progressive change in the width of the river over the years in this reach.

5. Reach 200-250: In this reach also, no major shifting of the river has been noticed except at Semra Mustakham where river has shifted from left to right of the order of 1 km over the years.

   The width of active channel varies from 100 m to 275 m with an average of 200 m in this reach. The width of the river in 1970 was about 100 m, however, over the years it has increased.

6. Reach 250-300 km: There is no any major change in course of the river in this reach over the years. Critical examination of shifting of center line of Rapti river from year 1970 to 2010 indicates that in the upper part of this reach the tendency of meandering of the river has increased over the years.

   The width of the active channel of the river varies from 125 m to 275 m with an average of 200 m in this reach. There is no any progressive change in the width of river over the years.

7. Reach 300-350 km: Major changes in the course of the river has been noticed in this reach. The river is wandering in a buffer of 2.5 km width. The maximum shift from left to right is of the order of 2 km at Kanchalpur and Parsauna. The maximum shift from

right to left of the order of one km has been noticed at Rautaila and Arjanpur, and also there is no progressive shift in this reach over the years.

The width of the active channel varies from 100 m to 325 m with an average of 200 m in this reach. The maximum width of the order of 400 m has been noticed at Bagahwa in year 1990. In general, the maximum width was noticed in year 1990.

8. Reach 350-400 km: Major changes in the course of the river has been observed in the lower part of this reach. In the upper part, major changes in the course of the river has been noticed only at Shankarnagar. River has meandering pattern in the lower part of this reach. The maximum shift of the river course from right to left is of the order of 3 km at Nandnagar from year 1970 to 2010, while river has shifted of the order of 1.5 km from left to right at Shankarnagar.

   Large variation in the width of active channel in this reach has been noticed. River has widened over the years in this reach. In general, minimum width was found in year 1970 and maximum in year 1980. Maximum width of the order of 400 m has been noticed at Mirazapur.

9. Reach 400-450 km: River has remarkable wandering and meandering behavior in this reach. The river course has wandered in a buffer of 3.5 km in this reach in the span of year 1970 to 2010. There is no any progressive change in the course of the river in this reach. The maximum shift from left to right of the order of 2 km is found at Jyonar, Shravasti and Ikauna from 1970 to 2010. However, maximum shift of the river course from right to left of the order of 2 km can be seen at Mankoa Kondri.

   Average width of the active channel in this reach is of the order of 225 m. In general, the width has increased over the years. The maximum width of the order of 500 m was noticed at Shravasti in year 2000 and of the order of 575 m at Itwaria in year 1990.

10. Reach 450-500 km: Major changes in the course of the river has been noticed in this reach. However, no progressive change in the course of river has been noticed over the years. In general, river has been wandering in a width of 3 km. It has an acute meandering pattern in this reach. River has maximum shift from left to right at Gujar Purwa and right to left at Keshwapur of the order of 2.5 km in the span of year 1970 to 2010.

    The average width of the active channel in this reach is of the order of 290 m. However, it varies from 150 m to 400 m in this reach. River had maximum width of the order of 650 m at chainage 475 km (Tribhaura) and 490 km (Lakshmannagar). The width of the active channel has increased over the years in this reach.

11. Reach 500-542 km: This reach has also wandering and meandering behaviour of the river. There is no progressive change in the course of river in this reach. However, river has laterally shifted from left to right of the order of 3 km at Devpura and Jamnagar. At Hansapur, river has shifted from right of the order of 1.25 km.

Average width of the active channel river is of the order of 290 m. The river width has increased from 1970 onwards. The maximum width is found at Jamnaha.

12. The sinuosity of Rapti river is calculated using the formulation given by Friend and Sinha (1993). From the sinuosity plot of Rapti river, the following data were extracted:

Year	Maximum Sinuosity	Minimum Sinuosity	Average Sinuosity
1970	3	1.37	1.8
1980	2.9	1.11	1.88
1990	2.83	1.14	1.79
2000	2.79	1.42	1.87
2010	2.8	1.55	1.92

13. The computed sinuosity ratio of the Rapti river in the reach under consideration is higher than 1.5 in the years 1970, 1980, 1990, 2000, and 2010, therefore, the Rapti is classified as a meandering river.

14. Almost whole reach of the river has meandering pattern, however, it is prominent in the reaches 25-50 km, 75-100 km, 300-375 km, 400-425 km and 450-475 km. The meandering is characterized by acute bend with high amplitude, however, they are relatively stable.

15. The plan form index (PFI) of Rapti River is calculated using the formula given by Sharma (2004). It has been observed that the Rapti River always flows in one channel, so negligible braiding is found in the Rapti River.

16. Major shifting of the river course in span of year 1970 to 2010 is in the reaches 75 -100 km, 300-375 km, 400-485 km and 500-542 km. At Devpura, Jamuha, Keshwapur, Nandnagar and Chitahari shifting is from left to righ,t while at Gujarpurwa, Ikauna, Jyonar and Kanchalpur shifting is from right to left. No progressive shifting of the course of the river with respect to time has been noticed.

17. Width of the active channel of the river and river width based on the extreme banks have been estimated using the satellite images of years 1970-2010. There is no definite progressive change in the width of the river over the span 1970-2010 in the whole studied reach of the Rapti river. From chainage zero to 450 km, the average width of the active channel is almost constant and is equal to about 206 m, however, in the upper reach i.e., chainage 450 km to 542 km, the average width is about 290 m - which may be attributed to silting in upper reaches and spreading of flow as the river descends from hilly areas.

18. The nodal points along the reach of the river i.e. wherein minimum morphological changes are seen, have been identified. This will be helpful in planning of structures, like barrage and bridge in the future.

c) Erosion and Siltation

The erosion and siltation are determined on the basis of shifting of extreme left and right banks and the following conclusions are drawn:

1. The total eroded, silted, eroded plus silted, and net eroded area in the Rapti river during the period 1970 to 2010 are 79.04 km^2, 57.24 km^2, 107.35 km^2 and 21.80 km^2, respectively. It may be concluded that over a span of 40 years i.e, 1970 to 2010, about 21.80 km^2 area of Rapti River has been eroded by the flowing water.
2. Erosion has been noticed in the entire reach of Rapti River starting from Nepalgunj to its confluence with Ghaghra River. Major erosion has occurred during the period 1970 to 2010 in the upper reaches (chainage 450-542 km) due to constant shifting of river course. At other locations, like Gorakhpur, Balrampur, Utraula, and Domrianganj, the erosion is not so severe. Minor deposition has taken place in the reaches 25 km - 50 km, 150 km - 175 km and 425 km - 450 km that are near Ekauna, Bhaksa and Ikauna, respectively.
3. Provision of embankments and other river training works in the Rapti river has controlled the shifting of the river. There are natural water bodies in the form of ox-bow lakes in vicinity of river due to its meandering nature.
4. In the reach 0-50 km, total eroded area, total deposited area and total eroded & deposited area are 617.48 ha, 549.55 ha and 501.37 ha, respectively. Net erosion in this reach is 67.93 ha. Erosion is observed on left bank near Gaighat and Ekauna while deposition near Sareya and Bahssua on the right bank. The possible reason behind this is meandering nature of the river.
5. In the reach 50-100 km, total eroded area, total deposited area and total eroded plus deposited area are 643.98 ha, 522.89 ha and 603.94 ha, respectively. Net erosion in this reach is 121.09 ha. Erosion is observed on left bank near Chhithari, Dumri, Chhopra and Borhi, while deposition has occurred near Malaon and Jagdishpur on the right bank. The possible reason behind this is meandering nature of the river and lateral shifting.
6. In the reach 100-150 km, total eroded area, total deposited area and total eroded & deposited area are 869.24 ha, 663.23 ha and 1168.91 ha respectively. Net erosion in this reach is 205.71 ha. Erosion is observed towards left bank near Dumri, Gorakhpur, Mainabhagar and Mirpur, on the other hand deposition was noticed near Bhauapur and Nausar on the right bank. The possible reason behind this is meandering nature of the river and provision of river training works.
7. In the reach 150-200 km, total eroded area, total deposited area and total eroded & deposited area are 625.93 ha, 668.49 ha and 491.20 ha, respectively. Net deposition in this reach is 42.56 ha. Erosion is observed towards left bank near Mirpur and Ojhapur, and on the other hand deposition was found near Indarpur and Karmalini on the right bank. The possible reason behind this is meandering is the nature of the river and lateral

shifting. There are natural lakes in this reach, and Bakhira taal is the largest among them.

8. In the reach 200-250 km, total eroded area, total deposited area and total eroded plus deposited area are 519.18 ha, 343.79 ha and 220.31 ha, respectively. Net erosion of this reach is 175.39 ha. No major changes are visible in this reach during the period 1970-2010. Minor erosion on left bank near Madhwapur and deposition near Charthari on the right bank has been noticed. The possible reason behind this is meandering nature of the river and lateral shifting.
9. In the reach 250-300 km, total eroded area, total deposited area and total eroded plus deposited area are 527.63 ha, 344.97 ha and 205.41 ha, respectively. Net erosion of this reach is 182.65 ha. No major erosion and deposition are visible in this reach.
10. In the reach 300-350 km, total eroded area, total deposited area and total eroded plus deposited area are 581.51 ha, 463.79 ha and 952.34 ha, respectively. Net erosion in this reach is 117.72 ha. Erosion is observed on left bank near Gopia, u/s of Arjanpur and Bharwatia on the other hand deposition was found near Raasulabad, Mahua Dhani and Nagwa; on the right bank. The possible reason behind this is meandering nature of the river and lateral shifting.
11. In the reach 350-400 km, total eroded area, total deposited area and total eroded plus deposited area are 595.41 ha, 426.30 ha and 997.27 ha, respectively. Net erosion in this reach is 169.11 ha. Major changes in the form of erosion and deposition are visible in this reach. There are erosion and deposition on both the banks. The possible reason behind this is meandering nature of the river and existing river training methods.
12. In the reach 400-450 km, total eroded area, total deposited area and total eroded plus deposited area are 836.24 ha, 770.37 ha and 1850.58 ha respectively. Net erosion in this reach is 65.87 ha. River has eroded and deposited on both the banks. Erosion is observed on left bank near Manoharpur, on the other hand deposition near Ikauna on the right bank was noticed. Major changes are visible near Jyonar and Balrampur. The possible reason behind this is meandering nature of the river, lateral shifting and constructed structures.
13. In the reach 450-500 km, total eroded area, total deposited area and total eroded plus deposited area are 996.64 ha, 513.39 ha and 1801.13 ha respectively. Net erosion in this reach is 483.26 ha. Noticeable amounts of erosion & deposition are visible in this reach, especially on the upstream of the barrage. The possible reason behind this is construction of barrages and braiding & meandering nature of the river due to topographical changes. Other areas are suffered with huge erosion and deposition.
14. In the reach 500-542 km, total eroded area, total deposited area and total eroded plus deposited area are 1091.65 ha. 457.44 ha and 1942.98 ha, respectively. Net erosion in this reach is 634.20 ha. Erosion is observed on right bank near Jamnaha and Kundwa. The possible reason behind this is braiding & meandering nature of the river due to topographical change.

15. Available measured cross sections of the Rapti river for different years at gauging stations of Balrampur, Rigauli and Birdghat have been analysed. No remarkable changes in the historical cross-sections of the Rapti river at Rigauli and Birdghat are noticed, however, river course has shifted towards left side by about 40 m at Balrampur which has resulted in both erosion and siltation at this location. Cross-section of the Rapti river is shallow at Balrampur, however, it is deep at Rigauli and Birdghat.

d) Major Structures & their Impact on the Morphology

There is only one barrage, named as Rapti barrage, in the reach of the river from Nepalgunj to Patana Ghat (confluence point of Rapti and Ghaghra Rivers). Following points may be noted from the identification of major structures and their impact on the morphology.

1. The river course has wandering behavior upstream of the barrage. However, no shifting has been observed downstream of the barrage over the years. The Rapti barrage was commissioned in year 2008. Since then no noticeable silting upstream of the barrage has been observed. Nevertheless, river in year 2015 was flowing in two channels upstream of the barrage.
2. There are about 22 bridges on the Rapti river from Nepalgunj to its confluence with Ghaghra river at Patana ghat. Morphological changes are noticed near the major bridges, however, proper river training works have been provided which are working satisfactorily.
3. Road bridge (SH 72, Patana Ghat) is located in relatively straight and stable reach of the Rapti river. In past, river had come close to the right approach road of the bridge - spurs were provided to protect the approach road. As such no measures are required for training the river at the bridge site. However, it is suggested to provide embankment towards right side, upstream of the bridge (SH 72 Bridge) to control the spread of flood water.
4. Road bridge (Kaithwalia) is located just downstream of an acute bend and major shifting of river towards its left side has been noticed upstream of the bend. It is suggested to provide series of spurs towards left side upstream of the bend to arrest such shifting so that out flanking of the bridge may be avoided.
5. Protection works are suggested in the vicinity of the bridges at Chainages 160 km, 205 km, 212 km, 251.5 km, 272.5 km and 418 km to train the Rapti river, as per detail below:
    a) Boulder revetment/porcupine/series of spurs on right bank over a length of 700 m upstream of the bridge at Peepeganj (Chainage = 160 km, Fig. 9.5)
    b) Provision of series of spurs towards left side at Dhani (Chainage = 205 km, Fig. 9.6)
    c) Boulder revetment to the existing both sides embankments at Dhani (Chainage = 212 km, Fig. 9.7)

d) Provision of protection to the left embankment upstream of the bridge (SH5) in the form of boulder revetment/short spurs at Rajendra Nagar (Chainage = 251.5 km, Fig. 9.8)

e) Provision of boulder revetment to both the approach roads at Tighra **(**Chainage = 272.5 km, Fig. 9.9)

f) Extension of the existing left guide bund of about 90 m downstream at Kodri ghat (Chainage = 418 km, 9.10)

e) Critical Reaches and River Training Works

1. Nine reaches of the Rapti river have been identified as critical. These reaches are chainages 68-80 km (Chhithari), 138-156 km (Mirpur), 304-322.5 km (Rasulabad), 326.5- 378 km (Utraula), 387-392 km (Shankarnagar), 399-433 km (Jyonar), 438-466 km (Ikauna), 470-492 km (Lakshmannagar) and 506-515 km (Jamnaha). In these reaches, river has wandering behaviour in wide width. No progressive shifting in either directions has been noticed over the years.
2. Methodology for the design of various river training works has been discussed and based on the morphological changes of the river, it is suggested to provide embankment/levees/spurs in critical reaches of the river.

Chainages 2-12.5 km	Embankment on right side
Chainages 75-77 km	Series of spurs on left side
Chainages 304-322.5 km	Embankments on both sides
Chaianges 326.5-378 km	Embankments on both sides

In the identified critical reaches, wherever river is striking to the existing embankments, porcupine/ boulder revetment/geo tubes shall be provided to avoid breach in the embankment.

3. Embankments are provided towards both sides of the river in its most of the length, in particular in the lower reaches. In some reaches, embankments are not continuous and these require to be plugged by construction new embankment as suggested in this study.

12.2 RECOMMENDATIONS

(i) It is recommended to implement the suggested measures in the identified four critical reaches of the Rapti and in the vicinity of the identified bridges. It is further suggested that such reaches/locations be studied in more details based on ground survey and analysis of high resolution satellite data.

