EXPERIMENTAL INVESTIGATIONS ON CHANNELIZATION OF RIVER KOSI FROM CHATRA TO NIRMALI

Ph.D THESIS

by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this thesis entitled "**EXPERIMENTAL INVESTIGATIONS ON CHANNELIZATION OF RIVER KOSI FROM CHATRA TO NIRMALI"** is partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Water Resource Development & Management, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out during the period from July, 2010 to August, 2015 under the supervision of Dr. Nayan Sharma, Professor, Water Resources Development & Management, Dr. Z. Ahmad, Professor, Civil Engineering Department and Dr. I. D. Gupta, Professor, Earthquake Engineering Department, Indian Institute of Technology Roorkee, Uttarakhand, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(SANJAY ANANDRAO BURELE)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The Kosi River is one of the most ancient rivers of India. It is also known as Kaushiki in Sanskrit literature. It is a perennial river. Its three main tributaries, viz. river Sun Kosi from West, river Arun from North and river Tamur from East, meet river Kosi at Tribeni to form the Sapt Kosi. River Arun, the longest of the tributaries, has cut through a gorge in the great Himalayan range and drains under the name of Phung Chu the entire Tibetan trough from Gosainthan to Kanchenjunga. Downstream of the confluence, the Sapt Kosi flows in a narrow gorge for a length of about 10 km and then debouches into the plains near Chatra. Further downstream, the river runs in a sandy, almost flat plain and flows southwards to join the Ganga near Kursela.

Abundant supply of sediment from the Himalayas and low slope results in shifting of the river. The river Kosi was shifting towards west, but, it suddenly changed its course towards east in the year 1883 near Purnea. Mr. W. A. Inglis was deputed to make a reconnaissance survey of the area, who suggested to take suitable measure to control the river. After surveying, he came to the conclusion that it was not possible to interfere with the natural flow. He recommended maintaining proper records of changes in the river course and of its flood levels. Subsequently a conference was held in 1896-97 at Calcutta and the conclusion of that conference was that no steps were feasible for controlling the course of the big river with numerous channels having wide and shallow bed. So, to protect human being area, short length embankment was constructed, without adopting standard section. During flood, the embankment breached frequently, which damaged large area. Later in November 1937, conference of official and non-official was called by the newly formed congress government at Bihar to tackle the problem, but the conference could not arrive at any concrete conclusion. In 1940, Sir Claude Inglis visited that area and suggested to check the soil erosion in Nepal. In 1945, Lord Wavell visited the flood stricken area and in his address in the annual session of the Institution of Engineers (India) held at Calcutta, he suggested that the problem needs to be referred to newly formed Water Irrigation and Navigation Commission for advice. The Water Irrigation and Navigation Commission advised to construct a barrage at Chatra in Nepal along with canal system and 90 MW of hydro-electric power station on eastern canal, which is also known as Kosi project. In 1951, the dam site proposed by Kosi project at Barahakshetra was shifted downstream near Belka hills. But Central Water and Power Commission (CWPC) came to the conclusion that the Belka dam proposal would not be much useful and so, the proposal

was dropped. Finally, in 1953 CWPC submitted proposal for construction of a barrage at Hannumannagar, 48 km downstream of Chatra to serve as a control point with a canal system and construction of embankments on both banks of the river to prevent flood and arrest westward shifting of the river course.

The river Kosi carries about 187 million metric tonnes of sediment, which is coming from the Himalayas. About 70% of the sediment is settling between two embankments/levees and the balance is flowing to the river Ganga. During past two centuries, river Kosi has shifted laterally towards west. It has shifted by across a width of over 100 km. The river Kosi has been provided with levees along the banks, at a width ranging from 6 km to 16 km to curb further shifting. The general bed level at many places has risen by 0.1 to 3.0 m over a period of just 50 years. This is due to inadequate velocities in the river for carrying away the sediments. For minimizing the silting and lateral shifting, it is desirable to explore the possibility of channelizing the river Kosi by using various techniques, which is thought to be a possible method for enhancing the velocities in the river to boost its sediment carrying capability. The reach considered for the present study is about 88 km long from Chatra to Nirmali, where the deposition of sediment is the highest and the embankments have breached about 22 times since their completion in 1958. The most recent breach causing colossal destruction took place on 18.08.2008 near village Kushaha, Nepal.

In view of the above, the following objectives have been envisaged for the present investigations, which are interrelated with a bearing on the proposed experimental model studies.

i. Modelling of stage-discharge and sediment-discharge rating at selected river gauging sites;
ii. Morphological study (plan form changes and cross-sectional changes) in the reach under consideration
iii. Mathematical and physical model studies for investigating channelization of river through the use of:
    - Progressive series of T-shape groyenes along both the banks of river reach from Chatra to Kosi barrage;
    - Levees along both the banks of the river for a reach from Chatra to Nirmali;
    - Progressive series of hockey-stick shape spurs along both the banks of the river reach from Chatra to Kosi barrage; and

- Regrading the bed of the river to suitable depth through excavation (Dr. S.V. Chitale's recommendation).

Rating curve based on regression analysis is used commonly by field engineers to estimate the stream flow as well as sediment load. The regression and curve fitting techniques are not adequate in view of the complexities involved in hydrological and fluvial processes. An inherent problem in the rating curve development using above techniques is the high degree of scatter, which may be reduced but not eliminated. To describe such processes, the applicability of Artificial Neural Network (ANN) to various problems of water resources has been amply demonstrated by different investigators. In the present study, ANN technique has been therefore used for modelling the stage-discharge and sediment-discharge rating relationships.

The ANN model has been trained, validated and cross-validated for two important gauging sites, namely Kosi barrage and Barahkshetra (gorge area). Daily data of stage-discharge at the gauging site of Barahkshetra for 17 years (January 1949 to October 1966) has been used for the modelling. Out of this, nine years six month data are used for training, three years nine month for validation, and three years nine month for cross validation. Similarly, sediment-discharge at the gauging site of Kosi barrage for 9 years (May 2002 to January 2009) has been used for ANN modelling. Out of this, five years have been used for training, two years for validation, and two years for cross validation. The performance of ANN model has also been compared with the conventional regression technique. It is found that discharge as well as sediment concentration estimates at gauging sites obtained by ANN technique are more realistic than the sediment rating curves. Corrected data obtained by ANN technique for sediment-discharge at Kosi barrage gauging site have been transferred to Chatra by using SCS modelling techniques for further model studies.

The study reach of river Kosi from Chatra to Nirmali (88 km) is also analysed to assess the channel morphological changes actuated by stream bank erosion process during recent times. Adopting Plan Form Index (PFI) developed by Nayan Sharma (2004), attempt has been made to assess the temporal and spatial variation of braiding intensities along the whole stretch from Chatra to Nirmali based on the remote sensing image processing. The basic data used for estimating Plan Form Index are derived from digital satellite images of Indian Remote Sensing Landsat5 sensor, comprising scenes for the years 1992, 2005, and 2011. The PFI values are seen to by and large decrease significantly with time, indicating increase in braiding intensities in majority of cross sections on both upstream and downstream sides of the Kosi barrage.

Model studies on channelizing the river by providing T-shape groynes: Three-dimensional physical model of river Kosi, covering the reach from 40 km upstream to about 47 km downstream of Kosi Barrage, was constructed to a horizontal scale of 1/500 and a vertical scale of 1/70. The velocity and discharge scales derived from these scales are 1/8.36 and 1/292831, respectively. The various river structures, viz. Kosi barrage, proposed Dagmara barrage, Rail & Road bridge, Eastern embankment, Ring bund, afflux bund and spurs are reproduced in the model. The bed configuration of the river including deep channels, shoals and spill portion are reproduced as per the survey data of post-flood 2002. T-shape groynes are provided in the model to channelize the river in the following four ways.

i) T-shape groynes of wing length of 2000 m were first provided with a spacing of 4000 m on both the banks to have a waterway of 3000 m. Using the dominant discharge of 15586 m^3/s in the model, the flow of water was not seen to touch the wings of the T- shape groynes in most cases.

ii) Next, the waterway in the model was reduced to 2000 m. In this case, though the flow was seen to touch the wings of the groynes, the velocity was inadequate to initiate the sediment motion.

iii) To increase the velocity, the waterway was further reduced to 1100 m. In this case, the flow velocity was adequate to wash out shoal and a regime channel was established.

iv) To examine the possibility for optimizing the above, another trial was made by increasing the spacing between T-shape groyenes from 4000 m to 8000 m, but it was not found effective.

Model studies on channelizing the river by providing levees: Although flow in natural rivers is three-dimensional (3D), however, one dimensional (1D) or two dimensional (2D) mathematical models are often used in engineering practice for shallow open channel flow. In particular, when simulating a very long river of multichannel in cross-section for a long period, 1D models (e.g., HEC-RAS) are more cost effective than 2D or 3D models, however, they are unable to simulate momentum exchange between main channel and floodplain, turbulence around engineering structures (e.g. bridges piers, spur dykes), and flow in highly sinuous channels (Duan et al., 2001; Duan and Julien 2005). To overcome these limitations, engineers commonly enhance 1D model with empirical formulas to approximate energy losses attributable to in-stream structures or meandering bends. The site of the present study is the Kosi River, a reach consisting of braided, transitional, and meandering channels with levees and dykes, and highly overloaded sediment supply, which requires an improved 1D model to simulate the hydraulic aspects of channelizing the river.

Due to very high annual sediment to the tune of 187 million metric tonne carried by the river, 70% of sediment settles between the embankments, it is desirable to explore the possibility of channelization, adopting same bed profile. With this objective in view, mathematical model studies were first conducted for channelization of river Kosi for a reach from Chatra to Nirmali by providing levees. This study was based on 1D mathematical model HEC-RAS 4.1 version to get an idea about hydraulic aspects of channelizing the river. Various channelization widths ranging from 800 m to 2000 m were examined adopting the same bed profile, which showed that the width of 1100 m would minimize the aggradations and degradation of the river for a dominant discharge of 15586 m^3/s.

The finding of mathematical model for waterway of 1100 m with levees along both the banks was also studied on the physical model; in the first phase for the reach from Chatra to Kosi barrage, which was extended upto Nirmali in the second phase. The physical model studies also confirmed the efficacy of channelization with 1100m water way over the complete reach from Chatra to Nirmali. However, in the first phase of the studies restricted upto the barrage, some deposition was observed on the downstream due to decrease in velocity as a result of sudden widening of the river. But, this deposition was not seen to have any adverse effect on the river hydraulics upstream of the barrage. Only the morphology of the river on the downstream was seen to be affected in this case. In the second phase, average velocity of 3 m/s was attained over the entire reach, and it was observed to be in regime similar to that in the mathematical model study.

Physical model studies were also conducted using levees to have 1100 m waterway from Chatra to Nirmali, which showed similar satisfactory performance.

Model study on channelizing the river by providing hockey-stick shape spurs: Hockey-stick shape spurs were provided with a spacing of 1500 m on both the banks to achieve a waterway of 1100 m. For the dominant discharge of 15586 m^3/s, it was seen that the hockey-stick shape spurs guide the flow of water with an average velocity of 3 m/s and form bed regime.

Mathematical model to study Channelization by re-grading the river bed through excavation (S. V. Chitale's recommendation):. S.V. Chitale suggested that by re-grading the stream bed by 0.44 m, velocity required to transport the sediment could be generated. In view of this, mathematical model studies were conducted for a reach from Chatra to Kosi barrage using the data of River cross-section post 2002 flood and sediment-discharge relationship as upstream boundary condition and normal depth as a downstream condition. The required river cross-sectional data were available in the month of May 2002. The cross sections of the river within the embankment were at a regular interval of 1.0 km, from 41 km upstream of Kosi barrage. Data pertaining to sediment and discharges recorded at the Kosi barrage were used for this study. Mathematical model (HEC-RAS) was run with the input data as a discharge variation of nine year hydrograph. The mathematical model study indicated that the velocity of flow along the channel increases and the bed level further deepens due to transportation of sediment by increased velocity, reducing shifting behaviour of river.

Detailed mathematical and physical model investigations have been carried out for channelization of river Kosi considering various alternatives for this purpose. The results of the investigations have brought out that the following three measures are equally effective for achieving channelization on technical grounds.

(i) Providing T-shape groynes along both the banks
(ii) Providing levees to have a constricted waterway of 1100 m
(iii) Providing hockey stick shape spurs along both the banks

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Chapter 1

INTRODUCTION

1.1 GENERAL

Kosi is the third largest Himalayan River originating from the snowy peaks in the Central Himalayas. The three main tributaries of Kosi are the Sun Kosi rising east of Kathmandu; the Arun Kosi rising north of the Mount Everest in Tibet and the Tamur Kosi rising west of Mount Kanchenjunga. These three tributaries join at Tribeni in Nepal and thereafter the river is known as Kosi. The river Kosi, after flowing over a length of about 10 km through a deep gorge, debouches into the plains at Chatra. From this point onward, the river runs in a sandy alluvial plain through Nepal upto Bhimnagar for a distance of 42 km and it further flows through north Bihar and eventually joins river Ganga near Kursela. The total distance from Bhimnagar to its outfall into river Ganga is about 260 km. The important tributaries that join Kosi in this reach are Trijuga, Bhutahi Balan, Kamla Balan and Bagmati. River Kosi has a steep gradient of about 1.5 m/km in the gorge portion upstream of Chatra. The slope at Chatra is about 0.95 m/km which flattens to 0.03 m/km in the tail reach at Kursela as shown in Fig. 1.1.

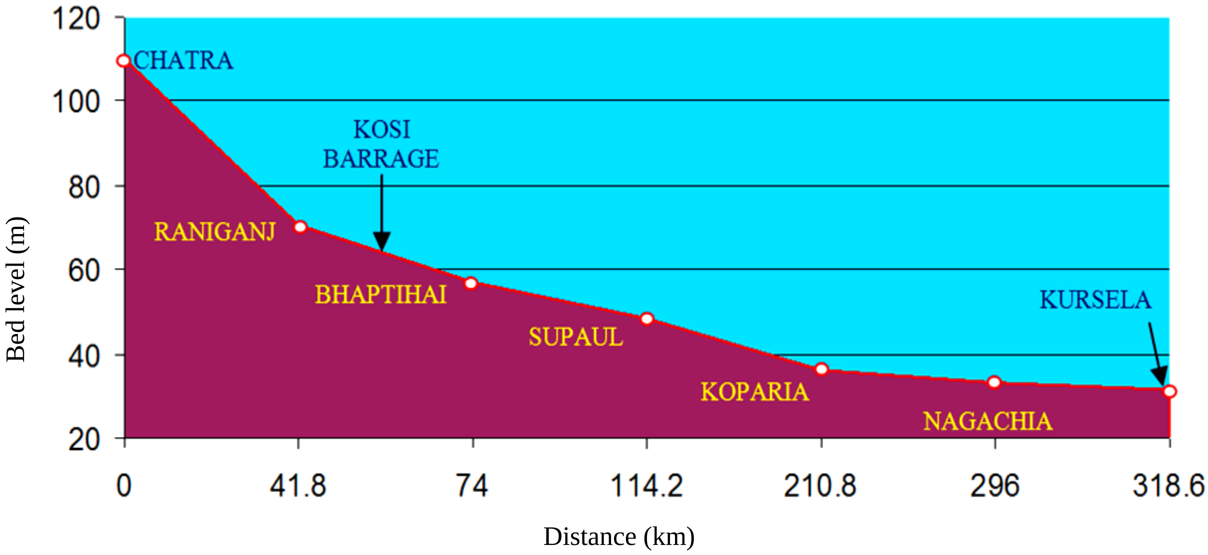


Figure 1.1 Bed level of river Kosi from Chatra to Kursela (Gole and Chitale, 1966)

The Kosi River is notorious for its capricious nature. Emerging from the young Himalayan Mountains, the river carries an estimated sediment load of about 187 million tonnes per year. Of the total sediment load, approximately 50% is contributed by the Sun Kosi while 25% each by the river Arun and Tamur. As it traverses through the plains, the velocities are reduced from about 5 m/s at the Chatra gorge to as low as 1.25 m/s in the plains, resulting in the deposition of 130 million tonnes of sediment load between Chatra and Kursela (Gole and Chitale, 1966). The drastic reduction in bed slope results in marked reduction of sediment transport capacity and causes significant aggradation. Figure 1.2 shows typical post flood cross-sections for six different years. Due to deposition of a large quantity of sediment charge, the river has been shifting its course from time to time. Figure 1.3, illustrates that the river has shifted by about 112 km to the west from Purnea to Supaul in the past 223 years (1731 to 1954).

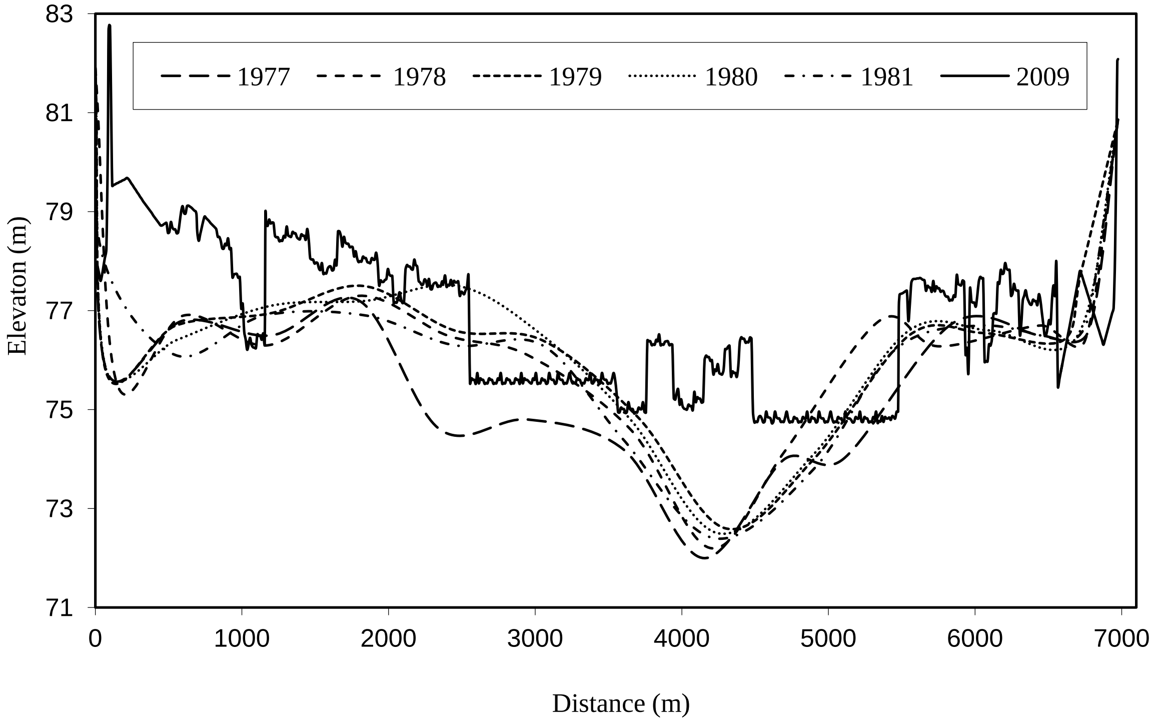


Figure 1.2 Typical Cross-sections (five km upstream of barrage) (CWPRS record)

To control further shifting of the river, a scheme was prepared in the year 1954 consisting of

a) A barrage across the river at Bhimnagar, with canals on both sides with a potential for irrigating 1.1 million hectare area.
b) Upstream afflux bunds extending to 13 km on the western side and 32 km on the eastern side of the barrage.
c) Flood embankments (stop banks or levees) below the barrage extending to about 100 km on the western side and 124.5 km on the eastern side.

Figure 1.3 Shifting courses of Kosi River channel (Gole and Chitale, 1966)

The work of construction of levees on both the banks was completed in the year 1959 and the river was diverted through the barrage in 1963. However, the width between the levees varies from around 6 to 16 km, and the river is free to take its own course in this width. As the flood wave gets reduced, the velocities also reduce, resulting in high deposition of sediments. At several places, the river Kosi is flowing between the stop banks at a relative bed level above the general ground level in the area. In view of this, it is felt that the river may be constricted to such an extent and given a particular cross-section whereby it will have self-cleaning velocities and will carry all its sediments downstream. This could be achieved by channelization of the river.

Channelization of a waterway prevents it from changing directions randomly, and the net erosion / deposition is reduced greatly (Gray and Harding, 2007). Channelization includes those engineering methods (re-sectioning, straightening, construction of levees, diversions, etc.) that modify existing river channels or create new channels, by changing the relationship between river channels and floodplains. The most common purposes of channelization are flood control, land drainage improvement, creation of new spaces for urbanization or agriculture, maintenance or improvement of navigation, and reduction in bank erosion. Channelization is carried out on both very large rivers and small streams: It is widespread in lowland rivers, but many upland (mountainous) rivers have also experienced this type of human intervention. Human impact on rivers has a long history. For instance, the Yellow River in China has been regulated for at least 4,000 years and most alluvial rivers in Europe have been channelized during the past 2,000 year (Surian and Rinaldi, 2003).

Danube River had been channelized in the 19th century to improve navigation, reduce flood plain area and reclaim the area. Channelization was done using levees, spurs and flood protection tools (Peter, 2002).

Between the 17th and the 19th centuries, most of the length of the Rhone River was confined within levees causing incision of the channel bed. Engineering works, such as catchment bank revetments, groynes, hydraulic deflectors and flood protection levees were designed to stabilize the plan-form and to limit the extent of overbank flooding (Arnaud-Fassetta, 2003).

The Salt River flows in the U.S. state of Arizona. The channel stability method was originally used for the channelization. To estimate suitable stable gradient for low flows, several methods were used. The U.S. Army Corps of Engineers' River Analysis System (HEC-RAS) (USACE, 1998) computer program was used to verify the channel capacity. The initial design was then developed using a sediment transport model. In addition, a low flow channel alignment was planned and grade control structures were located to reduce scour. Guide dykes were planned to protect the alignment of the low flow channel during flood events that go above the design capacity of the low flow channel (Schulte et al., 2000).

The reach considered in the present study is about 88 km long from Chatra to Nirmali, where the deposition of sediment is the highest and the embankments have breached 22 times. The most recent breach causing colossal destruction took place on 18.08.2008 near village Kushaha. The aim of this thesis is to investigate a model for the analysis of hydraulic aspects of channelizing the river using 1D mathematical model HEC-RAS 4.1 and physical model on a distorted scale of 1: 70 vertical and 1: 500 horizontal.

1.2 CREATION OF CHANNELS IN RIVERS

During flow of water from the source to the downstream, much of the energy is spent to overcome the resistive force due to friction at valley/river floor. The materials eroded from river beds, flood plains and banks get deposited when slope declines and the stream losses energy. Therefore, a natural grading system arises into force, with heavier/coarser materials deposited first. Sediment gradually becomes finer as the river goes downstream. Sand bars created by deposition of coarser sediment affect the flow of water and its depth. Sediment deposition forces the river to change its course, develop meanders, form new and secondary channels, and old channels are abandoned as shown in Fig. 1.4 (Tzilivakis et al., (2011).

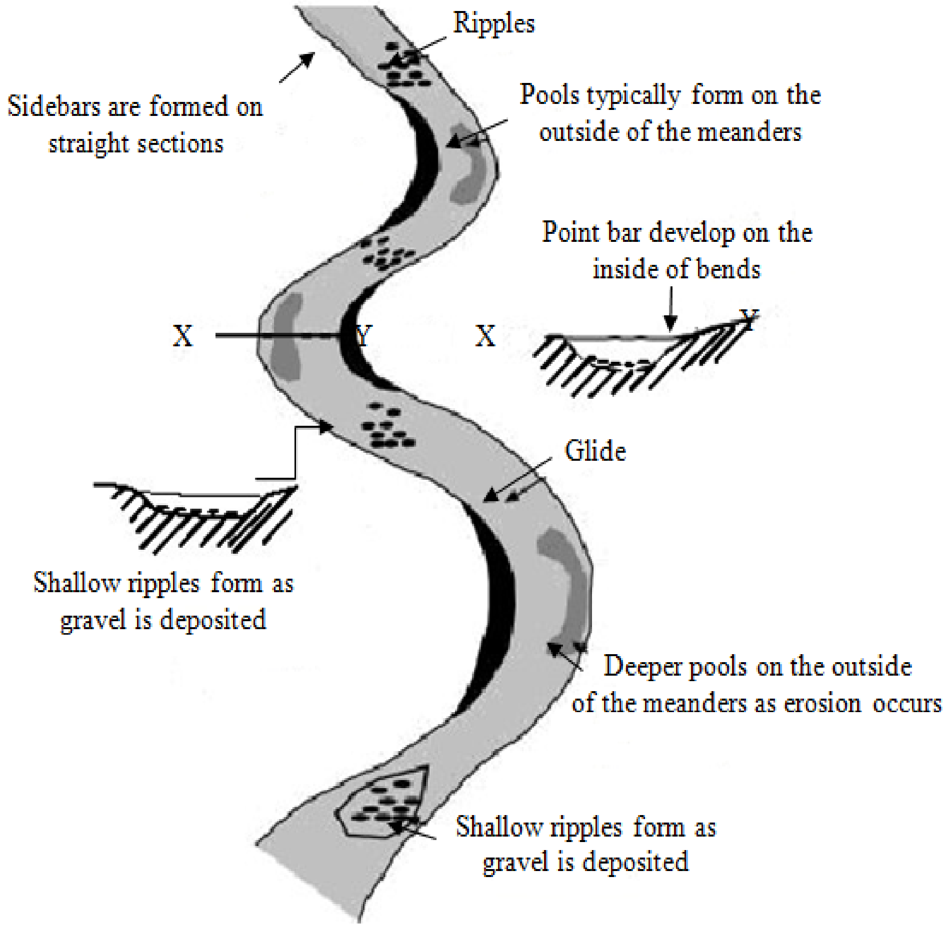


Figure 1.4 River form - meanders, pools and ripples

1.3 BRIEF REVIEW ON DYNAMICS OF ALLUVIAL RIVERS

The dynamics of a river is principally governed by the total sediment load and its capacity to carry the sediment. Excessive sediment deposition causes a river to leave its original course and flow along new one, devastating vast areas of habitable and agricultural land. It causes a river to split up into a number of interlaced channels.

In alluvial channels, available energy is balanced by the dissipation of energy due to bed, side and internal frictions, as well as by the energy required to transport the sediment load. Because of the interplay of these two factors, there is an incessant tendency to attain stability. Though such a state is never attained fully in nature–except under controlled conditions – it is closely approached in a channel running with a constant discharge.

The set of conditions of a river is, however, constantly changing. Conditions like stage, discharge silt charge, etc., along a river course keep on changing and the channel is rarely able to attain the equilibrium condition. Moreover, channel characteristics depend upon the relative resistances of bed and bank materials, distribution of boundary shear and velocity, etc., in a cross section of a river. If, for instance, the bed is of sand and banks are composed of cohesive material, the river will be subjected to bed scour. If, on the other hand, the bed and banks are composed of non-cohesive sandy material, the resistance of material on the banks being smaller, lateral erosion will generally take place and the river will tend to became shallow.

It is well known that for a rigid boundary channel with a constant discharge and no material in movement, the most efficient shape is a semicircle. But, with a small amount of material in movement, consisting of particles of various sizes, the equilibrium section would approximate to a semi-ellipse. The material in movement is transported, partly as suspended material and partly as bed material; the latter movement includes particles in saltation. The finer particles tend to deposit at the sides, where the velocity is low to form the banks, while the coarser particles move along the bed with a gradation of mean size from coarser in the middle of the channel to finer towards the banks. The sequence of events taking place in a natural watercourse having bends would be as follows: In high water, an excessive deepening of the pools occurs with a marked shoaling at crossings. During this period, the river gradient is more or less uniform, resulting in a uniform sediment movement. As the water-level drops, slope variation occurs and it becomes flatter in the pools and steeper at the crossings, because the crossing acts like a weir. Scouring and transporting action decrease at a rate, relatively greater in the pools than that at the shoals. Thus the shoal tends to scour. The rate of scouring is much smaller than that of the fall of water surface so that at low water the river shows deterioration. In the low stage, the larger particles are first deposited, followed by relatively smaller size particles. River section is normally found with complete sorting of bed material. This action is not restricted to selected reaches, but is generally present all along the river course. In the upper reaches, the material is coarse and slope is, steep; whereas along the lower reaches, the sediment size becomes progressively smaller and slopes become flatter. In the

Kosi river, as it emerges from the Himalayas, to the slope in the upper reaches is as steep as 0.95 m/km, which flattens gradually to 0.2 m/km at the end. When it joins the Ganga, the slope becomes very flat around from 0.076 m to 0.0019 m/km as shown in Fig. 1.1.

Sediment movement is maximized in what is known as the dominant stage of a river, when most of the changes in the bed configuration take place. It has been observed that the high water stage is decisive for sediment movement, since its effective period is very short to have an effect comparable to that at other stages. The dominant or bankful stage of a river corresponds to a discharge from 1/2 to 2/3 of the maximum.

1.4 ALLUVIAL FAN OF THE KOSI RIVER

As a mountainous river enters the plains the slope suddenly becomes flat and the velocity drops. This causes deposition of sediments and bed gradations. When the bed is raised, the river shifts laterally, forming a fan shaped delta, known as alluvial fan. The Kosi river presents a well-known example of inland delta as described below.

As already stated, the three major streams of the Kosi River are the Sun Kosi, the Arun and the Tamur which unite at Tribeni. The Kosi River above Tribeni and for about 10 km downstream flows in a deep gorge in the Himalayas until it debouches into the Gangetic plain at Chatra. The river slope after leaving the gorge flattens progressively from 0.2 m per km near Chatra to 0.06 m per km at Kursela where the Kosi joins the river Ganga. Average suspended sediment concentration at Kursela is only 24 per cent of that in the gorge. The remaining 76 percent of the sediment load is deposited in the plains, which has formed the alluvial fan of the Kosi, extending over 112 km east-west and 160 km north-south.

After formation of the alluvial fan the river slope became deficient for carrying sediment further downstream. This invited the river to shift along the adjoining part of the cone with lower ground level. When the flowing channels got silted up, new side channels, were opened up and developed. By this process, the river progressively went on shifting from one end of the fan to the other traversing a distance of 112 km from Purnea on the east to Nirmali to the west in a period of about 200 years (Fig.1.3).

The base plane on which the Kosi fan is built has a slope from north to south and west to east. On this plane, the Kosi has built up a conical delta. The limit of this conical delta on the east and the west and the toe line along which the Kosi flowing in its end reach is shown in Fig. 1.5. Cone formation of the Kosi delta is seen to be more or less perfect.

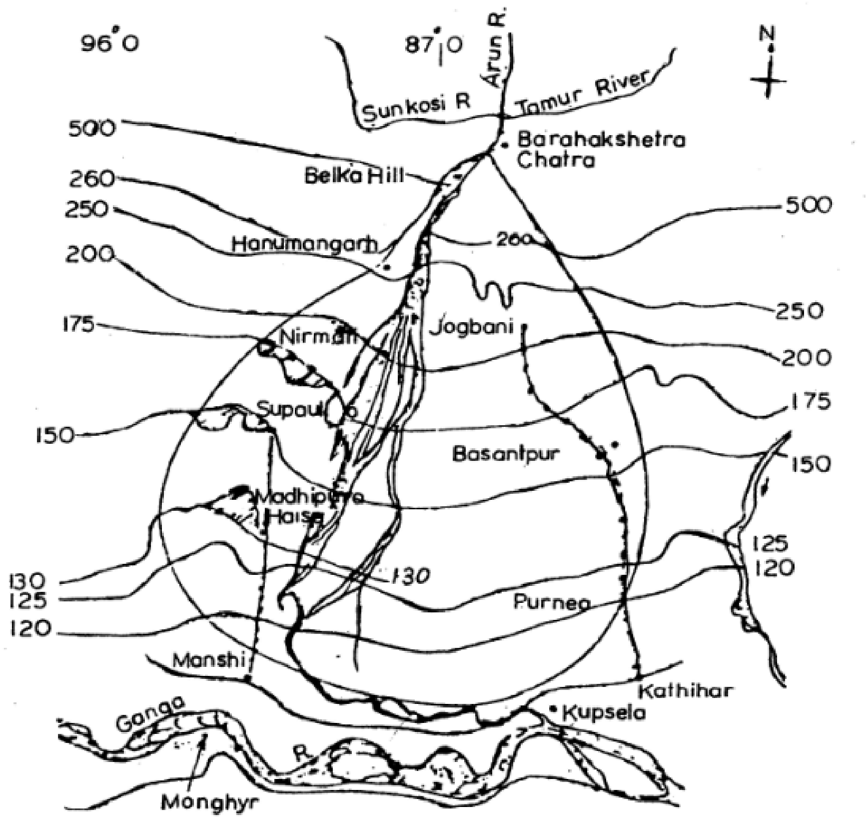


Figure 1.5 Alluvial fan of the river Kosi (Gole and Chitale, 1966)

1.5 PROBLEM IDENTIFICATION

In view of highly braided and shifting nature of river Kosi as described above, it is desirable that the river is constricted and given a particular cross-section, whereby it will have self cleaning velocities. This could be achieved by the well known procedure called the channelization, which is thought to be one of the methods by which the velocities in the river could be increased. The aim of this thesis is to analyze the hydraulic aspects of channelizing the selected reaches of river Kosi by using 1D mathematical model HEC-RAS 4.1 and physical model on a distorted scale of 1: 70 vertical and 1: 500 horizontal.

1.6 OBJECTIVES

In view of the above, the following objectives have been envisaged for the present investigations, which are interrelated with a bearing on the proposed model studies.

i. Modelling of stage-discharge and sediment-discharge rating of river gauging sites;
ii. Morphological study in the reach under consideration to get a quantitative idea about the plan form and cross-sectional changes since 1977.
iii. Mathematical and physical model studies for channelization of the river with the use of:

- Progressive series of T-shape groynes along both the banks of the river reach from Chatra to Kosi barrage;
- Levees along both the banks of the river for a reach from Chatra to Nirmali;
- A progressive series of hockey-stick shape spurs along both the banks of the river reach from Chatra to Kosi barrage; and
- Lowering the bed of the river to a suitable depth through excavation

iv. Arriving at the recommendations for channelization of river Kosi.

To run the mathematical and physical models, stage-discharge and sediment-discharge rating relationships are required as an upstream and downstream boundary condition. For this purpose, ANN technique has been used for modelling the stage-discharge and sediment-discharge rating relationships.

1.7 METHODOLOGY

a) Development of stage-discharge and sediment-discharge rating curves

Assessment of stream flow and volume of sediment transported in a river is important for a variety of hydrologic applications, such as water resources planning and operation, water and sediment budget analysis, hydraulic and hydrological modelling, design of storage and conveyance structure, hydroelectric power generation and water supply, determination of the effect of watershed management and environmental impact assessment. Rating curve based on regression analysis is used commonly by field engineers to estimate the stream flow as well as sediment load. The regression and curve fitting techniques are not adequate in view of the complexities involved in hydrological process. An inherent problem with the rating curve technique is the high degree of scatter, which may be reduced but not eliminated. To describe such processes, the applicability of Artificial Neural Network (ANN) to various problems of water resources has been amply demonstrated by different investigators. In the present study, ANN technique shall be used for modelling the stage-discharge and sediment-discharge rating relationships.

b) Morphological changes of river Kosi from Chatra to Nirmali.

The Kosi River carries with it an enormous load of sediment, which it is unable to transport. As the river traverses through the plains, the velocities are reduced from about 5 m/s at the Chatra gorge to as low as 1.25 m/s, depending on the slope and depth of flow, which results in the deposition of 130 million tonnes of sediment load between Chatra and Kursela.

The river, downstream of Chatra builds up its plain and flows through several channels spread over a width varying from 6 to 16 km. The braiding process is, however, seen from Belka hills on downstream, where interlacing channels are spread over a width of about 5 to 6 km. In view of this, to identify the relative extent of braiding in different reaches, the braiding indicator Plan Form Index (PFI) formulated by Sharma (2004) for Brahmaputra River shall be adopted.

The study reach of river Kosi from Chatra to Nirmali would be considered to assess the channel morphological changes actuated by the stream bank erosion process. An attempt has been made to assess the temporal and spatial variation of braiding intensities along the whole stretch from Chatra to Nirmali based on the remote sensing image processing, which is the forcing function of erosion and thereby causing severe yearly land loss.

c) Model studies for channelization by providing a progressive series of T-shape groynes

Three-dimensional physical model of river Kosi, covering the reach from 40 km upstream to about 47 km downstream of Kosi Barrage, was constructed to a horizontal scale of 1/500 and a vertical scale of 1/70. The velocity and discharge scales derived from these scales are 1/8.36 and 1/292831, respectively. The various river structures, viz. Kosi barrage, proposed Dagmara barrage, rail-cum-road bridge, Eastern embankment, Ring bund, afflux bund and spurs are reproduced in the model. The bed configurations of the river, including deep channels, shoals and spill portion are reproduced as per the survey data of post flood 2002. T-shape groynes are provided in the model to channelize the river in four ways as described in the following.

i) T-shape groynes of wing length 2,000 m were first provided with a spacing of 4,000 m on both the banks to have a waterway of 3,000 m
ii) Next, the waterway in the model was reduced to 2,000 m.
iii) To increase the velocity, the waterway was further reduced to 1,100 m.
iv) To examine the possibility for optimizing the above, another trial was used by increasing the spacing between T-shape groynes from 4,000 m to 8,000 m.

d) Channelizing the river by providing levees along both the banks

i) Mathematical model studies

Mathematical model studies were conducted for channelization of river Kosi for a reach from Chatra to Nirmali by providing levees. This study shall present the analysis of hydraulic aspects and the change in the bed level of channelizing the river by using 1D mathematical model HEC-RAS 4.1. Various channelization widths ranging from 800 m to 2,000 m examined.

ii) **Physical model studies**

The satisfactory result obtained from the mathematical model studies with levees along both the banks were used in the physical model and studies conducted for a reach from Chatra to Kosi barrage. Observations were taken on the physical model regarding shoals flushed and sediment settling in the channel.

e) Channelizing the river by providing Hockey-stick shape spurs

Studies were conducted using Hockey-stick shape spurs with a spacing of 1,500 m on both the banks to achieve a waterway indicated by mathematical model studies.

f) Channelization by lowering the river bed through manual excavation

In the Report No. 1 of Kosi Judicial Enquiry Commission - regarding Kusaha breach of 2008 under the Chairman of Honorable Justice Rajesh Balia (former Chief Justice, Patna High Court), submitted at Bihar Legislative Assembly, Government of Bihar, in 2014. It is mentioned that by lowering the riverbed by 0.44 m may help in may reduce and enhance the sediment carrying capacity of the river. The recommendation is made by the technical member of the committee Dr. S. V. Chitale, Ex. Joint Director, CW & PRS, Pune. In view of this, mathematical model studies were conducted for a reach from Chatra to Kosi barrage using the data of river cross-section post 2002 flood with sediment-discharge relationship as an upstream boundary condition and normal depth as a downstream condition.

1.8 STRUCTURE OF THESIS

The thesis contains 8 chapters, which are organized in the following way. Chapter-1 describes the introductory aspects of the topic studied, underlying objectives and the layout of the thesis. Chapter-2 presents comprehensive review of relevant literature on all the concerned topics associated with the present work, like river channelization using various techniques in physical and mathematical modelling, morphological changes and the stage-discharge and sediment-discharge rating relation. Chapter-3 describes the catchment characteristics, geological formation and hydrology of River Kosi. Chapter-4 covers the importance of rating curve in assessment of river gauging sites. Conventional rating curves and artificial neural network have been described and both the techniques have been compared. Chapter-5, presents braiding indicator PFI for morphological changes. Chapter-6 numerical simulation for channelization of a reach of river Kosi using levees and by lowering the river bed through manual excavation. Chapter-7 presents construction works in physical model, availability of data, model proving study and experimental studies for channelization using levees, T shape groynes and Hockey stick shape spurs. Chapter-8 presents the conclusions and scope for future work.

1.9 LIMITATIONS

Mathematical model and Physical model studies were carried out for channelization of river Kosi. The study has the following limitations:

- The software HEC-RAS 4.1 version used for the mathematical study, being a 1-D program, it was not possible to reproduce the structures like spur, guide bund of barrage, etc.
- Hydraulic model studies were conducted on the distorted mobile bed model of river Kosi with a horizontal scale 1:500 and vertical scale 1:70. Providing sediment and inflow hydrograph as an upstream boundary condition was not possible in the physical model, so, studies were conducted for dominant discharge of 15,586 m^3/s (i.e. from 1969 to 2009) and sediment injected at the rate of 0.25-0.3 m^3/hr, i.e. about 100 ppm.

Chapter 2

THEORY AND LITERATURE REVIEW

2.1 INTRODUCTION

Kosi River originates from Tibet and flows in the gorge area of the Himalayas. The river carries huge quantity of sediment, due to high velocity in the gorge area. The sediment carrying capacity of sediment is high; however, when the river flows in plain areas, velocity of flow is reduced drastically and the river gets braided. A braided river consists of a number of small channels separated by small and mostly temporary islands called braid bars. A river becomes braided, if its slope suddenly changes from very high to low and if it carries huge sediment load (Schumm and Khan, 1972).

Several studies related to braided river and channelizations of rivers have been reported in the literature. Channelization is done either for making a stream suitable for navigation or for further development of navigation to make possible movement of larger vessels with heavy draughts. Another reason can be to control water to a defined area of a stream's natural lower land so that the mass of such lands can be made available for agriculture. One more reason can be for flood control. Channelization can give a river an adequately large and deep channel to carry ample flow so that flooding beyond these limits can be minimized. One major reason is to decrease natural erosion. The common purposes of river channelization are flood control, creation of new spaces for urbanization or agriculture, maintenance or improvement of navigation, land drainage improvement and reduction of bank erosion. In a meandering river, sand and gravel are generally deposited towards the convex bank of the meander, where the velocity are low, and erosion takes place on the concave side, when the velocity are high due to change in direction. Channelization of a waterway by straightening prevents the water from changing directions randomly, which reduces net erosion (Gray and Harding, 2007).

This chapter presents a review of literature on morphological studies, stage-discharge and discharge-sedent relationships and channelization of river. This chapter also examines objectively the various approaches for channelizing a river. Channelization includes modification in cross sectional area of the stream, straightening, construction of embankments, diversion of flow, etc. This modifies the existing river channels or creates new channels. This may change the association between river channels and floodplains. Channelization is carried out on all the types of rivers. The Yellow River in China has been regulated for at least 4,000 years and the majority of alluvial rivers in Europe have been channelized during the last 2,000 years (Surian, 1999).

2.2 MORPHOLOGICAL STUDIES

Several studies had been conducted in the past to differentiate among the straight, meandering, and braided streams on the basis of discharge and channel slope. Lane (1957) suggested the following criterion for the occurrence of braiding.

$$S > 0.004\ (Q_m)^{-0.25} \tag{2.1}$$

Where, Q_m = mean annual discharge; and S= channel slope.

Using bank full discharge Q_b, Leopold and Wolman in 1957 (Richards et al., 1982) proposed the relationship for braiding to occur, which also predicts braids at higher slopes and discharges:

$$S > 0.013\ Q_b^{-0.44} \tag{2.2}$$

Antropovskiy (1972) developed the following criterion for the occurrence of braiding

$$S > 1.4 Q_b^{-1} \tag{2.3}$$

Leopold and Wolman (1957) also indicated that braided and meandering streams can be separated by the relationship:

$$S = 0.06\ Q^{-0.44} \tag{2.4}$$

Where, S = channel slope; and Q = water discharge.

However, these indicators have been criticized by Schumm and Khan (1972), as none of these recognizes the importance of sediment transport. These results imply a higher power expenditure rate in braided streams, a conclusion reinforced by Schumm and Khan's (1972) flume experiments. Since, bed material transport and bar formation are necessary in both meander and braid development processes, the threshold between the patterns should relate to bed load.

Henderson (1961) re-analyzed Leopold and Wolman's data to derive an expression including d_{50}, the median grain size (mm):

$$S > 0.002\ d_{50}^{\ 1.15} Q_b^{-0.46} \tag{2.5}$$

According to Eq. (2.5), a higher threshold slope is necessary for braiding in coarse bed materials. Bank material's resistance affects the rate of channel migration and should also influence the threshold, although its effect may be difficult to quantify, and would also be non-linear since high stream power is required to erode clays and cobbles compared to the sands.

Parker's stability analysis (1976) indirectly illustrates the effects of bank material's resistance by defining the meander - braid threshold as:

$$S/F_r = D/B \quad (2.6)$$

Where, D = mean depth of the flow; B = width of the stream, and Fr = Froude number. However, depth, width and Froude number may be expressed in terms of discharge and bank silt-clay percentage, as suggested by Schumm (Richards, 1982). Meandering occurs when S/Fr ≤ D/B, braiding occurs when S/Fr ≥ D/B, and transition occurs in between S/Fr ~ D/B.

Ferguson (1981) suggested that for braiding to occur in silty banks rivers,

$$S > 0.0028\ Q_b^{-0.34}\ B_c^{0.90} \quad (2.7)$$

Where, B_c= percentage of silty clay content in the bank material.

Measures of the degree of braiding generally fall into two categories: (i) the mean number of braid bars or active channels per transect transversely the channel belt; and (ii) the ratio of sum of channel lengths in a reach to a measure of reach length "total sinuosity". The sinuosity, P is thalweg length / valley length.

Smith (1970) illustrated the measurement of cross - section bed relief by the index.

$$BRI = \frac{2[(T1 + T2 \ldots\ldots Tn) - (t1 + t2 + t3 + \ldots\ldots tn)] \pm Te_1, Te_2}{B_L} \quad (2.8)$$

Where, T_i = height of maxima between hollows; t_i = minima between peaks; B_L= transect length; and T_e = end heights.

Plan Form Index (PFI), cross-slope ratio, and Flow Geometry Index (FGI) were developed by Sharma (2004) for identifying the level of braiding in the highly braided rivers (Fig. 2.1). The Plan Form Index, Flow Geometric Index and Cross-Slope ratio can be expressed as

$$\text{Plan Form Index} = \frac{\frac{T}{B} \times 100}{N} \quad (2.9)$$

$$\text{Flow Geometry Index} = [\frac{\sum d_i\ x_i}{WxD}] \times N \quad (2.10)$$

$$\text{Cross-Slope ratio} = \frac{\frac{B_L}{2}}{(Bank\,level - Av.\,bed\;level)} \qquad (2.11)$$

Where, B_L = Transect length across the river width; T = flow top width; B= overall width of the channel; D = hydraulic mean depth and N = number of braided channel: Quantities d_i and x_i are depth and top lateral distance of submerged sub-channel.

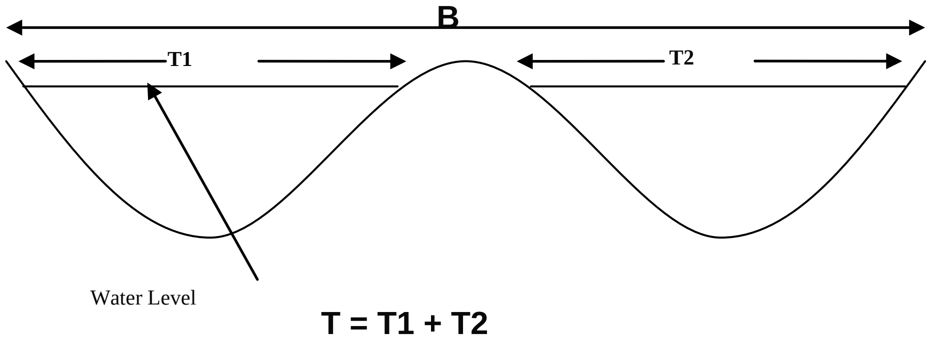


Figure 2.1 Definition sketch of PFI (Sharma, 2004)

Plan Form Index (PFI) defined in Eq. (2.9) reflects the fluvial landform disposition with respect to a given water level. Low value of PFI indicates a higher degree of braiding. For classification of the braiding phenomenon, the following threshold values for Plan Form Index (PFI) are proposed by Sharma (2004).

Highly Braided:	PFI < 3
Moderately Braided:	19 > PFI > 3
Low Braided:	PFI > 19

2.3 STAGE-DISCHARGE AND DISCHARGE-SEDIMENT RELATIONSHIPS

The ANN approach to modelling the discharge and sediment rating relation has produced a very hopeful outcome as reported by various investigators. ANN models for simulation of stage-discharge rating curves at two locations on the river white Nile have been developed by Tawfik et al. (1997), which proved to be more accurate than the conventional techniques, although the ANN model was based on a simple fixed network arrangement and the results were validated by means of records that were incorporated in training the network. Three layer feed-forward ANNs have been developed by Jain and Chalisgaonkar (2000) to establish stage-discharge relationship for two gauging sites on Kolar river and Narmada river in India. The authors found the ANN approach very efficient in modelling the relationship and have reported its superiority over the conventional curve-fitting approach.

In a study by Jain (2001), an integrated stage-discharge-sediment concentration relation for two sites on the Mississippi river has been established using ANNs. The author evaluated five combinations of inputs together with water stage, water discharge and sediment concentration at current and previous time steps and concluded that ANN could provide estimates closer to observed suspended sediment concentration compared to the conventional curve-fitting method. Jain (2001) also found that the bias correction approach proposed by Ferguson (1986) does not yield results better than those obtained by way of ANNs. Cigizoglu (2002) has carried out a study for two rivers with very similar catchment areas and characteristic in the north of England and made a comparison between ANNs and conventional sediment rating curves. In addition to the higher modelling accuracy, ANNs could also provide information about the structure of events (hysteresis), which was not possible with sediment rating curves (Cigizoglu, 2002). Sudheer and Jain (2003) have addressed the problem of stage-discharge curve and hysteresis curve modelling using ANNs. Their analysis was based on idealized hypothetical looping rating curves instead of actual field measurements. However, the authors concluded that a properly designed ANN for a given gauging site is a convenient and easy-to-use option for the current practice. Supharatid (2003) has developed an ANN model for prediction of tidal-level variations at the mouth of a river in Thailand. The ANN technique has been applied to develop stage-discharge rating curves in the present study.

Stage-discharge and sediment-discharge rating curves are developed for Hydrodynamics and Morphological studies.

2.4 CHANNELIZATION OF RIVERS

Different engineering methods are adopted to carry out channelization which can be used separately or simultaneously at the same time, depending upon the geometric requirements (e.g., channel cross section, channel slope, bed and bank material, vegetation) and the purposes of channelization “flood control, urbanization, agriculture, navigation”. The most frequently adopted methods are described briefly in the following.

a) Re-sectioning by deepening and widening

Deepening and widening of the river channel enhances the cross sectional area of the channel. Hence, the capacity of the channel to carry flow is increased, thereby reducing inundation of floodplain. In some cases, this technique is adopted to lower the water table for the development of agriculture. Mostly trapezoidal cross sections are used for designing channels, but if the banks are relatively stable, like concrete banks, rectangular sections can also be adopted. Triangular sections are beneficial in small ditches.

b) Straightening

Straightening is done with a reason to decrease the flood heights. River bends are cut in shortening the river channel length. Cutting leads to rise of the slope and increasing in flow velocity.

c) Levees (or Embankments)

Levees are constructed to increase the carrying ability of the river. The flow thus remains restricted to the channels and the adjacent areas are not flooded. Generally, trapezoidal sections are adopted for the construction of Levees. Levees can be built close to channel banks, provided enough height is considered in the design or far at a distance so that ‘‘shifting belt’’ or the ‘‘erodible corridor’’ of the river is taken care of. This type of construction requires widespread maintenance of the structure. This is used both in rural and urban areas for flood control. The Geotechnical properties of materials used for the construction may degrade with time. Also, river bed may get aggraded once the flows have been confined within embankments; similar to, several lowland rivers in the PO Plain (Italy) and braided rivers in New Zealand (Davies and McSaveney, 2001).

d) Flood Walls and Lined Channels

This method of channelization is normally used in urban areas where other forms are imperfect or where the accessibility for maintenance is restricted (Brookes, 1987). Lined channels generally have a rectangular cross section with vertical sides prepared in concrete. This type of channelization helps to reduce channel roughness remarkably, thereby increasing flow velocity.

e) Bank Protection Structures

Groynes or spurs are the structures which are built oblique to the river flow. These structures are extending from the banks into the channel, and deflect the direction of the flow. The purpose of the construction of groynes is to protect the banks from processes of erosion (using permeable groynes) and, in some cases to promote sediment deposition (using impermeable groynes). The use of revetments is another technique used to prevent bank erosion. Different materials such as gabions, synthetic materials, concrete, live or dead vegetation can be used for revetments.

f) Diversion Channels

To divert flows from existing channels, new channels could be constructed (like, the Danube River in Vienna). The purpose of constructing diversion channels is usually for flood control and agricultural requirements. These channels are also constructed in such cases where the river channel cannot be re-sectioned or where levees cannot be constructed or its height cannot be increased.

g) Culverts

The culvert is often used in urban areas. However, it is being used for small rural mountain streams, where large-diameter concrete pipes are used. Culverting the stream is the ardent type of channelization, because it implies the disappearance of the stream below ground surface for short or long reaches.

2.5 EXAMPLES OF RIVER CHANNELIZATION

The examples described in this section include: a) Danube river, Austria; b) Rhone river, France; c) Garonne river, France; d) Main river, Ireland; e) Skawa and Wisloka river, Poland; f) Spoon river, Illinois; g) Wolf river, Tennessee; h) Kissimmee river, Florida; i) Salt river, Arizona; j) Rio Puerto Nuev, Puerto Rico; k) Kuchoro, Japan.

a) Danube river, Austria

The Danube River starts after the confluence Brigach and Breg at German town Donaueschingen, and flows southward for a distance of 2850 km, passing through four Central and Eastern European capitals, before it meets the Black Sea via the Danube Delta in Romania and Ukraine as shown in Figs. 2.2. The 350 km long Austrian section of Danube river has been changed dramatically by channelization in the 19th century to improve navigation, reduce flood plain area and reclamation of the area (Fig. 2.3). Figure 2.4 shows the change in channel configuration from the year 1812 to 1991 (Peter, 2002).

Figure 2.2 Danube river **Figure 2.3** Channelization of Danube River Austria (Wikipedia)

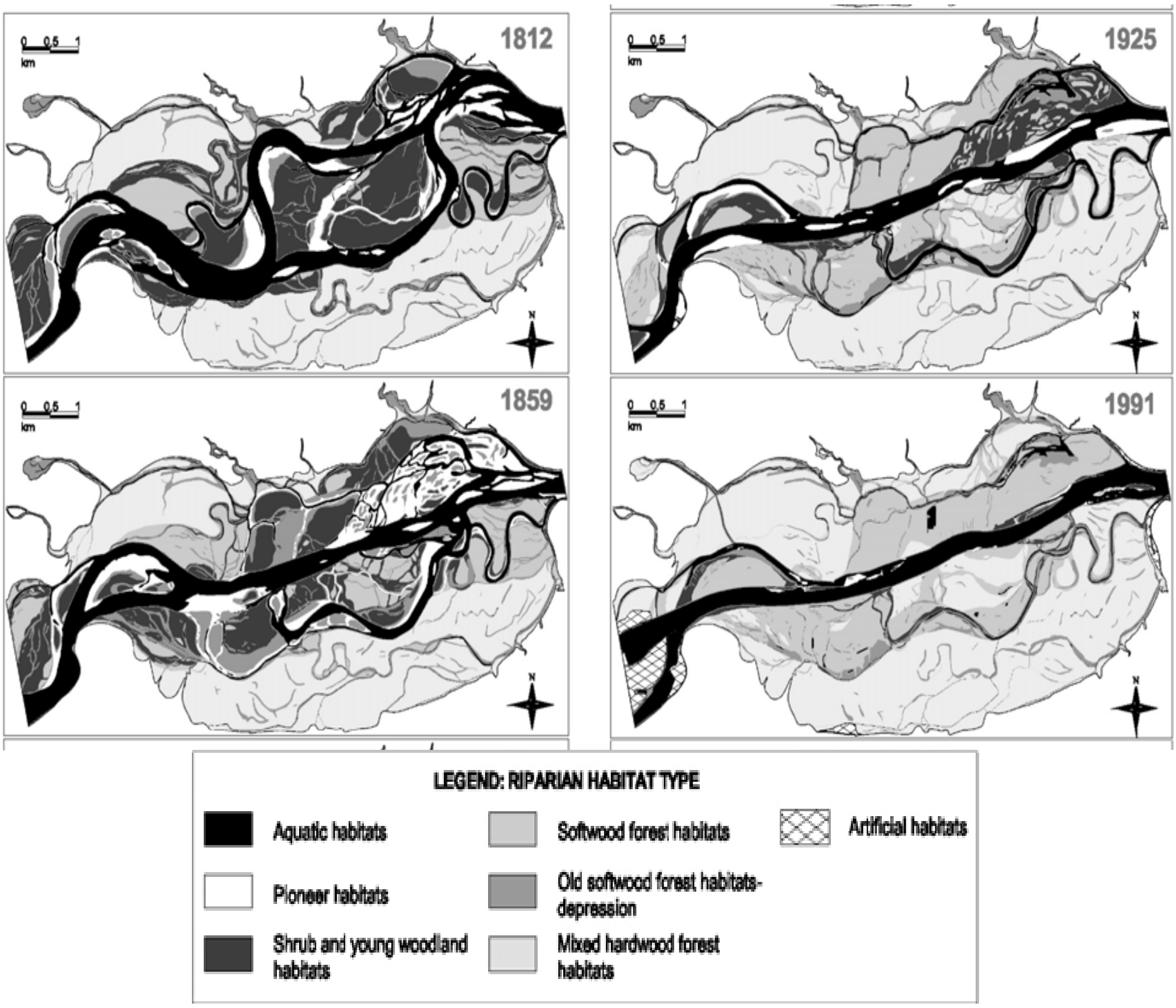


Figure 2.4 Change in channel configuration of river Danube from the year 1812 to 1991 (Peter, 2002)

b) Rhone river, France

The Rhone river originates in Switzerland and is one of the major rivers of Europe as shown in Fig.2.5. It flows throughout the southeastern corner of France. At Arles, the river divides into two branches, near its mouth at the Mediterranean Sea, known as the Great Rhone (French: Grand Rhone) and the Little Rhone (Petit Rhône). The river has been channelized shown in Fig. 2.6.

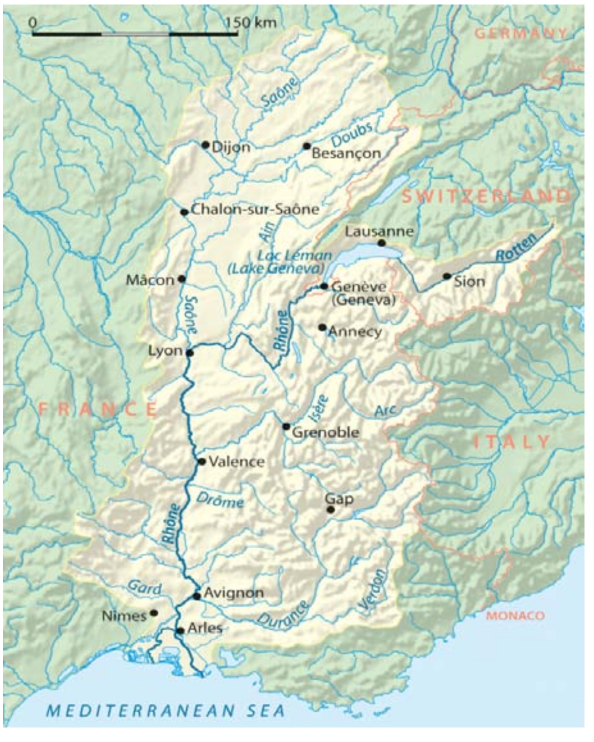


Figure 2.5 Rhone River, France **Figure 2.6** Channelization of Rhone river, France (Wikipedia)

Engineering works, such as catchment bank revetments, groynes, hydraulic deflectors and flood protection levees were designed to stabilize the plan-form of Rhone and to limit the extent of overbank flooding as shown in Fig. 2.7. Between the 17th and the 19th centuries, most of the length of the Rhone River was confined within levees causing incision of the channel bed; thus, a reduction in the area of the floods accelerated sedimentation rates on the proximal floodplain (i.e. Inter-embankment floodplain zone). Since the completion of the levees at the end of the 19th century in the Rhone Delta, accretion of 1 – 3 m has been observed within the inter-embankment floodplain, increasing the local relief and unevenness between the inter-embankment floodplain and the surface outside the levees. Combined with channel incision and the growth of the inter-embankment floodplain surface, reduced overbank flooding extent and greater concentration of flow within the channel zone by hydraulic deflectors and flood protection levees have increased the channel capacity (Arnaud-Fassetta, 2003).

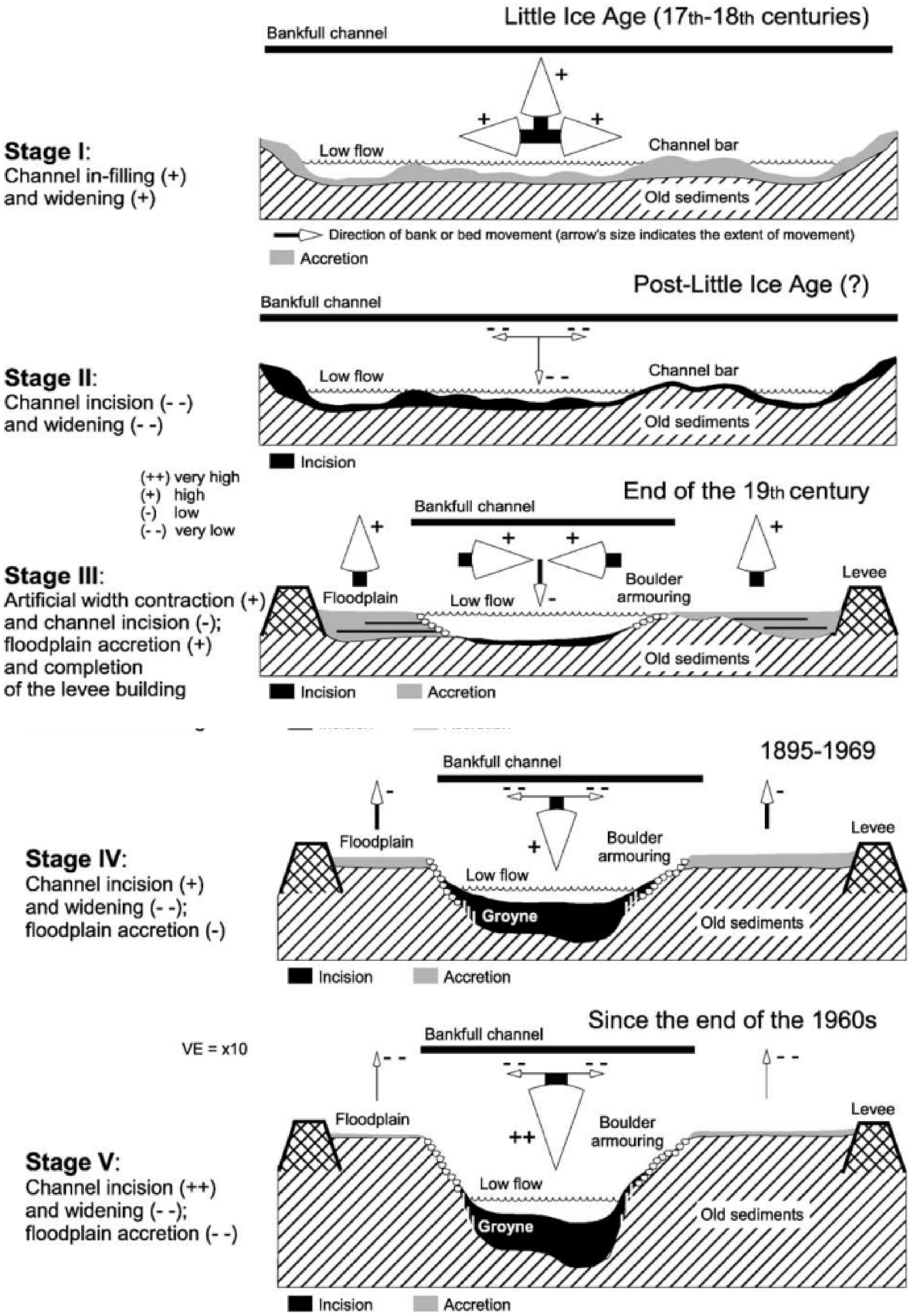


Figure 2.7 Sequential changes of the Rhone channels in the delta (Arnaud-Fassetta, 2003)

c) Salt river, Arizona

The Salt River flows in the U.S. State of Arizona as shown in Fig. 2.8. It is the largest tributary of the River Gila. Salt river flows over about 320 km length before meeting River Gila. Its catchment area is about 15,500 km^2.