(ii) Suggested measures are prioritized as follow:

a) Extension of the existing left guide bund of about 90 m downstream at Kodri ghat (Chainage = 418 km, Fig.9.10)

b) Provision of series of spurs towards left side at Dhani (Chainage = 205 km, Fig. 9.6)

c) Boulder revetment/porcupine/series of spurs on right bank over a length of 700 m upstream of the bridge at Peepeganj (Chainage = 160 km, Fig. 9.5)

d) Provision of protection to the left embankment upstream of the bridge (SH5) in the form of boulder revetment/short spurs at Rajendra Nagar (Chainage = 251.5 km, Fig. 9.8)

e) Provision of boulder revetment to the existing both sides embankments at Dhani (Chainage = 212 km, Fig. 9.7)

f) Provision of boulder revetment to both the approach roads at Tighra (Chainage = 272.5 km, Fig. 9.9)

g) Provision of series of spurs on left side in the reach at Chainages 75-77 km (Fig. 11.3b).

h) Provision of embankment on right side in the reach at Chainages 2-12.5 km (Fig. 11.3a)

i) Provision of embankment on both sides in the reach at Chainages 304-322.5 km (Fig. 11.3c)

j) Provision of embankment on both sides in the reach at Chainages 326.5-378 km (Fig. 11.3d)

(iii) It is recommended to plan hydraulic structures like barrage, bridge etc. at the identified nodal points (wherein minimum morphology of the river has occurred) on the Rapti river to avoid outflanking of the river and to minimize protection works.

(iv) Large scale de-silting from the rivers is not recommended. Efforts shall be made to manage the sediment in the river through deploying suitable river training works. However, from the utility consideration like siltation at water intake, minimum draft requirement for navigation, skewed distribution of flow across bridges/barrages etc., it is recommended to desilt the sediment from that location.

(v) River training works or any other structure shall be designed in such a way that it should not encroach the flood plains of the river or it should not delink the lakes, depressed areas, wetlands etc. as such bodies provide additional storage to the river and which results in lowering the peak discharge that controls the flood.

(vi) Sediment management in the vicinity of a barrage shall be explored by operation of the barrage gates. For an example, gates of the barrages shall be operated in such a way that incoming sediment can be passed downstream during the flood time, to maintain the sediment equilibrium.

(vii) Detailed ground survey of the area and data collection/analysis is proposed before implementing the recommendations, so as to incorporate the current ground conditions and river behaviour.

12.3 SUGGESTED FURTHER STUDY

(i) Unauthorized, unscientific and unplanned mining of sand and gravel from the river has resulted in major morphological changes in river in the terms of stream bank shifting, bed degradation, bank erosion, disrupting the sediment mass balance, danger to the hydraulic structures etc. It is suggested to carry out replenishment study so that quantity of the sand and gravel to be mined can be estimated and morphological changes can be controlled.

(ii) Erosion and siltation in the River river has been studied herein on the basis of the shifting of the banks of the river as well as analysis of satellite images. This approach of the study is an indicative and does not provide the eroded/silted sediment in the terms of volume/weight. In view of this, it is suggested that the eroded/silted sediment may be quantified on the basis of the sediment mass balance study i.e., quantity of eroded/silted sediment in a reach of the river is equal to mass of the sediment entered into the reach minus mass of the sediment gone out from the reach during a period.

(iii) Flood zones of the river should be identified and delineated along both the banks of river. Based on flood zone boundaries, habitation and development activities may be prohibited in such areas.

(iv) In future, morphological studies are required to be carried out using 3D data of the terrain, as topography and slope of the region play an important role to study the morphological behavior of the river.

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Annexure-A

DESIGN METHODOLOGY FOR VARIOUS RIVER TRAINING WORKS

A1. GUID BANKS (IS 10751:1994)

General

The alignment should be such that the pattern of flow is uniform with minimum return currents. The guide banks can be straight or elliptical with a circular or multi-radii curved head (Fig. A1). Elliptical guide banks have been found more suitable in case of wide flood plain rivers for better hydraulic performance. In case of elliptical guide banks, the ratio of major axis to the minor axis is generally in the range of 2 to 3.5.

Length of Guide Banks

Upstream Length

The general practice is to keep the upstream length of guide banks as 1.0 L to 1.5 L, where L is the length of structure between the abutments. For elliptical guide banks, the upstream length (that is semi major axis a) is generally kept as 1.0 L to l.25 L. This practice is generally applicable where the waterway is within the close range of L that is, Lacey's waterway.

For wide alluvial belt, the length of guide banks should be decided from two important considerations, namely (a) the maximum obliquity of current (it is desirable that obliquity of flow to the river axis should not be more than 30^0), and (b) the limit to which the main channel of the river can be allowed to flow near the approach embankment in the event of the river developing excessive embayment behind the guide bank. The radius of worst possible loop should be ascertained from the data of acute loops formed by the river during past. In case of river where adequate past surveys are not available, the radius of worst loop can be determined by dividing the average radius of loop worked out from the available surveys of the river by 2.5 for river having a maximum discharge up to 5000 m^3/s and by 2.0 for discharging above 5000 m^3/s. The above considerations are illustrated in Fig. A2. The limit to which the main channel of the river can be allowed to flow near approach embankment has to be decided based on importance of structure and local conditions.

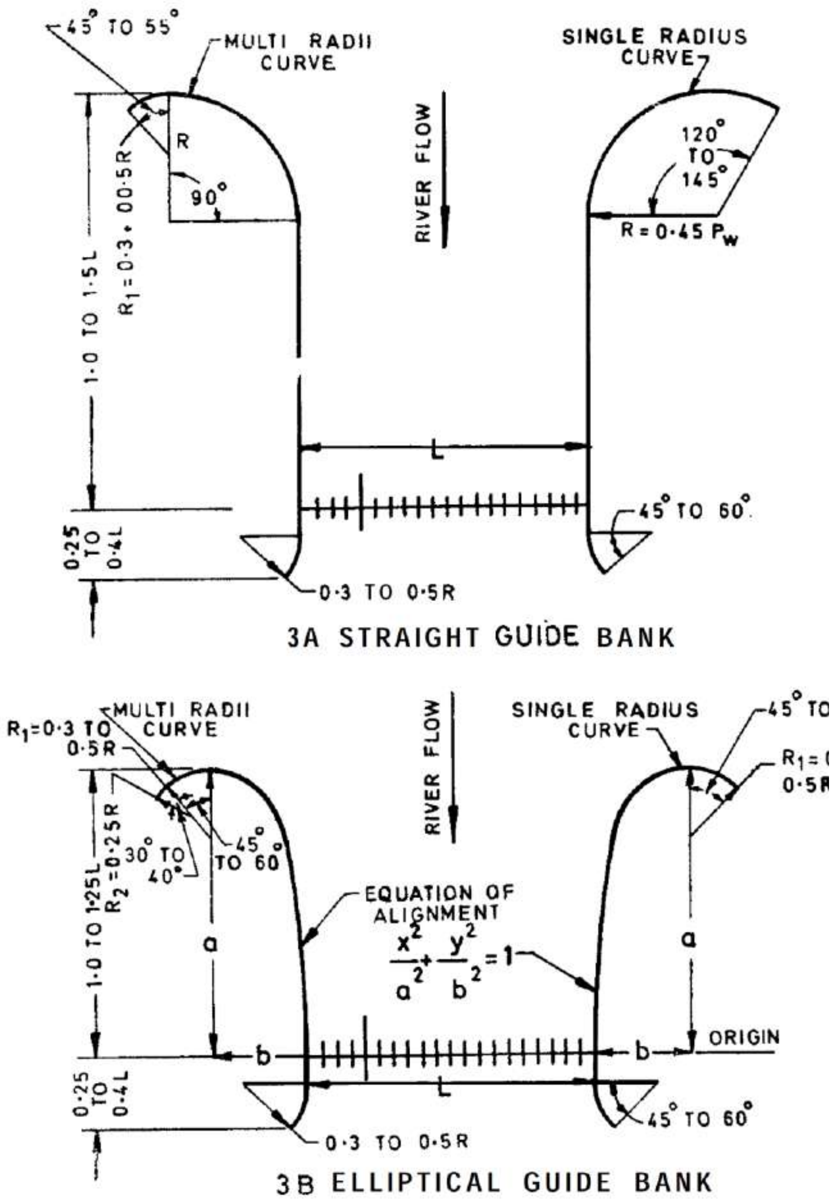


Figure.A1 A) Straight guide bank, and B) Elliptical guide bank

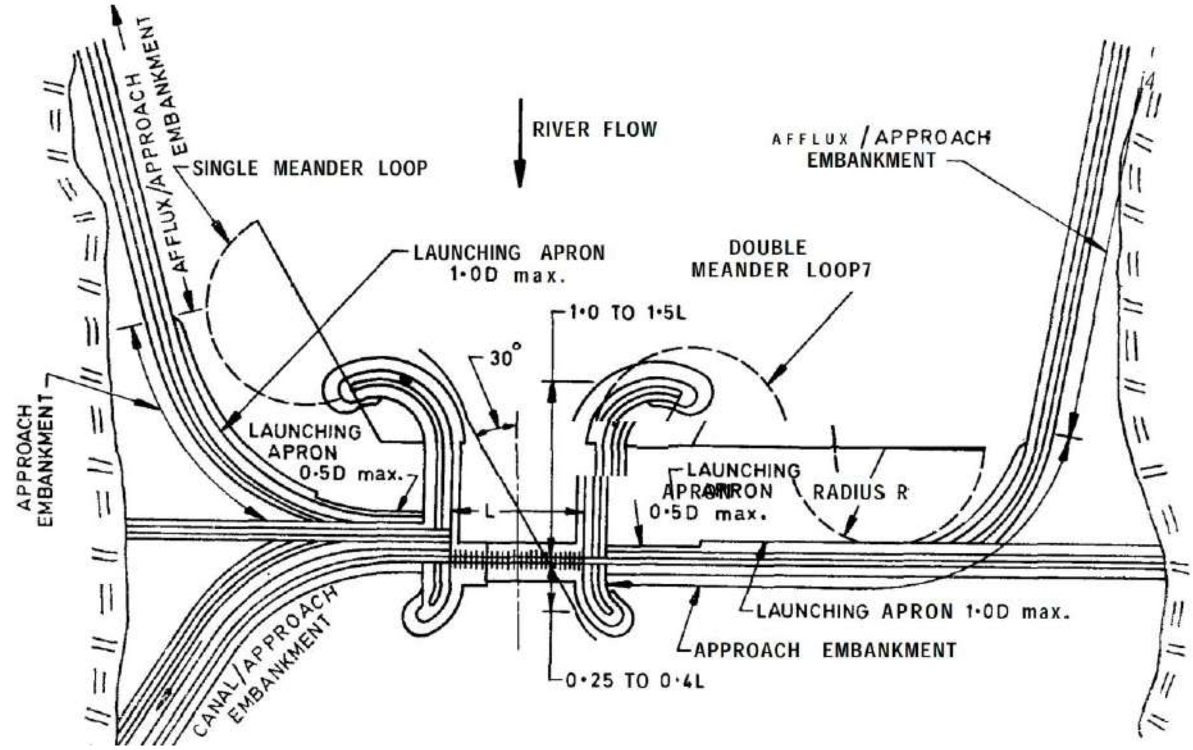


Figure. A2 Typical layout of the guide bank

Downstream Length

On the downstream side the river tries to fan out to regain its natural width. The function of guide bank is to ensure that the river action does not adversely affect the approach embankment. The downstream length will therefore, has to be determined so that swirls and turbulence likely to be caused by fanning out of the flow downstream the guide bank do not endanger the structure and its approach. The length of 0.2L to 0.4L is recommended.

Radius of Curved Head and Tail

Radius of curve head equal to 0.45L has been found to be satisfactory. Radius of curved tail may be 0.3 to 0.5 times the radius of curved head.

As per IRC: The radius of upstream mole head should not be less than 150 m nor more than 600 m unless indicated otherwise by model studies.

The radius of the upstream mole can also be estimated by

$$R_1 = 2.2\sqrt{Q} \quad \text{in SI units}$$

in which Q is the design flood discharge.

The radius of the downstream mole head R_2 is given by

$R_2 = 1.1\sqrt{Q}$ in SI units

Sweep Angle

The sweep angle is related to the loop formation. For curved head the angle of sweep may range from 120^o to 145^o according to river curvature. For curved tail it varies from 45^o to 60^o. As per IRC: 89-1997.

Design of Guide banks

Material

Guide banks may be made of locally available materials from river bed, preferably silt, sand or sand-cum-gravel.

Top Width

The top width should be 6 to 9 m to permit transport of material. At the nose of guide banks, the width may be increased suitably to enable vehicles to take turn and for stacking stones.

Free board

A free board of 1.0 m to 2.0 m may be provided above the design flood level. Where heavy wave action is apprehended and/or aggravation is anticipated, a higher free board may be provided. As per IRC: 89-1997: The minimum free board to top of guide bank above the pond level is generally kept as 1.5 m to 1.8 m.

Side slope

It depends on the angle of repose of the material of guide banks and the height. Side slope of 2H:1V to 3H:1V are generally recommended.

Protection of structures

Curved head is prone to damage due to concentration of discharge caused by collection of over bank flow and direct attack of current obliquely. The shank is subjected to attack by parallel/oblique flow. The curved tail is subject to attack by fanning out of current.

Toe Protection

Launching apron should be provided for protection of toe and it should form a continuous flexible cover over the slope of the scour hole in continuation of pitching up to the point of deepest scour.

Bank Revetment

Thickness of pitching on slope should be equal to two layers of stones of size given by Eq. (A1) in the case of free dumping of stones.

The weight of the stones required on sloping surface to withstand erosive action of flow may be determined using following relationship

$$W = \frac{0.02323 G_s}{K(G_S - 1)^3} V^6 \quad \text{(A1)}$$

$$K = \left[1 - \frac{\sin^2\theta}{\sin^2\phi}\right]^{\frac{1}{2}} \quad \text{(A2)}$$

where W = weight of stone in kg, G_s = specific gravity of stones, ϕ = angle of repose of protection material, θ = angle of sloping bank, and V = velocity in m/s.

Alternatively, the thickness of the bank revetment can be estimated by the following empirical equation of Inglis (Garde and Ranga Raju, 2000):

$$T = 0.04 \text{ to } 0.06\ Q^{1/3} \quad \text{in SI units} \quad \text{(A3)}$$

As per IRC 89, the thickness of stone pitching computed from the above formula shall be subject to an upper limit of 1.0 m and lower limit of 0.3 m.

In the case of crates, the thickness of crates be decided for negative head created due to velocity from following formula:

$$t = \frac{V^2}{2g(G_s - 1)} \quad \text{(A4)}$$

Where, t = thickness in m; V in m/s; g in m/s^2. The crate openings should not be larger than the smallest size of stone used. Shape of crates or blocks should be as far as possible cubical. Crates may be made of G.I. wire or nylon ropes of adequate strength and should be with double knots and close knits.

Size of stone

The stones used for slope protection and launching apron must be heavy enough to stay in place against the force of the current. For stones of relative density 2.65, the minimum size of stone is given by (Garde and Ranga Raju, 2000):

$$d_{min} = 0.023 \text{ to } 0.046\ U_{max}^2 \quad \text{(A5)}$$

in which d_{min} is expressed in m, and U_{max} is the maximum velocity of flow (in m/s) in the vicinity of the guide bund.

As per IRC 89, the size of stone required for slope protection and launching apron to resist mean design velocity (average velocity) is given by the formula:

$$V = 4.893\, d^{1/2} \qquad \text{(A6)}$$

Where, V = mean design velocity in m/s and d = equivalent diameter of stone in m.