Figure 2.8 Salt River, Arizona (Wikipedia)

The channel stability method was originally used for the channelization of Salt River. To estimate suitable stable gradient for low flows, several methods were used. The initial design was based upon the results of the stable channel analysis, velocity constraints, and the normal depth technique. The U.S. Army Corps of Engineers' River Analysis System (HEC-RAS) (Corps, 1998) computer program was used to verify the channel capacity. The initial design was then developed using a sediment transport model. In addition, a low flow channel alignment was planned and grade control structures were located to reduce scour. Guide dykes were planned to protect the alignment of the low flow channel during flood events that go above the design capacity of the low flow channel. Plan of the reach are shown in Fig. 2.9 (Schulte et al., 2000).

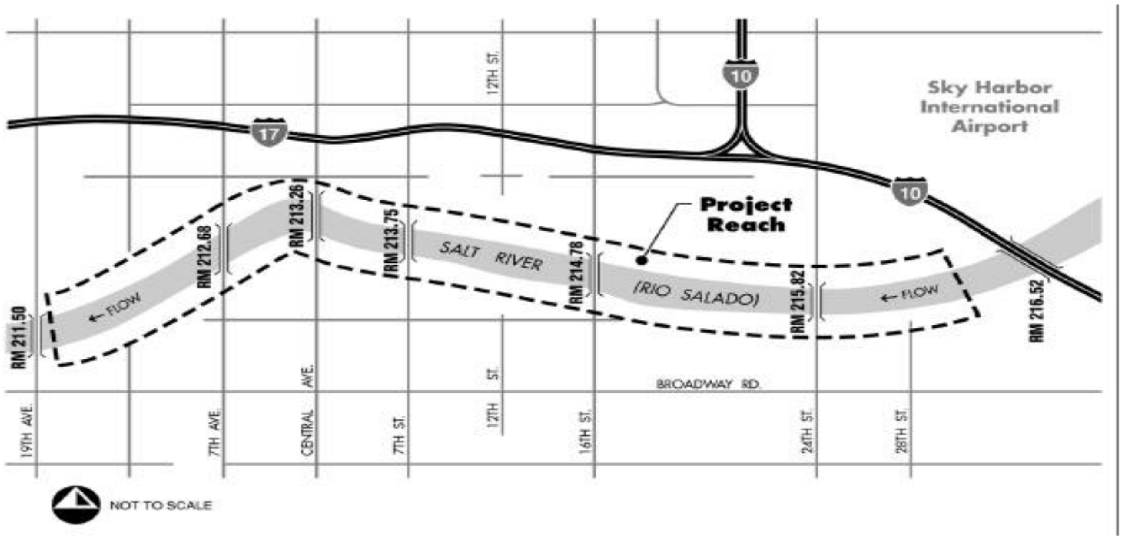


Figure 2.9 Location map of project reach in Phoenix, Arizona (Schulte et al., 2000)

d) Kissimmee river, Florida

A stretch of the Kissimmee River in central Florida, USA was considered for channelization. The original meandering river path was widened, straightened, and excavated by the U.S. Army Corps of Engineers between 1962 and 1971 for flood control in central Florida. As of 2007, the Kissimmee River Restoration Project was underway to restore parts of the river to its original condition as shown in Figs. 2.10 and 2.11 (Toth, 1989).

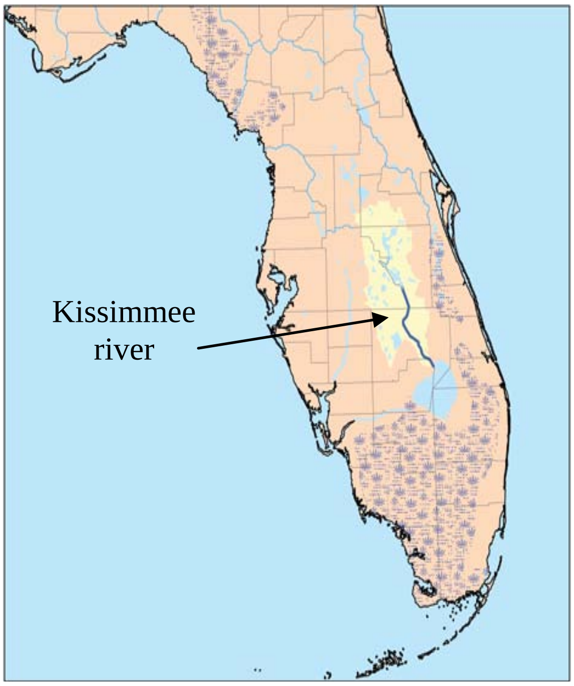


Figure 2.10 Kissimmee river

Figure 2.11 channelization of Kissimmee river, Florida (Toth, L. A., 1989)

e) Los Angeles River, California

The Los Angeles River has a total length of 82 km from its origin in the San Fernando Valley, in the Simi Hills and Santa Susana Mountains up to its mouth in Long Beach. It flows through Los Angeles County, California, from Canoga Park in the western end of the San Fernando Valley. Several tributaries join the river. This river was once known for its free flowing and frequently flooding characteristics and was forming alluvial flood plains along its banks. It now flows through a concrete channel on a fixed course as shown in Fig. 2.12. (Haltiner et al., 1996).

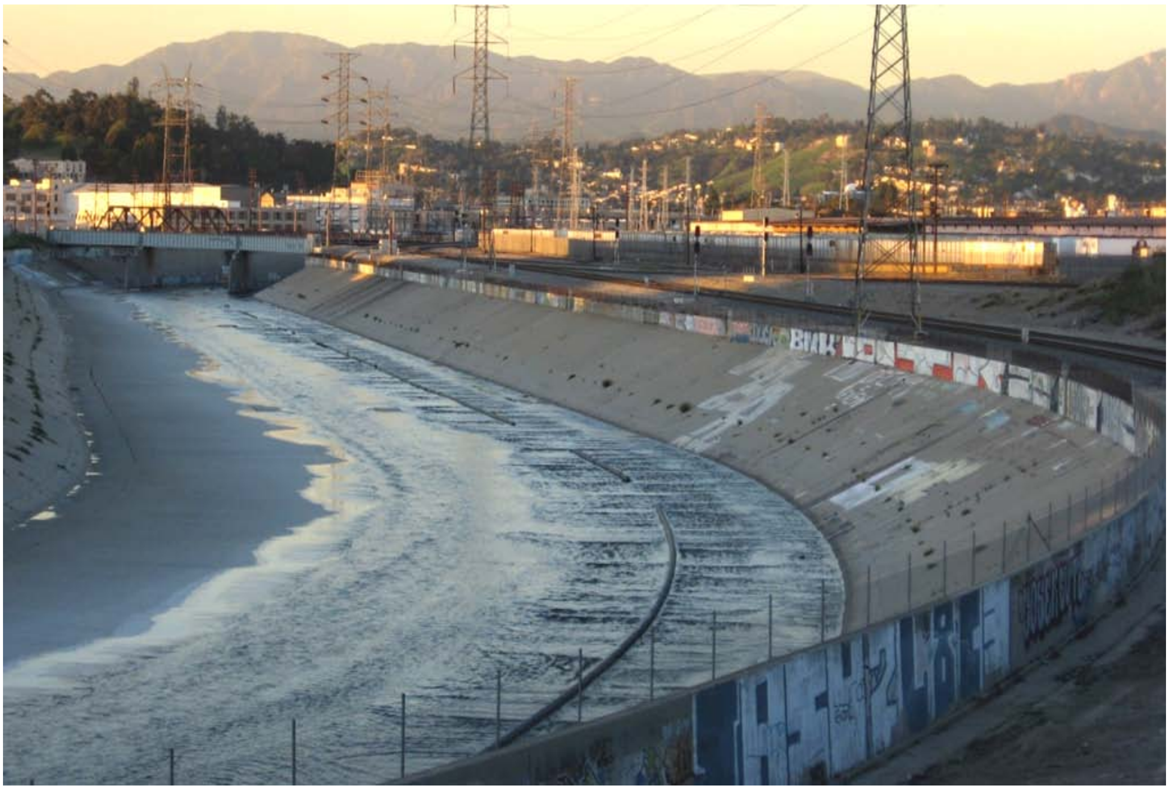


Figure 2.12 The Los Angeles River is extensively channelized with concrete embankments (Haltiner et al., 1996)

f) The Floyd River, Iowa

The Floyd River originates from northwestern O'Brien County near the town of Sanborn and flows in the south-west direction through Sioux, Plymouth and Woodbury Counties. Further, it passes through the towns of Sheldon, Hospers, Alton, Le Mars, Merill, and Hinton. Floyd River's largest tributary, West Branch Floyd River with a length of 65 km, joins Floyd River at Merrill. The Western Branch has its origin near Boyden in northeastern Sioux County and travels southward into Plymouth County further passing through Maurice and Struble. The Floyd enters Woodbury County near the Leeds neighborhood of Sioux City.

The Floyd River has caused disastrous flooding in Sioux City in 1892 and 1953. Since then, an intensive flood control project has been operated on the river. The Floyd's lower channel through Sioux City has been straightened, channelized, lined with riprap and banked by a high earthen levee as shown in Fig. 2.13.

Figure 2.13 A channelized section of the Floyd River in Sioux City, Iowa (Wikipedia)

g) The Crow River, USA

The Crow River is a tributary of the Mississippi River in south-central Minnesota in the United States. The Crow River was straightened and channelized by earthen levee, which is shown in Fig. 2.14.

Figure 2.14 A channelized section of the South Fork of the Crow River in Meeker County, Minnesota (Wikipedia)

2.6 EFFECT OF CHANNELIZATION

Several studies reveal that channelization may have various effects on channel morphology, floodplain ecology, human infrastructures, etc. Effects of channelization on various parameters carried out an various rivers are given in Table 2.1. These effects address not only the channelized reaches of the river, but also the upstream and downstream reaches (e.g., nick point migration; increased flood discharges in the downstream reaches). In the early days, sediment transport and river dynamics were not considered in the design of channelization projects. Therefore the effects of channelization have been really dramatic. The effects of channelization may be grouped into the following categories: river morphology and dynamics; hydrology; ecology; manmade structures and activities. It should be noted that channelization alone is not the only human interference on river regimes and their drainage basins. The effects mentioned below can be a combined effect of other such human impacts (channelization, dams, sediment mining, and land use changes).

Table 2.1 Examples of studies documenting the effects of channelization (Surian, 2008)

Location	**Effects (channel morphology, ecology, structures, etc.)**
Danube River, Austria	Ecology
Rhone River, France	Incision; destabilization of infrastructures; lowering of water table
Garonne River, France	Ecology
England and Wales	Channel adjustment
Main River, Ireland	Flows
Skawa and Wisloka Rivers, Poland	Incision; decrease of overbank flow and deposition
Raba River, Poland	Increased flood magnitude
Denmark	Channel adjustments
Italy	Channel adjustments
Spoon River, Illinois	Channel aggradation; good ecological effects
Wolf River, Tennesse	Incision; habitat destruction; increase earthquake risk
Iowa	Degradation; loss of land; damage to infrastructures
Several River in Tennessee	Incision; aggradation; riparian vegetation
Kissimmee River, Florida	Ecology
Salt river, Arizona	Channel changes
Rio Puerto Nueva, Puerto Rico	Groundwater changes
Kuchoro River, japan	Aggradation; vegetation changes in wetlands
New Zealand	Riparian ecology; channel morphology
Autralia	Aquatic habitat

The Mach land reach of the Austrian Danube formed a basin with a braided, highly dynamic river system before the systematic channelization in the 19th century (Hohensinner et al. 2004). Maps from the 18th and 19th century as well as written documents from earlier periods demonstrate that all river banks and islands were used intensively for agriculture and forestry. Agrarian literature from the mid-19th century clearly indicates that societies depending on natural fertilizers considered the richness of nutrients in the Danube floodplains as compensation for the risk of erosion and flooding. Cultivated land was eroded from one location while new land emerged somewhere else due to aggregation processes. The consequences of fluvial dynamics are reflected in laws regulating property rights or in tax registers from the 17th century. Regularly the payment of taxes for a parcel ceased due to its erosion, or new taxes had to be paid for aggregated and cultivated land. Land use patterns, i.e. the distribution of different categories such as arable land, meadows, pastures or forests, were mainly determined by environmental conditions such as persistence of land, groundwater table or water level of floods. A sample of land use in the Danube floodplains is shown in Fig. 2.15.

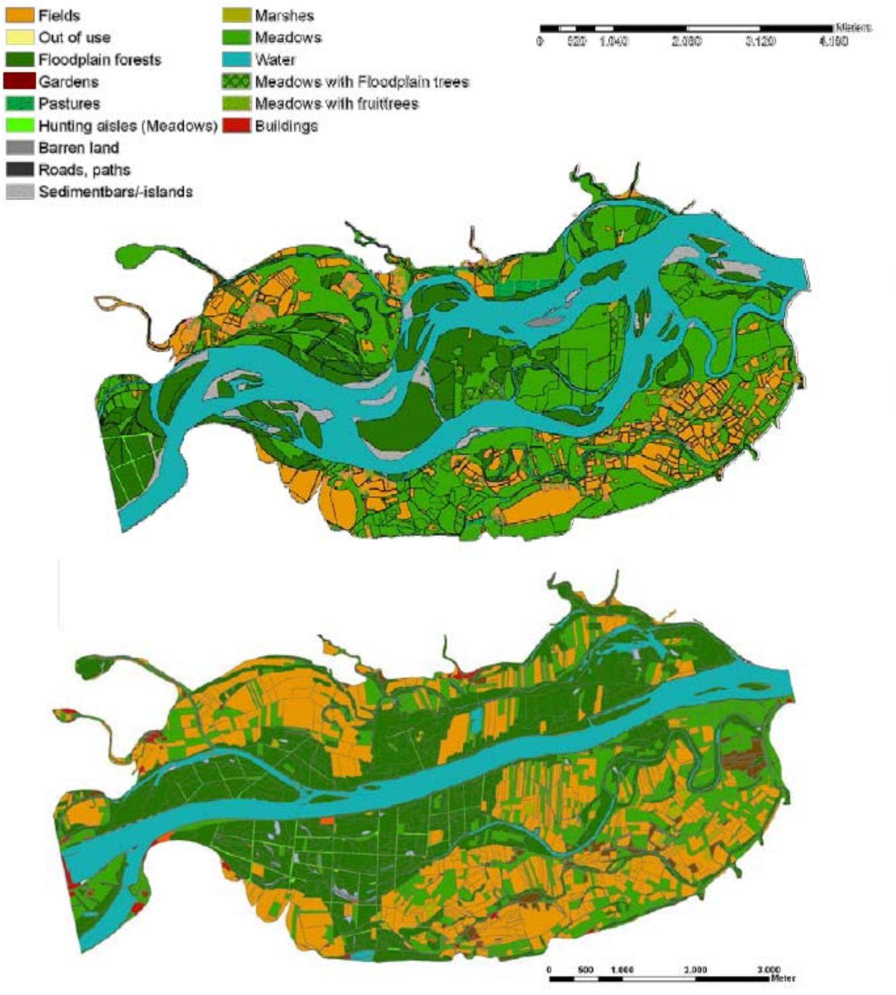


Figure 2.15 Land use in the Danube floodplains in the Machland section 1820-2000 (Hohensinner et al. 2004)

The Viennese Danube floodplains are a contrasting example to those from Machland. With few exceptions the river was, until its channelization, an obstacle to urban development. In addition, various reasons, in particular property and use rights, hampered the development of agriculture at least in the immediate vicinity of the river. Until the 19th century, people settled in the Viennese Danube floodplains mainly for specific reasons, for example accessibility to water for professional purposes. In the 18th century it also became popular for wealthy Viennese residents to establish “summer homes” in the floodplains. This situation changed upon completion of the Danube regulation along the city between 1870 and 1875. The channelization of the Danube was mainly designed to improve the navigation route. In the decision regarding the final river bed, the potential for urban development was part of the considerations. From the 1880 onwards the former floodplains became an important land resource in the fast-growing, industrializing city. Reclamation of the former floodplains for built-up areas is an ongoing process as shown in Fig. 2.16 (Eigner and Schineider, 2005).

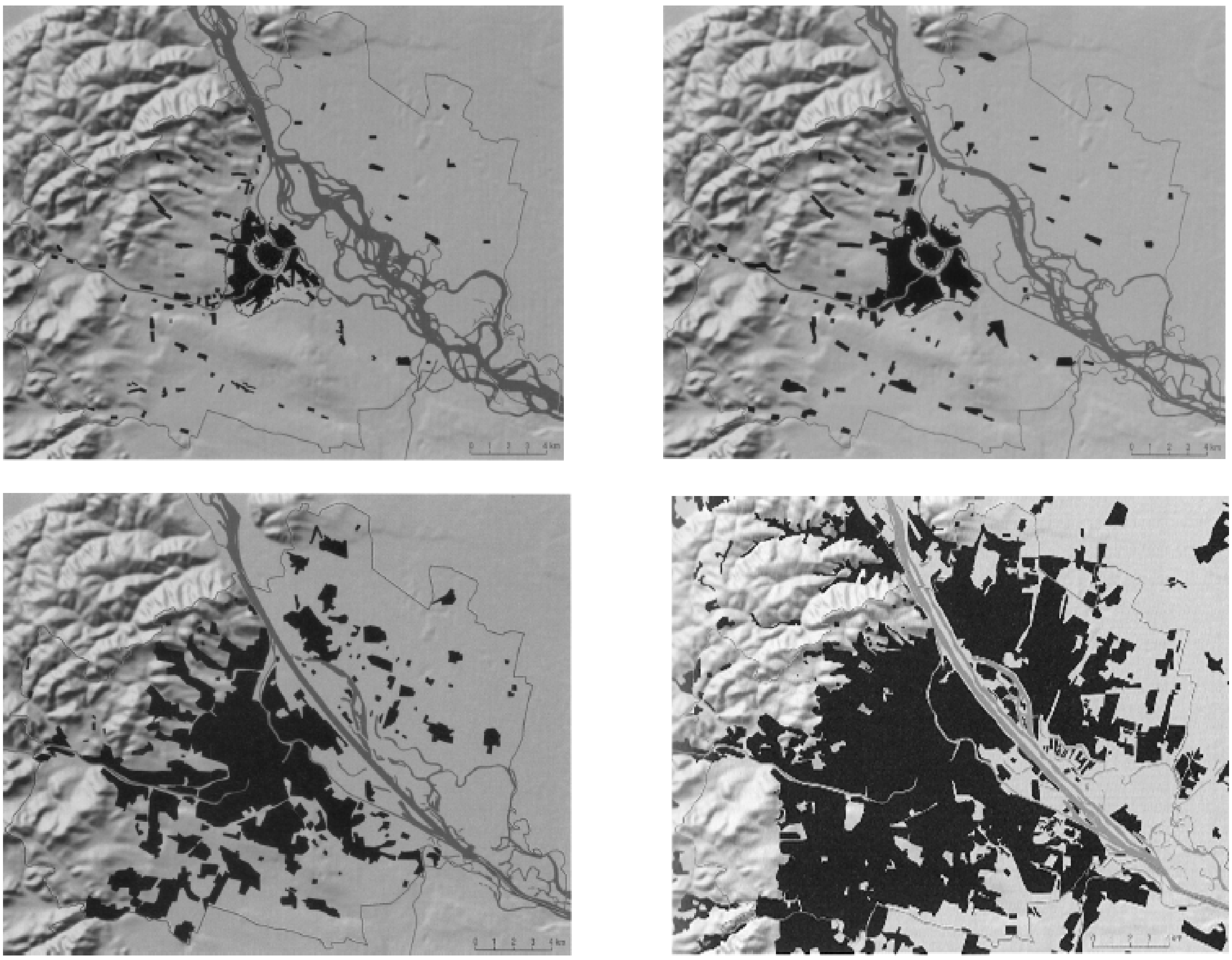


Figure 2.16 Urban development in the Viennese Danube Floodplains (1770, 1850, 1913 and 2000) (Eigner and Schineider, 2005)

2.7 CLASSIFICATION OF CHANNEL PATTERNS

As per Leopold and Wolman, (1957), river patterns are divided as straight, meandering, and braided. Further, Schumm, (1963) divided patterns into two main groups- meandering and transitional stage, which is between straight and meandering. Further, meandering is sub-divided into a) tortuous, b) irregular and c) regular meanders. Also Schumm advances the classification in terms of sinuosity, which is defined as the ratio of thalweg length LR to valley length LV (Fig. 2.17). According to him, sinuosity for the tortuous pattern (LR/LV) ratio for normal pattern would be 2.3, for the irregular pattern 1.8, for the regular pattern 1.7, for the transitional pattern 1.3, and for the straight channel 1.1. The logic applied to these definitions follows the concept of a continuum of channel patterns, which is a law of natural process. However, Chitale, (1970) concluded that the classification suggested by Schumm does not reflect the descriptive meaning of channel pattern. On the contrary, it should be classified, if the sinuosity could better it would be considered by the sharpness of the bend without reference to regularity or irregularity.

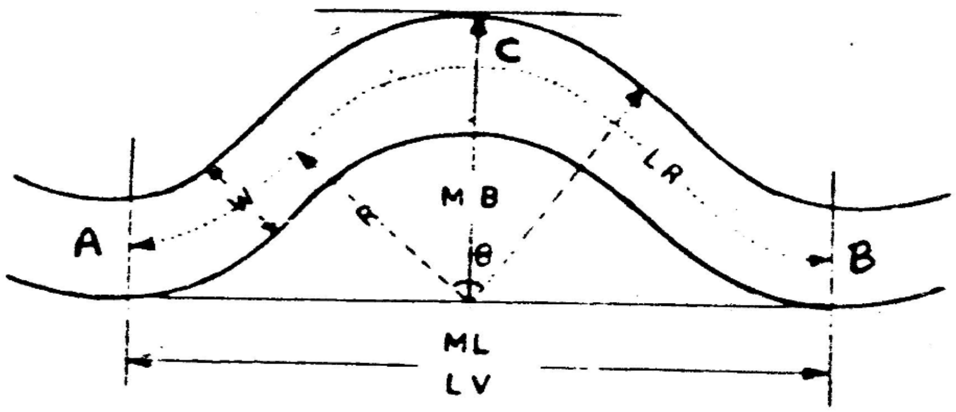


Figure 2.17 Definition sketch for meander dimensions (CBIP, 1989)

The rivers have been divided into two categories, stable and unstable (Charlton, 1969). Braided channels are classified as unstable, whereas meandering and straight channels are usually considered to be stable. He has been restricted the use of the word stability, which mean no substantial change in bed levels of a channel. Plan configuration of a channel might also adjust both with braided and meandering patterns. If the channel is having aggradations and degradation in the bed and meandering in the vertical plane may be stable, but if the meander bed is slowly moving downstream which could be viewed as instability in the horizontal plane.

Chitale classified the channel as single and multi-thread channels. Between these two classifications, a transitional pattern exists wherein the stream may show an incipient inclination to change from a single channel to a multiple one. Single channel streams were further subdivided into (1) straight, (2) meandering and (3) transitional between straight and meandering multi-thread stream. Multi-thread stream were subdivided into; (a) braided channels forming in the sub-mountainous regions and (b) numerous separate channels branching out from the parent stream leading to building up of an alluvial fan or delta near the sea.

2.7.1 Straight river channels

When the river section is wide and shallow and slope steep, the river can be straight over a long reach. An example of this type of channel is the Damodar River near Durgapur barrage (Fig. 2.18). It has a width of 1920 m, average depth of 2.6 m and slope of about 0.511 m per km. The bed material is sand of 0.34 mm average diameter. The Luni river near the railway bridge in Rajastan is another example of straight river. It has a width of 945 m, average depth of 2.13 m, and slope of 0.67 m per km. The river bed material is sand of 0.26 mm mean diameter.

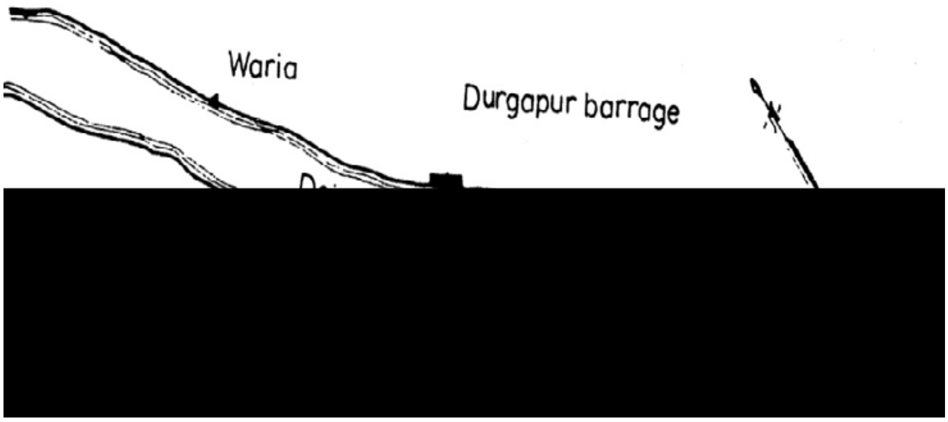


Figure 2.18 Damodar River-straight river course (CBIP, 1989)

In case of incised river, even if the cross section is narrow and deep, the river reach can be straight over a long distance. In the straight reach, the cross-section of such a river has the shape of a trough with high velocity of flow in the middle of the section. The water surface in the center of the river is, therefore, lower than at the sides, resulting in a transverse gradient from sides towards the center. Consequently, transverse and rotary currents exist in such a cross-section (Fig. 2.19).

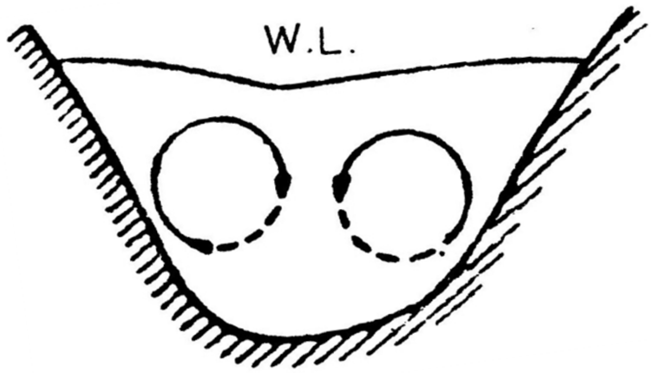


Figure 2.19 Transverse currents in a regular cross-section and straight channel (CBIP, 1989)

2.7.2 Meandering nature of Rivers

Meandering rivers have a lower slope and therefore have less velocity. These rivers have a higher amount of suspended sediment as compared to the bed load. A meandering river channel has curves that meander to and fro on a slightly sloping plain. The flow velocities in these channels vary with the curves. Water has to travel faster on the concave bend than on the convex bends as shown in Fig. 2.20. From the Reynold's number and bed shear stress relationship, it is clearly understood that higher velocities promote transporting of coarser sediment. Thus, it can be seen that there is more erosion on the concave bends, and the convex bends will be accumulating sediment which will be fine grained. Difference in flow velocity also produces different sediment patterns. Upper planar lamination and dune cross stratification are common, where Reynold's number is the highest, and ripple cross lamination is common where Reynolds number is lower.

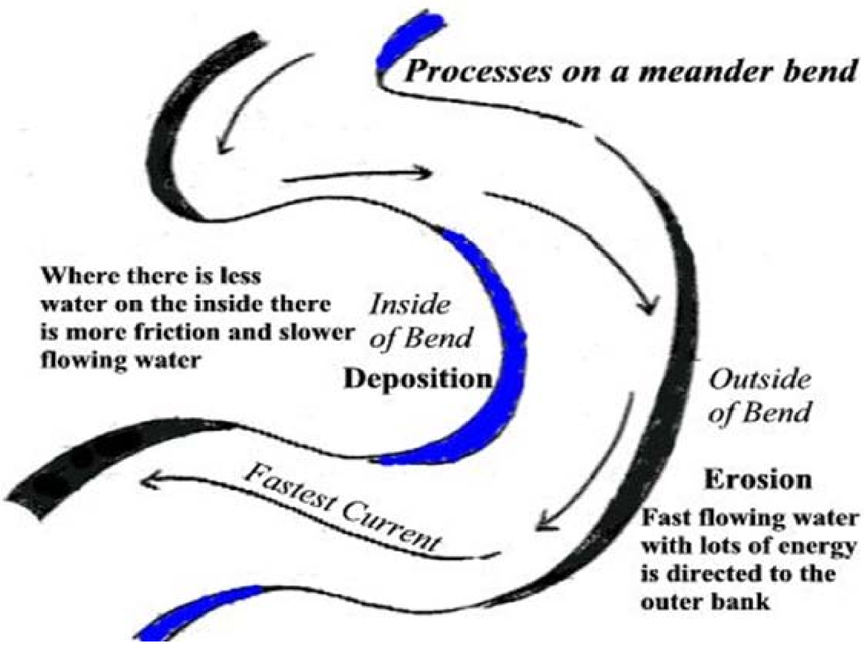


Figure 2.20 Process on a meander bend

2.7.2.1 Causes of Meander formation

Meandering has been attributed to the earth's rotation by Chatley (1938), Lacey (1923), Quraishy (1943) and Eakin (1911). Russel (1936) suggested the cause to be the changes in river stage. Friedkin (1945) well thought-out that meandering leads primarily from local bank erosion and subsequent local overloading and deposition of heavier sediment from the river. Inglis (1949) attributed the formation of meanders to overload sediment, stating that primary meanders were the result of extreme sediment being washed into the channel while secondary meanders develop when the gradient is steeper than that required to carry the sediment load, resulting in bed scour. Lane (1957) thought that steeper the gradient the more braided a stream become, the flatter the slope the more tortuous it becomes, and the gradient of a comparatively straight stream is even flatter than that of a meandering stream. Ackers and Charlton (1970) advanced the concept of limiting slope, whereas Yang (1971) adopted the concept of the minimum time rate of expenditure of energy to explain the formation of meanders. Langbein and Leopold (1966) showed that the effect of meanders is to introduce flow resistance due to curvature in such a way that uniform utilization of energy occurs through the whole length of the meander reach. In this way the meander pattern approaches more closely the condition of equilibrium, as defined by entropy concept, than does the non meandering one. They, therefore, mentioned that meandering is the most probable form of channel geometry which is more stable and natural than a straight channel.

Chitale's (1973) paper "Theories and relationship of river channel patterns". The hypothesis which appears sound is the one advanced by Friedkin (1945) that meanders result from local bank erosion and Warner's (1972) suggestion that local disturbance causes meanders to form which implies non-uniformity and non-homogeneity in the fluid flow and boundary conditions. Because of such non-uniformity, the flow direction would be deflected away from the line of steep down valley slope. This local deflection cause flow concentration on one side of the channel leading to curvilinear flow, which in turn would result in the development of a meander. In the process of the formation of a meander its tail end becomes skewed to the direction of valley slope and the phenomenon of one sided flow giving birth to meander.

2.7.3 Braided Rivers

2.7.3.1 Braiding Pattern

A distinctive characteristic of braiding pattern is multiple channels. There are however two types of multi-channel streams; one is the interlaced multichannel stream separated by islands at low stages giving an appearance of a hair braid. At high flow stages, the islands may get submerged and the stream may flow from high bank to high bank. This is called a braided pattern.

The other kind of multichannel stream is of distributary type in which several separate channels branch out of the parent stream as in case of a river building an alluvial fan or a debris cone. These entire multi-channels again combine at the foot of the cone. The distributary type multichannel stream is also formed in building up of the delta where all these different channels finally disappear in sheet flow at the sea end. Figure 2.21 shows the braided pattern as distinct from distributary channels.

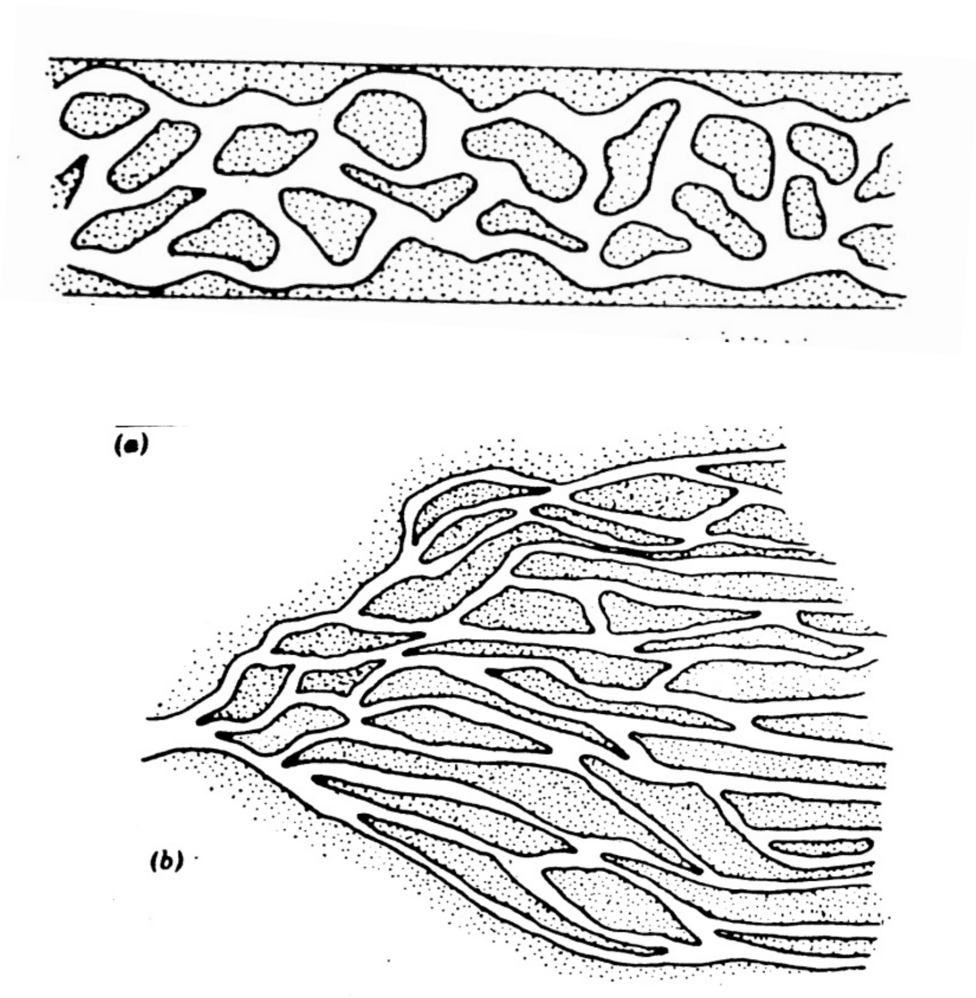


Figure 2.21 (a) Braided and (b) Distributary channels (CBIP, 1989)

Real case illustration of these two types of channels is shown in Figs. 2.22 and 2.23 for Bramahaputra and Kosi rivers, respectively. Out of these, the Brahmaputra river in Assam carries about 34,000m^3/s discharge at bankfull stage and is intensely braided at about 29 km upstream of Gauhati city within a width of about 9.6 km. The Kosi river in north Bihar has an annual maximum discharge of 5,550 m^3/s to 8,500 m^3/s, an average width of 6.4 km and has got several distributary channels formed in the process of building of an alluvial fan.

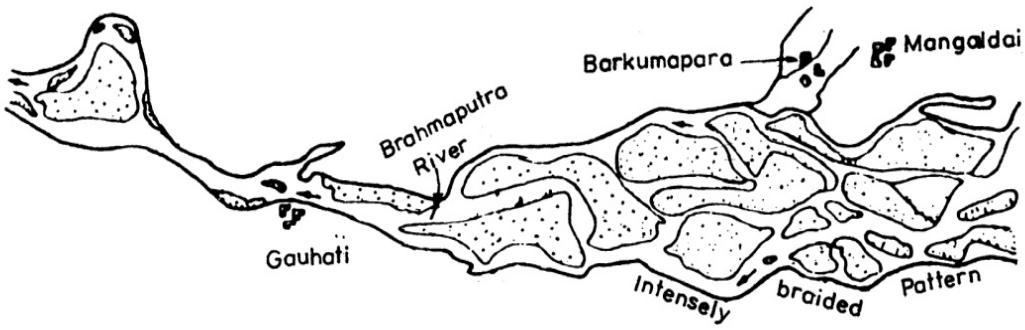


Figure 2.22 Braided pattern in Brahmaputra river (CBIP, 1989)

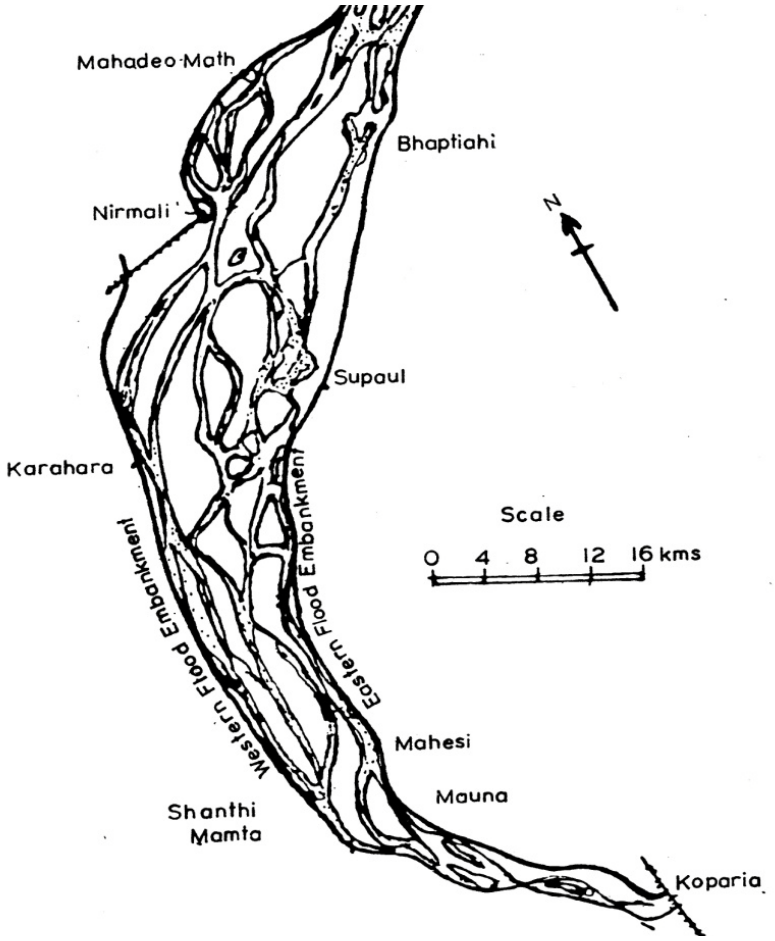


Figure 2.23 Distributary channels of the Kosi River (CBIP, 1989)

2.7.3.2 Causative Factors

A number of investigators have discussed that reduction in carrying capacity of sediment in the river results into formation of braiding. Ackers and Charlton (1970) said that if a slope is insufficient for the development of the hydraulic gradient necessary to transport the discharge and sediment, effects on formation of braided channel patterns develops in which deposition occurs and slope gradually increases. Lane (1957) suggested that steep slopes also cause formation of bars and islands in the channel which makes braided channel by the process of carving a wide and shallow section. Leopold and Wolman (1957) expressed that a quasi-equilibrium between discharge, sediment load and sediment transport capacity is maintained in braided pattern. Yang (1971) observed that the division of the channel into smaller and steeper channel is caused in a braided river to keep the balance between sediment inflow and outflow. It was further maintained by him that channel braiding is likely to occur where the channel width exceeds that is necessary to carry the given discharge. Chitale’s (1973) hypothesis is that all braided channels carry a heavy charge of bed load. In order to generate sufficient transporting capacity for this heavy bed load, a wide and shallow cross-section is formed in which conditions for building of braided pattern are favourable. This explanation is elaborated further below.

In a given channel, velocity is governed by slope, depth and boundary rugosity coefficient. The slope is normally dependent on general ground or valley slope. With a given discharge, the velocity obtained with this slope may or may not be sufficient for transport of bed load. If the bed load is heavy, the velocity may become inadequate for its transport and there would be deposition of bed load material. On the other side if the velocity is high may causes bank erosion and the channel widens. Wider the channel, bed load per unit width reduces, which helps to diminish deposition of bed load in the channel. By this self correcting process, the channel adjusts its cross-section and slope so as to generate adequate capacity for bed load transport and tries to be free from the tendency of deposition or scour and reach stability. In this attempt, a wide and shallow cross-section with steep slope is formed. When the cross-section is wide and shallow, it is difficult to obtain uniform discharge distribution all across the channel. The resulting nonuniformity of discharge distribution leads to the development of interlacing channels. This reasoning appears to provide a rational explanation of the formation of a braided pattern.

2.7.3.3 Characteristic of Braided Pattern

a) Aggradation

Since braided pattern emerges when bed load transport is heavy, braiding of channels is often associated with a tendency for aggradation. Braiding channels, however, need not always experience aggradations. For instance, Brahmaputra river upstream of Guwahati having intensely braided pattern as shown in Fig. 2.22, is not having an aggrading trend.

b) Channel Alignment

Heavy bed load, generating a wide and shallow cross-section, was seen to be the basic reason for formation of braiding pattern. Associated characteristics were found to be steeper slope, coarser bed material and higher velocities. All these factors are unfavorable for meander formation. The alignment of braided channel is more or less straight, subject to constraint of valley boundaries.

c) Movement of Islands

Islands in braided rivers get eroded on their upstream faces and build up on the downstream faces. The islands therefore appear to be unstable and moving downstream. The rate of this apparent movement is slow and depends on several factors like frequency and duration of high floods, size and gradation of material forming the island, its susceptibility to erosion, vegetal cover which retard velocity, clay content which retards erosion, etc. Tendency for movement of islands therefore can be significant in some rivers and not noticeable in others. Movement of a typical island in the lower Brahmaputra river is shown in Fig. 2.24.

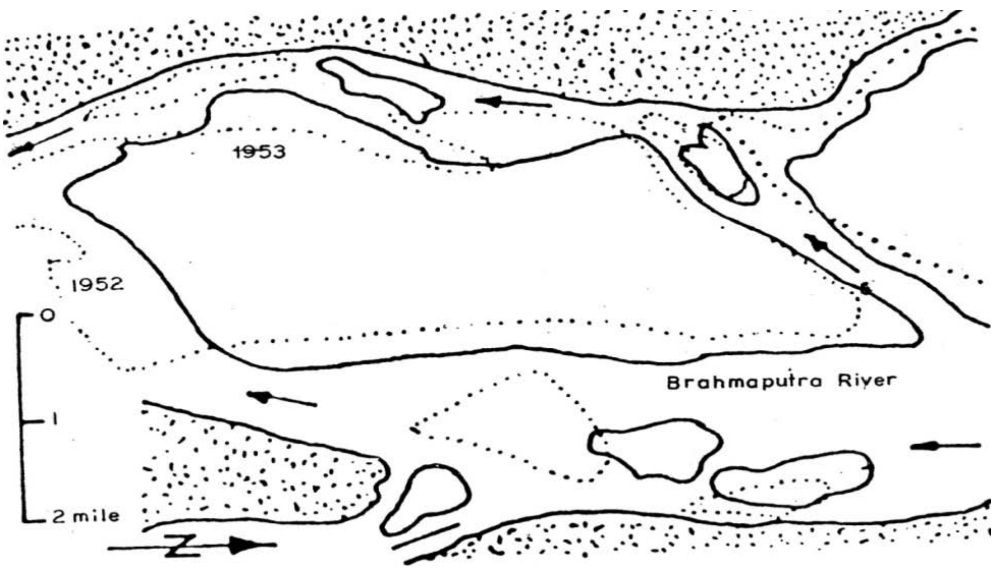


Figure 2.24 Shifting of an Island in Brahmaputra (CBIP, 1989)

d) **Bank Erosion**

Islands in some of the braided rivers have a tendency to move downstream. With the movement of the islands the channel along the bank gets squeezed causing an increase in discharge concentration, thus leading to local bank erosion.

e) Relationships for Braided Channels

Several investigators have noticed a significant difference in the slopes of braided and meandering rivers. Slope of a braided river is found to be much steeper than that of a meandering river, Lane (1957) found a general relationship of the form $S = k\,Q^{-0.25}$, where the value of K is 0.0017. This relationship was applicable to all meandering streams in an equilibrium condition with the sediment of the size found in the lower Mississippi river and having a similar tortuosity ratio. For braided streams of high slope and sandy beds, the slope discharge relationship suggested by him was $S = 0.01\,Q^{-0.25}$. Thus the slope for a specific discharge in case of braided streams would be almost 6 times that of a meandering stream.

Leopold and Wolman (1957) sought similar relationship and found that braided channels were separated from meandering channels by a line defined by the relation $S = 0.06\,Q^{-0.44}$, which indicates that for a given discharge meandering would occur with smaller slopes and braiding with steeper slopes.

Henderson (1966) attempted to refine the criterion given by Leopold and Wolman (1957) by taking the size of bed material into account. He found that in 67% of the cases, meandering channels follow the line given by $S = 0.517\,d^{1.14}\,Q^{-0.44}$, where d is the median size of bed material in meter. Braided channels had slope substantially steeper that indicated by this equation. Since the bed material in braided rivers is coarser than that in meandering ones, the implication of Henderson criterion is that the estimated slope would be steeper on account of coarser material as well.

Chitale (1973) verified the above criteria and found that the criterion of Leopold Wolman (1957) was superior and was borne out by 80% of field data. He also observed that width to depth (W/D) ratio was a physical factor governing formation of braiding pattern and for all braided rivers, the value of this ratio was found to be more than 400 in the field data examined by him.

2.8 MATHEMATICAL MODELLING

Although flow in natural rivers is three-dimensional (3D), one (1D) or two (2D) dimensional models are used commonly in engineering practice for shallow open channel flow.

In particular, when simulating a very long river of multiple channels in cross sections for a long period, the 1D models (e.g., HEC-RAS) are more cost effective than 2D or 3D models. However, they are unable to simulate momentum exchange between the main channel and floodplains, turbulence around engineering structures (e.g., bridge piers, spur dykes), and flow in highly sinuous channels (Duan et al, 2001; Duan and Julien, 2005). To overcome these limitations, engineers commonly enhance 1D model with empirical formulas to approximate energy losses attributable to in-stream structures or meandering bends. The site of the present study is the Kosi River, a reach consisting of braided, transitional, and meandering channels with levees and dykes, and highly overloaded sediment supply, which requires an improved 1D model to simulate the hydraulic aspects of channelizing the river.

2.9 PHYSICAL MODELLING

Scale model have been extensively used for long to study the phenomena related to flow through rivers. River model could be either of rigid bed or mobile bed. Where the water levels, flow pattern, discharge distribution, etc. are required to be studied without allowing changes in the river bed, the rigid bed models are preferred. On the other hand, where bed changes are important, the river bed is molded in an erodible material and the model is then called a mobile bed model.

Design of rigid bed model is relatively simpler since the requirement is to adjust the friction in the model vis-à-vis the model scales so that water levels are reproduced correctly. Regarding mobile bed models, several design approaches have been followed in India as well as abroad. The Indian approach is developed mostly adopting Lacey regime equation through suitable additional requirements to ensure proper bed movement in the model keeping with reasonably accurate similitude of water levels.

Newton's Law of motion is the fundamental relation governing the hydraulic phenomena related to irrotational motion of flow over weirs and sluices, turbulent flow in pipes and open channels, sediment transportation and control, etc. Besides the forces of inertia or mass, other forces are due to gravity, fluid friction, capillarity and elasticity. Corresponding to these forces, there are dimensionless numbers, viz. Froude number, Reynolds number, Weber number and Cauchy or Mach number. The solution to a hydraulic problem consists essentially in controlling only three fundamental quantities, viz. pressure, velocity and potential (water surface elevation) involved in the Bernoulli's equation.

There are mainly three types of similarities to be modeled in physical model simulations.

- Geometric similarity – similarity of form and shape
- Kinematic similarity – similarity of form and motion
- Dynamic similarity – similarity of masses and forces.

For a specific problem, initially one has to identify that which of the force predominate and influence the hydraulic phenomena. If gravity is the main force governing the motion, Froude's Law will be applicable, and if frictional forces govern the motion, Reynolds Law will be applicable. Frauds law postulates direct variation of velocity with respect to the square root of the depth, whereas Reynolds law requires an inverse variation of velocity with depth.

Hydraulic models are mainly of two types, viz. Geometrically similar and distorted. In the former, all dimensions are reduced to the same scale, whereas in the latter, the scales for vertical and horizontal dimensions are different. In order to get accurate quantitative results in respect of flow condition, velocity and acceleration of flow, forces involved, etc., a close dynamic similarity is to be obtained while operating the models. this is possible only when geometrically similar model are used.

Distortion becomes necessary to design a model of wide and shallow streams in which large horizontal dimensions call for a model scale which is too small for application to the vertical direction. Such small depth would often cause laminar flow in the model which cannot be used to represent the turbulent prototype flow. Distortion becomes necessary when prototype dimensions are scaled down, hydraulic forces are so much reduced that bed movement is not properly reproduced in the model unless very large models are used. Large models areas are generally impracticable owing to the consideration of cost, available space, water supply, etc.

The three main criteria on which the design of a geometric model should be based are

(i) Adequate tractive force to ensure satisfactory bed movement

(ii) Proper discharge scale, and

(iii) Sufficiently high Reynolds number to indicate fully turbulent flow.

Subsidiary and other practical considerations which are also to be taken into account are

a) Length scale to be appropriate to the available space
b) Actual model depths to be neither too small nor too big

Different approaches are to be followed to achieve the desired specific requirements. The different scale designs so worked out are to be finally compared and the best one to be selected.

Vertical exaggerations of some mobile bed models used at CW&PRS, Pune are given in Table 2.2.

Table 2.2 Examples of distorted model (CBIP, 1989)

Model	Horizontal Scale	Vertical Scale	Vertical Exaggeration
Kosi river	1:500	1:70	7.1
Ganga river	1:500	1:70	7.1
Yamuna river	1:300	1:60	5.0
Brahmaputra river	1:500	1:66	7.6
Brahmani river	1:350	1:70	5.0

Vertically exaggerated models can be rigid, semi-rigid or mobile. A rigid bed model does not show the changes directly in the bed configuration and inferences have to be drawn indirectly by means of velocity observations. In semi-rigid models, the sides and sometimes parts of the bed are made more rigid. In movable bed models, both bed and sides are erodible. However, banks may have to be made rigid if they become steeper than the natural angle of repose of the bed material.

2.9.1 Design of model scales

a) Longitudinal scale (Lr)

This is determined by considering the availability of space to accommodate the required river reach and the discharge in the model. Generally, models having discharge between 0.2 to 0.3 m^3/s are convenient for operation. The scale selected should be such that the widths of channels are adequate. A minimum width of 0.9 to 1.2 m is considered satisfactory.

b) Depth Scale (Dr)

Once the length is determined, the depth scale can be worked out considering one of the following formulae:

i) $Dr = (Lr)^{0.75}$…………………………According to Manning's formula

ii) $Dr = f^{(1/3)} (Lr)^{0.67}$ …………………..According to Lacey's formulae

where f = silt factor = $1.76 (d_{50})^{0.5}$, with d_{50} as mean diameter of sand in mm

Results obtained from these formulae differ appreciably from one another and hence neither can be taken as accurate guide. It is desirable to have as low vertical exaggeration (V.E.) as possible so that the flow pattern in the model does not get too much distorted. Small V.E. is necessary to keep the depth of water in the models of deep rivers low, as for a depth exceeding 0.5 m it is difficult to observe flow conditions near the bed even though the water is clear. It should be ensured that during low floods, sufficient tractive force would be available in the model with the particular bed material. In addition, depth of water should be sufficiently large for taking observation with instruments like current meter. Effect of surface tension, wind and bed ripples will be excessive in case of shallow depths. For these reasons, depth less than 8 cm should be avoided as far as possible. To produce a turbulent flow and necessary tractive force the V.E. becomes necessary. The side slopes resulting from high V.E. are relatively much steeper in the model than in the river. Thus, a gradually sloping bank of the river will be reproduced in a highly vertically exaggerated model by an almost vertical bank. The effect of such steep banks in the model is to cause scour along it and thus attract the deep channel on to it, which in the river may be quite a distance away from the bank. High V.E. is also undesirable as the steep slopes may exceed the angle of repose of the bank material of the model and the deep channels in the river cannot be reproduced and maintained in the model. Also, it should be ensured that the tractive force in the model is not too high to cause intense bed movement, which would result in washing out of the model bed material during its operation with high discharges.

c) Slope Scale (Sr)

Bed movement is governed not only by the depth, but also by the slope. Both of these together determine the available tractive force. It is therefore likely that slope scale required to give the bed movement with the selected depth scale may not always be equal to V.E. In addition the V.E. and slope exaggeration (S.E.) chosen has to be suitable for the sand grade to obtain correct water surface profiles in the model. Even the correct choice of depth and slope scale of a model which ensure satisfactory bed movement, at a particular stage may still be incapable of correct reproduction at other stages. This is because the depths and slopes are dependent on the velocity through formulae of Chezy or Manning type. The ratio of hydraulic radii not being the same as the ratio of depth of flows at different stages, it is not possible to design model depth and slope scales applicable accurately over the whole range of discharges. Adoption of a slope scale for a model with erodible bed equal to its vertical exaggeration is desirable, since the laying operation and interpretation of the model behavior in terms of different model scales and the bed material should in many cases be able to achieve. While operating a hydraulic model, it is convenient to have slope exaggeration = vertical exaggeration, since it results in considerable simplification.

(d) Discharge Scale (Qr)

Models are operated according to Froude's relationship; velocity scale = (depth scale)$^{1/2}$, and hence the discharge scale = (horizontal scale) X (depth scale)$^{1/2}$. In case of models of alluvial rivers it is necessary to ensure that the adopted discharge scale satisfies the natural law of meanders. For alluvial rivers, the meander length and width are proportional to the square root of the discharge carried by the stream. This means that the discharge scale should be equal to (horizontal scale)^2. The best practice is to make Lr X Dr$^{1/2}$ equal to Lr^2 to avoid complications when rigid structures are to be tested in the reach. Obviously, some trial and error will be necessary to work out the discharge scale to satisfy all these requirements.

(e) Choice of bed material

Sufficient bed movement is the criterion for deciding the choice of bed material, so that bed configuration is properly simulated. Various channel flow formulae incorporating rugosity coefficient can be used in this regard. The general experience is that the more close agreement between the actual and model velocities and hence discharge can be worked out using Manning's formulae. Generally, the coefficient of rugosity in movable bed models is higher than that in the prototype; but no exact formulation of the deviation has, however, been possible. Starting from the slope scale as computed by the tractive force method, the requisite scale can be determined by trial and error. Bed material should move in the model at the stage corresponding to which active bed movement exists in the prototype. Where velocities in model are not enough to move sand on bed, lighter materials like coal dust, pumice stone, shellac mixed with barites, powdered Bakelite, etc. are used. In the distorted model, the roughness scale is 1: Dr$^{1/6}$/V.E$^{1/2}$, where V.E. is vertical exaggeration.

(f) Time Scale (Tr)

Theoretically, the time scale is equal to Lr/(Dr)$^{1/2}$. Model discharge stages are based on the nature of the hydrograph. Duration of each run is determined according to the theoretical time scale and adjustments are made by trial and error.

(g) Rate of Injection of silt

Sediment load in nature comes from the catchment area. In models, material has to be injected artificially at suitable places to simulate this effect. The rate of injection is adjusted so that material collected at the tail end of the model is equal to that injected upstream, to obtain equilibrium conditions. The rate of injection is usually worked out by trial and error depending on the materials used and flow conditions simulated.

2.10 CONCLUDING REMARKS

From the preceding review it has become apparent that the river channelization is an effective method for transporting the sediment in braided rivers.

PFI index reflects the fluvial land form deposition with respect to a given water level and its lower level value is indicative of higher degree of braiding. Higher degree of braiding also indicates that the velocity, which is required to transport the sediment, is not available. In view of this, channelization (constricting waterway) of this type of rivers is one of the ways to transport the sediment.

The ANN based rating curves simulate the river flow and sediment characteristics, which intensely influence morphological inconsistency, more realistically. The formulation of rating relationship models on a daily basis (for an important gauging station at Barahakshetra and at Kosi barrage on river Kosi) by capturing the intrinsic trend have thrown light on the inconsistency pattern of the discharge and sediment at these points. Such daily rating curves are useful for deriving rating curves at sub-daily time scales required for real time forecasting.

Channelization of a river may have to be done on account of several reasons, like navigation, land reclamation for agriculture, and flood control. Flood is controlled, by giving a stream an adequately large and deep channel, to avoid flooding limit. Kosi river flowing in the Himalayan area with a high velocity does not allow the sediment to settle, and as it comes in plain, the velocity of flow reduces, which affects carrying capacity of sediment resulting in braiding formation. In these studies, various types of channelization method are used to increase carrying capacity of sediment in the flow by using physical and mathematical models.

Chapter 3

KOSI RIVER

3.1 DESCRIPTION OF THE RIVER KOSI

The Kosi river is one of the most ancient rivers of India. It is also known as Kaushiki in Sanskrit literature. It is a perennial river. Its three main tributaries viz. river Sun Kosi from West, river Arun from North and river Tamur from East, meet river Kosi at Tribeni to form the Sapt Kosi as shown in Fig. 3.1. River Arun, the longest of the tributaries has cut through a gorge in the great Himalayan range and drains, under the name of Phung Chu, the entire Tibetan trough from Gosainthan to Kanchenjunga. Downstream of the confluence, the Sapt Kosi flows in a narrow gorge for a length of about 10 km and then debouches into the plains near Chatra. Further downstream, the river Kosi runs in a sandy, almost flat plain and flows southwards to join the Ganga near Kursela as shown in Fig. 3.2.

Figure 3.1 Main tributaries of River Kosi (Image from Google Earth)

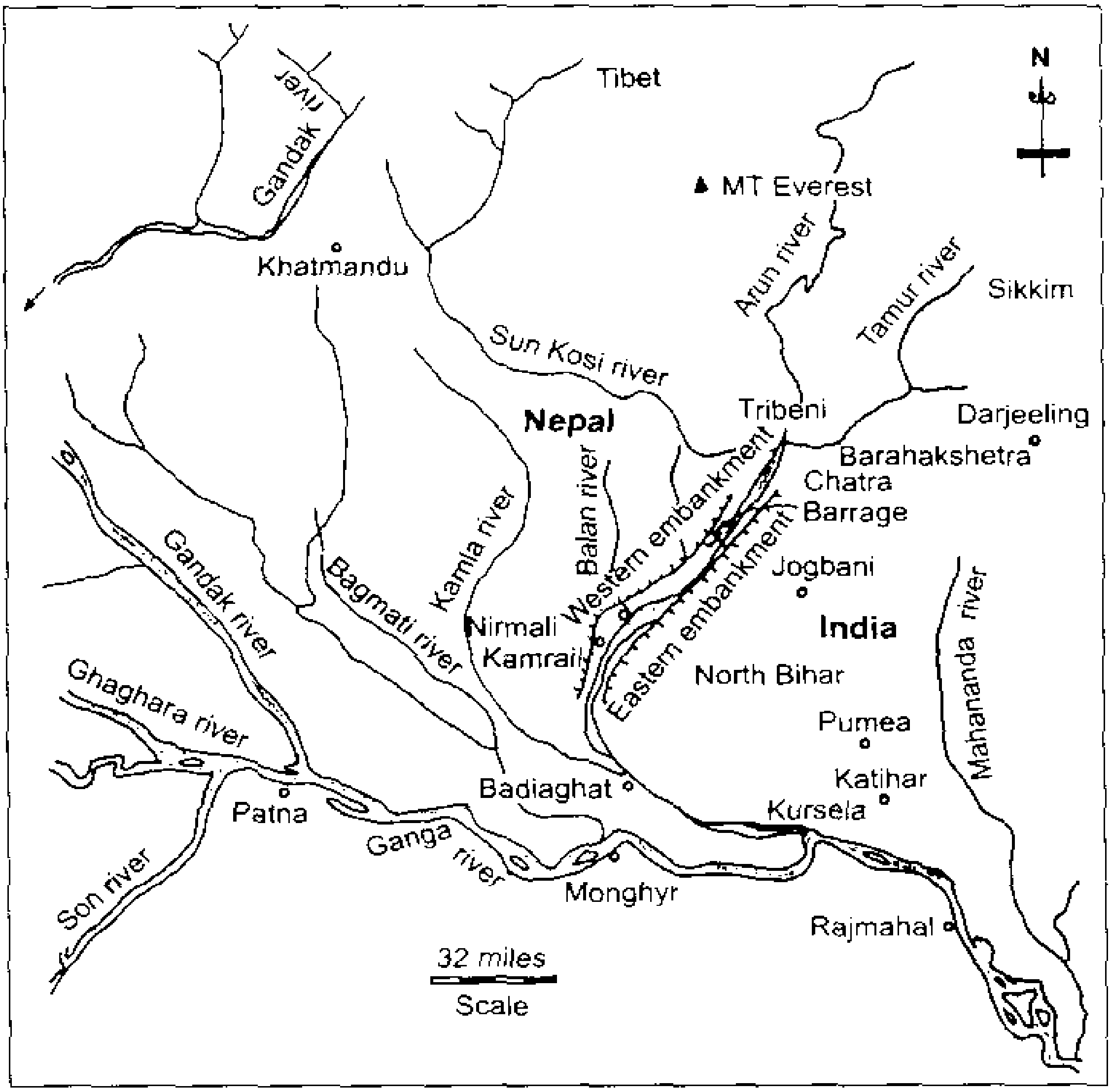


Figure 3.2 Index plan of Kosi River (Gole and Chitale, 1966)

Prior to the construction of the Kosi project, the Kosi river used to break up into numerous inter–lacing channels. In each of these channels, the bed rose gradually on account of deposition of huge quantity of sand and silt brought down by the river. During floods, the river cut through friable banks and formed new channels, which subsequently got enlarged and became the main course of the river. The river, since time immemorial, has been building a fan shaped inland delta with its apex at Chatra and sides passing near Purnea in the East and Darbhanga on the West as shown in Fig. 3.3

During about past 250 years, the Kosi river is known to have changed its course across a width of about 112 km. Its main right bank tributaries are the Kamla-Balan and the Bagmati. The other important tributaries are the Trijuga and the Bhutabi Balan.