For velocities up to 5.0 m/s, the size and weight of stone is given in Table A1 below.

Table A1. Minimum size and weight of stone for slope protection

Mean design velocity in m/s	**Minimum size and weight of stone**			
	Slope 2:1		**Slope 3:1**	
	Diameter (cm)	**Weight (kg)**	**Diameter (cm)**	**Weight (kg)**
Upto 2.5	30	40	30	40
3.0	30	40	30	40
3.5	35	59	30	40
4.0	45	126	35	59
4.5	57	257	55	118
5.0	71	497	54	218

Launching Apron

Figure A3 shows the general arrangement of a launching apron that is generally provided at the mole head and the straight portion of the guide bund to prevent undermining of the bank revetment and consequent failure of the guide bund. It is assumed that the launching apron placed on the river bed would launch into the scour hole to take a slope of 1V: 2H with an average thickness of 1.25T. The slope of launched apron may be taken as 1.5H:1V for concrete blocks or stones in wire crates. To ensure this volume of boulder material, the average thickness of the launching apron on the river bed comes to 1.86T. This launching apron is placed on the river bed over a length equal to 1.5 times D, where D is the scour depth measured below the river bed.

The design of the launching apron, therefore, requires the estimation of the maximum scour below the river bed level that is likely to occur at the mole head and straight reach of the guide bund. The extent of scour depends on angle of attack, discharge intensity, duration of flood and silt concentration, etc.

The regime depth R may be determined as given below:

$$R = 0.473\left(\frac{Q}{f}\right)^{1/3} \quad \text{(A7)}$$

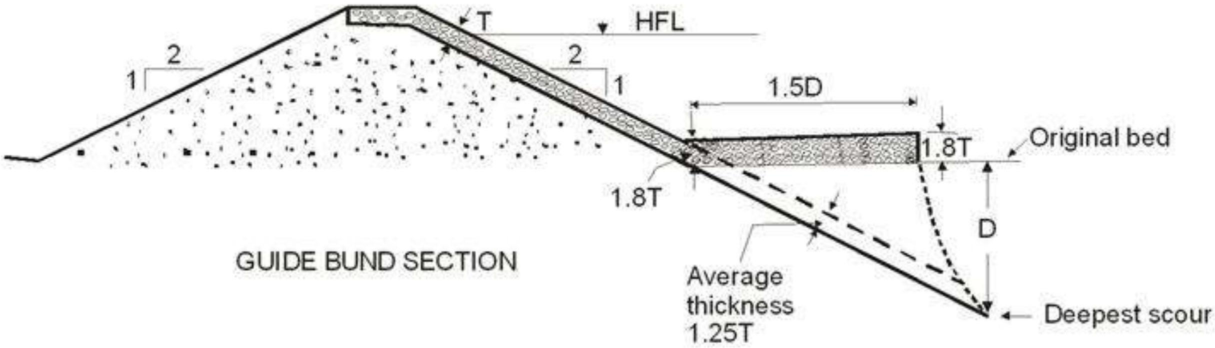


Figure. A3 A typical sketch of guide bund & launching apron

For waterway equal to or more than Lacey's waterway. In case where the waterway is less than Lacey's waterway and also the flow is non-uniform, D may be calculated as:

$$R = 1.35\left(\frac{q^2}{f}\right)^{1/3} \quad \text{(A8)}$$

Where R =scour depth in m, f = silt factor $=1.76\sqrt{d}$ where d is the mean diameter of river bed material in mm, Q = discharge in m^3/s, q = intensity of discharge in $m^3/s/m$.

The depth of design scour for different portions of the guide banks may be adopted as below:

Location	**Design Scour Depth to be adopted (R×Scour factor)**
Upstream curved head of guide bank	2.0 R to 2.5 R
Straight reach of guide bank to nose of downstream guide bank	1.5 R
Downstream curved tail of guide bank	1.5 R to 1.75 R

However, as per IRC: 89-1997

Location	**Maximum scour depth to be adopted**
Upstream curved mole head of guide bank	2-2.5 R
Straight reach of guide bank including tail on the downstream of guide bank	1.5 R

Slope Protection

The river side earthen slope of guide banks are protected against river action by covering them with dumped or hand placed stones and concrete blocks. This pitching is intended to remain in its laid position.

The rear slopes of guide banks are not subjected to direct attack of river and may be protected against wave splashing by 0.3-0.6 m thick cover of spawls or by turfing, In case however, a parallel or back flow leading to erosive action is likely as evident from model studies at the rear face, suitable pitching may be necessary.

The thickness of pitching should be equal to the size of stone determined from the velocity consideration from Eq. (A1) for hand placed pitching. For dumped stone pitching the thickness may be two times the size of stone. In general the following guidelines are followed:

a) Brick on edge can be adopted up to an average velocity of 2 m/s,
b) Quarried stones of size 350 mm and/or weighing 40-70 kg should be used up to an average velocity of 3.5 m/s, and
c) For higher velocity cement concrete blocks/crated stone could be used.

As per IRC 89, rear slopes of guide banks are not subjected to direct attack of the river and may be protected against ordinary wave splashing by 0.3- 0.6 m thick cover of clayey or silty earth and turfed. Where moderate to heavy wave action is expected slope pitching should be laid up to a height of 1 m above the pond level.

Drainage Arrangement

A system of open paved drains (Chutes) along the sloping surface terminating in longitudinal collecting drains at the junction of berm and slope should be constructed at 30 m center to drain the rain water. The drains are to be formed of stone pitching or with precast concrete section.

A2. DESIGN OF SPURS (IS 8408:1994)

General

Spurs may be aligned either normal to the dominant flow direction or at an angle pointing upstream or downstream. Spurs serve one or more of the following functions:

(a) Training the river along the desired course to reduce the concentration of flow at the point of attack,
(b) Protecting the bank by keeping the flow away from it,
(c) Creating a slack flow with the object of silting up the area in the vicinity of the river bank, and
(d) Improving the depths for navigation purpose.

Classification of Spurs

(a) The methods and materials of construction, namely permeable, impermeable and slotted;
(b) Height of spur with respect to water level, namely submerged, non-submerged and sloping (partially and/or submerged);
(c) Action, namely deflecting, attracting and repelling (see Fig. A4); and
(d) Special shapes, namely T-headed, hockey type or Burma type, kinked type, etc.

For repelling spur the angle upstream varies from 60^o to 80^o with the bank while in attracting spur the angle is usually 60^o with the bank.

In case of deep and narrow rivers or rivers carrying considerable suspended sediment, permeable spurs are preferred. Following type of permeable spurs are generally in use:

(a) Pile spurs
(b) Tree spurs
(c) Porcupine spurs

Design of spurs

The design discharge for the spur should be equal to that for which any structure in close proximity is designed or 50 year flood whichever is higher.

Length and Spacing of spur

Normally the effective length of spur should not exceed $1/5^{th}$ of width of the flow in the case of single channel. In case of wide, shallow and braided rives, the protrusion of the spur in the deep channel should not exceed the length over the bank. The spacing of the spur is normally 2 to 2.5 times its effective length.

Shorter length may also cause bank erosion upstream of the spur whereas too long spur may dam up the river. Normally spur should not obstruct more than 20% of the channel width at ordinary flood level.

As per IRC 89, in a straight reach the spacing is about 3 times the length of spur. Spurs are spaced further apart (with respect to their length) in a wide river than in a narrow one, if their discharges are nearly equal. In a curved reach a spacing of 2 to 3.5 times the length of spur is recommended. Larger spacing (3 to 3.5 times) can be adopted for concave banks and smaller spacing (2 to 3 times) can be adopted for convex banks.

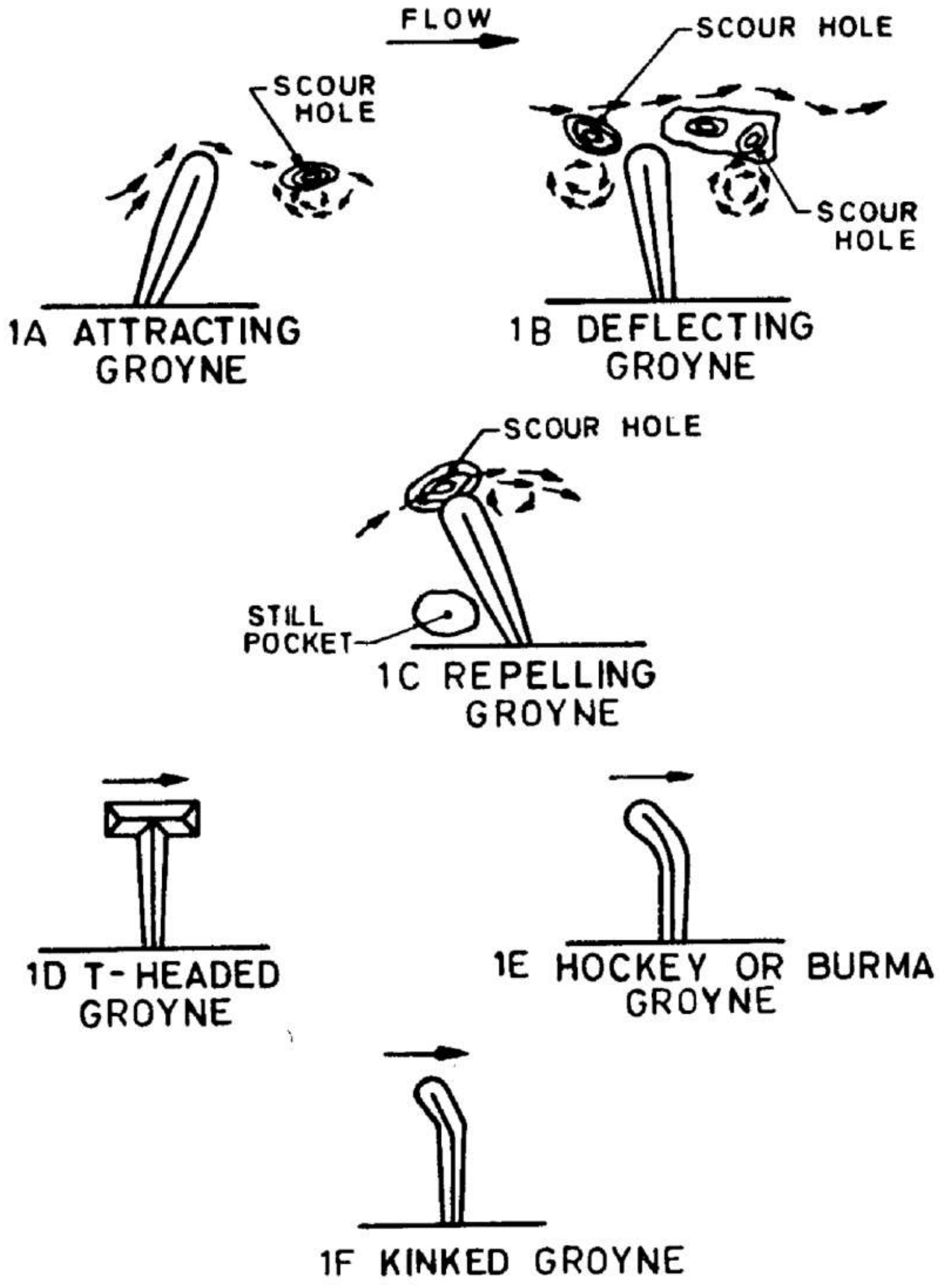


Figure. A4 Types of spurs

Top level and Top width of spur

In case of non-submerged spurs the top level should be above design flood level with a free board of 1 to 1.5 m. The top width of spur should be 3 to 6 m as per requirements.

Side slopes

Slopes of the sides and nose of the spurs would be between 2H:1V and 3H:1V depending upon the material used.

A typical layout of the spur is shown in Fig. A5. Methodology for the bank protection and Launching apron discussed in the design of Guide banks shall be adopted for the spur also. However, scour depth at different locations of the spur shall be taken as

S.N.	Location	Maximum Scour Depth to be Adopted
(i)	Nose	2.0 R to 2.5 R
(ii)	Transition from nose to shank and first 30 to 60 m in upstream	1.5 R
(iii)	Next 30 to 60 m in upstream	1.0 R
(iv)	Transition from nose to shank and first 15 to 30 m in downstream	1.0 R

A3. PILOT CHANNEL /ARTIFICIAL CUT OFF

In order to divert the flow and reduce pressure on the protection works, wherever feasible, pilot channels are provided. It is made is initially constructed of small cross-section so as to carry 8 to 10% of the flood discharge. This channel is then allowed to develop by itself and sometimes such gradual development is assisted by dredging.

The following points are worth considering for the design and execution of the pilot channels (Garde and Ranga Raju, 2000).

1. The pilot channel should be tangential to the main direction of river flow approaching and leaving the cut.
2. The pilot channel is usually made on a slight curve, the curvature being less than the dominant curvature of the river itself.

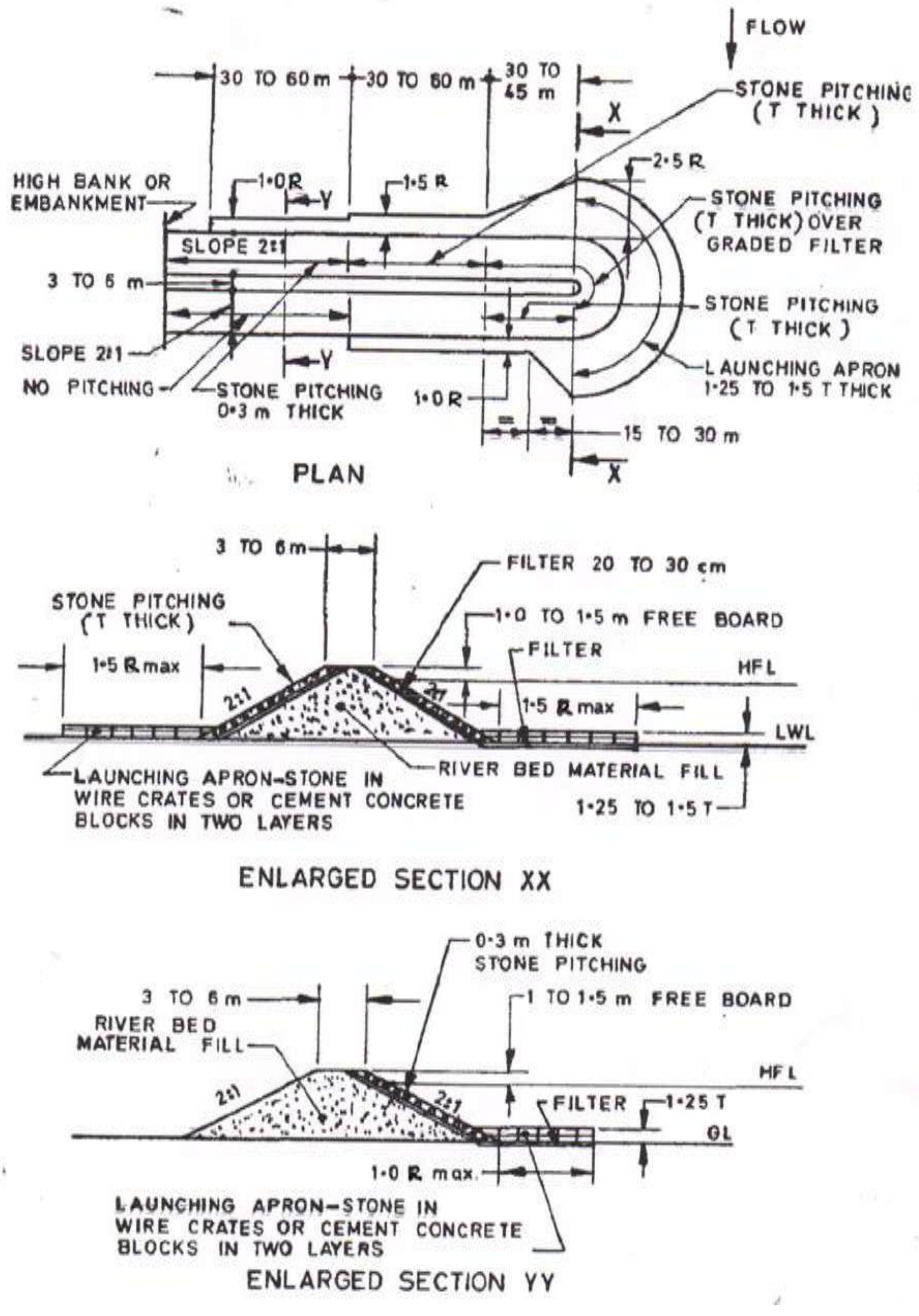


Figure. A5 Layout of a typical spur

3. Entrance of the pilot channel is made bell-mouthed. Such transition at the exit is considered unnecessary because the cut develops first at the lower end and works progressively upstream.
4. The cut, when unlikely to develop because of coarseness of the material or of low shear stress, should be excavated to mean river cross-section.
5. The width of the pilot channel is unimportant as the cut ultimately widens due to scouring, Hence, in practice, the width is determined by consideration of the type and size of the dredging equipment used.
6. When a series of cutoff is to be made, the work should progress from downstream to upstream.

It is desirable that the dimensions of this pilot channel should be such that with flow in it, the actual shear stress is much more than the critical shear stress required to move the bed material. It is hypothesized that with this excess shear stress, the channel will develop on its own during the period when discharge increases in the main river.

Let consider a pilot channel having

Length	= 1000 m
Upstream bed level	= 97.0 m
Downstream bed level	= 96.0
Channel slope	=1/1000
Base width	= 10 m
Side slopes	= 1V:2H

For a depth of flow of 1.0 m provided in the pilot channel, the values of flow area, A and hydraulic radius, R for this channel are 12.0 m^2 and 0.829 m, respectively. Using Manning's equation with n = 0.025, the discharge in the pilot channel may be calculated as -

$$Q = \frac{1}{0.025} \times 12 \times 0.829^{2/3} \times (10^{-3})^{1/2} = 13.40\ m^3/s$$

The average shear stress τ_o in this channel is given by

$$\tau_o = \gamma_f R S = 9810 \times 0.829 \times 10^{-3} = 8.132\ N/m^2$$

The critical shear stress τ_c as per Yalin-Karahan (Garde and Ranga Raju, 2000) for the average size of 0.32 mm comes out to be 0.19 N/m^2.

Thus, the proposed pilot channel has an average shear stress on its boundary much more than the critical shear stress and this would help in the development of this channel during the flood. And once this happens, this channel would carry a much higher discharge than the calculated discharge of 13.40 m^3/s, giving relief to its tendency to move in bend.

A4. DESIGN OF RIVER EMBANKMENTS (LEVEES) (IS 12094:2000)

General

Embankments/Levees are used for the containment of spread of the flood water. These are designed for a flood of 25 years frequency in the case of predominantly agricultural areas and for flood of 100 years frequency for works pertaining to protection of town, important industrial and other vital installations. It would better consider flood of a particular frequency based on the benefit-cost ratio.

In general, embankment should be aligned on the high ridge of the natural banks of a river, where land is high and soil suitable for the construction of embankments. Their alignment has to be determined in such a way that the high velocity flow is sufficiently away from them. Where it is not possible to avoid high velocity flow, protection in the form of spurs and revetments is necessary.

Embankment should be aligned so that important towns and properties along the river bank are left outside the embankment. Where it is not possible to set back embankments to avoid the high velocity flow, some form of protection is necessary. Protrusions and sudden changes in the alignments and forming kinks should be avoided as far as possible.

The spacing between the embankments in jacketed reach of river should not be less than 3 times Lacey's wetted perimeter for the design flood discharge. In no case should an embankment be placed at distance less than Lacey's wetted perimeter from the river bank or one and a half times the Lacey's wetted perimeter from the midstream of the river.

Length of embankment directly depends upon the alignment. However, it is to be ensured that both ends of the bund are tied up to some high-ground or existing highway or railway or any other embankment nearby conforming to the design height of the embankment.

Design of Embankment

Embankments can be classified into two types as given below:

a) *Homogeneous Embankment*

b) *Zoned Embankment*

The essential requirements for design of the embankment are design high flood level (HFL), hydraulic gradient, free board, side slopes, top width etc. The stability of the structure should be checked under all stages of construction, condition of saturation and drawdown. Typical cross-sections of the homogenous and Zoned embankments are shown in Figs. A6, and A7, respectively.

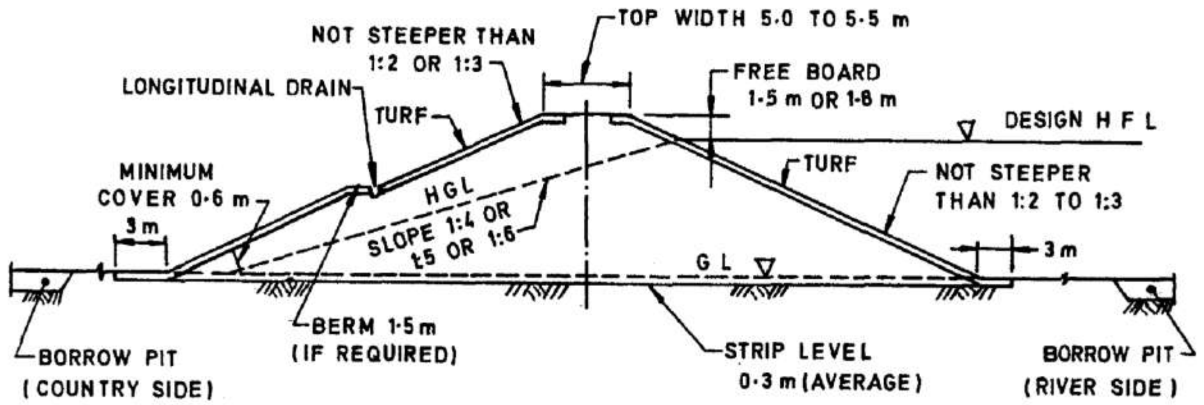


Figure. A6 Typical cross-section of Homogeneous embankment

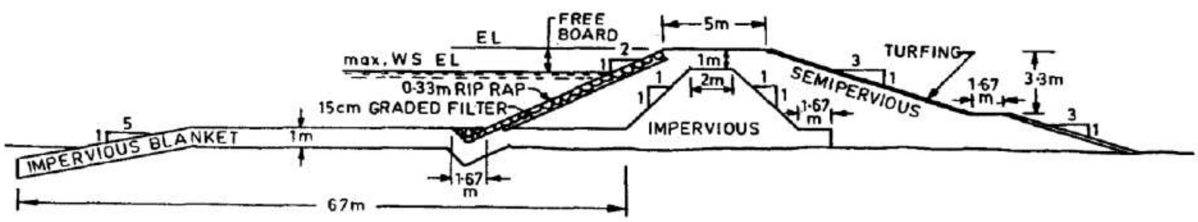


Figure. A7 Typical cross-section of Zoned embankment

Design discharge & HFL: To be obtained from the hydrological analysis.

Free Board: As a guideline, minimum free board of 1.5 m over design HFL including the back water effect, if any, should be provided for the river carrying design discharge up to 3000 m^3/s. For higher discharges or for flashy rivers, the minimum free board should be of 1.8 m. This should be checked also for ensuring a minimum of about 1.0m of free board over HFL corresponding to 100 years frequency flood.

Top width : The top width of the embankment should be of 5.0 m. The turning platforms, 15 to 30 m long and 3.0 m wide with side slope 1:3 along the countryside of the embankment should be provided at every km (Fig. A8).

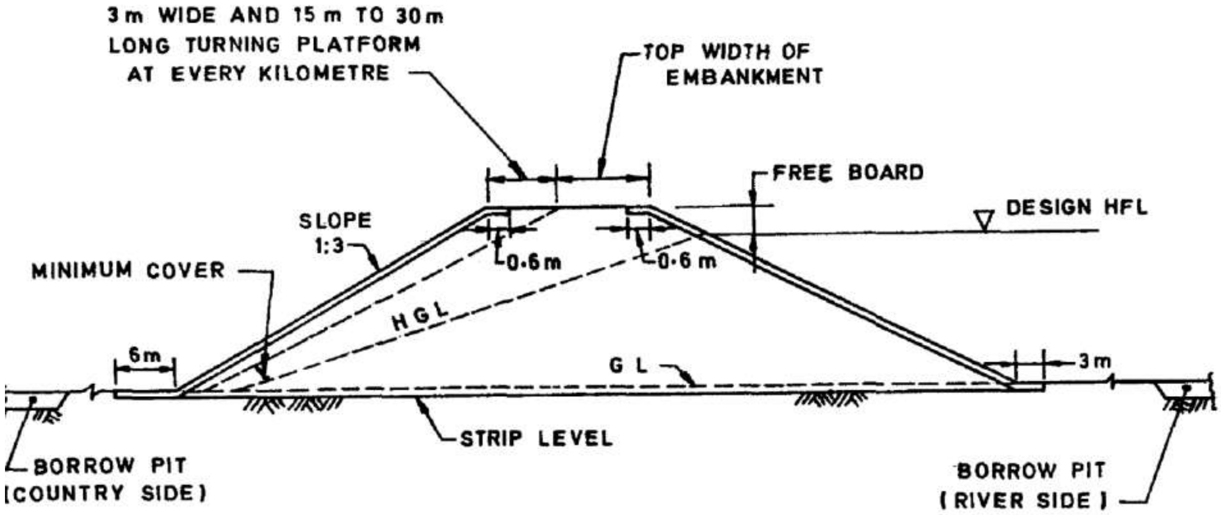


Figure. A8 Typical cross-section showing turning platform

Hydraulic Gradient :

Type of fill	Hydraulic Gradient
Clayey soil	1V: 4H
Clayey sand	1V:5H
Sandy soil	1V:6H

River Side Slope: The river side slope should be flatter than the underwater angle of repose of the material used in fill. Up to an embankment height of 4.5 m, the slope should not be steeper than 1 in 2 and in case of higher embankments slopes should not be steeper than 1 in 3, when soil is good and to be used in the most favorable condition of saturation and drawdown.

a) In case of higher embankment protected by rip-rap, the slope of embankments up to 6 m high may be 1 in 2 or 1 in 2.5 depending upon type of slope protection.
b) If the construction material is sandy, the slope should be protected with a cover of 0.6 m thick good soil.

c) It is usually preferable to have more or less free draining material on the river side to take care of sudden drawdown. In case of high and important embankment stone rip-rap either dry dumped or hand placed and concrete pavements/ concrete blocks with open joints are adopted to protect the embankment against drawdown and/or erosive action of the river; in less important embankments where rip-rap is costly, willow mattress can be used.

Countryside Slope: A minimum cover of 0.6 m over the hydraulic line should be provided.

a) For embankment up to 4.5 m height, the countryside slope should be 1 in 2 from the top up to the point where the cover over HG line is 0.6 m after which a berm of suitable width, with the countryside slope of 1 in 2 from the end of the berm up to ground level should be provided.
b) For embankment of height between 4.5 to 6.0 m, the corresponding slopes with respect to above point (a) should be 1 in 3. Berm should be of width of 1.5 m normally.
c) For embankments of height more than 6.0 m detail design should be made.

A5. PITCHED ISLAND

The device of a pitched island is a recent innovation in the armoury of river training hydraulics. The basic principle underlying the behavior of a pitched island, used as a river training measure, is its ability to cause re-distribution of velocity and tractive force. The tractive force near a pitched island begins to increase rapidly after the construction of the island, with the result that deep scour begins to form round the island and gradually draws the, main river channel into itself and ultimately holds it permanently. Because of this property, the pitched island can be used, either singly or in series for the following purposes:

(i) Correcting oblique approach upstream of weirs, barrages and bridges by training the river to be axial.

(ii) Rectification of adverse curvature for effective sand exclusion.

(iii) Redistributing harmful concentration of flow for relieving attack on marginal bunds, guide banks and river bends.

(iv) Training the river in the reach away from control points.

(v) Improve channel for navigation.

Generally, pitched island consist of a sand core pitched with boulders along its side slopes and protected at the toe by a falling boulder apron. As deep scour occurs round the pitched island creating heavy concentration of flow in its vicinity, the boulder pitching and apron have to be designed for the maximum scour under worst condition, generally taken equivalent to 2R (Lacey).

The general shapes adopted are triangular, elliptical or egg-shaped. Scour at the toe of a steeper slope is deeper that the toe of a flatter slope. The steeper slope, usually 2:1 is adopted on the side on which a concentration of flow is desired, while the flatter slope is given on the side where a throw-off becomes necessary.

A6. DESIGN OF PORCUPINES

According to IRC: 089-1997 and River Behavior Management and Training Volume-I (CBIP, 1989), these is one particular type of permeable spurs which help to induce siltation along the banks. These are made of steel, bamboo or timber and are provided on a scouring bank in a line normal to the flow. These spurs increase the roughness of the channel thereby deflecting the eroding current away from the bank. In course of time, vegetation within the jacks and action of spur is enhanced further.

One type of porcupine, known as Kellner Jack comprises of three steel angles about 5 m long bolted together at the center with the wire string between the legs (Fig. A9).

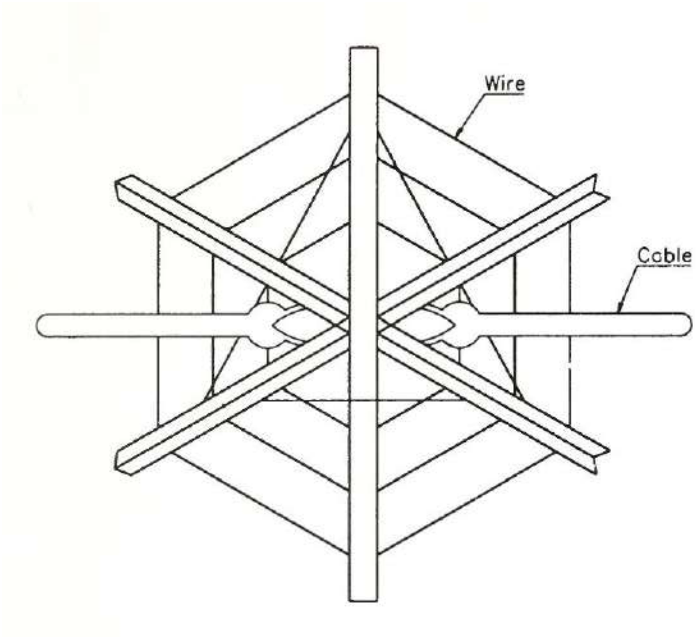


Figure. A9 Kellner Jack type porcupine

Other type of porcupine used for similar purpose is made of bamboo (Fig. A10). These are made of 3 to 6 m long bamboo of 75 mm diameter tied together at the center in the form of a space angle and are weighed down by tying boulder stones packed in wire cage at the center.