Figure 3.3 View of the River Kosi (Image from Google Earth)

3.2 CATCHMENT CHARACTERISTIC

The Kosi basin falls within longitude 85° to 89° (E) and latitude 25° 20’ to 29° (N). On its north is the Tsangpo (Brahmaputra) and on the south is the Ganga river. On eastern side is the ridge separating it from the Mahananda catchment and on the west is the ridgeline separating it from the Gandak/Burhi Gandak catchment. There is an 87 m drop in elevation in the 160 km reach between the Chatra gorge and Kursela near the confluence with the Ganga. The total catchment area of Kosi is 95,156 km^2 out of which 20,376 km^2 lies in India. Thus, nearly eighty percent of the total catchment of Kosi lies in Tibet and Nepal. The rivers Trijuga, Kamla Balan, Bhutahi Balan and Bagmati are the tributaries, which join Kosi river from the west side in the plains of Bihar. The distribution of the catchment area of the Kosi river system is given in Table 3.1.

Table 3.1 Distribution of catchment area of Kosi river system

	In India (km^2)	Outside India (km^2)	Total (km^2)
Kosi including hilly tributaries	11070	63430	74500
Kamla Balan	2980	2465	5445
Bagmati	6320	7080	13400
Trijuga	-	706	706
Bhutai Balan	-	1105	1105
Total	20370	74786	95156

The three hilly tributaries are the Arun, the Sun Kosi and the Tamur. The Arun Kosi is the longest of the hilly tributaries, which drains the Mount Everest. Its catchment area is 34,650 km^2 and it contributes 37 percent of flow and 36 percent of sediment load of the Kosi at Tribeni. The Sun Kosi is the second longest tributary. Its catchment area is 19,000 km^2 and it contributes 44 percent of flow and 42 percent of sediment load of Kosi at Tribeni. Tamur Kosi drains the Mount Kanchenjunga; the catchment area of which is 5,900 km^2 and which contributes 19 percent of flow and 22 percent of sediment load of Kosi at Tribeni. The Bagmati originates in Sheapore range hills at an elevation of 1,500 m and has a catchment area of 13,400 km^2 and length of 589 km. The Kamla Balan originates in Nepal and has a catchment area of 5,445 km^2 almost half of which is in the plains. Its length is 320 km. The Trijuga and the Bhutai Balan have catchment areas of 706 km^2 and 1105 km^2, respectively.

3.3 GEOLOGICAL FORMATION

The geology of the Kosi basin can be divided into three parts. The geology of the Mount Everest and the Kanchenjunga in the upper northern most part forms the upper catchment, the Siwalik deposits towards south of Mount Everest and up to Chatra, and the terraces below Chatra. The upper-most part is made up of folded Jurassic strata composed of black shale and argillaceous sand stones. This stratum is 100 to 150 m thick, and contains calcareous, pyrites and ferrous partings. Underlying the Jurassic shale are the dark limestone and overlying thick series of metamorphosed limestone, quartzite, etc. The Siwalik deposits are alluvial detritus derived from wastes of mountains, which are swept down by streams and deposited at their foot. These former alluvial deposits have been involved in the upheaval of the Himalayas, folded and elevated into their outermost foothills. Weathering of Siwalik rocks has been proceeding at an extraordinarily rapid rate since their deposition. Because of this, the topography produced is made up of very large escarpments and dip-slopes separated by broad longitudinal valleys intersected by deep meandering ravines. The terraces below Chatra are made up of conglomerates and thick beds of sand, boulders and shale. The Kosi flood plain is made up of alluvial deposits in the form of a trough, which is tectonic in nature and is formed in front of Himalayan chains. Figure 3.4 shows the geological map of the Kosi basin.

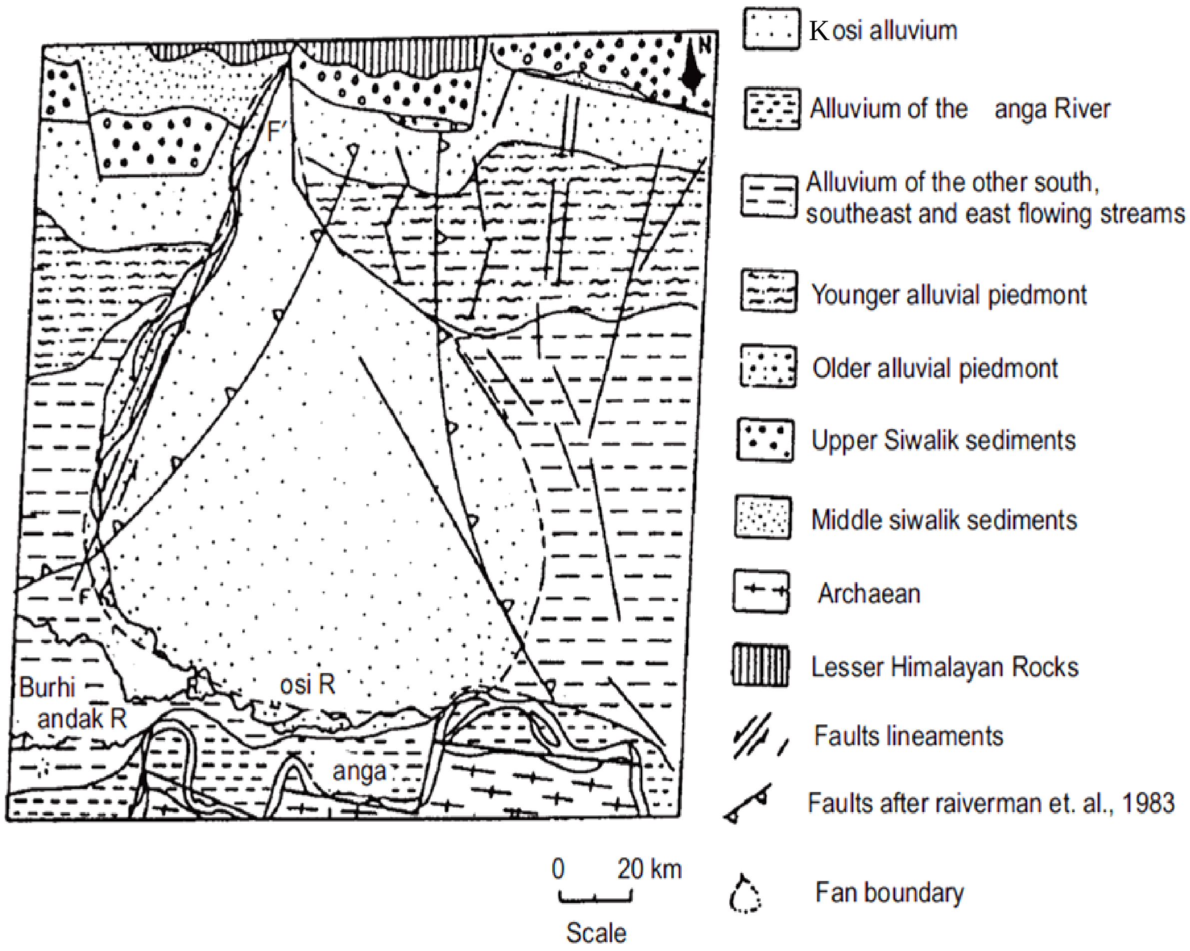


Fig. 3.4 Geological map of the Kosi alluvial fan and adjacent area (Gohain and Parkash, 1990)

3.3.1 Geotectonics

The entire Kosi basin has been the subject of study by Gohain and Parkash, (1990). The major north dipping thrusts – the Main Central Thrust and Main Boundary Thrust – are present in the area and are active even at present. One can see from Fig. 3.4 a major fault FF' at the edge of the Kosi fan which causes an offset of the Siwaliks by about 20 m. This area has also experienced over 45 earthquakes of magnitudes ranging from 4.0 to 8.3 on Richter scale. The most severe earthquake being the one that occurred on 15th January 1934 and was of magnitude 8.3. This earthquake had its epicenter within 100 km of Barahakshetra where a high dam was earlier proposed on the Kosi. This earthquake was felt all over north Bihar and Nepal and the cities of Munger and Bhatgaon (in Nepal) were completely destroyed while the cities of Patna, Kathmandu and Darjeeling felt the shocks of the earthquake. Kosi basin is also subjected to slow geotectonic upheaval, which may be partly responsible for its westward migration.

3.4 HYDROLOGY

The Kosi catchment is fed by monsoon rainfall as well as snowmelt. As mentioned earlier, ten percent of the catchment up to Chatra is above perpetual snow zone of the Himalayas. Kosi catchment gets rainfall due to monsoon, which begins around June, and retreats upto middle of October. This accounts for eighty percent of the annual rainfall. During April and May, thunderstorms occur in the catchment. The annual rainfall decreases from 1,200 mm at the foothills to 350 mm on the southern slopes of the Himalayas. In the Tibetian catchment it is about 250 mm while in the lower parts of the Kosi catchment it varies from 1,380 mm to 1,500 mm. July and August provide the maximum rainfall. Mookerjea and Aich (1963) have estimated that 74 percent of the discharge of Kosi can be accounted for by the precipitation in the form of rainfall. Analysis of peak flow in Kosi indicates that the peak flow can be ten times as large as the mean discharge in a single year. Flow duration curve for the Kosi at Barahakshetra is given by Gohain and Parkash, (1990), accordingly to which the monthly average discharge and the percent of time it is exceeded are given in Table 3.2

Table 3.2 Flow duration data for Kosi at Barahakshetra

Monthly average discharge in m^3/s	300	400	600	700	1400	3600	4300	4800	5800
Percent of time equaled or exceeded	100	80	60	50	40	20	10	5	1

The average annual runoff at Barahakshetra is estimated to be 53.40 Mm^3, out of which 80 percent is contributed during June to October. The minimum annual runoff at the same place is approximately 38.83 Mm^3.

3.4.1 Discharge and Sediment data

It was only after 1947 that the government agencies realized the necessity of having adequate and accurate flow and sediment data for the management of river Kosi and established gauging sites. At present the Kosi river has eight sediment and gauge-discharge observation sites. These are at Barahakshetra, Bhim Nagar barrage, Baltara and Basua on the Kosi, on the Sun Kosi, the Arun and the Tamur at Tribeni, and at Machhuaghat on the Arun. The annual peak flows observed at Barahakshetra between 1948 and 1997 are given in Table 3.3. It can be seen that the maximum observed flow at Barahakshetra was 25,880 m^3/s in 1968 and water surface elevation for this discharge was observed to be 132.18 m.

Table 3.3 Peak flows at Barahakshetra during 1948-1997

Year	Discharge in m^3/s	Year	Discharge in m^3/s	Year	Discharge in m^3/s	Year	Discharge in m^3/s	Year	Discharge in m^3/s
1948	13587	1958	10570	1968	25880	1978	9829	1988	11332
1949	12283	1959	5979	1969	8142	1979	13343	1989	13391
1950	9647	1960	7198	1970	13880	1980	7792	1990	11346
1951	11226	1961	8309	1971	12186	1981	7990	1991	10223
1952	9646	1962	10514	1972	10718	1982	6912	1992	9257
1953	5424	1963	7651	1973	9456	1983	8818	1993	6987
1954	24236	1964	10769	1974	11428	1984	14322	1994	7136
1955	7085	1965	6660	1975	9209	1985	9170	1995	6949
1956	5441	1966	10825	1976	9489	1986	8171	1996	8379
1957	7538	1967	8842	1977	7783	1987	14831	1997	7190

Analysis of sediment load carried by the Kosi at Barahakshetra for the period 1948-1981 has revealed that on an average it carries 95 Mm^3 of sediment annually, of which coarse, medium and fine sized materials are 18.95, 25.11 and 55.94 percent, respectively. Similar measurement made at Baltara between 1973-1981 have given average sediment load of 57.35 Mm^3, of which coarse, medium and fine are 8.2, 19.8 and 72.0 percent respectively. Garde et al. (1990) analyzed the sediment load data at the barrage and found that the sediment load in tonnes/day is related to Q in m^3/s the median size of sediment d in mm as

$Q_T \sim Q^{3.86}$ for $d < 0.075$ mm

$Q_T \sim Q^{2.86}$ for $0.075 \text{ mm} < d \leq 0.15$ mm

$Q_T \sim Q^{2.76}$ for $d > 0.15$ mm

These are shown in Figure 3.5 in the form of sediment rating curves. It is observed that sediment concentration of the Kosi river increases in the head reach, from Chatra to Hanuman Nagar.

This increase in sediment load is primarily due to increase in the fine fraction of sediment due to erosion of Belka hill region. However, beyond the Hanuman Nagar the sediment concentration progressively reduces due to deposition of coarse and medium fractions. At Kursela, where the Kosi river joins the Ganga river, the average sediment concentration is only 24 percent of that at the gorge (i.e. Himalayan area). This progressive deposition causes great instability in the river (Godbole, 1986). Tables 3.4 and 3.5 indicate how the silt load carried by Kosi river compares with that carried by some other important rivers in India and other countries of the world.

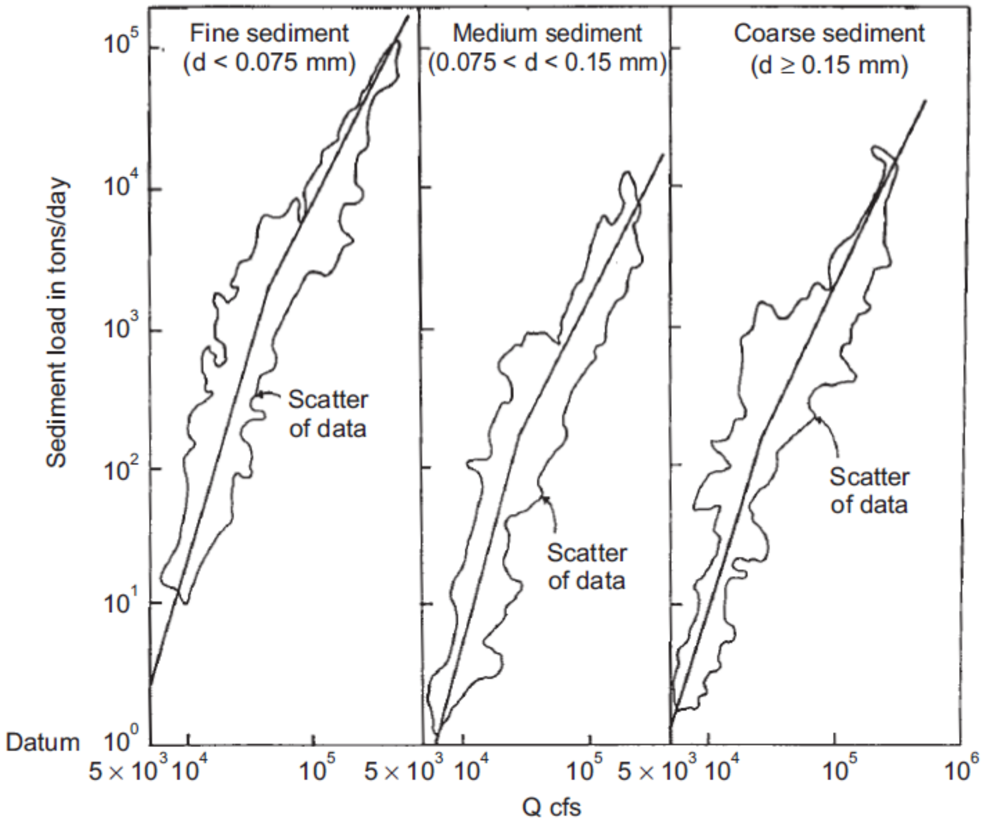


Figure 3.5 Relation between sediment load and discharge at the barrage (Garde et al., 1990)

Table 3.4 Average percentage of silt carried by the Kosi River and some of the other important rivers of the world (CBIP)

River	Country	Catchment Area in km^2	Silt Contents g/l
Colorado	U.S.A.	6,26,780	1.0
Salt	U.S.A.	14,918	0.2
Mississipee above Missouri	U.S.A.	4,40,300	0.01
Mississipee below Missouri	U.S.A.	18,13,000	0.2
Mississipee below Ohio		23,31,000	0.05
Illinois	U.S.A.	33,670	0.004
Missouri	U.S.A.	12,95,000	0.4
Ohio	U.S.A.	5,18,000	0.02
Kosi (at Chatra)	**INDIA**	**61,663**	**0.29**
Mahanadi (at Hirakund)	INDIA	83,398	0.087
Gandak (at Bhanslotan)	INDIA	37,845	0.205
Yellow river	CHINA	7,77,000	4.4 Highest

Table 3.5 Rivers of the world ranked by sediment yield (CBIP)

		Average annual	suspended load		
River	**Country**	**Drainage basin X10^3 km^2**	**Million tonnes**	**Tonnes per km^2**	**Average discharge at mouth, m^3/s**
Yellow	China	674	2113	3135	1484
Ganges	India	956	1626	1701	11620
Brahmaputra	Bangladesh	666	813	1221	12040
Yangtze	China	1944	559	288	21560
Indus	Pakistan	969	488	504	5488
Ching (Yellow Trib.)	China	57	457	8018	56
Amazon	Brazil	5780	406	70	179200
Missipee	U.S.A.	3223	350	108	17640
Irrawaddy	Burma	430	325	779	13412
Missouri	U.S.A.	1371	244	178	1932
Lo (Yellow China Tributary)	China	26	213	8192	-
Kosi (Ganges Tributary)	India	622	193	3113	1792
Mekong	Thailand	796	190	239	10920
Colorado	U.S.A.	638	151	237	154
Red	North Vietnam	119	145	1218	3864
Nile	Egypt	2981	124	42	2800

3.5 STRUCTURES ACROSS KOSI RIVER

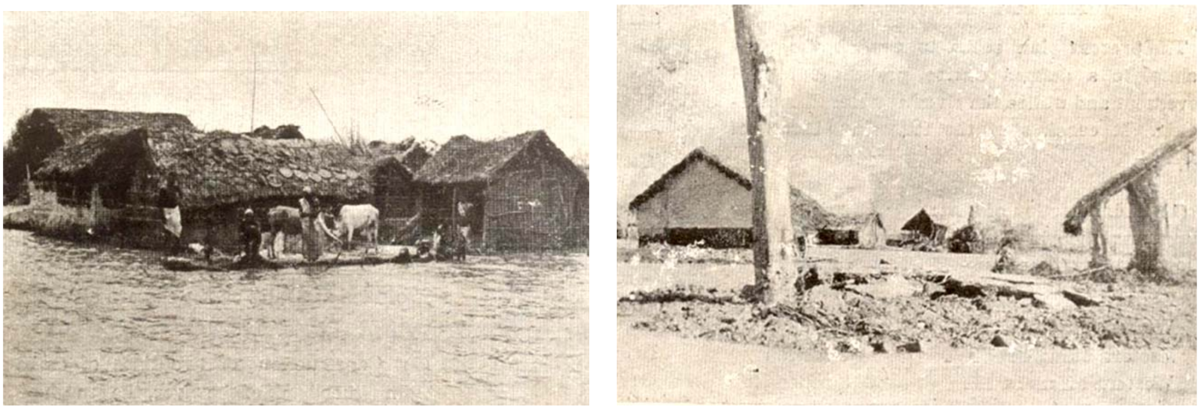
In the year 1954, massive flood took place in the Kosi river and the discharge was 24230 m^3/s. Village Kanauli and Nirmali experienced that flood and a lot of structures were partially buried with sediment as shown in Figs. 3.6 to 3.8. The Prime Minister Shri. Pandit Jawaharlal Nehru visited the affected place and decided to jacket the river to avoid further shifting (Fig. 3.9). In order to provide relief to the north Bihar and Nepal, Kosi project was envisaged. This consisted of construction of levees on both banks to confine flood spill and construction of a barrage near Hanuman-nagar (Figs. 3.10 and 3.11). The work of construction of about 268 km levees on both the bank was completed by 1959 and the river was diverted through barrage in 1963. Since then in the reach from 40 km upstream of barrage to about 100 km downstream, the river is flowing between the embankments. Since the levees/embankments cannot prevent tendency of shifting of the river course, the river has been attacking levees at different locations during the process of channel shifting within the confined reach. Numbers of spurs were constructed to protect the embankment by keeping the main river flow away from the banks as shown Fig. 3.12. Hydraulic model studies of this river reach were carried out at CWPRS, Pune, India to design Kosi Barrage and flood embankments with number of spurs. In addition to this, aggradation of the river bed has been noticed in the levee reach. This resulted into increase in flood levels at various locations. Since the construction of Barrage and flood embankments, the migration tendency of river has been arrested. However, during some of high floods in the river, breaches have developed in the Eastern and Western embankments at some locations resulting into heavy inundation.

(a) (b)

Figure 3.6 Effect of flood a) Enormous silt-the aftermath of flood (1954)
b) Temple silted up to its arch. (CWPRS record)

(a) (b)

Figure 3.7 a) Building near railway Nirmali station silted upto roof level in 1954
b)Flooded streets of Nirmali (CWPRS record)



(a) **(b)**

Figure 3.8 Scenes of flood- a) flooded villages; b) Houses washed away (CWPRS record)

Figure 3.9 Prime Minister- way to Kosi flooded area (Nirmali, Bihar) in 1954 (CWPRS record)

Figure 3.10 Kosi Barrage (downstream view) **Figure 3.11** (upstream view)

3.6 REQUIREMENT OF THE STUDIES

Out of estimated 187 million metric tonnes of sediment load in river Kosi about 70% settles in the delta region extending from Chatra town to Kursela. As the river slope is deficient for carrying sediment further downstream due to heavy silting, the adjoining part remained lower inviting the river to flow near the flood embankments. The river has been eroding the embankment at different locations during the process of channel shifting within the afflux bund and flood embankments. Numbers of spurs were constructed to protect the embankments by keeping main river flow away from the bank. Embankment/levees were constructed at the spacing ranging from 6 to 16 km to avoid shifting. Due to inadequate slope and huge spacing of embankment/levees, the river does not produce sufficient scouring velocity to carry the sediments, which resulted in rise of bed level at many places by 0.1 to 3 m in a period of 50 years. In view of the above, it is desirable to explore the possibility of channelizing the river Kosi, which is thought to be one of the method by which the velocities in the river could be increased, thereby increasing the sediment carrying capacity of the river.

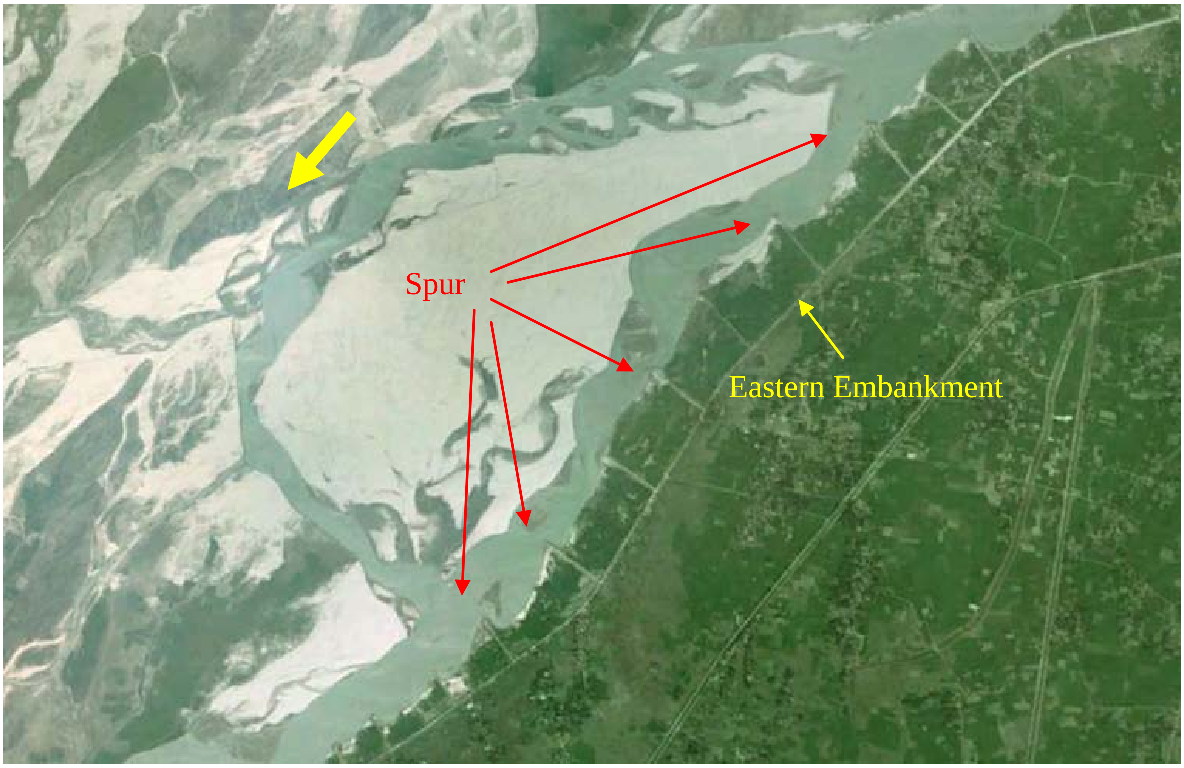


Figure 3.12 Series of spurs on eastern embankment of river Kosi (Image from Google Earth)

DEVELOPMENT OF STAGE-DISCHARGE AND SEDIMENT-DISCHARGE RATING

4.1 INTRODUCTION

Assessment of stream flow and volume of sediment transported in a river is important for variety of hydrologic applications, such as water resources planning and operation, water and sediment budget analysis, hydraulic and hydrological modelling, design of storage and conveyance structures, hydroelectric power generation and water supply, determination of effect of watershed management, and environmental impact assessment. However, discharge measurement in rivers on a permanent basis is time consuming, costly and cumbersome, especially during large flood. Compared to stream discharge, measurement of stage is faster, less expensive, and easier. Hence, it has been a general practice to transfer records of water stages into discharges by means of a pre-established stage-discharge relationship. A graph of stage versus discharge represents the stage-discharge relationship, also known as rating curve. The stage-discharge rating relationship is an approximate technique in use for estimating discharge in streams and rivers. The stage-discharge relationship at a particular river cross-section, even under conditions of particular observation, is not necessarily exclusive as rivers are frequently influenced by a number of other factors which are neither all the time understood, nor straightforward to compute. This is due to the fact that in reality, discharge is not a function of stage only. It depends also upon the geometry of channel, longitudinal gradient of river, bed roughness, back water and flow instability. As such, the measurement of these parameters at each time step and section is not achievable. Thus the common practice of curve fitting by regression analysis to estimate the stream flow and sediment load is not adequate, in view of the complexities involved in hydrological processes (Kisi, 2005). An inherent problem in the rating curve technique is the high degree of scatter, which may be reduced but not eliminated (Jain, 2001). To describe such processes more consistently with the observations, applicability of Artificial Neural Network (ANN) has been demonstrated amply by several investigators.

In the present study, ANN technique has been applied for modelling the stage-discharge and sediment-discharge rating relationships for two typical gauging sites on river Kosi, namely

Kosi barrage and Barahakshetra (gorge area) about 42 km upstream of the barrage. Daily data on stage-discharge is available for 17 years (January 1949 to October 1966) at Barahakshetra and the data on sediment-discharge is available for 9 years (May 2002 to January 2009) at Kosi barrage site. An ANN model has been trained, validated and cross-validated by partitioning these data into three different intervals. Comparison of the performance of ANN model with the conventional regression technique has indicated that discharge as well as sediment concentration estimates at gauging sites obtained by ANN model are more accurate than those obtained from sediment rating curves.

The discharge and sediment for a flood on a rising stage differs from that for a falling stage under some conditions like flatter gradients and constricted channels. This phenomenon results in looped stage-discharge and sediment-discharge curves, known as hysteresis. Tawfik et al. (1997) have proposed three approaches for development of a rating curve; the single curve approach, the rising and falling approach, and the Jone’s approach. DeGagne et al. (1996) have developed a decision support system for the analysis and use of stage-discharge rating curve. Yu (2005) also proposed other possible models of rating curve development. Ferguson (1986) has reported that the rating curve method based on log-log rating curve can underestimate sediment loads by up to 50%, even when the full time series of concentration is available. In order to remove most of the biases and to improve the precision of estimate of river load, Ferguson (1986) proposed a simple correction factor based on statistical considerations. Phillips et al. (1999) have also proposed a potential procedure to decide the accuracy and precision of suspended sediment flux estimate by using high-frequency suspended sediment concentration and discharge data. Asselman (2000) has prepared sediment rating curves by means of least squares regression on logarithmic transformation data at four different locations along the River Rhino and its main tributaries. He established an underestimation in the sediment transport rates by about 10% to more than 50%. Some other studies (Walling and Webb, 1988; Asselman, 2000) on the application of conventional rating curve techniques for estimation of suspended sediment concentrations also reported substantial underestimation of actual sediment concentrations. A number of researchers (Ferguson, 1986; Walling and Webb, 1988; Singh and Durgunoglu, 1989, Philips, et al., 1999; Assselman, 2000) have planned different methods for the development of rating curves by employing a variety of statistical correction factors, using nonlinear regression, or classifying the discharge and sediment data into various ranges.

As such, the difficulty in modelling the discharge and sediment rating relationship in the Kosi basin becomes highly complex due to the high variability in various hydrologic, meteorological as well as hydraulic parameters, changing land use/land cover and high seismic movement in the region. Therefore, the artificial neural network (ANN) models, which are capable of modelling the complex non-linear hydrological process with limited data, are the best choice for the present modelling problem. Models of stage-discharge and sediment-discharge rating relation using artificial neural networks (ANN) technique as well as regression based conventional rating curve methods are developed and discussed in the present chapter.

4.2 ARTIFICIAL NEURAL NETWORK (ANN) TECHNIQUE

a) Chronology and Application

The development of artificial neural networks was inspired by a desire to understand the functioning of human brain that processes the patterns with high efficiency and speed. Initial research to emulate its functioning began approximately 70 years ago (McCulloch and Pitts, 1943). ANN's have been developed as a generation of mathematical models of human cognition or neural biology as shown in Fig. 4.1. Their development is based on the following rules:

(i) The processing of information takes place at many single elements called neurons, also referred to as nodes, cells or units.

(ii) Connection links pass the signal between nodes.

(iii) A weight is associated with each connection link which signifies its connection strength.

(iv) Each node receives certain net input which undergoes a nonlinear transformation in the form of activation function to determine its output signal.