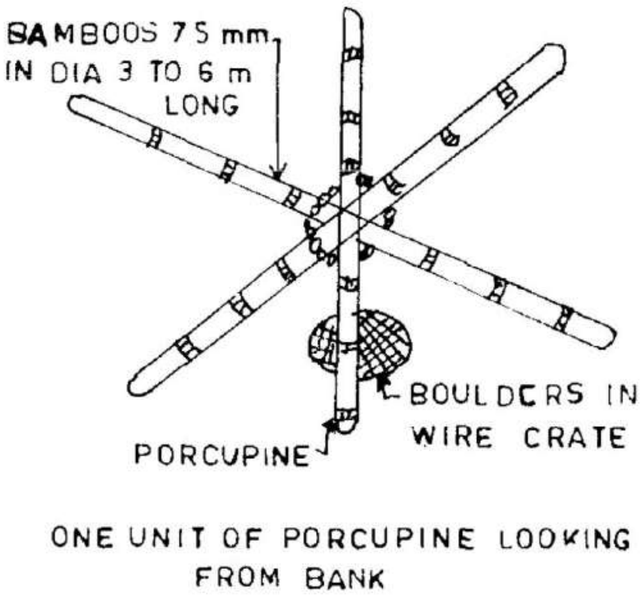


Figure. A10 Bamboo type porcupine

The spacing between the two consecutive units of porcupines will depend upon the desired permeability varying from 30 to 50 %. The spacing of two consecutive rows of porcupines varies from 3L to 4L, where L is the length of spur.

Cribs

These are similar to porcupines with the difference that the ballies/bamboos from a pyramid type structure with a box at the bottom for holding stones for the stability of individual units. The spacing between the consecutive cribs and the consecutive rows of cribs will be similar to that of porcupines.

Balli/bamboo frames

A framed structure made with driven poles of bamboos/shawls with longitudinal, cross and diagonal bracing is constructed across the flow.

Willow/brushwood spurs

Willow is a type of bush available in plenty across the country, has sufficient rigidity and strength are not easily decomposed. These or other brushwood available locally are filled and weighted by heavy stones in alternate layers within the framed structures. Such spurs, however, entrap sediments and lose their initial permeability and eventually behave like impermeable spurs with deep scour near their noses.

Submergence of spurs

Unlike impermeable spurs which are un-submerged with freeboard, permeable spurs may be either un-submerged or submerged. The submergence up to 50% is acceptable for porcupines, 20% for cribs and 5% to 10% for tree and willow spurs with framed structure.

A7. SUBMERGED VANES

Introduction

Recently at Iowa Institute of Hydraulic Research (IIHR) a new technique using submerged vanes has been suggested to alleviate the above sediment problems. The vanes are small submerged flow-training structures or foils designed to modify the near-bed flow pattern and redistribute the flow and sediment transport within the channel cross-section at relatively lesser cost (Fig. A11). Number, size and layout of these vanes depend on the channel, flow and sediment parameters. Vanes stabilize a channel reach without inducing changes upstream or downstream of that reach. Vanes may not be visible at times as they become buried by depositing sediment and assist streams by redistributing the flow energy to produce a uniform cross-section without an appreciable increase in the energy loss through the reach. The vanes function by generating secondary circulation in the flow. The circulation alters magnitude and direction of the bed shear stresses and causes a change in the distribution of velocity, depth, and sediment transport in the area affected by the vanes. As a result, the riverbed aggrades in one portion of the channel cross-section and degrades in another.

The available laboratory and field studies on the submerged vanes reveal that these vanes have broad range of applications in (a) changing the cross-sectional profile of the bed of a straight laboratory channel, (b) protecting the river bend against erosion, (c) reducing the bed load from entering into the water intake, (d) controlling the scour at vertical wall abutments and (e) Checking the shoal formation at pump station intake. To the knowledge of the writers, the vane technique has not been used in India for the sediment management so far in spite of its great potential for the same. However, some laboratory study related to the performance of the submerged vanes in two-meanderings channels and scour near the nose of the vanes have been conducted at IIT Roorkee.

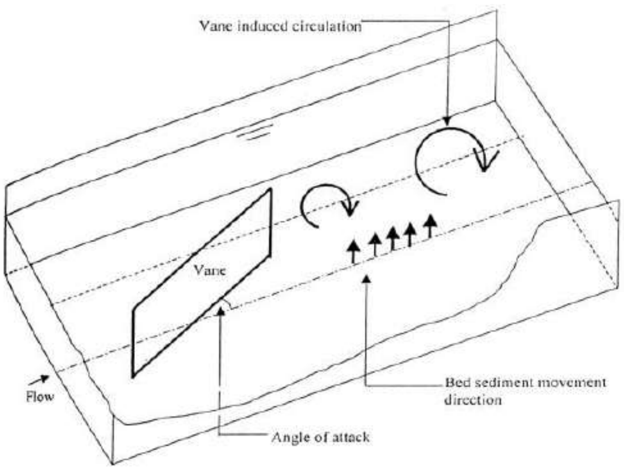


Figure. A11 Definition sketch of a submerged vane

On the basis of theoretical and physical model studies, Odgaard and Kennedy (1983), and Odgaard and Spoljaric (1986) have proposed that short vertical submerged vanes, installed with small angle of incidence to the channel axis in the outer half of a river bend channel, significantly reduce the secondary currents and also the high velocity attack on the outer bank. In addition, these vanes do not increase the local channel roughness as much as other traditional methods do when used for reduction of near bank velocity. On the basis of theoretical studies in a curved channel Odgaard and Wang (1991a, b) have shown that vanes having height equal to 0.2–0.4 times the local water depth and installed at an angle of attack within 15^0- 25^0 with the flow are quite successful in straight as well as meandering channels. Their findings also reveal that by introducing relatively small changes in the bed shear stresses, array of vanes could generate local changes in the bed elevation of the order of vane height. Odgaard and Mosconi (1987) carried out laboratory tests and found that the vane system does not interfere with the overall sediment balance and stability of channel while protecting the bank. Experimental work of Johnson et al. (2001) using rock vanes, angled to the flow and embedded into the stream bed such that the tip of the vane is submerged even during low flow, also clearly demonstrates the effectiveness of vanes for preventing scour at vertical wall abutments. Sinha and Marelius (2000) have shown that the optimal angle of attack close to 40^0 produces strongest vane-induced circulation. Islam et al. (2003) carried out experiments on both straight and curved reaches and have shown that for straight reach, increasing the angle of attack in a vane array results in increasing the navigation depth.

Laboratory study of Barkdoll et al. (1999) shows that submerged vanes placed at the diversion entrance admits only a negligible rate of bed-sediment entry into the water intake when the ratio of unit discharge in the diversion to unit discharge in the main channel q_r is less than about 0.2. Beyond this value, the effectiveness of the vanes diminishes.

The performance of vanes for sediment control can be enhanced in several ways. One is to use of a skimming wall in conjunction with the vanes and this is effective for values of q_r up to about 0.3. Another way is to widen the diversion entrance such that at the entrance q_r does not exceed about 0.3. Further enhancements like modified vane shape, uniformity of flow distribution into the diversion, and increased flow velocity into the diversion are not effective.

Figures A12a and A12b show a system of submerged vanes used by Odgaard and Mosconi (1987) to protect the bank erosion of a bend of Wapsipinicon River, Iowa. Fig. A12(a) shows vanes being installed in the bend in the summer of 1988 during low-flow, and the condition of the same bend two years later; Fig. A12(b). Substantial deposition of sediment induced by these vanes can be clearly seen in Fig. A12(b), thus demonstrating the capacity of these vanes in preventing the scour along the river bend.

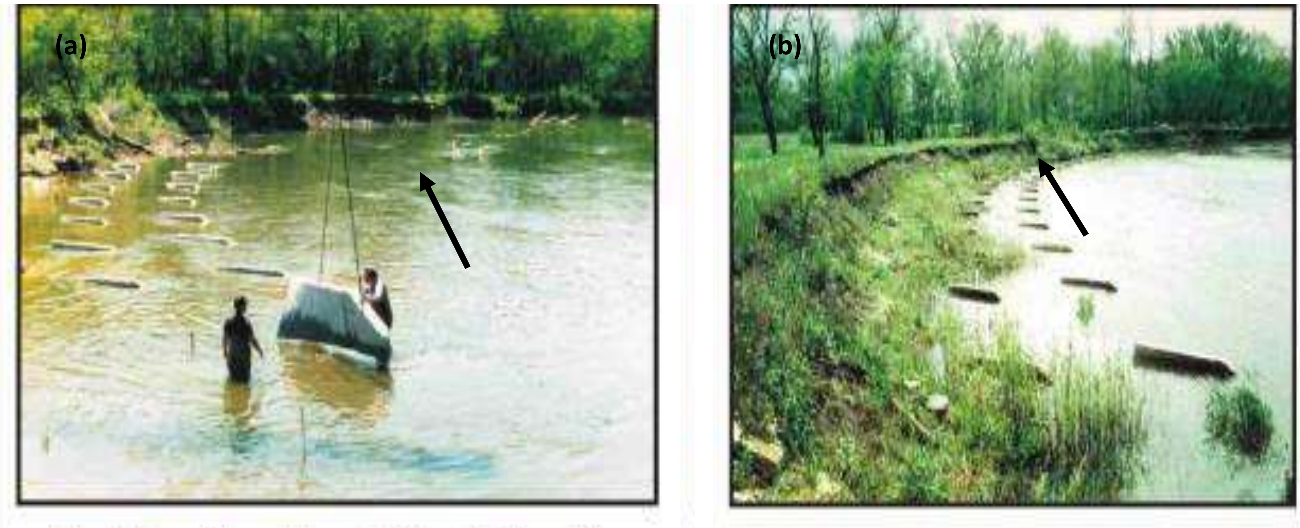


Figure. A12 Installation of Iowa Vanes in Wapsipinicon river bend
(a) During low flow in the Summer of 1988 (b) Low flow, May 10, 1990

Submerged vanes installed outside a water intake on Kosi River in Nepal is shown in Fig. A13. The vane system prevents sediment from being entrained into the intake (left). Each vane is 6 m long and 1.5 m-tall (with 0.8 m of vane below average bed level). Longitudinal spacing varies between 30 m and 40 m; lateral spacing is 5 m.

2. Design of a Submerged Vane System

The design variables of a vane system are shown in Fig. A14. The design procedure generally consists of selecting values of vane height H_0, vane length L, angle of incidence α, vane submergence T, vane spacings δ_n and δ_s, and vane-to-bank distance δ_b using the following known values: (a) the average depth of flow prior to the vane installation, d_0; (b) the velocity in the channel u_0; (c) the resistance parameter m; (d) the channel's width-depth ratio b/d_0; (e) the radius of bend-width ratio r/b; and (f) the sediment Froude number F_D, defined as $F_D = u_0 / \sqrt{gD}$ where g = acceleration due to gravity; and D = median grain diameter. The resistance parameter, m is defined as $m = \kappa\sqrt{8/f}$, where f = friction factor and κ =Karman's constant taken as 0.4.

Figure. A13 Vanes installed at a water intake on Kosi river, Nepal

To facilitate design, Odgaard and Wang (199a,b) prepared a number of graphs relating maximum changes in depth of flow d_0–d_v, as a function of vane, flow and sediment parameters where d_0 = maximum pre-vane flow depth; and d_v = vane induced flow depth. These graphs were prepared for arrays with one, two, and three vanes arrangement; relative vane submergence of T/d_0=0.5, 0.7, and 1.0; Froude numbers F_D = 5, 15, and 25; aspect ratio of H_0/L=0.3; angle of incidence $\alpha = 20^0$; and resistance parameter m = 4 and 3. Further these graphs were for vane spacing of $\delta_n = 3H_0$ and $\delta_s = 15H_0$ and $30H_0$, and for channels with depth-width ratio of 0.03. In these graph the values of $(d_0–d_v)/d_v$ were shown as function of width/radius of river bend (b/r). For a straight channel, radius of the bend can be considered as infinity. Therefore, width/radius tends to zero. For this value of b/r ,i.e, for straight channel the value of $(d_0–d_v)/d_v$ was found to be zero for T/d_0 = 1. This shows that for straight channels, vanes will not have any effect on bed level variation if relative submergence is close to unity. The design chart as proposed by Odgaard and Wang (1991a) can be reproduced in a tabular form as shown in Table A2.

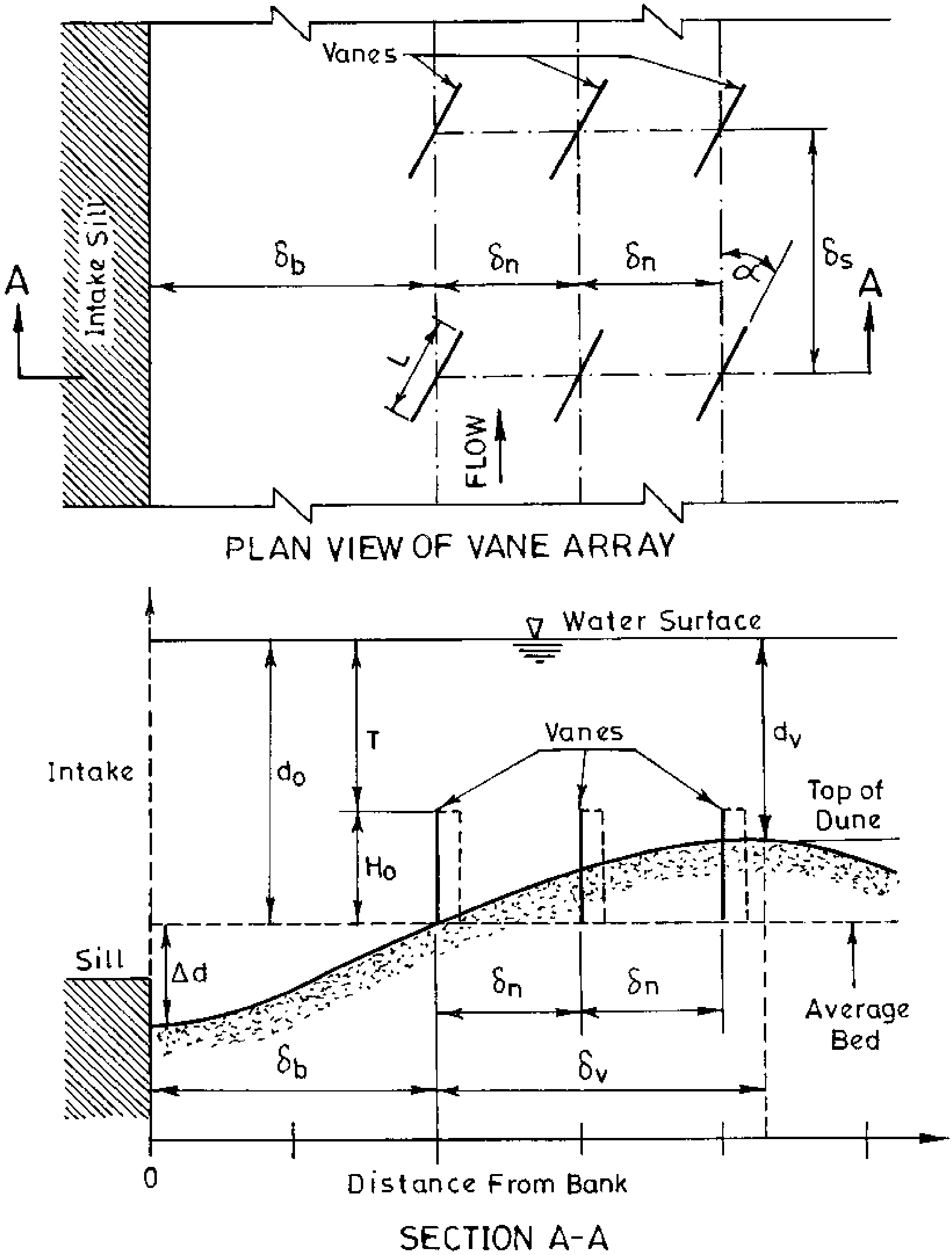


Figure. A14 Design variables of a submerged vane system

Table A2 Vane induced maximum increase in bed level along the bank of a stream.