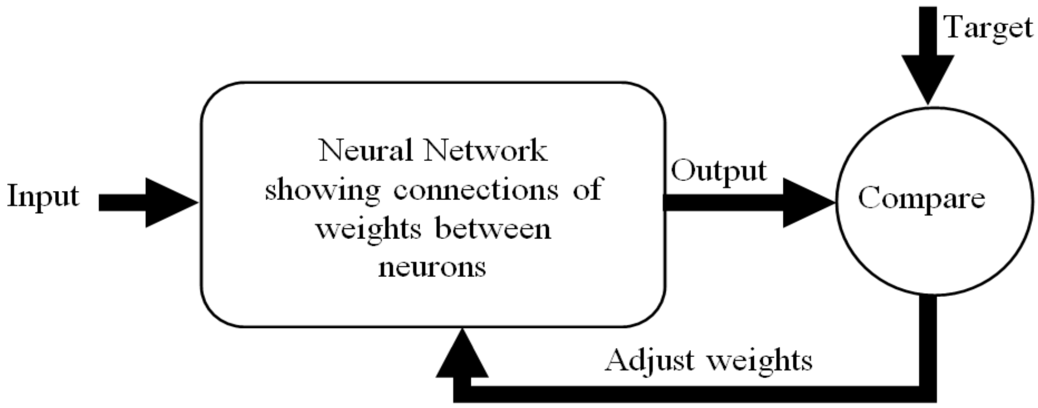


Figure 4.1 Basic principle of ANN (Gurney, 1997)

b) Biological Basis of ANN's

The fundamental unit of a network is neuron as shown in Fig. 4.2. It consists of nucleus in its cell body of soma. Neuron or nerve is the complex biochemical and electrical signal processing factory. Tree like nerve fibers called dendrites are associated with cell body, which receive signals from other neurons. Soma is the main body of the nerve cell. The outer boundary is cell membrane and the interior and outside of the cell is filled with intracellular and extra cellular fluid. As the chemical mechanism operates at the synapses, the electrical activity is generally confined to the interior of a neuron. Transmission of the generated activity to other cells (inter-neuron) is done by the axon and the receptors of signals from other neurons are dendrites.

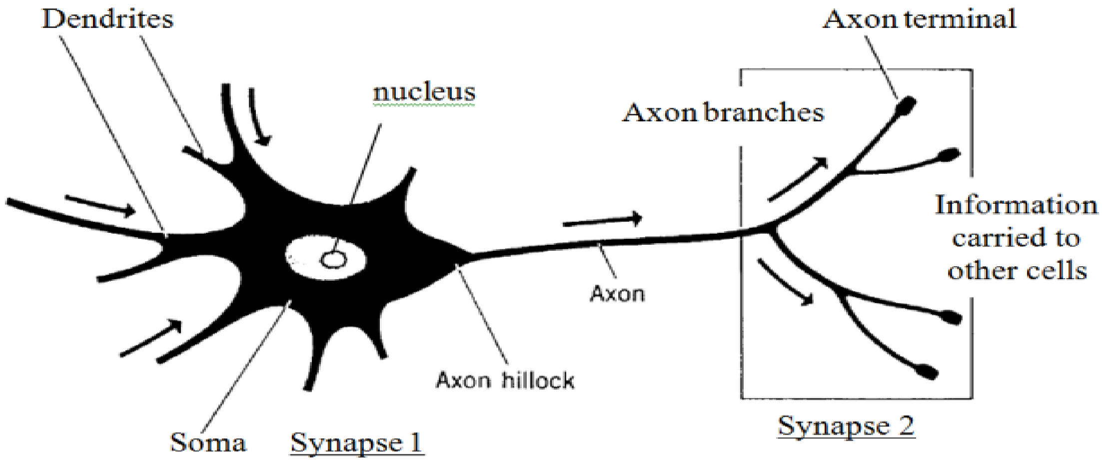


Figure 4.2 Typical biological neuron (Arbib, 2003)

c) The ANN Structure

An ANN is a network of parallel distributed information processing system that relates an input vector to an output vector. It consists of a number of information processing elements called neurons or nodes, which are grouped in layers. An ANN has an input layer, an output layer, and one or more hidden layers between the input and the output layers. The input layer processing elements receive the input vector and transmit the values to the next layer of processing elements across connections where this process is continued. Weight of the interconnections determines the strength of the signal passing from one neuron to the other. The hidden layers improve the network's ability to model complex functions.

d) Model of an Artificial Neural Network

The main function of an ANN model is to map a set of inputs to a set of outputs. A single processing unit or neuron is shown in Fig. 4.3. The incoming signals are multiplied by respective weights through which they are propagated towards the neurons or node, where they are aggregated (summed up) and the net input is passed through the activation function to produce the output.

Let x_i *(I = 1,2,…… n)* be the inputs and w_i *(I = 1,2,…… n)* the respective weights. The net input to the node can be expressed as

$$net = \sum_{i=1}^{n} x_i w_i \tag{4.1}$$

The net input is then passed through an activation function $f(.)$ and the output y of the node is computed as

$$y = f(net) \tag{4.2}$$

Sigmoid function is the most commonly used nonlinear activation function for solving ANN problems in hydrology which is given by

$$y = f(net) = \frac{1}{1+e^{-net}} \tag{4.3}$$

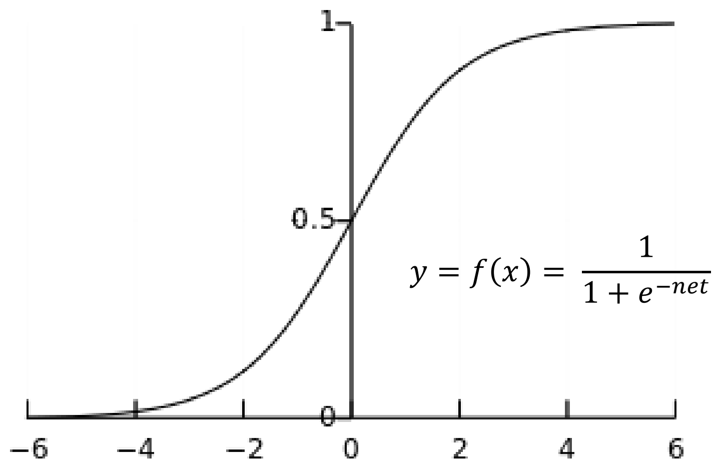


Fig. 4.3 Sigmoid function (Haykin, 1994)

e) Architecture of ANN

Architecture of ANN is the manner in which the neurons of a neural network are structured and intimately linked with learning algorithm used to train the network. There are various ways to classify a neural network. Neurons are usually arranged in several layers and this arrangement is referred to as the architecture of a neural network as shown in Fig. 4.4.

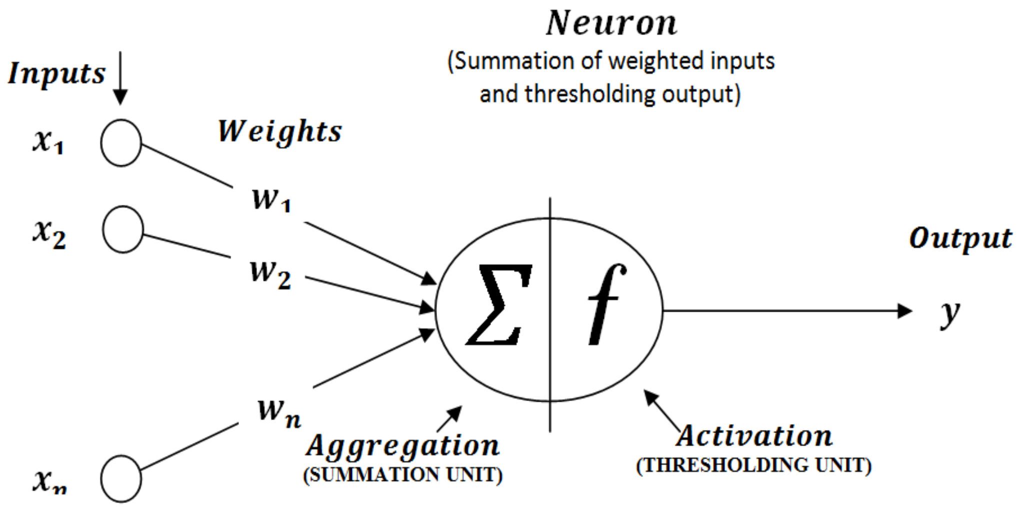


Figure 4.4 A single artificial neuron (Haykin, 1994)

f) Learning/Training of Artificial Neural Network

Once a network has been structured for a particular application, it is ready for learning/training. The learning/training process in biological neural networks is based on the change of the interconnection strength among neurons. In artificial neural networks, various learning concepts are used as given in Table 4.1. A comprehensive description of all these learning algorithms can be found in Freeman and Skapura (1991) and Haykin (1994).

Table 4.1 Basic learning algorithms in ANN

S.no.	Algorithm	Initial Weights	Learning
1	Hebbian	0	Unsupervised
2	Perception	Random	Supervised
3	Delta	Random	Supervised
4	Widrow-Hoff	Random	Supervised
5	Correlation	0	Supervised
6	Winner-take-all	Random (normalized)	Unsupervised
7	Outstar	0	Supervised

Table 4.1, indicates two different learning methods, viz. supervised and unsupervised learning. In supervised learning, the network is supplied with both the input values and the actual output values, and weight adjustments during training are based upon minimization of the error between computed output and actual output values. Whereas, in unsupervised learning, the network is supplied with the input values only, and the weight adjustments are thus based only on the values and the current network output.

4.3 DATA USED AND SELECTION OF INPUT/OUTPUT VARIABLES

In case of stage-discharge relationships, inputs are the stage and discharge with time lag and outputs are the discharge. Similarly in sediment-discharge relationships, inputs are discharge and sediment with time lag and outputs are the sediment.

Daily data of stage-discharge at the gauging site of Barahakshetra for 17 years (January 1949 to October 1966) has been used for modelling in the present study. Location of gauging site is shown in Fig. 4.5. Out of this, nine years six month data is used for training, three years nine month for validation, and three years nine month for cross validation. Similarly sediment-discharge at the gauging site of Kosi barrage for 9 years (May 2002 to January 2009) has been used for modelling. Out of this, five years have been used for training, two years for validation, and two years for cross validation.

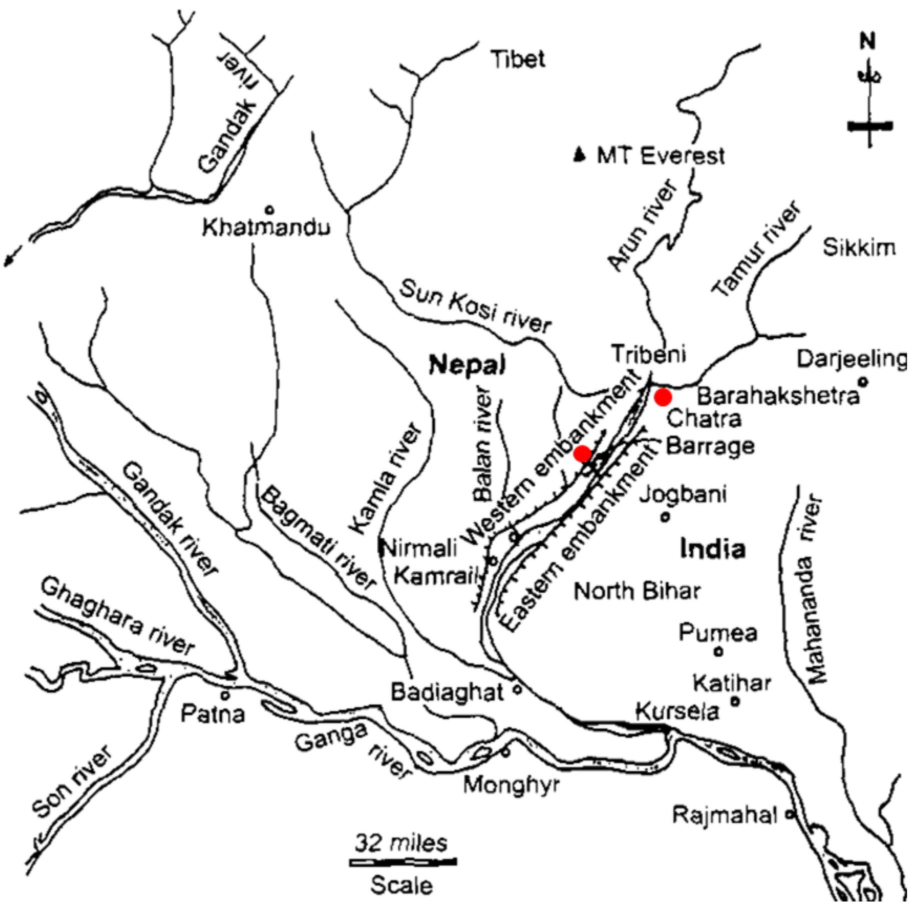


Figure 4.5 Plan showing site of recording data-Barahakshetra & Kosi barrage (Gole and Chitale, 1966)

4.4 REGRESSION BASED RATING CURVES

a) Stage- Discharge Curves

Stream flow measurements are normally estimated using the stage-discharge rating curve which transforms observed stage to corresponding river discharge. The most commonly used form of stage-discharge rating curve is expressed as follows:

$$Q = a(H - H_o)^b \tag{4.4}$$

Where Q is the discharge (m^3/s); H is the river stage (m); and a and b are regression constant. The H_o is the stage (m) at which discharge is almost zero.

By investigating the characteristics of the historical stage data, an initial estimate of H_o is usually made and then final value of H_o is chosen by trial and error to get the best fit. The stage-discharge rating curve obtained is shown in Fig. 4.6.

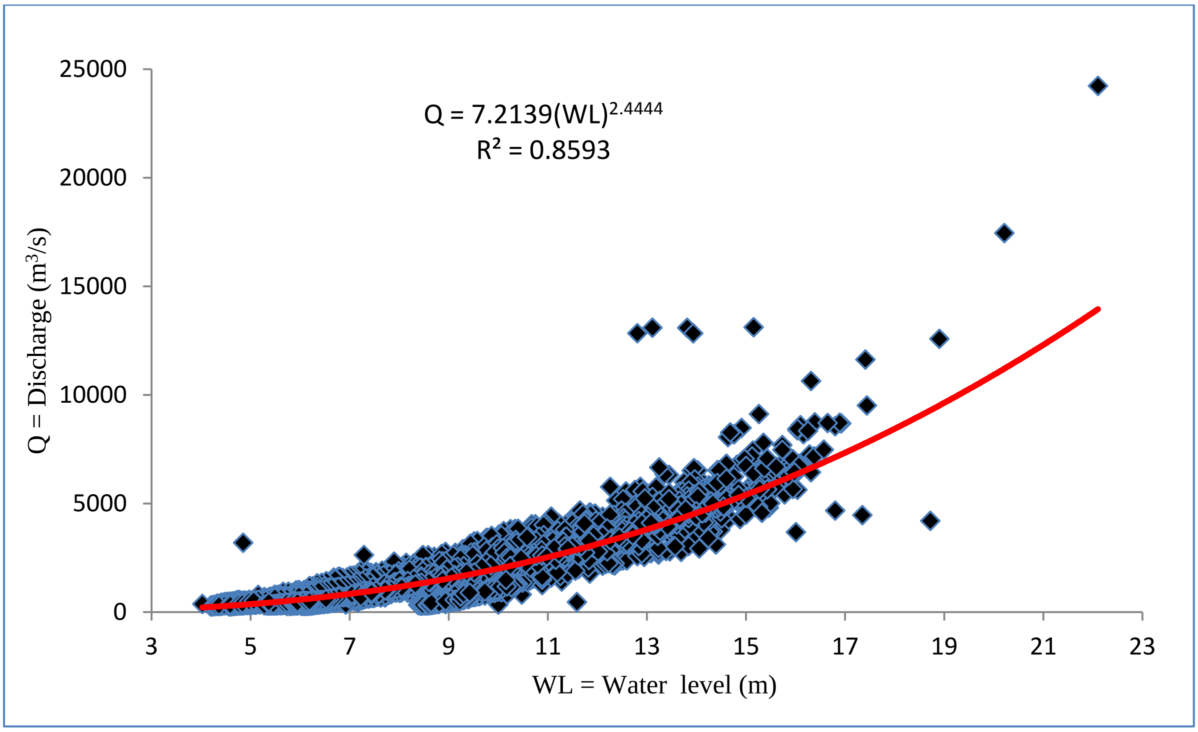


Figure 4.6 Stage discharge Rating Curve for Barahakshetra site on Kosi River

b) Sediment Rating Curves

Sediment rating curves (SRC) represent the relationship between sediment load and river discharge. An SRC can be constructed on daily, monthly, or other time scales by plotting average sediment concentration or load as a function of average discharge. Mathematically, a sediment rating curve may be developed by using linear least square regression method of curve fitting (the line of best fit) between the data and also by log-transforming all data. The log-log relationship between load and discharge is of the form

$$S = aQ^b \tag{4.5}$$

And the log-transformed form of the above relationship is of the following form which represents a straight line on log-log paper:

$$\log S = \log a + b \log(Q) \tag{4.6}$$

Where, S = sediment concentration (mg/l); Q = discharge (m^3/s) and a and b are regression constants.

The sediment-discharge rating curve obtained is shown in Fig. 4.7.

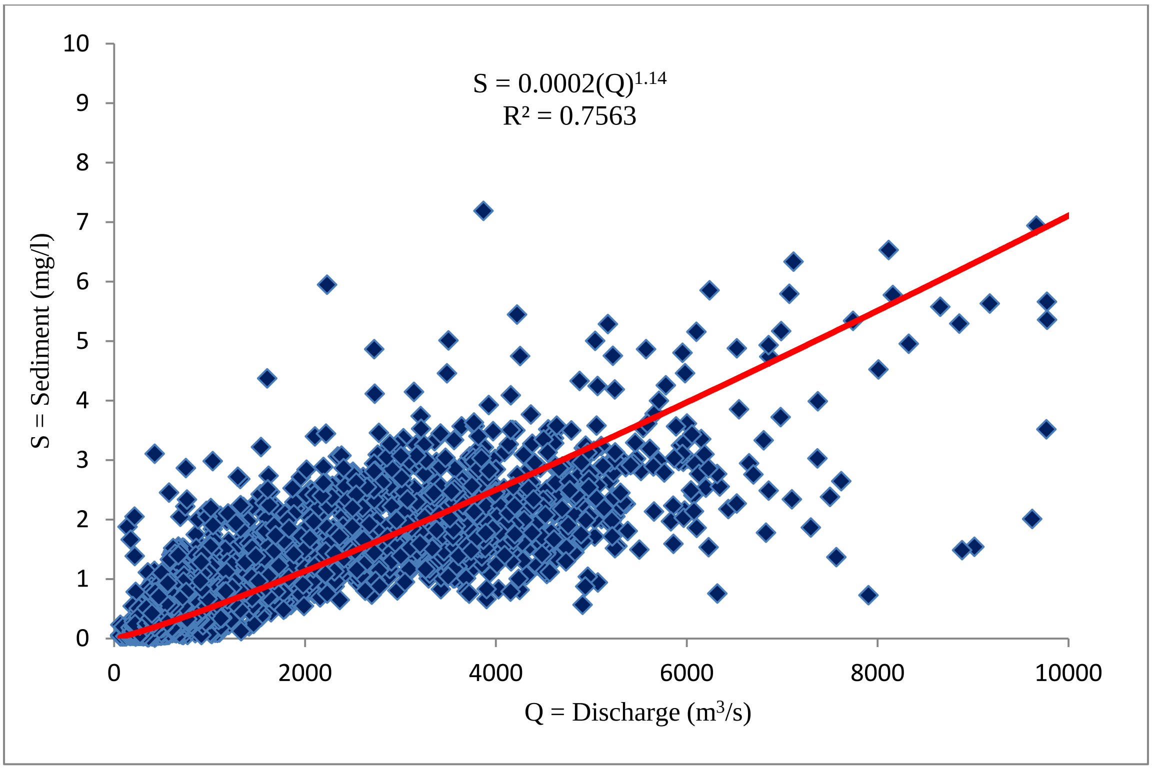


Figure 4.7 Sediment discharge Rating Curve for Kosi barrage site on Kosi River

4.5 ANN BASED RATING RELATIONS

Before applying the ANN, the data were standardized. Minns and Hall (1996) emphasized the importance of the correct standardization. The input data were normalized to fall in the range [0, 1] by dividing with the maximum value.

$$H_s = {}^{H}/_{H_{max}} \tag{4.7}$$

Where H_s = standardized stage; and H_{max} = maximum of the stage values.

Identification of the input and output variables is the first step in developing any ANN model. Output from the models is the discharge, Q_t and suspended sediment concentration, S_t at time step t for the stage-discharge rating modelling and sediment - discharge rating modelling, respectively. It has also been shown by many investigators that current discharge can be better modeled by considering antecedent values of stage and discharge, in addition to the current value of stage (Jain and Chalisgaonkar, 2000). Accordingly, various combinations of antecedent stage, discharge and suspended sediment concentration for the two stations were considered in the present study. These different combinations of input data considered for training of ANN models for stage-discharge rating modelling and sediment-discharge rating modelling are given in Table 4.2 and Table 4.3 respectively.

4.6 RESULTS AND DISCUSSIONS

In this section, results of the regression based conventional rating curve technique and ANN technique have been described.

a) Stage-discharge rating curve models

It is observed from Table 4.2 that the correlation coefficient (R) values are high (more than 0.90) for all the ANN models, in all the three phases, i.e., training, testing as well as validation. It is also observed that there is not much decrease in the R values during validation as compared to the training phase. The performance of model at Sr. no.30 is the best in R statistics. The R values for ANN are 0.945, 0.9086 and 0.96971 during training, testing and validation, respectively. The increase in R values of Sr. no.30 during validation indicates good generalization capability of the ANN model.

Figure 4.8 presents the plots of observed and estimated discharge for ANN model at Sr. No. 30 during training (a), testing (b) and validation (c). It is observed that there is very little mismatch between the observed and estimated discharge series model during all the three phases.

b) Sediment-discharge rating curve models

It is observed from Table 4.3 that the correlation coefficient (R) values are very high (more than 0.90) for all the ANN models, in all the three phases, i.e., training, testing as well as validation. It is also observed that there is not much decrease in the R values during validation as compared to the training phase. The performance of model at Sr. No. 31 is the best in R statistics. The R values are 0.9838, 0.97861 and 0.97612 during training, testing and validation, respectively.

Figure 4.9 presents the plots of observed and estimated discharge for ANN model at Sr. No. 31 during training (a), testing (b) and validation (c). It is observed from Fig. 4.9 that there is very little mismatch between the observed and estimated discharge series for ANN model during all the three phases.

The observed stage-discharge value and the estimated values from the conventional technique and ANN model are compared in Fig. 4.10. It is observed that ANN estimates very closely follow the observed values; whereas the conventional approach gives the mean trend. Similarly, plot of observed values, ANN values and values from conventional regression technique for of sediment-discharge at the site of Kosi barrage on river Kosi is shown in Fig. 4.11. Here also, it is observed that the ANN estimates follow the observed values more closely, whereas, the conventional approach gives only the mean trend.

4.7 CONCLUDING REMARKS

For designing any type of structure, analyst requires perfect data, because the structure life considers being about 100 years. As per above studies the inherent problem in the rating curve technique is the high degree of scatter, which may be reduced but not eliminated. But by using Artificial Neural Network (ANN) helps in eliminating the time delay between various parameters in the engineering field.

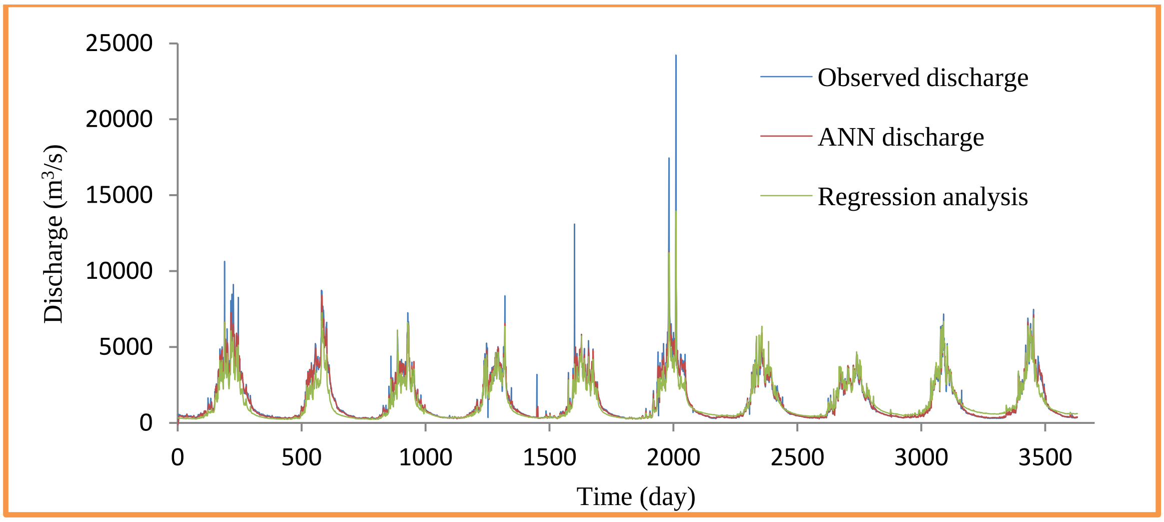
4.8 USE OF DEVELOPED RATING CURVES

While designing any type of hydraulic structures on river, hydrological data should be precise, more the data accurate than more reliable be the design of structure. Therefore the parameters like sediment-discharge and a stage-discharge rating curve plays an important role for designing the structure. By using ANN network, helps in improving the quality of data. In the present study, results of ANN have been used for mathematical model.

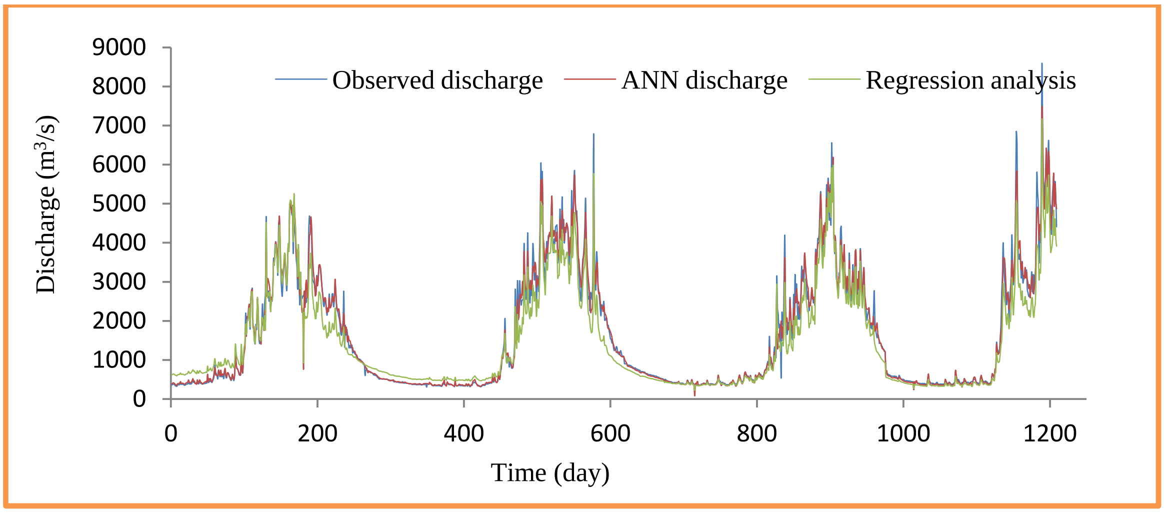
Table 4.2 Various ANN stage-discharge rating models investigated

Sr.No.	ANN model inputs	Output	Nodes in hidden layers	Correlation coefficient		
				Training	Validation	Test
1	Ht	Qt	1	0.89253	0.90875	0.91523
2	Ht	Qt	2	0.89595	0.91411	0.90239
3	Ht	Qt	3	0.8925	0.92524	0.90093
4	Ht,Ht-1,Qt-1	Qt	1	0.92682	0.94914	0.92709
5	Ht,Ht-1,Qt-1	Qt	2	0.92478	0.95161	0.94514
6	Ht,Ht-1,Qt-1	Qt	3	0.926	0.93316	0.95909
7	Ht,Ht-1,Qt-1	Qt	4	0.94985	0.94787	0.99431
8	Ht,Ht-1,Qt-1	Qt	5	0.944	0.9111	0.94655
9	Ht,Ht-1,Ht-2,Qt-1,Qt-2	Qt	1	0.93236	0.92043	0.94254
10	Ht,Ht-1,Ht-2,Qt-1,Qt-2	Qt	2	0.94594	0.95513	0.88714
11	Ht,Ht-1,Ht-2,Qt-1,Qt-2	Qt	3	0.93581	0.92955	0.94521
12	Ht,Ht-1,Ht-2,Qt-1,Qt-2	Qt	4	0.91978	0.95316	0.94087
13	Ht,Ht-1,Ht-2,Qt-1,Qt-2	Qt	5	0.95397	0.93142	0.89369
14	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	1	0.92486	0.94947	0.93472
15	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	2	0.94151	0.93143	0.8972
16	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	3	0.94841	0.94241	0.91049
17	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	4	0.92797	0.94824	0.94115
18	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	5	0.92272	0.93752	0.94551
19	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	6	0.93114	0.94368	0.95302
20	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	7	0.93614	0.94419	0.93058
21	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	8	0.94517	0.989705	0.95977
22	Ht,Ht-1,Ht-2,Ht-3,Qt-1,Qt-2,Qt-3	Qt	9	0.94738	0.91343	0.93252
23	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	1	0.92114	0.94285	0.95218
24	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	2	0.92829	0.93305	0.94655
25	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	3	0.93861	0.92056	0.96006
26	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	4	0.94121	0.94422	0.9015
27	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	5	0.92414	0.94056	0.94907
28	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	6	0.93631	0.95256	0.92231
28	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	7	0.95186	0.95242	0.89884
30	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	8	0.94492	0.90869	0.96971
31	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	9	0.94995	0.92633	0.91004
32	Ht,Ht-1,Ht-2,Ht-3,Ht-4,Qt-1,Qt-2,Qt-3,Qt-4	Qt	10	0.94564	0.92136	0.92839