F_D	m	$(d_0\text{-}d_v)/d_0$											
		Three vanes array				Two vanes array				One vane array			
		T/d_o=0.5	0.5	0.7	0.7	0.5	0.5	0.7	0.7	0.5	0.5	0.7	0.7
		$\delta s/H_o$=15	30	15	30	15	30	15	30	15	30	15	30
5	4	0.20	0.20	0.18	0.15	0.16	0.15	0.12	0.10	0.10	0.09	0.07	0.05
5	3	0.25	0.20	0.20	0.16	0.20	0.16	0.14	0.11	0.12	0.10	0.08	0.05
15	4	0.46	0.40	0.30	0.27	0.36	0.34	0.25	0.23	0.24	0.2	0.17	0.13
15	3	0.50	0.45	0.30	0.28	0.45	0.38	0.30	0.25	0.26	0.22	0.2	0.15
25	4	0.50	0.50	0.30	0.28	0.50	0.45	0.30	0.30	0.4	0.34	0.25	0.22
25	3	0.50	0.50	0.30	0.28	0.50	0.50	0.30	0.30	0.41	0.35	0.30	0.30

3. Design Procedure

At the design stage, the depth of the flow d_0, bed slope of the river S, velocity in the channel u_0, and median size of sediment D are known. If the vane system is to be designed for a river bend, the radius of the bend r is also known. However, for the installation of vane in straight channel like in the case of water intake, radius of the bend will be equal to infinity. Assuming the channel to be wide, calculate $\sqrt{8/f} = u_o/\sqrt{(gSd_o)}$ and then the channel's resistance parameter $m = \kappa\sqrt{8/f}$. Also calculate the sediment Froude number from the median diameter of the sediment. Odgaard and Wang (1991a) and Odgaard and Kenedy (1983) recommended that the height of vane H_0 should be equal to 0.2 -0.4 times the depth of flow. Choose some value of T/d_0 out of 0.5, 0.7 and 1.0. Calculate the length of vane L keeping the aspect ratio H_0/L=0.3. Take $\delta_n = 3H_0$ and $\delta_s = 15H_0$ or $30H_0$. Now corresponds to known values of T/d_0, m, δ_s/H_0, F_D, b/r and number of vanes per array, read $(d_0\text{–}d_v)/d_0$ from the Table 1. Finally, one can calculate the vane-induced depth of flow d_v. It is to be noted that a number of alternate designs are possible for a specific problem.

A8. FLOOD RETAINING WALL

There a several types of floodwalls, including gravity, cantilever, buttress and counter fort. The gravity and cantilever floodwalls are the more commonly used types.

Gravity Floodwalls

As its name implies, a gravity floodwall depends upon its weight for stability. The gravity wall's structural stability is attained by effective positioning of the mass of the wall, rather than the weight of the retained materials. The gravity wall resists overturning primarily by the dead weight of the concrete and masonry construction.

Frictional forces between the concrete base and the soil foundation generally resist sliding of the gravity wall. Soil foundation stability is achieved by ensuring that the structure neither moves nor fails along possible failure surfaces. Gravity walls are appropriate for low walls or lightly loaded walls. They are relatively easy to design and construct. The primary disadvantage of a gravity floodwall is that a large volume of material is required. As he required height of a gravity floodwall increases, it becomes more cost-effective to use cantilever wall.

Cantilever Floodwall

A cantilever wall is reinforced-concrete wall that utilizes cantilever action to retain the mass behind the wall. Stability of this type of wall is partially achieved from the weight of the soil on the heel portion of the base. A comfortable safety factor is taken when considering the unpredictability of the flood. Backfill can be placed along the outside face of the wall to keep water away from the wall during flooding conditions.

Buttressed Floodwall

A buttressed wall is very similar to a counterfort wall. The only difference between the two is that the transverse support walls are located on the side of the stem, opposite the retained materials. The counterfort wall is more widely used than the buttress because the support stem is hidden beneath the retained material, whereas the buttress occupies what may otherwise be usable space in front of the wall.

Counterfort floodwall

A counterfort wall is similar to a cantilever retaining wall except that it can be used where the cantilever is long or when very high pressures are exerted behind the wall. Counterforts or intermediate traverse support bracing, are designed and built at intervals along the wall and reduce the design forces.

Floodwall design

(i) Determine wall height and footing depth

(a) Determine wall height based on the highest flood level (HFL) plus 1.5 m of freeboard.

(b) Determine minimum footing depth based on the Lacey scour depth. Take depth of foundation at $1.5d_{sm}$, where d_{sm} mean depth of scour

(ii) Assume dimensions

Based on the following guidelines or reference to engineering handbooks, assume dimensions for the wall thickness, footing width and footing thickness.

(a) The choice of wall thickness depends on the wall material, the strength of material and the height of the wall. Typical wall thicknesses are 8, 12 and 16 inches for masonry, concrete or masonry/concrete walls.

(b) The footing width depends on the magnitude of the lateral forces, allowable soil bearing capacity, dead load and wall height. Typically, the footing is located under the wall in such a manner that 1/3 of its width forms the toe and 2/3 of the width forms the heel of the wall. Typical footing thickness is based upon strength requirements.

(iii) Calculate forces

There are two types of forces acting on all and its footing: lateral and vertical.

(a) Vertical forces: The vertical forces are buoyancy and the various weights of the wall, footing, soil and water acting upward on the floodwall.

Lateral forces: These forces are mainly the hydrostatic and differential soil/water forces on the heel side of the wall and the saturated soil force on the toe side of the wall.

Annexure-B

FLEXIBLE SYSTEM IN FLOOD CONTROL AND MITIGATION PLAN

I. Use of Geo-Textile Filters in Flood Management Works

For better performance of embankments, retaining walls, pavements and other structures, drains are provided to relieve hydrostatic pressure by allowing passage of water while preventing loss of soil. Traditionally granular filters are provided to serve these two functions. In last 25 years or so, geo-textile filters have emerged as a better alternative to traditional granular filter but since long term experience is limited, geo-textiles should not be used as a substitute for granular filter within or on the upstream face of earth dams or within any inaccessible portion of the dam embankment. Caution is advised in using geotextiles to wrap permanent peizometers and relief wells where they form part of the safety system of a water retaining structure.

During monsoon period, rivers undergo bank and bed erosion at many stretches. Traditionally anti-erosion works to protect river bank and bed consists of a granular filter below the revetment and also below apron at Low Water Level (LWL). This anti-erosion work provides a good protection against erosion by preventing excessive migration of soil particles, while at the same time allowing water to flow freely through the filter layer. But this granular filter is often difficult to obtain, expensive to purchase, time consuming to install and segregates during placement, thus compromising its filtration ability. While the launching elements slide easily over the subsoil, they do not do so over each other. The falling apron, therefore, results in an about one-layer thick coverage. This layer is not stable and prone to loss of fines through the gaps in the protection. Many of the shortcomings of traditional filter can be overcome using geotextiles. Specially, a single layer of geo-textile fabric can replace a graded filter comprising of two or three layers. Geo-textiles are easy to install, especially, working underwater becomes much easier because the filter system can be assembled above the water and lowered into position. On negative side, geotextiles are sensitive to UV exposure and punching. Due care, therefore, must be taken while the installation of geo-textiles. Geo-textiles are comparatively costlier but more effective with longer serviceability.

Design of Bank Protection/ Anti-Erosion/ River Training works using Geo-textile Filters

Geo-textiles are frequently used in armoured erosion control and drainage applications. Geo-textiles are used to retain soil particles while allowing liquid topass freely. Designing with geo-textiles for filtration is essentially the same as designing graded granular filters.

Mechanism of Filtration

A filter should prevent excessive migration of soil particles, while at the same time allowing liquid to flow freely through the filter layer. Filtration is therefore summarized by two seemingly conflicting requirements:

1. The filter must retain soil, implying that the largest size of filter pore spaces or openings should be smaller than a specified maximum value; and
2. The filter must be permeable enough to allow a relatively free flow through it, implying that the openings of the geo-textile filter are sufficiently large enough and in large number to allow water flow while preventing clogging.

Design Philosophy

The design philosophy includes the estimation of scouring potential of river which is a function of the discharge intensity and Lacey's scour depth. The fineness of riverbed material is indicated in terms of silt factor which along with discharge intensity governs the Lacey's scour depth. The thickness of sloped bank pitching is determined on the basis of velocity of flow along the bank. Thickness and length of launching apron is determined once the scour depth, High Flood Level (HFL), and Low Water Level (LWL) are known. Proper drainage arrangement behind revetment is necessary. A suitable filter is also provided below the sloped pitching and launching apron to prevent fine soil particles from being removed. The provisions regarding Design of revetment and design of apron are available in IS 14262 and IS 10751, respectively.

Design of Geo-textile Filter

Before the introduction of geo-textiles, granular materials were widely used as filters for geotechnical engineering applications. Drainage criteria for geo-textile filters are largely derived from those for granular filters. The criteria for both are, therefore, similar. In addition to retention and permeability criteria, several other considerations are required for geo-textile filter design. Some considerations are noted below:

1. Retention: Ensures that the geo-textile openings are small enough to prevent excessive migration of soil particles.
2. Permeability: Ensures that the geo-textile is permeable enough to allow liquids to pass through without causing significant upstream pressure build up.
3. Anti-clogging: Ensures that the geo-textile has adequate openings, preventing trapped soil from clogging openings and affecting permeability.
4. Survivability: Ensures that the geo-textile is strong enough to resist damage during installation.
5. Durability: Ensures that the geo-textile is resilient to adverse chemical, biological and ultraviolet (UV) light exposure for the design life of the project.

The specified numerical criteria for geo-textile filter requirements depends on the application of the filter, filter boundary conditions, properties of the soil being filtered, and construction methods used to install the filter. These factors are discussed in the following step-by-step geo-textile design methodology.

Design Methodology

The proposed design methodology represents years of research and experience ingeo-textile filtration design. The approach presents a logical progression through seven steps.

Step 1: Determine Soil Retention Requirements
Step 2: Define Boundary Conditions
Step 3: Define the Application of Filter Requirements
Step 4: Determine Permeability Requirements
Step 5: Determine Anti-Clogging Requirements
Step 6: Determine Survivability Requirements
Step 7: Determine Durability Requirements

STEP 1: DETERMINE SOIL RETENTION REQUIREMENTS

Analysis of the soil to be protected is critical to proper filtration design. The particle-size distribution of the soil to be protected should be determined using test method ASTM D 422. The grain size distribution curve is used to determine parameters necessary for the selection of numerical retention criteria.
The maximum allowable opening size (O95) of the geo-textile is one that will provide adequate soil retention. It is also known as the geo-textile's Apparent Opening Size (AOS) and is determined from test procedure ASTM D 4751. AOS can often be obtained from manufacturer's literature.

STEP 2: DEFINE BOUNDARY CONDITIONS

Confining Stress: The confining pressure is important for several reasons:

1. High confining pressures tend to increase the relative density of coarse grained soil, increasing the soil's resistance to particle movement. This affects the selection of retention criteria.
2. High confining pressures decrease the hydraulic conductivity of fine grainedsoils, increasing the potential for soil to intrude into, or through, and thegeo-textile filter.
3. For all soil conditions, high confining pressures increase the potential for thegeo-textile and soil mass to intrude into the flow paths. This can reduce flow capacity within the drainage media, especially when geo-synthetic drainagecores are used.

Flow Conditions: Flow conditions can be either steady-state or dynamic. Defining these conditions is important because the retention criteria for each are different. Examples of applications with steady-state flow conditions include standard dewatering drains, wall drains and leachate collection drains. Inland waterways and shoreline protection are typical examples of applications where waves or watercurrents cause dynamic flow conditions.

STEP 3: DEFINE THE APPLICATION OF FILTER REQUIREMENTS

Geo-textile filters are used between the soil and drainage or armoring medium. Typical drainage media include natural materials such as gravel and sand, as well as geo-synthetic materials such as geo-nets and cuspated drainage cores. Armoring material is often Revetment/ foundation or concrete blocks. Often, anarmoring system includes a sand bedding layer beneath the surface armour. The armoring system can be considered to act as a "drain" for water seeping from the protected slope.

Drainage Material: The drainage medium adjacent to the geo-textile must be identified. The primary reasons for this include:

1. Large voids or high pore volume can influence the selection of the retention criterion
2. Sharp contact points such as highly angular gravel or rock will influence the geosynthetic survivability requirements

STEP 4: DETERMINE PERMEABILITY REQUIREMENTS

Soil Permeability (ks): The soil permeability should be lab measured using representative field conditions in accordance with test procedure ASTM D 5084.
Minimum Allowable Geo-textile Permeability (kg): The requirement of geotextile permeability can be affected by the filter application, flow conditions and soil type. The following equation can be used for all flow conditions to determine the minimum allowable geo-textile permeability (Giroud, 1988):

$kg \geq is.ks$; where:

kg= minimum allowable geo-textile permeability

ks= the soil permeability

is= desired hydraulic gradient (based upon the filtration application)

Permeability of the geo-textile can be calculated from the permittivity test procedure (ASTM D 4491). This value is often available from manufacturer'sliterature. Geo-textile permeability is defined as the product of the permittivity, Ψ, and the geo-textile thickness, tg:kg= Ψ.tg

STEP 5: DETERMINE ANTI-CLOGGING REQUIREMENTS

To minimize the risk of clogging, one should follow the provisions of IS 14262.

STEP 6: DETERMINE SURVIVABILITY REQUIREMENTS

Minimum strength properties of the geo-textile fabric should be specified that fit with the severity of the installation procedure, to ensure construction survivability.

STEP 7: DETERMINE DURABILITY REQUIREMENTS

During installation, if the geo-textile filter is exposed to sunlight for extended periods, high carbon black content and UV stabilizers are recommended for added resistance to UV degradation. Polypropylene is one of the most durable geo-textiles today. It is inert to most naturally occurring chemicals in civil engineering applications.

However, if it is known that the geo-textile may exposed to adverse chemicals (such as in waste containment landfill applications), use test method ASTM D5322 to determine its compatibility.