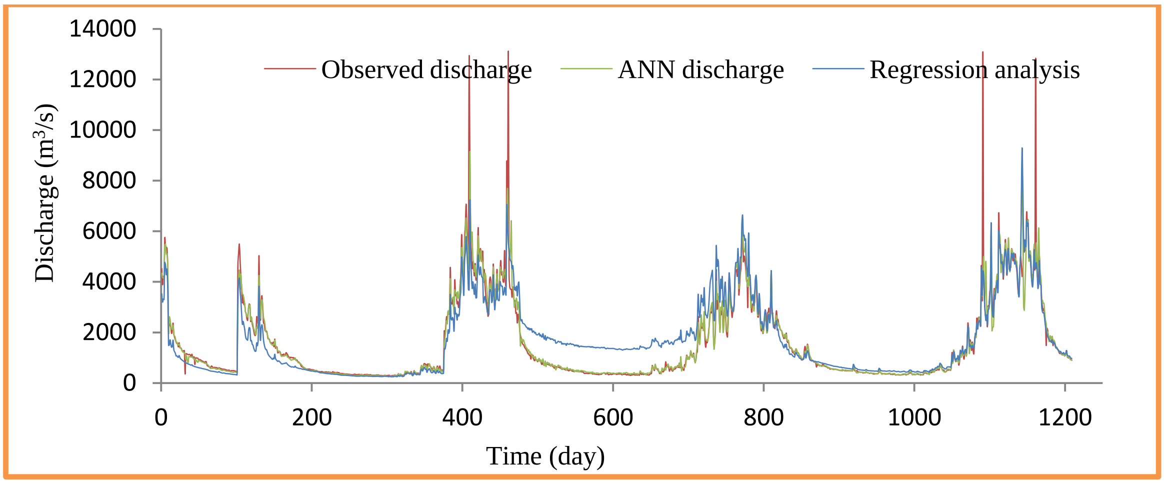
Where, Q = Discharge in m^3/s, H = stage in m, t represents the time step



a) Training



b) Validation



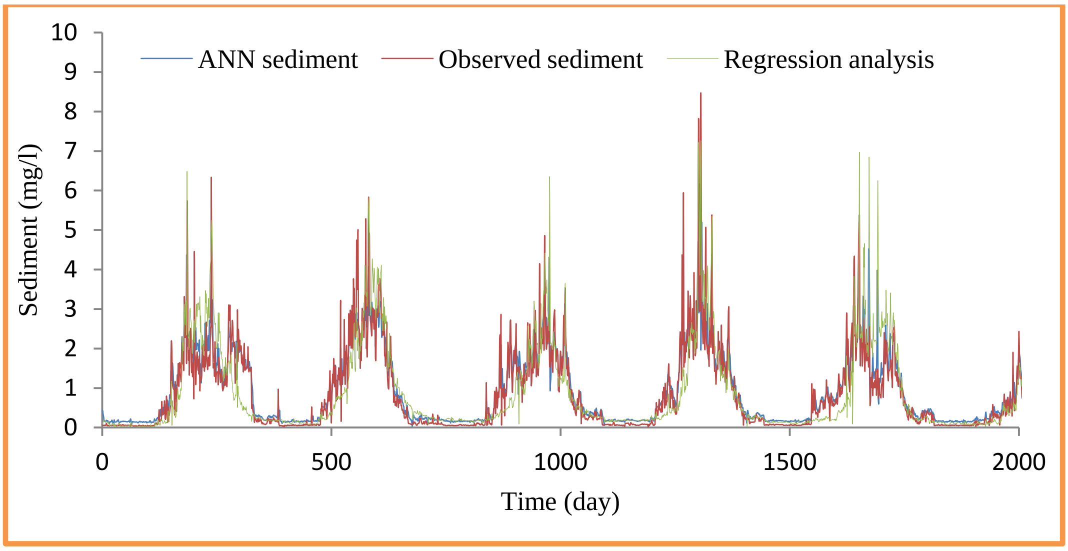
c) Testing

Figure 4.8 Comparative performance of observed discharge with estimated Discharge using Sr. no.30 models for Barahakshetra

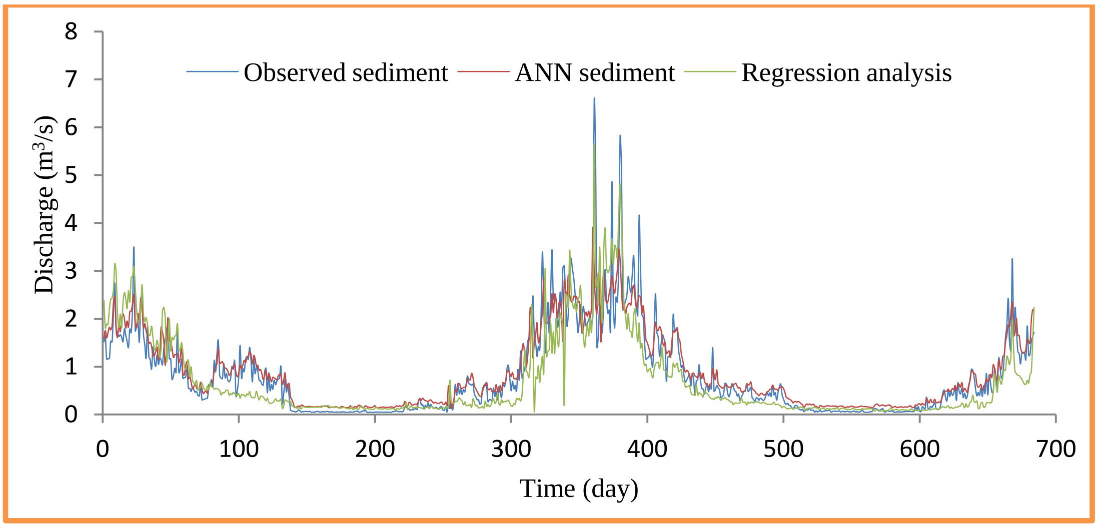
Table 4.3 Various ANN sediment-discharge rating models investigated

Sr. no	ANN model inputs	Output	Nodes in hidden layers	Correlation coefficient		
				Training	validation	Test
1	Qt	St	1	0.89253	0.90875	0.91523
2	Qt	St	2	0.89595	0.91411	0.90239
3	Qt	St	3	0.8925	0.92524	0.90093
4	Qt,Qt-1,St-1	St	1	0.92682	0.94914	0.92709
5	Qt,Qt-1,St-1	St	2	0.92478	0.95161	0.94514
6	Qt,Qt-1,St-1	St	3	0.926	0.93316	0.95909
7	Qt,Qt-1,St-1	St	4	0.94985	0.94787	0.99431
8	Qt,Qt-1,St-1	St	5	0.944	0.9111	0.94655
9	Qt,Qt-1,Qt-2,St-1,St-2	St	1	0.93236	0.92043	0.94254
10	Qt,Qt-1,Qt-2,St-1,St-2	St	2	0.94594	0.95513	0.88714
11	Qt,Qt-1,Qt-2,St-1,St-2	St	3	0.93581	0.92955	0.94521
12	Qt,Qt-1,Qt-2,St-1,St-2	St	4	0.91978	0.95316	0.94087
13	Qt,Qt-1,Qt-2,St-1,St-2	St	5	0.95397	0.93142	0.89369
14	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	1	0.92486	0.94947	0.93472
15	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	2	0.94151	0.93143	0.8972
16	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	3	0.94841	0.94241	0.91049
17	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	4	0.92797	0.94824	0.94115
18	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	5	0.92272	0.93752	0.94551
19	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	6	0.93114	0.94368	0.95302
20	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	7	0.93614	0.94419	0.93058
21	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	8	0.94517	0.98970	0.95977
22	Qt,Qt-1,Qt-2,Qt-3,St-1,St-2,St-3	St	9	0.94738	0.91343	0.93252
23	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	1	0.92114	0.94285	0.95218
24	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	2	0.92829	0.93305	0.94655
25	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	3	0.93861	0.92056	0.96006
26	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	4	0.98102	0.98051	0.98024
27	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	5	0.98228	0.97818	0.97969
28	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	6	0.98065	0.9852	0.97428
29	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	7	0.97957	0.98292	0.98063
30	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	8	0.98032	0.98044	0.98413
31	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	9	0.98358	0.97861	0.97612
32	Qt,Qt-1,Qt-2,Qt-3,Qt-4,St-1,St-2,St-3,St-4	St	10	0.98247	0.98106	0.9762

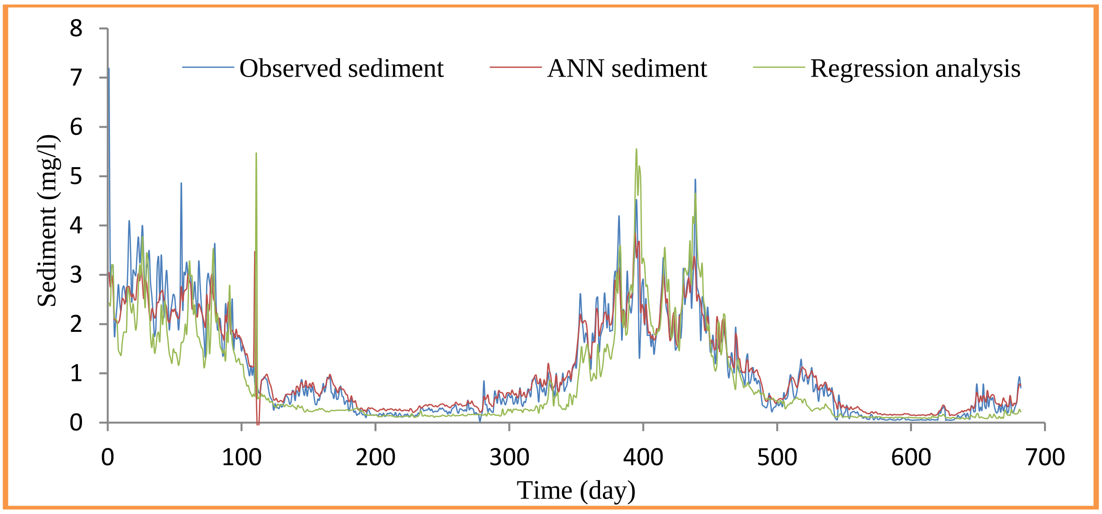
Where, S = Suspended sediment concentration in mg/L, Q = Discharge in m^3/s, t represents the time step



a) Training



b) Validation



c) Cross-Validation

Figure 4.9 Comparative Performance of observed sediment-discharge using Sr. no. 31 for Kosi barrage gauging site.

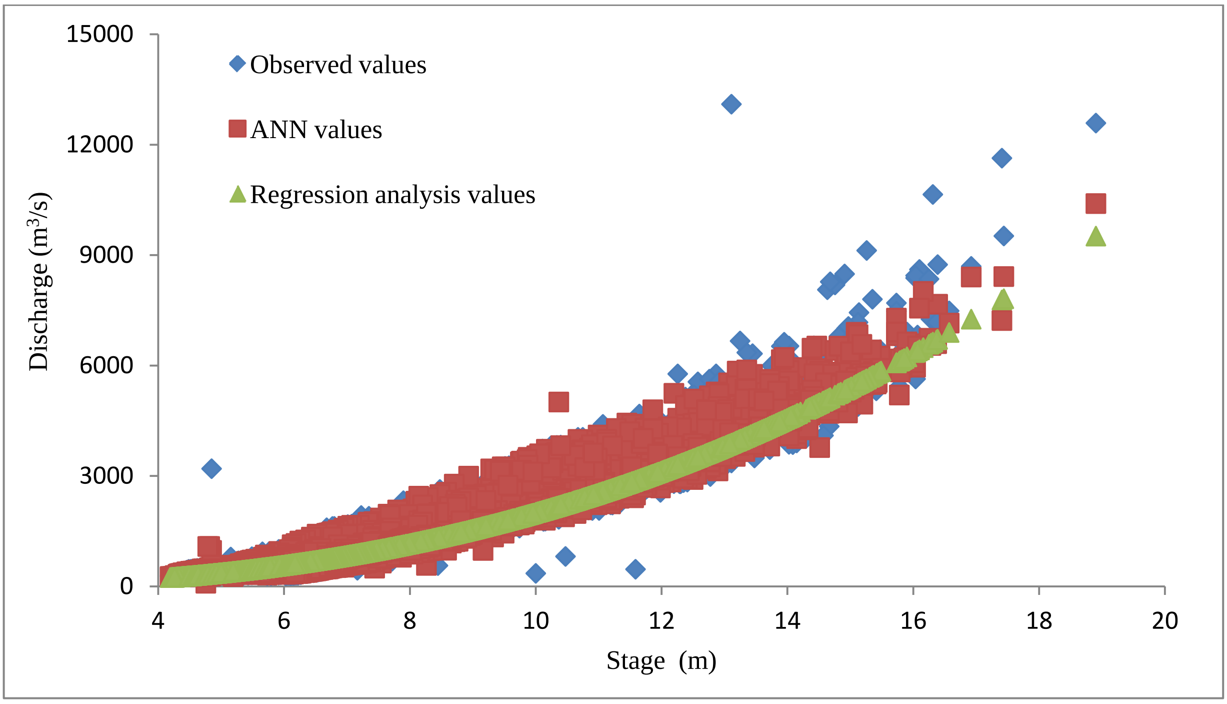


Figure 4.10 Comparison of scatter plots of simulated & observed Gauge-discharge for Barahakshetra gauging site

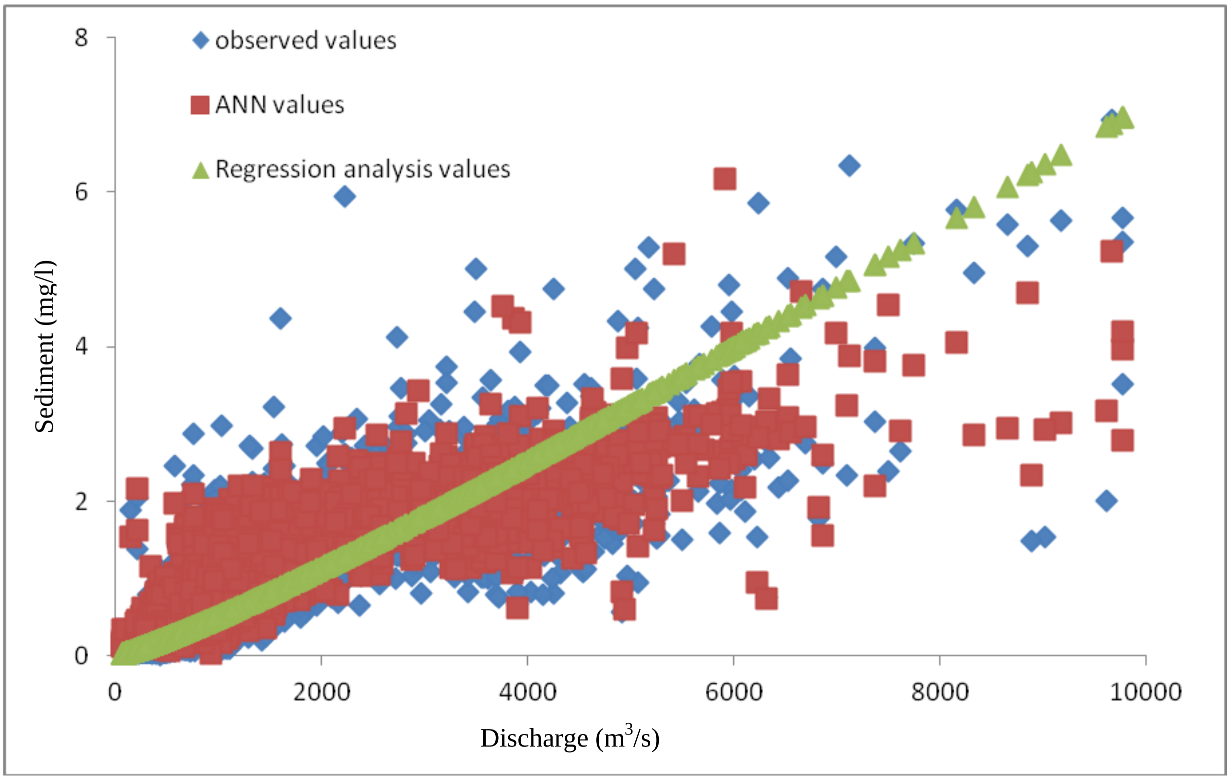


Figure 4.11 Comparison of scatter plots of simulated & observed sediment-discharge for Kosi Barrage gauging site

Chapter 5

MORPHOLOGICAL STUDIES

5.1 INTRODUCTION

Almost 70% of the high sediment load to the tune of 187 millions tones per year brought by river Kosi from the Himalayas is deposited between Chatra and Kursela due to reduction in velocity from about 5 m/s at Chatra gorge to as low as 1.25 m/s at Kursela. The river, downstream of Chatra builds up its plain and flows through several channels spread over a width varying from 6 to 16 km. The braiding process is, however, seen downstream of Belka hills, where interlacing channels are spread over width of about 5 to 6 km. To identify the relative extent of braiding in different reaches, the braiding indicator plan form index (PFI) formulated by Sharma (2004) for Brahmaputra River has been adopted in this study.

The study reach of river Kosi from Chatra to Nirmali (89 km) is considered to assess the channel morphological changes actuated by stream bank erosion process. Attempt has been made to assess the temporal and spatial variation of braiding intensities along the whole stretch from Chatra to Nirmali based on historical images. A morphological change of a river causes severe yearly land loss. The basic data used for estimating PFI are derived from digital satellite images of Indian Remote Sensing Landsat5 sensor, comprising images for the years 1992, 2005, and 2011.

Kosi megafan is one of the important examples of megafans occurring in the Ganga plain as can be seen in Fig. 5.1. (Geddes, 1960; Gohain and Prakash, 1990; Singh et al., 1993; Collinson, 1996). The Kosi River has shifted about 113 km from the eastern margin to its present position at the western extremity of the megafan over the last two centuries (Mookerjea, 1961; Mookerjea and Aich, 1963; Gole and Chitale, 1966; Wells and Dorr, 1987; Gohain and Prakash, 1990; Duff and Duff, 1993; Singh et al., 1993; Mackey and Bridge, 1995; Collinson, 1996; DeCelles and Cavazza, 1999; Bridge, 2003; Assine, 2005). The observed shift was always towards west, sweeping across the entire megafan surface at an unusually fast rate. However, in August 2008, an avulsion relocated the Kosi River by about 60 km to the east (measured in the central part of the megafan) and a major flood water channel, 20 km wide, started flowing along the axial part of the megafan (Fig. 5.1); marooning hundreds of villages, destroying croplands and bringing disaster to thousands of people living in these areas. This region was not considered flood-prone as it was located far off the existing channel belt of the Kosi River. The administration and the people of this area were, therefore, less prepared to face the calamity, aggravating the damage done by the unexpected change of the river course. In contrast to overtopping of the banks, an annual phenomenon known to the people living close to the present-day course of the Kosi, this was a major change in the course of the river (Sinha, 2009).

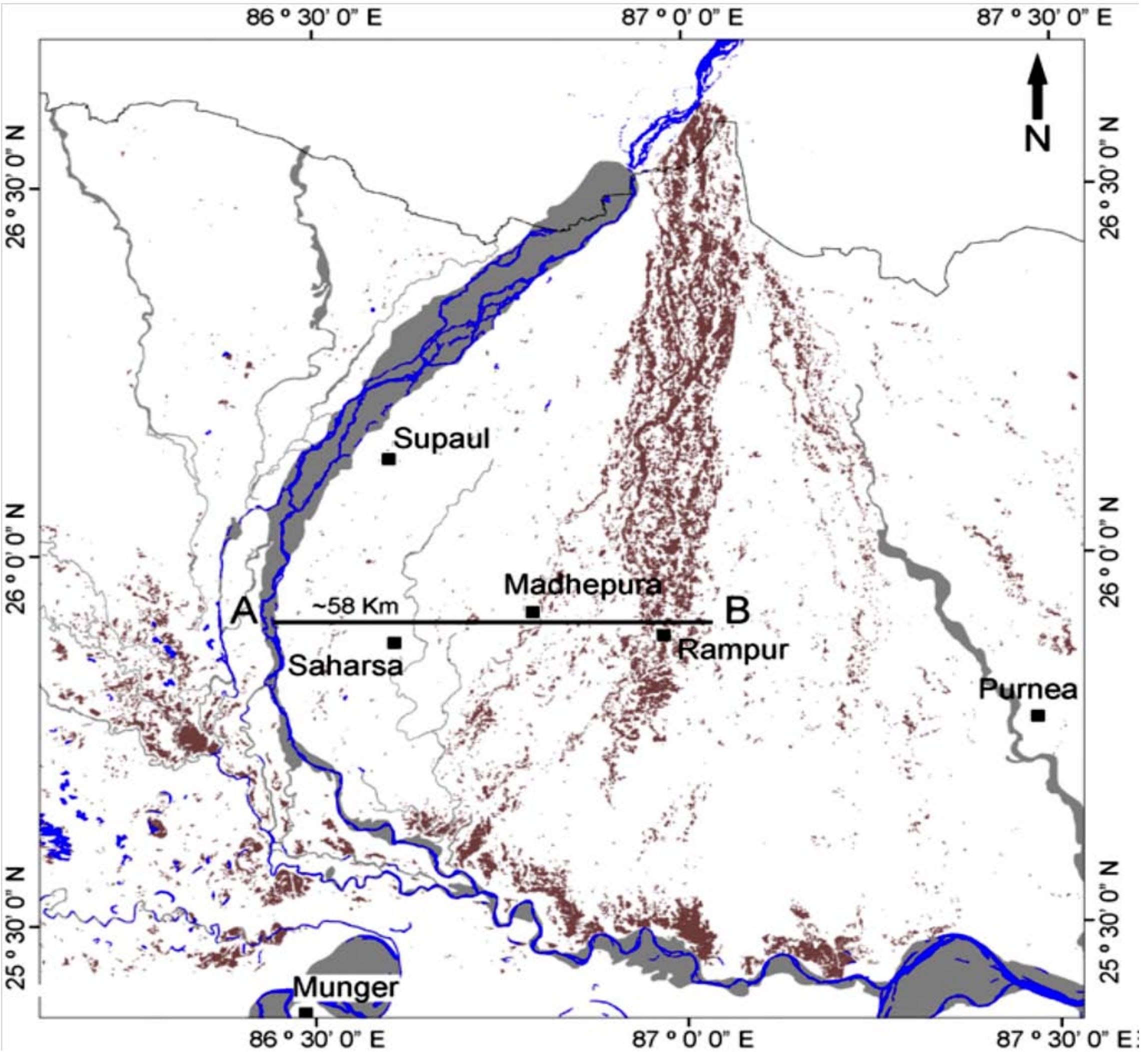


Figure 5.1 Kosi mega fan showing the flood water flow path after the August 2008 avulsion (after NRSA,ttp://fmis.bih.nic.in/Kosi_Flood%20Map/aug22-23_Bihar-Nepal- map.pdf) Note a shift of the Kosi channel by about 60 km to the east (Chakraborty et al., 2010)

The avulsion exposed the inadequacy of the understanding of the behaviour of the Kosi River. A better understanding of the underlying factors that control river course changes are essential for better flood prediction and for adopting more effective strategies for disaster management (Sinha, 2008, 2009). Behaviour of the Kosi River is inextricably interlinked with the geomorphology of the Kosi megafan and its formative mechanism.

Fluvial landforms are produced by the action of flowing water in the terrestrial environment, whereas fluvial geomorphic processes are those natural processes that produce, maintain and change fluvial landforms. The channel pattern or landform of a reach of an alluvial river reflects the hydrodynamics of flow within the channel and the associated processes of sediment transfer and energy dissipation. Channel patterns form a continuum in response to varying energy conditions ranging from straight and meandering to braided forms. Generally, braiding is favoured by high energy fluvial environments with steeper gradients, large and variable discharges, dominant bed load transport and non-cohesive banks lacking stabilization by vegetation (Richards, 1982). The secondary flow component also contributes to the growth of channel deformations (Bathurst et al., 1979).

However, a comprehensive study of channel migration of river Kosi with most recent data has not yet been reported in the literature. So, attempt has been made to assess the temporal and spatial variation of braiding intensities along the whole stretch from Chatra to Nirmali based on the remote sensing image processing

5.2 OBJECTIVES OF THE STUDY

The present study briefly describes a study of the River Kosi from Chatra to 47 km downstream of barrage for a stretch of around 88 km for a period of recent 19 years (1992-2011) using an integrated approach of Remote Sensing and Geographical Information System (GIS). The satellite data has provided the information on the channel configuration of the river system on repetitive basis, revealing much needed data on the changes in river morphology, erosion pattern and its influence on the land, stable and unstable reaches of the river banks, and changes in the main channel of the Kosi River.

In this study, it is endeavored to assess the channel morphological changes actuated by stream bank erosion process. The newer braiding indicator PFI for Brahmaputra River formulated by Sharma (2004) has been adopted in the study to analyze the braiding behavior. Attempt has been made to assess the temporal and spatial variation of braiding intensities along the whole stretch of Kosi River in Nepal plains and in Bihar plains of Indian Territory based on the remote sensing image analyses.

5.3 STUDY AREA

The study area considered for channelization of river Kosi is from Chatra to Nirmali. The River Kosi meanders between Eastern and Western embankments with a bed load consisting of unconsolidated fine sand and silt. The river is approximately 720 km in length from source to where it joins to the river Ganga at Kursela. Out of 720 km length of river Kosi, about 200 km flows in plains. From Chatra to Kosi barrage the distance is 42 km and that from Kosi barrage to Nirmali is about 47 km (Fig. 5.2). So, 88 km reach is considered for study.

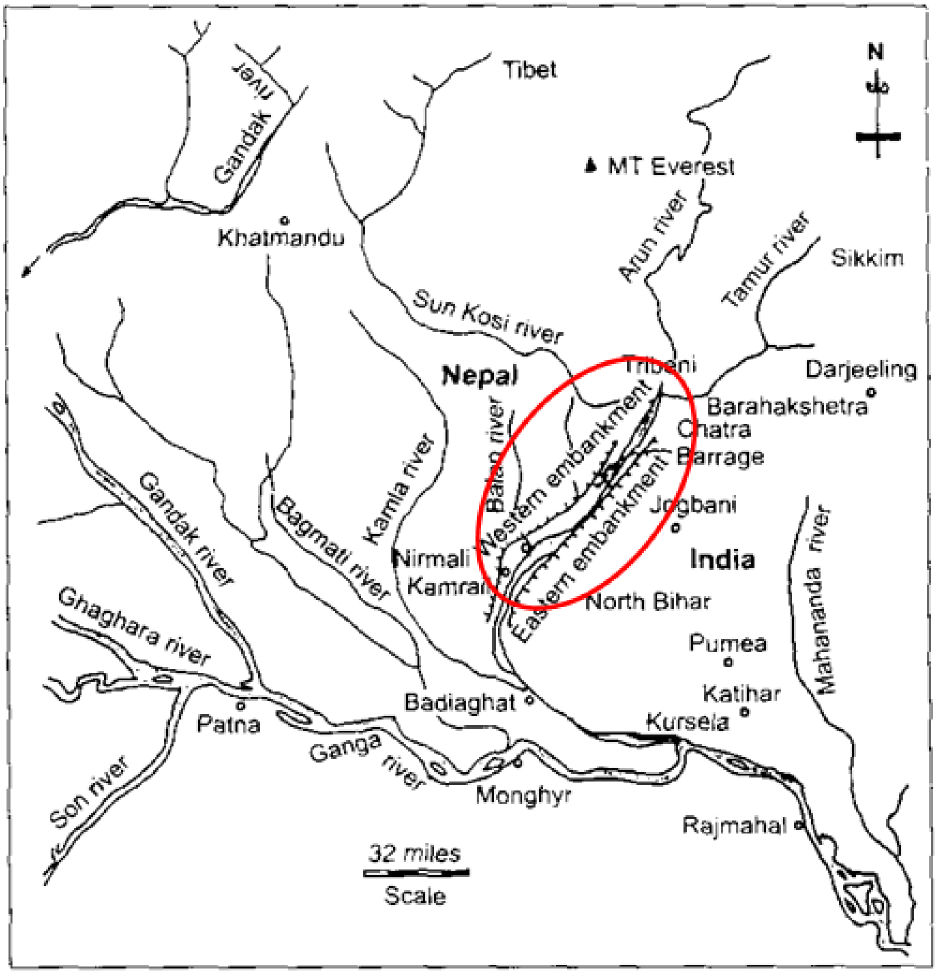


Figure 5.2 Plan showing the study area (Gole and Chitale, 1966)

5.4 METHODOLOGY

The basic data used in this study are digital satellite images of Indian Remote Sensing (IRS) Landsat 5 sensor, comprising scenes for the years 1992, 2005, and 2011. In order to bring all the images under one geometric co-ordinate system, these are geo-referenced with respect to Survey of India (1:50,000 scale) topo-sheets using second order polynomial. The UTM projection and WGS 84 datum has been taken for geo-referencing. Rectification of the images was done with a residual RMS (root mean square error) of less than 1. Subsequently the re-sampling was performed at 30 m resolution using Nearest Neighborhood technique.

The stretch of river from Chatra to Nirmali has been divided into 11 reaches as shown in Fig. 5.3. Each reach comprised of eight cross sections. On the upstream of Kosi barrage, cross-section are superimposed on imaginary at a distance of 1 km interval upto Chatra, similarly on the downstream side upto Nirmali. The bank line of the Kosi River is demarcated from each set of imageries and the channel patterns are digitized using Arc GIS software. Locations of cross sections are shown in Fig. 5.3.

The spatial resolution of Landsat 5 is 30 m. The data used in the analysis have been presented in Table 5.1. ERDAS IMAGINE 8.6 image processing software has been used to perform the image processing works. Then satellite images of the other years were co-registered using image-to-image registration technique.