BIS Specifications (IS 14262):

Geo-textile filters may be recommended because of ease in installation and their proven effectiveness as an integral part of protection works. A 15 cm layer of sandis provided over filter fabric to avoid its mechanical rupture by protection material. The following criteria, depending on the gradation of bed material, may be used to select the correct filter fabric:

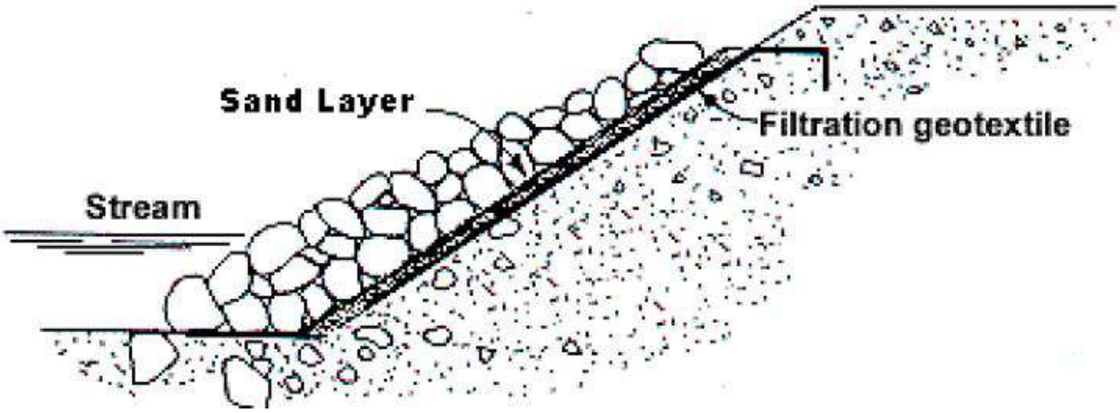
a) For granular material containing 50 percent or less fines by weight, the following ratio should be satisfied:

$$\frac{85\%\ passing\ size\ of\ bed\ material\ (mm)}{Equivalent\ opening\ size\ of\ bed\ of\ fabric\ (mm)} \geq 1$$

   In order to reduce the chances of clogging, no fabric should be specified with an equivalent opening size smaller than 0.075 mm. Thus the equivalent opening size of fabric should not be smaller than 0.149 mm and should be equal to or less than 85 percent passing size of the bed material.

b) For bed material containing at least 50 percent but not more than 85 percent fines by weight, the equivalent opening size of filter should not be smaller than 0.149 mm and should not be larger than 0.211 mm.

c) For bed material containing 85 percent or more of particles finer than 0.074 mm, it is suggested that use of non-woven geo-fabric filter having opening sizeand permeability compatible to the equivalent values given in a) above may be used.



Typical Layout

II. Use of Geo-bags/ Geo-textile in Flood Management Works/ Anti-Erosion Works

Erosion is caused by a group of physical and chemical processes by which the soil or rock material is loosened, detached, and transported from one place to another by flowing water, waves, wind, moving ice, or other geological sheet and bank erosion agents. Clayey soils are less erodible than fine sands and silts.

Boulders are used conventionally for revetment / apron in the country. It is neither cost effective (at location where its availability is less) nor environmental friendly. Transporting and handling the material to work site is also difficult. Geo-Bags is a appropriate alternative; which are cost effective in long term. Bags can be transported long distance and filled at site and also the handling the Geo-Bags is easier than boulders. They are also sufficiently durable if not exposed to sunlight. Geo-bags are flexible armour system made of Geo-textile, fabricated in form of bags. They can be designed in any size and shape depending on site requirement and can be filled with locally available material (local earth). Geo-bags are well proven system of erosion control across the world. Geo-textile bags are made of woven or non woven geo-textile fabrics which are specially designed for good soil tightness and high seam efficiency. Geo-textile bags range in volume from 0.05 m^3 to around 5 m^3, and are pillow shaped, box shaped or mattress shaped depending on the required application. Geo-textile bags have also been used as revetment, breakwaters, etc to build erosion protection measures.

Design of anti-erosion works using Geo-Textile

Geo-textile bags as protective elements have to satisfy four main criteria

1. Stability against flow and wave attack
Field Experience and Physical Modeling indicated that bags of 126 Kg are stable to depth-avg. velocity of 3 m/s and that only very few bags would displace at high velocities of 4.5 m/s.

2. Filtration

Geo-textile in the Bags also to act as filter for preventing loss of fines between bags, this type of failure is called as winnowing failure. This can be prevented by using multiple layer coverage.

3. Launching

4. Longevity
- UV stability
- Abrasion resistance

Design steps
- Application evaluation
- Obtain soil samples from the site
- Evaluate armor material and placement
- Calculate anticipated reverse flow through erosion control system.
- Determine geo-textile requirements
  - Retention criteria
  - Permeability criteria
  - Clogging criteria
- Estimate costs
- Prepare specifications
- Obtain samples of the geo-textile before acceptance.
- Monitor installation during construction and control drop height. Observeerosion control systems during and after significant storm events.
-

The provisions regarding design of revetment and design of apron are available in IS 14262 and IS 10751 respectively. All structural parameter need to be designed similar to revetment/ spur using boulders.

Size of Bags

- For velocity up to 3 m/s, bags of size 1.1m x 0.7m x 0.15m (weight around 126 kg) may be used.
- For higher velocity, weight should be more than that calculated as under:

$$W = \frac{0.0232\ 3\ S_s}{K\,(S_s - 1)^3} V^6$$

$$K = \left[1 - \frac{\sin^2\theta}{\sin^2\phi}\right]^{\frac{1}{2}}$$

where

W - weight in kg

V – velocity in m/sec

Ss - Specific Gravity of protection material (adopted between 1.5 to 1.8)

θ - Angle of sloping bank

φ - Angle of repose of protection material

- The geo-synthetic material should be safe against the UV rays and abrasion.

Thickness of Pitching

- Thickness should be more than that calculated as under:

$$T = \frac{V^2}{2\,g\,(S_s - 1)}$$

T - thickness in m

V – velocity in m/sec

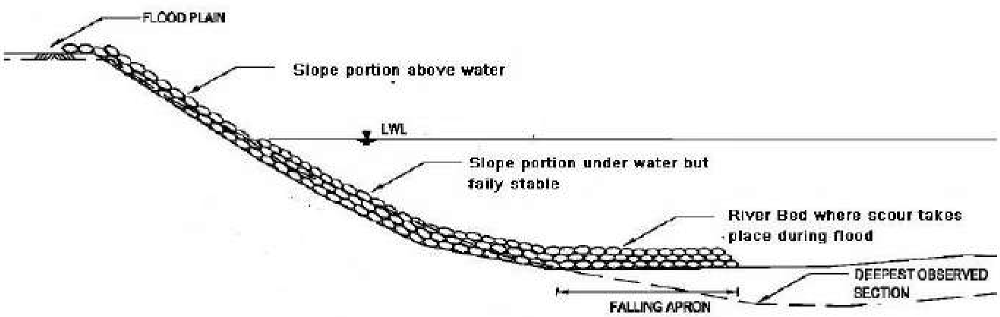
Ss - Specific Gravity of protection material (adopted between 1.5 to 1.8)

g - Acceleration due to gravity (9.81 m/s^2)

- Pitching may be provided in double layers of geo-bags (in loose) and single layer (encased with nylon/polypropylene ropes)

Filter

- A layer of Geo-textile filter may be provided under Geo-Bags.



Typical layout

III. Use of Geo-tubes/ Geo-textile in Flood Management Works/Embankments

Geo-tubes are basically containment systems in tubular forms filled with locally available sand which are formed in-situ on land or in water to protect shore and marine environments. It is in tubular shape made of geo-textile and is generally filled with sand or dredged material. These tubes are generally about 1 m to 3 m in diameter, though they can be customized to any size depending on their application. Today, geo-textile tubes ranging in diameters from 1.5 m to 5.0 m are used in many coastal and flood protection applications.

Earthen embankments are constructed for Flood Protection. Availability of good quality earth is a major bottle neck in ensuring the quality of embankment. Embankment quality can be substantially improved by the use of geo-tubes. Use of geo-tubes also provides enhanced security against breach and hence reduces investment on anti-erosion measures. Geo-tubes are very effective in breach closure without back shifting.

Quite often, conventional construction techniques will not allow dikes or levees to be constructed on very soft foundations because it may not be cost effective, operationally practical, or technically feasible. Nevertheless, geo-tube reinforced dikes have been designed and constructed. Geo-tubes used in those dikes alleviated many soft-ground foundation dike construction problems because they permit better equipment mobility, allow expedient construction, and allow construction to design elevation without failure. Embankments constructed on soft foundation soils have a tendency to spread laterally because of horizontal earth pressure acting within the embankment. These earth pressures cause horizontal shear stresses at the base of the embankment which must be resisted by the foundation soil. If the foundation soil doesn't have adequate shear resistance, failure can result.

Design of Embankments using Geo-Tube

The cross section of the embankment made using Geo-tube is to be designed as per usual earthen embankment. The Geo-Tubes are placed in the core of such embankment generally in a pyramid shape. As with ordinary embankments on soft soils, the basic design approach for reinforced embankment is to design against failure. To successfully design a dike on a very soft foundation, three potential failure modes must be investigated:

- Horizontal sliding and spreading of the embankment and foundation.
- Rotational slope and/or foundation failure.
- Excessive vertical foundation displacement.

The geo-tube must resist the unbalanced forces necessary for dike stability and must develop moderate-to-high tensile forces at relatively low-to moderate strains. It must exhibit enough soil fabric resistance to prevent pullout. The geo tube tensile forces resist the unbalanced forces, and its tensile modulus controls the vertical and horizontal displacement of dike and foundation. Adequate development of soil-geo-tube friction allows the transfer of dike load to the geo-tube.

Developing geo-tube tensile stresses during construction at small material elongations or strains is essential. In addition, potential creep of the reinforcement must also be considered. Because the most critical condition for embankment stability is at the end of the construction, the reinforcement only has to function until the foundation soils gain sufficient strength to support the embankment.The cross section of the embankment made using Geo-Tube is to bedesigned as per usual earthen embankment. The Geo-Tubes are placed in the core of such embankment generally in a pyramid shape. Double layer of sheets of woven textiles is also used for added UV protection for a prolonged life and sufficient abrasion resistance.

Design Steps

The following is a step-by-step procedure for design of reinforced embankments.

STEP 1 Define embankment dimensions and loading conditions

A. Embankment height, H
B. Embankment length
C. Width of crest

D. Side slopes, b/H

E. External loads

- Surcharges
- Temporary (traffic) loads
- Dynamic loads

F. Environmental considerations

- Frost action
- Shrinkage and swelling
- Drainage, erosion and scour

G. Embankment construction rate

- Project constraints
- Anticipated or planned rate of construction

STEP 2 Establish the soil profile and determine the engineering properties of the foundation soil

A. From a subsurface soils investigation, determine

- Subsurface stratigraphy and soil profile.
- Groundwater table (location, fluctuation)

B. Engineering properties of the sub-soils

- Undrained shear strength, cu, for end of construction
- Drained shear strength parameters, c' and Φ', for long-term conditions.
- Consolidation parameters (Cc, Cr, cv, σP ')

- Chemical and biological factors that may be detrimental to the reinforcement

C. Variation of properties with depth and areal extent.

STEP 3 Obtain engineering properties of embankment fill materials

- Classification properties
- Moisture-density relationships
- Shear strength properties
- Chemical and biological factors that may be detrimental to the reinforcement.

STEP 4 Establish minimum appropriate factors of safety and operational settlement criteria for the embankment. Suggested minimum factors of safety are as follows

- Overall bearing capacity: 1.5 to 2
- Global (rotational) shear stability at the end of construction: 1.3
- Internal shear stability, long – term: 1.5
- Lateral spreading (sliding): 1.5
- Dynamic loading: 1.1
- Settlement criteria: dependent upon project requirements

STEP 5 Check bearing capacity

A. When the thickness of the soft soil is much greater than the width of theembankment, use classical bearing capacity theory : $q_{ult} = \gamma_{fill} * H = cuNc$; Where Nc, the bearing capacity factor, is usually taken as 5.14 – the value for a strip footing on a cohesive soil of constant un-drained shear strength, cu, with depth.This approach underestimates the bearing capacity of reinforced embankments.

B. When the soft soil is of limited depth, perform a lateral squeeze analysis.

STEP 6 Check rotational shear stability

Perform a rotational slip surface analysis on the unreinforced embankment andfoundation to determine the critical failure surface and the factor of safety againstlocal shear instability.

A. If the calculated factor of safety is greater than the minimum required, then reinforcement is not needed. Check lateral embankment spreading (Step 7).

B. If the factor of safety is less than the required minimum, then calculate the required reinforcement strength, Tg, to provide an adequate factor of safety where :

$$T_g = \frac{FS\,(M_D) - M_R}{R\cos(\theta - \beta)}$$

STEP 7 Check lateral spreading (sliding) stability

Perform a lateral spreading or sliding wedge stability analysis

A. If the calculated factor of safety is greater than the minimum required, thenreinforcement is not needed for this failure possibility.

B. If the factor of safety is inadequate, then determine the lateral spreading strength of reinforcement, Tls required. Soil/geo-synthetic cohesion, Ca should be assumed equal to 0 for extremely soft soils and low embankments. A cohesionvalue should be included with placement of the second and subsequent fills in staged embankment construction.

C. Check sliding above the reinforcement.

STEP 8 Establish tolerable geosynthetic deformation requirements and calculatethe required reinforcement modulus, J, based on wide width (ASTM D4595) tensile testing.

Reinforcement Modulus: $J = T_{ls} / \epsilon_{geosynthetic}$

Recommendations for strain limits, based on type of fill soil materials and for construction over peats, are:

Cohesonless soils: $\epsilon_{geosynthetic}$ = 5 to 10%

Cohesive soils: $\epsilon_{geosynthetic}$ = 2%

Peats: $\epsilon_{geosynthetic}$ = 2 to 20%

STEP 9 Establish geosynthetic strength requirements in the embankment's longitudinal direction (i.e. direction of the embankment alignment).

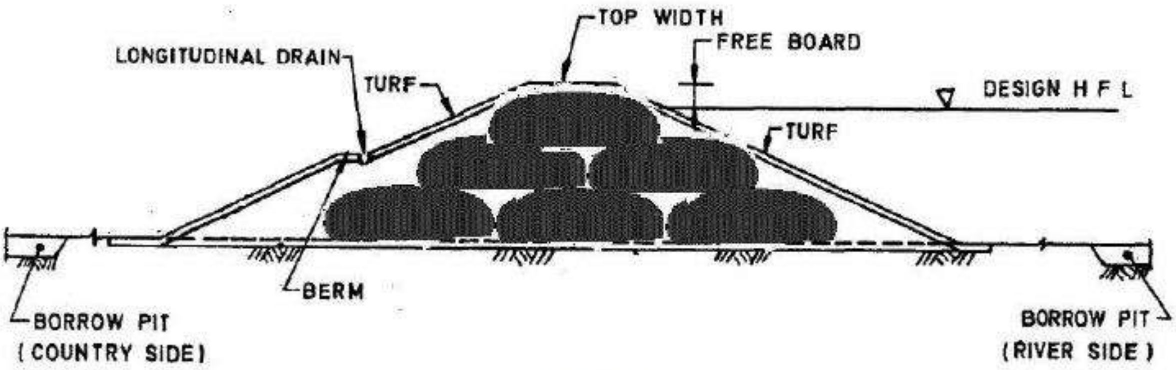
A. Check bearing capacity and rotational slope stability at the ends of the embankment (Steps 5 and 6)
B. Use strength and elongation determined from Steps 7 and 8 to control embankment spreading during construction and to control bending following construction.
C. As the strength of the seams transverse to the embankment alignment control strength requirements, seam strength requirements are the higher of thestrengths determined from Steps 9A or 9B.

STEP 10 Establish geosynthetic properties.

A. Design strengths and modulus are based on the ASTM D 4595 wide width tensile test. This test standard pewits definition of tensile modulus in terms of:
(i) initial tensile modulus; (ii) offset tensile modulus; or (iii) secant tensile modulus. Furthermore, the secant modulus may be defined between any two strain points. Geosynthetic modulus for design of embankments should be determined using a secant modulus, defined with the zero strain point anddesign strain limit (i.e., 2 to 10%) point.
B. Seam strength is qualified with ASTM D 4884 test method, and is equal to the strength required in the embankment's longitudinal direction.
C. Soil-geosynthetic friction, Φsg , based on ASTM D 5321 with on-site soils. For preliminary estimates, assume $\Phi sg = 2/3\Phi$; for final design, testing is recommended.
D. Geo-textile stiffness based on site conditions and experience.
E. Select survivability and constructability requirements for the geosynthetic based on site conditions, backfill materials, and equipment.

STEP 11 Estimate magnitude and rate of embankment settlement- Use conventional geotechnical procedures and practices for this step.
STEP 12 Establish construction sequence and procedures.
STEP 13 Establish construction observation requirements.
STEP 14 Hold preconstruction meetings- Consider a *partnering* type contract with a disputes resolution board.
STEP 15 Observe construction.

Geo-textile tubes fabric undergoes several stress cycles during its installation as well as during its life cycle. Theoretically the tube fabric is subjected to maximum stresses, both in circumferential and axial, directions at the time of filling. The Geo-textile skin of the Tube and it's component parts should have adequate tensile strength to resist the various forces generated during filling as well as during the life time of the structure. The required Ultimate Tensile Strengthof the Geo-textile Tube Fabric is: [Tu]c>= FS [Tu]c
The FS must account for factors such as Geotextile Tensions, Creep, seam factors and Durability. If any specific analysis is not undertaken a minimum FS of 4-5 shall be applied. With this the required fabric strength should be 150 N/mm^2.



Typical layout

IV. Use of Gabion Revetments as Anti-Erosion Works

Wire-enclosed rock, or gabion, revetments consist of rectangular wire mesh baskets filled with rock. These revetments are formed by filling pre-assembled wire baskets with rock, and anchoring to the channel bottom or bank. Wire-enclosed rock revetments are generally of two types distinguished by shape:

The primary advantages of wire-enclosed rock revetments include:

- Their ability to span minor pockets of bank subsidence without failure.
- The ability to use smaller, lower quality, and less dense, rock in the baskets.

Besides its use as a general bank revetment, wire-enclosed rock in the form of either mattresses or blocks is also used as bank toe protection. In some instances the wire-enclosed rock is used alone for protection of the bank also. In other cases, the wire-enclosed rock is used as toe protection along with some other bank revetment.

Design Guidelines for the Gabion Revetments:-

Components of a rock and wire mattress design include layout of a general scheme or concept, bank and foundation preparation, mattress size and configuration, stone size, stone quality, basket or rock enclosure fabrication, edge treatment, filter design. Design guidance is provided below in each of these areas.

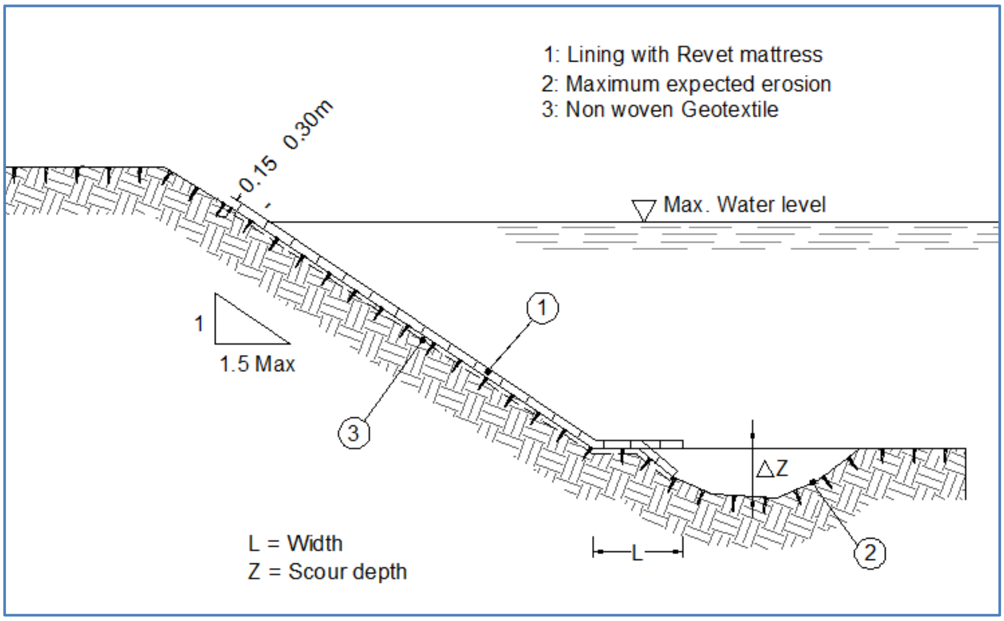
Rock and wire mattress revetments can be used to protect either the channel bank or the entire channel perimeter. When used for bank protection, rock and wire mattress revetments consist of two distinct sections: a toe section and upper bank and toe protection.

Bank and Foundation Preparation: Channel banks should be graded to a uniform slope. The graded surface, either on the slope or on the stream bed at the toe of slope on which the rock and wire mattress is to be constructed, should not deviate from the specified slope line by more than 150 mm. All blunt or sharp objects (such as rocks or tree roots) protruding from the graded surface should be removed.

Large boulders near the outer edge of the toe and apron area should be removed. The thickness of the mattress is determined by three factors:

1. The erodability of the bank soil
2. The maximum velocity of the water, and
3. The bank slope.

The mattress thickness should be at least as thick as two overlapping layers of stone. The thickness of mattresses used as bank toe aprons should always exceed 150 mm. The typical range is 150 to 510 mm. The maximum size of stone should not exceed the thickness of individual mattress Units. The stone should be well graded within the sizes available and 70 percent of the stone, by weight, should be slightly larger than the wire-mesh opening.



Typical Layout

Note: This chapter is contributed by Mr. Dheeraj Kumar, Maccaferi Pvt. Ltd. and edited by Prof. Z Ahmad

Annexure-C

A BRIEF REPORT ON WORKSHOP ON "MORPHOLOGICAL STUDY OF RIVERS GANGA, SHARDA AND RAPTI USING REMOTE SENSING TECHNIQUE" HELD AT LIBRARY BUILDING, CWC, NEW DELHI DURING 18-19 SEPT. 2017

Indian rivers experience large seasonal fluctuations in discharge and sediment load resulting in significant changes in their morphology. Shifting of the river course is generally accomplished by erosion of habitated and pricey agricultural area that causes tremendous losses. The sediments deposited and eroded in the river have a tremendous effect on river cross-section, gradient, intensity of water flow and its discharge. Understanding of changes in the morphology of the rivers is required in all engineering projects for their planning, design and execution. With this in mind, CWC, New Delhi desires to carry out morphological study of the major Indian rivers. In this direction, CWC awarded a project entitled "Morphological study of rivers Ganga, Sharda and Rapti using remote sensing techniques" to IIT Roorkee. Accordingly, IIT Roorkee carried out the morphological study of Ganga river from Devprayag to Farakka barrage; Sharda river from Tanakpur to its conflunece with Ghaghra river and Rapti river from Nepalgunj to Patana ghat near confluence of Ghaghra river for the period 1970 to 2010. The broad objectives of the study were hydrological aspects of flow and sediment; stream bank shifting; plan form changes; erosion & siltation; impacts of major hydraulic structures on the river morphology; vulnerable reaches and suggestion for training/protection works; morphology of islands; recommendations in the respect of actionable points & suggestions for the further study.

For the dissemination of outcomes of the study carried out under the cited project to the potential users, a workshop on *Morphological Study of Rivers Ganga, Sharda and Rapti Using Remote Sensing Technique* was organized by Indian Institute of Technology Roorkee in association with Central Water Commission at Library building, CWC, New Delhi during 18-19 Sept. 2017.

The workshop was inaugurated by Hon'ble Union Minister of State, Water Resources, River Development & Ganga Rejuvenation and Parliamentary Affairs Shri Arjun Ram Meghwal. Prof. A K Chaturvedi, Director, IIT Roorkee; Shri Narendra Kumar, Chairman, CWC; Shri Pradeep Kumar, Member (RM); Shri N.K. Mathur, Member (D&R); Shri S Masood Husain, Member, (WP&P); Shri Ravi Shankar, CE (P&D), Prof. C S P Ojha, Head Civil Eng., IIT Roorkee; Prof. P K Garg, Professor, IIT Roorkee & Vice Chancellor, UTU; Shri P N Singh, Project Director, DRIP were also present.

Prof. Z Ahmad, Org. Secretary presented the gist of the study in the inaugural session. Shri Meghwal emphasizes the importance of water and its conservation. He also stressed upon the study on morphology of the rivers prior to the independence subject to availability of the required data.

The workshop was attended by more than 160 participants from various Institutions, organizations, Public & private sectors, NGO etc. like CWC, New Delhi; IMD, New Delhi; IWAI, Noida; GFCC, Patna & Lucknow; NMCG, MoWR, RD & GR, New Delhi; NDMA, New Delhi; BSRDCL, Patna; CWPRS, Pune; RITES Ltd., New Delhi; DHI, India; C2S2, New Delhi; PWD, Uttarakhand; JNU, New Delhi; AMU, Aligarh; MANIT, Bhopal; Wildlife Inst. of India, Dehradun; Myway Education Charitable Trust, New Delhi; MGCGVV, Satna (MP); GEU, Dehradun.

Prof. Z. Ahmad, Prof. P K Garg, and Dr. R D Garg presented the outcomes of the morphology of the Ganga, Sharda and Rapti rivers before the participants which were well responded by them. Details of the delivered talks are as follow:

18 October 2017: Ganga River

- Introduction covering scope of study, basin, study reach, data, methodology, geology, Land use land pattern, flood affected area, reconnaissance etc. : Prof. Z Ahmad
- Analysis of hydrological data - Exceedance curve, Frequency Analysis, Trend Analysis : Prof. Z Ahmad
- River Morphology : Planform (Meandering & Braiding), Shifting of course of river, Width of river & Shifting of confluence points : Prof. P K Garg, Dr. R D Garg & Prof. Z Ahmad
- River Morphology - Islands in Ganga river : Prof. Z Ahmad
- Erosion and Siltation (including aggradation & degradation): Prof. P K Garg & Dr. R D Garg
- Major structures & their impacts on the morphology: Dr. R D Garg & Prof. Z Ahmad
- Critical reaches and suggested training works : Prof. Z Ahmad
- Panel discussion

19 October 2017: Rapti River

- Introduction covering scope of study, basin, study reach, data, methodology, geology, Land use land pattern, flood affected area, reconnaissance etc. : Prof. Z. Ahmad
- Presentation of outcomes of the hydrological data - Exceedance probability curves, peak discharge for different return periods & trend analysis: Prof. Z. Ahmad
- River Morphology: Planform (Meandering & Braiding), Shifting of course of river & Width of river : Prof. P K Garg, Dr. R D Garg & Prof. Z Ahmad
- Erosion and Siltation (including aggradation & degradation) : Prof. P K Garg & Dr. R D Garg Major structures & their impacts on the morphology: Prof. Z Ahmad
- Critical reaches and suggested training works : Prof. Z Ahmad

19 October 2017: Sharda River

- Introduction covering scope of study, basin, study reach, data, methodology, geology, Land use land pattern, flood affected area, reconnaissance etc. : Prof. Z. Ahmad
- Presentation of outcomes of the hydrological data - Exceedance probability curves, peak discharge for different return periods & trend analysis: Prof. Z. Ahmad

- River Morphology : Planform (Meandering & Braiding), Shifting of course of river & Width of river, Erosion and Siltation (including aggradation & degradation) : Prof. P K Garg & Dr. R D Garg
- Major structures & their impacts on the morphology and Critical reaches and suggested training works : Prof. Z Ahmad
- Panel Discussion

Shri Pradeep Kumar (CWC), Prof. M K Mittal, Shri Ravi shankar; Shri R K Sinha (CWC), Shri Sanjay Kumar (BSRDCL), Shri NN Rai (CWC), Shri Arun Kaumar (GE Univ.), among others actively participated in the discussion. The work of the IIT Roorkee was well appreciated by the participants.

After deliberation, the following actionable points were suggested for enhancing the scope of the study from the consideration of its wide usage :

1. The 10-daily discharge and sediment data of terminal sites of river Ghaghra, Gandak, Sone, Burhi Gandak and Kosi may be considered and the effect of sediment brought by tributaries, on sedimentation of main stem of Ganga may be studied.
2. The reach between Farraka to Revalganj (0-450kms) may be divided into two considering geology and probable broad reasons for morphological changes occurring there may be identified.
3. It has been observed that there is progressive increase in the area of islands from Farakka barrage to Krusela. It may also be analyzed if the other diaras are also increasing. A correlation in increase of sizes of islands may be found out.
4. In context of many islands, participants in the conference from various State Organizations suggested that with time these islands have become highly habitated and vegetated. Road networks are coming up in Raghopur diara. This is likely to disturb the natural nesting sites for wildlife. Further, these diaras are likely to be submerged frequently during floods. Hence, as a recommendation in the report encroachment of these areas should be strictly prohibited. Flood Plain Zoning should be encouraged.
5. State Governments may share the success stories (if any) of how people are living with the floods in highly flood prone areas of these diaria regions. This may help CWC to come up with non-structural solutions for flood protection.
6. In total, thirty five reaches/locations have been identified by IIT Roorkee as critical in Ganga river, however, in twenty seven critical reaches of the Ganga river areas are either protected by using spurs, embankments etc. or being in agricultural area, protection works are not required. At the remaining eight critical reaches/locations near Haripur Kalan, Kangri, Sidholia Kham, Saharpur Makanpur Kham, Gunir, Bhagalpur, Rajmahal to Maharajpur and Manikchak, protection measures are suggested. The critical locations may further be prioritized so that suggested river training works may be taken up on the selected reaches on pilot basis.
7. Other critical locations near major structures like Bridges etc. may also be highlighted.

8. Some key economical flood management structures which may be suitable for these reaches as available globally may also be indicated along with the report. An economical flood protection work scheme which may try to utilize locally available silt / sand in the river for protection through geo bags & geo tubes, etc. for immediate relief, a suitable design of this tentative proposal may also be included in the report. Similar globally adopted structures may also be indicated. Non conventional method of flood control in critical areas may also be discussed.
9. The trends of aggradations/degradation in the river may be established and certain conclusions be drawn from it.
10. The suggested future studies by IIT Roorkee may be prioritized according to the need and importance. Further, similar small studies if carried out by IIT Roorkee in past in form of Phd or M. Tech. thesis may be shared with CWC.
11. The dates corresponding to the remote sensing images used to determine the width of the river may be provided, so that discharge corresponding to the same day may be provided. The same may be used to infer, if possible some relationship between water level, discharge and the width of the river.
12. The existing embankments on the Ganga River may be marked in GIS environment and included in the final report.
13. The trend analysis of hydrological parameters like discharge etc. carried out by IIT Roorkee may result in wrong interpretations due to lack of complete daily hydrological data; hence the same may not be included in the final report. However frequency analysis may be published in the final report.
14. The nodal points along the reach of the river i.e. wherein minimum morphological changes are seen in the river be identified. This will be helpful in planning of structures like bridge in the future.
15. Where ever possible Disclaimers may be provided for more clarification.
16. Effect of vegetation on both sides of river and Existing Embankment on river morphology may be discussed.

Few photographs of the workshop are as follow:


MORPHOLOGICAL STUDY OF
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