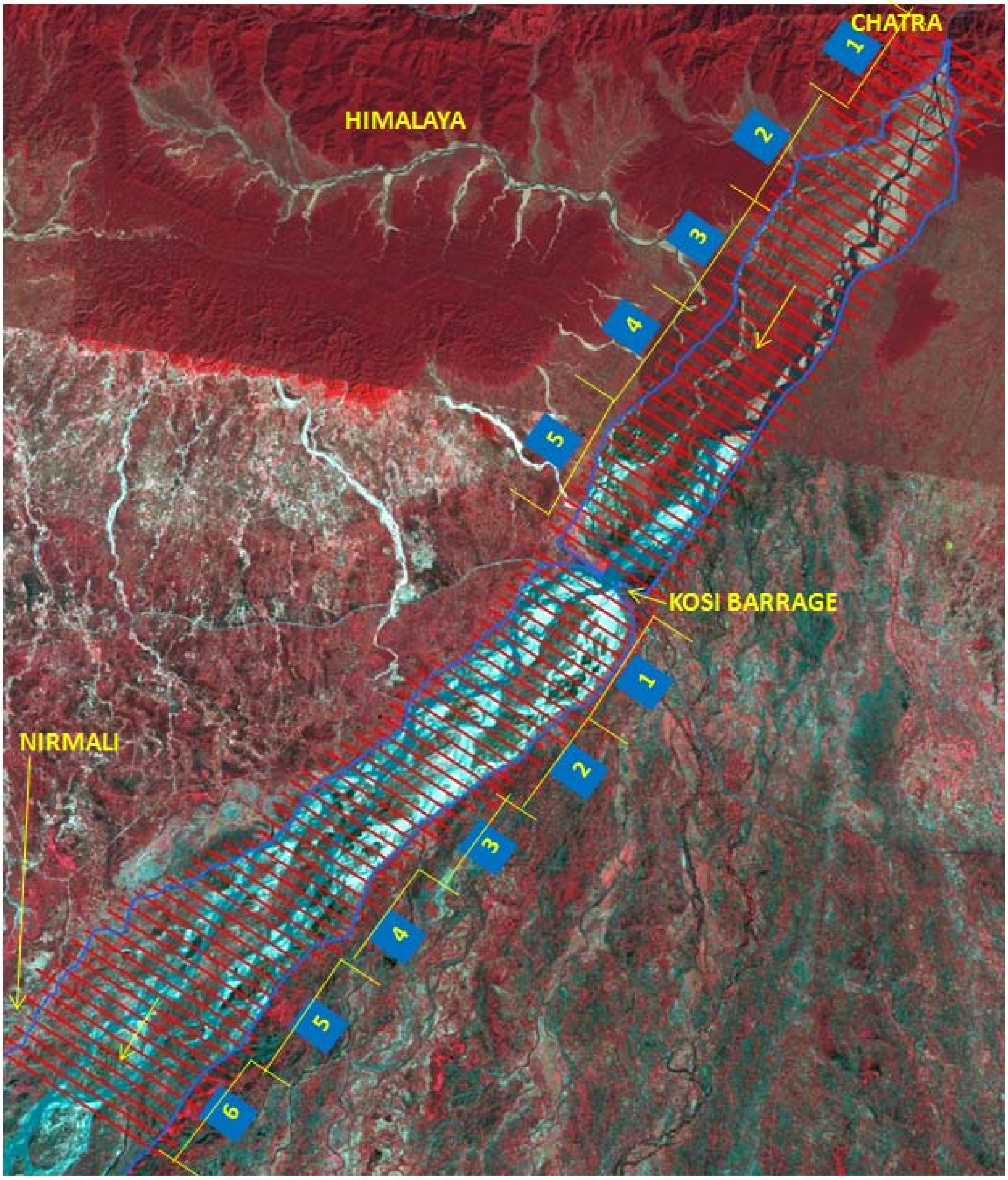


Fig. 5.3 Study Area (USGS)

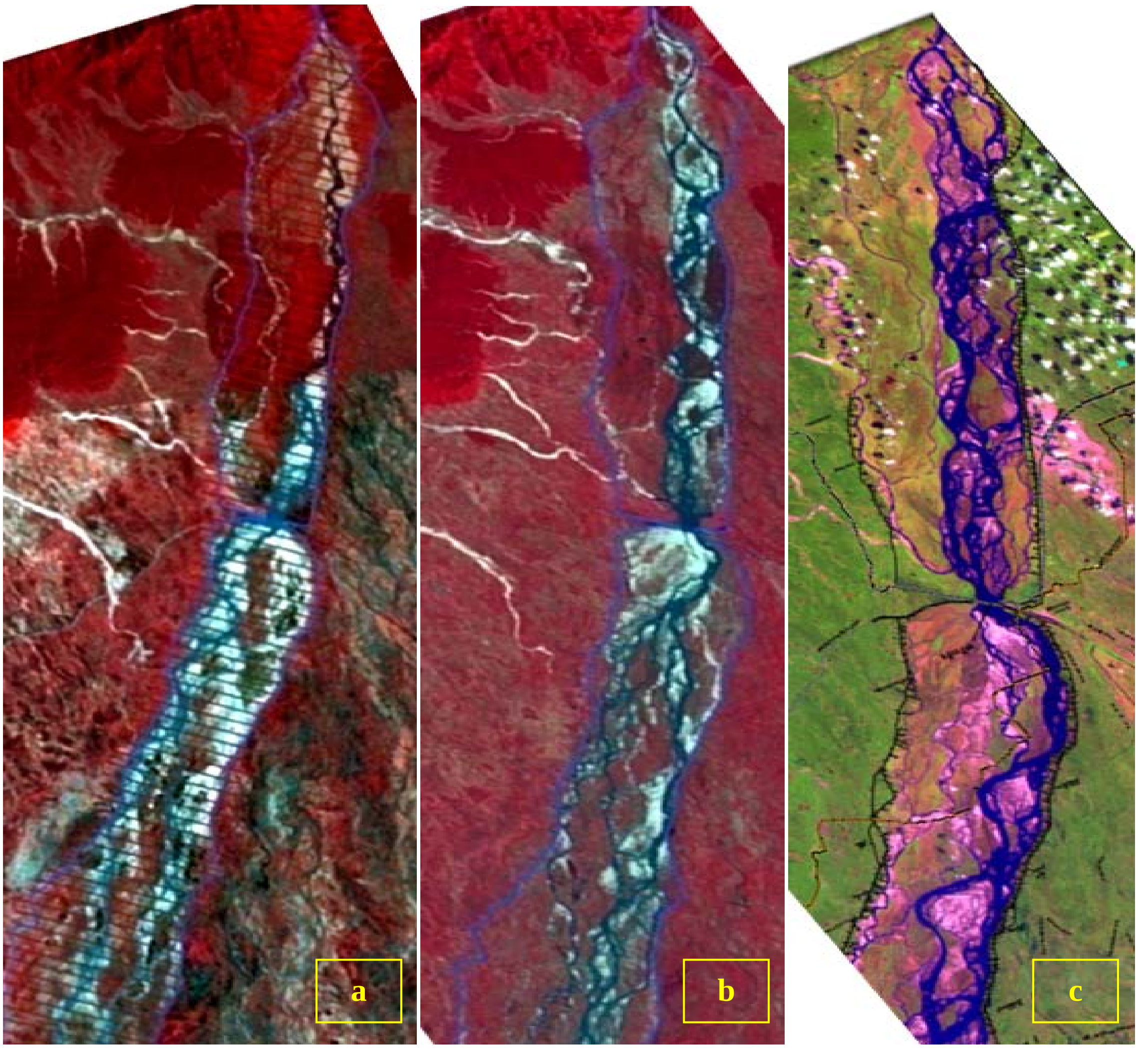
Table 5.1 Characteristics of the remote sensing data used

Satellite/Sensor	Path/row	Acquisition	Spatial resolution	Spectral bands and channels
IRS Landsat 5 (Standard Product	140/42	1992, 2005, 2012 (Fig. 5.4)	30 m	Visible band-(Green channel) (0.52-0.59 μm)

Remote sensing satellite data are able to provide comprehensive, synoptic view of fairly large area at regular interval with quick turnaround time integrated with GIS techniques. Therefore, it makes appropriate and ideal for studying and monitoring river erosion and its bank line shifting. Various studies in this regard have been carried out for some major rivers all over the world. Through a historical analysis using maps and aerial photographs, Surian (1999) reported the channel changes of the Piave River in the Eastern Alps, Italy, which occurred in response to human interventions in the fluvial system. A typical study of channel migration by Yang et al. (1999) in Yellow river (China) made use of both analog and digital data with a time sequential imageries of 19 dates from 1976 to 1994. Rinaldi (2003) presented changes in channel width of the main alluvial rivers of Tuscany (central Italy) during the 20th century by comparing available aerial photographs (1954 and 1993-98). Surian and Rinaldi (2003) reviewed all existing published studies and available data on most Italian rivers that experienced considerable channel adjustment during the last centuries due to various types of human disturbance. Fuller et al. (2003) quantified three-dimensional morphological adjustment in a chute cutoff (breach) alluvial channel using Digital Elevation Model (DEM) analysis for a 0.7 km reach of the River Coquet, Northumberland, UK. Li et al. (2007) examined human impact on channel change in Jianli reach of the middle Yangtze River of China employing 1:100,000 channel distribution maps of 1951, 1961 and 1975 and 1:25,000 navigation charts of 1981 and 1997 to reconstruct channel change in the study reach. Kummu et al. (2008) assessed bank erosion problems in the Vientiane–NongKhai section of the Mekong River, where the Mekong borders Thailand and Lao PDR, using two Hydrographic Atlases dated 1961 and 1992, and SPOT5 satellite images of 2004 and 2005 with a resolution of 2.5m in natural colours.

5.5 PLAN FORM CHANGES

The braided pattern of river Kosi between Chatra and Nirmali can be seen clearly in the imagery of the year 1992, 2005 and 2011, (Fig. 5.4). A comparison of the imagery of the year 1992, 2005 and 2011 indicates that in the year 1992, the river was flowing (hugging) along the eastern side with a low braided pattern, but as the time elapsed the braided pattern of river increased. At the downstream of barrage reach, it is observed that the river was flowing along the western side, but it shifted towards east with laps of time.

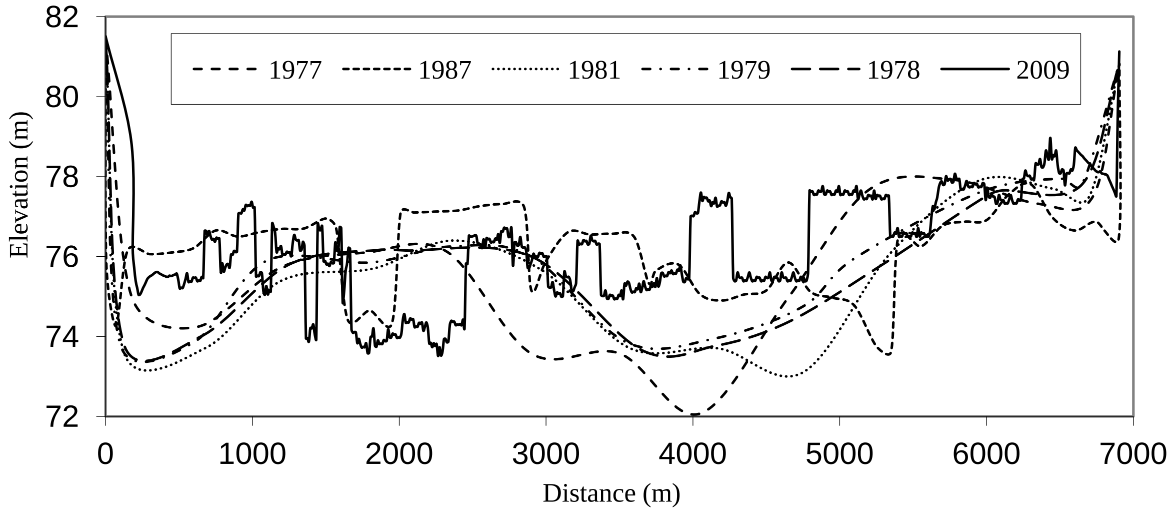


(a) (b) (c)

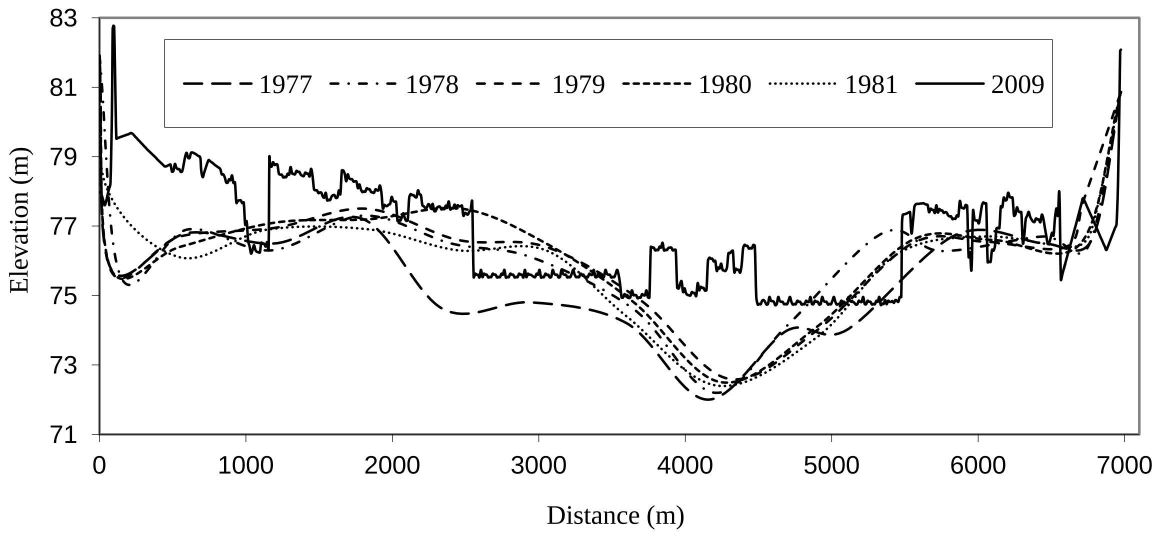
Figure 5.4 Satellite imagery of river Kosi from Chatra to Nirmali of the year (a) 1992, (b) 2005 and (c) 2012 (USGS)

Due to deposition of huge quantity of sediment between the banks in the river Kosi every year in the reach from Chatra to Kursela, the bed level is raised by 0.1 m to 3 m at many locations. Figure 5.5(a)-(d) show year-wise bed level changes for the years 1988, 1987,1981,1979,1978, and 2009 in the cross-section of river at 2 km and 5 km upstream of barrage and at 2 km and 5 km downstream of barrage, respectively. It can be seen that the bed level has gone up over a period from 1977 to 2009 due to yearly sediment deposited. It is also observed that the channel configurations are not fixed and changing between the embankments. The river is flowing in multichannel, because of non-cohesive material, no rigid boundary and low slope.

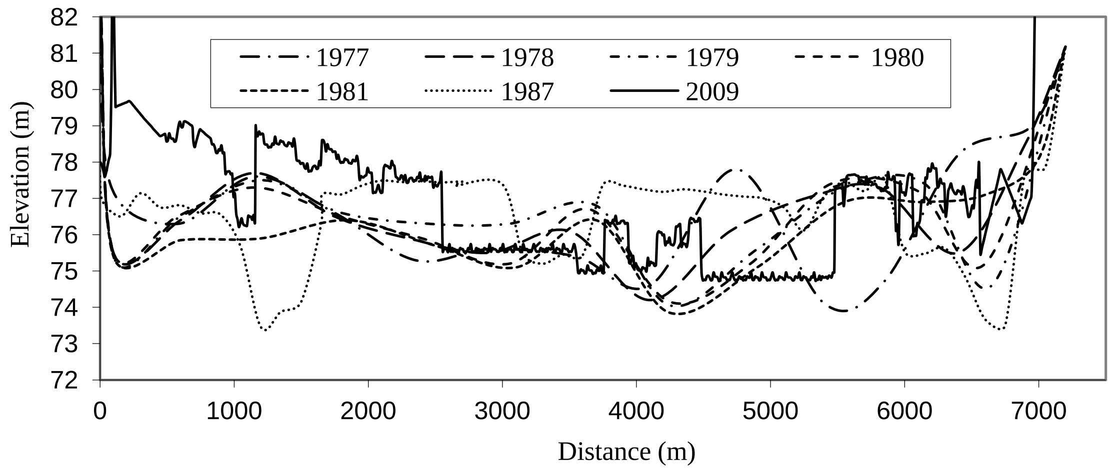
The left embankment of the Kosi river at 11 km upstream of the barrage near Kusaha village breached in 18.8.2008. After the breach, the major flow was passing through the breached section, which was about 0.7 km wide. Heavy deposits of sediment occurred in the existing section of the river downstream of its breached points. Subsequently, after the flood, the breach was plugged and dredging was carried out in the downstream. The dredging was in the form of multiple channels and arbitrary. The cross-section in Figure 5.5 of year 2009, which is having different pattern than that for the other years is due to this dredging of the Kosi river.



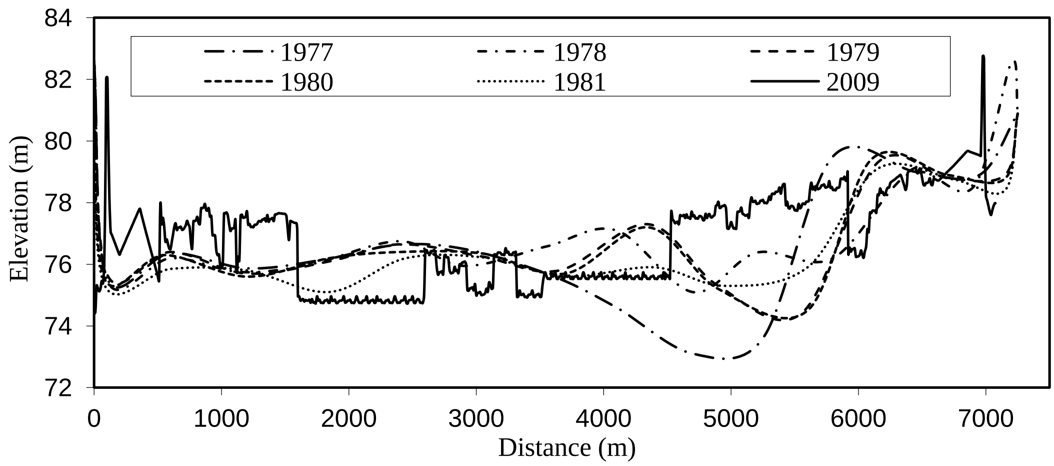
(a) Cross-Section No. 2 – two km upstream of Barrage



(b) Cross-Section No.5 - five km upstream of Barrage



(c) Cross-Section No.2 - two km downstream of Barrage



(d) Cross-Section No.5 - five km downstream of Barrage

Figure 5.5 Yearly changes in bed level (CWPRS Record)

5.6 PLAN FORM INDEX (PFI)

Plan Form Index (PFI) reflects the fluvial landform disposition with respect to a given water level and its lower value is indicative of higher degree of braiding.

Computed mean PFI values for reach-1 to reach 11, each comprising nine cross-sections, are given in Table 5.2 for the three years of imageries. The maximum values of PFI (indicating least braiding within the reach) and minimum values of PFI (indicating highest braiding within the reach) are computed and given in Table 5.2 for each reach. The corresponding plot for minimum, maximum and mean, PFI against reach numbers are shown in Figs. 5.6, 5.7 and 5.8, respectively. Mean PFI enveloping with maximum and minimum cross-sectional PFI suggest the ranges of variation in braiding intensities within a reach. It can be easily figured out that maximum values are predominant in the year 1992, whereas in 2005 and 2012 minimum values are predominant in the upstream of barrage. While at the downstream of barrage, irrespective of the time, the aforementioned six discrete reaches show little changes in the braiding intensity and pattern.

Table 5.2 Comparison of Plan Form Index (PFI) for the year 1992, 2005 and 2011 for river Kosi

Reach No	PF - 1992			PF - 2005			PF - 2011			Remark
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	
1U/S	66.26	45.40	87.13	43.26	31.46	55.05	55.7	38.43	73.09	
2 U/S	3.55	3.12	3.98	3.92	3.56	4.28	2.63	2.29	2.98	
3 U/S	32.98	27.45	38.51	15.82	12.51	19.12	2.77	2.67	2.88	PFI<3
4 U/S	12.33	11.86	12.80	9.5	8.56	10.44	2.08	1.97	2.20	highly
5 U/S	4.15	4.23	4.08	4.58	3.94	5.22	3.53	2.96	4.10	braided
BARRAGE										
1D/S	2.51	2.22	2.79	3.96	3.87	4.05	4.72	3.98	5.45	19>PFI>3
2 D/S	2.50	2.15	2.85	2.89	2.77	3.01	2.84	2.73	2.94	moderate
3 D/S	1.98	1.78	2.18	4.17	3.56	4.78	4.18	3.21	5.14	braided
4 D/S	2.57	2.17	2.98	4.98	3.82	6.15	5.91	4.33	7.49	PFI>19
5 D/S	2.38	1.99	2.78	4.57	4.01	5.13	5.44	3.15	7.72	low
6 D/S	1.77	1.56	1.98	1.96	1.78	2.14	6.83	5.24	8.41	braided

Note: - U/S – Upstream reach, D/S – Downstream reach.

5.7 DISCUSSIONS

The graphical plots of Plan Form Index for the Kosi river from Chatra to Kosi barrage shows increasing trend thereby registering an increasing level of braiding, as can be seen from the threshold limits given in Table 5.3. Plots for all reference cross sections for the years 1992, 2005 and 2011 for PFI vs. cross section numbers shows an increasing trend of braiding with time. These plots clearly demonstrate the rationality of using the Plan Form Index as a measure of braiding and closely conform to the actual physical situation of the occurrence of braiding vividly depicted in satellite images. Similarly, from Kosi barrage to Nirmali minor decreasing trends can be seen, indicating a decrease in level of braiding, as can be seen from the threshold limits given in Table 5.3. Plots for all reference cross sections for the years 1992, 2005 and 2011 for PFI vs. cross section numbers show minor decreasing trend of braiding with time. In light of the threshold values of Plan Form Index, it can be readily inferred from graphical plots showing maximum, minimum and mean values of PFIs of cross sections that have heavy, moderate and low braiding characteristics, resulting in a very complex channel hydrodynamics. Typical reaches are presented in Fig. 5.9 differentiating PFI values.

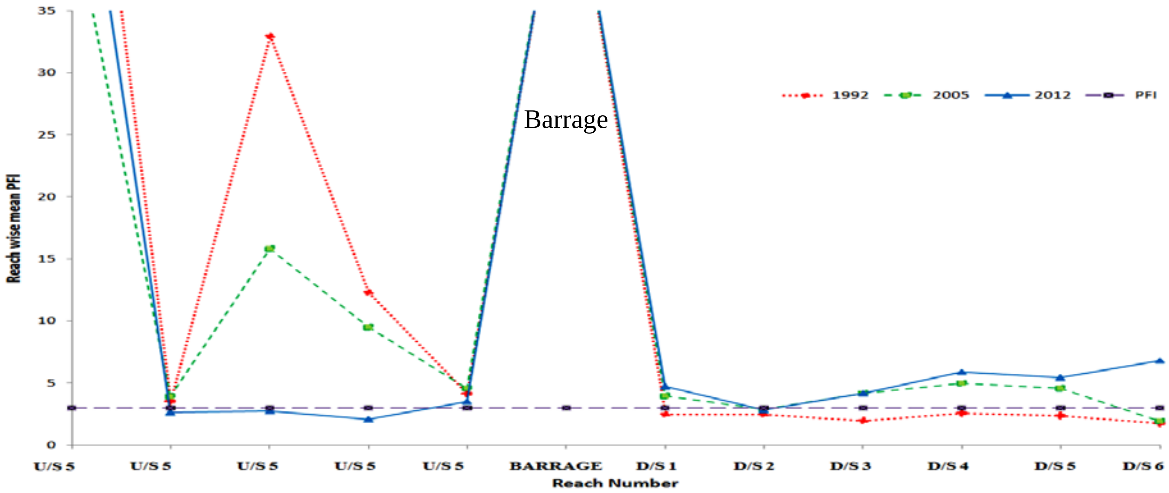


Figure 5.6 Change in the reach wise mean (PFI) values in different reaches from Chatra to Nirmali for the years 1992, 2005 & 2012

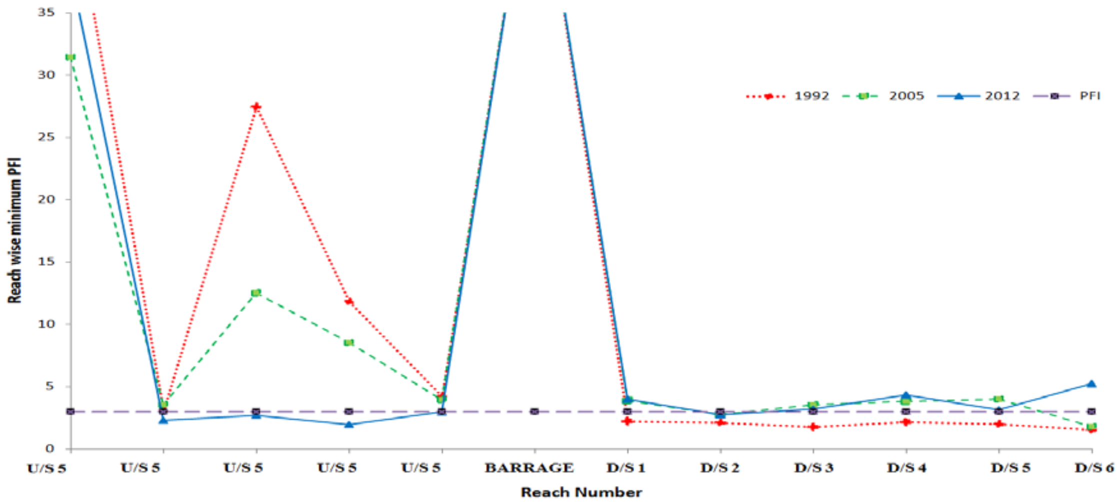


Figure 5.7 Change in the reach wise minimum (PFI) values in different reaches from Chatra to Nirmali for the years 1992, 2005 & 2012

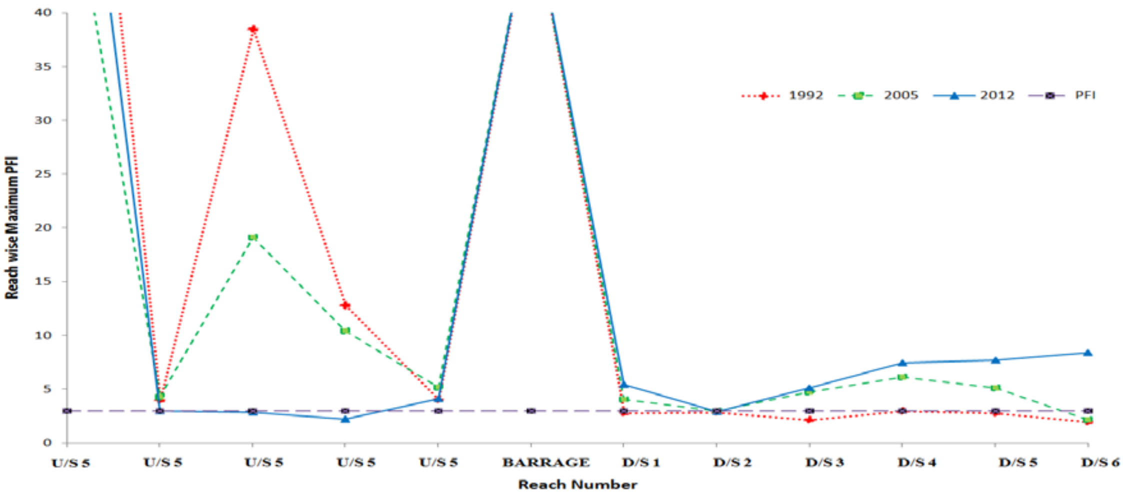
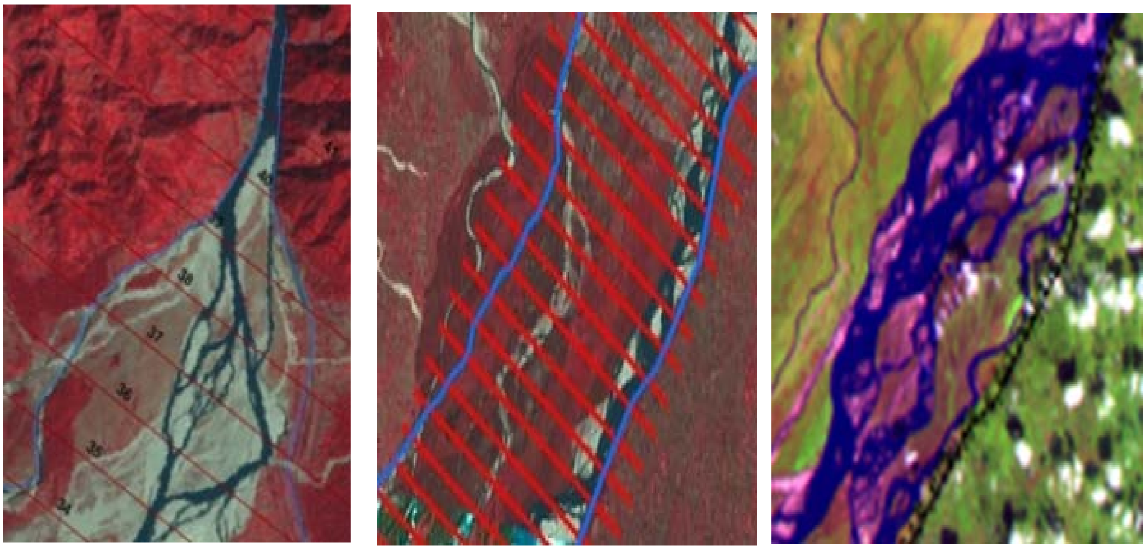


Figure 5.8 Change in the reach wise maximum (PFI) values in different reaches from Chatra to Nirmali forthe years 1992, 2005 & 2012



a) b) c)

Figure 5.9 Typical reach-a) Low Braided, PFI = 66.26, b) Moderate braided, PFI =12.33 and c) highly braided, PFI = 2.08 (USGS)

Table 5.3 Estimated extent of braiding based on Plan Form Index (mean PFI) of Kosi river

Reach	Year 1992			Year 2005			Year 2012	
	PFI	Threshold Indicator		PFI	Threshold Indicator		PFI	Threshold Indicator
1U/S	66.26	Low Braided		43.26	Low Braided		55.76	Low Braided
2 U/S	3.55	Moderate Braided		3.92	Moderate Braided		2.635	Heavily Braided river
3 U/S	32.98	Low Braided		15.82	Moderate Braided		2.775	Heavily Braided river
4 U/S	12.33	Moderate Braided		9.5	Moderate Braided		2.085	Heavily Braided river
5 U/S	4.15	Moderate Braided		4.58	Moderate Braided		3.53	Moderate Braided
BARRAGE								
1D/S	2.51	Heavily Braided river		3.96	Moderate Braided		4.72	Moderate Braided
2 D/S	2.50	Heavily Braided river		2.89	Heavily Braided river		2.84	Heavily Braided river
3 D/S	1.98	Heavily Braided river		4.17	Moderate Braided		4.18	Moderate Braided
4 D/S	2.57	Heavily Braided river		4.98	Moderate Braided		5.91	Moderate Braided
5 D/S	2.38	Heavily Braided river		4.57	Moderate Braided		5.44	Moderate Braided
6 D/S	1.77	Heavily Braided river		1.96	Heavily Braided river		6.83	Moderate Braided

Note:- U/S – Upstream reach, D/S – Downstream reach.

5.8 CONCLUDING REMARKS

It can be concluded from Fig. 5.5, that yearly sediment was depositing in the river bed and therefore, the bed level has gone up over a period from 1977 to 2009. It can be further observed that the channel configuration is not fixed. It is changing between embankment and the river is flowing in multichannel, because of non-cohesive material, no rigid boundary and low slope.

Similarly, it can be concluded from Fig. 5.4, that in the year 1992, the river was flowing (hugging) along the eastern side with a low braided pattern. But as the time elapsed the braided pattern of river increased. At the downstream of barrage reach, it is observed that the river was flowing along the western side, but as the time elapsed the river shifted towards eastern side.

It can be easily figured out that maximum values 66.26 are predominant in the year 1992, whereas in 2005-12 minimum values 1.96 are predominant in the upstream of barrage. While at the downstream of barrage, irrespective of the time, the aforementioned six discrete reaches show little changes in braiding intensity and pattern.

Chapter 6

MATHEMATICAL MODELLING

6.1 INTRODUCTION

For minimizing the silting and lateral shifting in Kosi river, possibility of channelizing the river is investigated for a stretch of 88 km from Chatra to Nirmali. Channelization is one of the methods by which the velocities in the river could be increased to increase its sediment carrying capacity. This chapter presents the analysis of hydraulic aspects of channelizing the river by using 1D mathematical model HEC-RAS 4.1. Various channelization widths ranging from 800 m to 2,000 m are examined.

6.2 DEVELOPMENT OF MODEL

Although the flow in natural rivers is of three-dimensional (3D) nature, one (1D) or two (2D) models are often used in engineering practice for shallow open channel flow. In particular, when simulating a very long river of multiple channels in cross sections for a long period, 1D models (e.g., HEC-RAS) are more cost effective than 2D and 3D models. However, they are unable to simulate momentum exchange between main channel and floodplains, turbulence around engineering structures (e.g., bridges piers, spur dikes), and flow in highly sinuous channels (Duan et al, 2001.; Duan and Julien 2005). To overcome these limitations, engineers commonly enhance 1D model with empirical formulas to approximate energy losses attributable to in-stream structures or meandering bends. In the present study, the reach of Kosi river analyzed is consisting of braided, transitional, and meandering channels with levees and dykes. Also highly overloaded sediment supply is to be simulated in respect of various hydraulic aspects.

6.2.1 Model reach and data

The reach considered for channelization study of river Kosi is from Chatra to Nirmali. In this reach, Kosi river meanders between eastern and western embankments with a bed load consisting of unconsolidated fine sand and silt. From Chatra to Kosi barrage, the distance is 41 km and Nirmali is located 47 km downstream of the Kosi barrage. The stretch of the Kosi river from Chatra to Nirmali is consider for channelization as shown in Fig. 6.1.

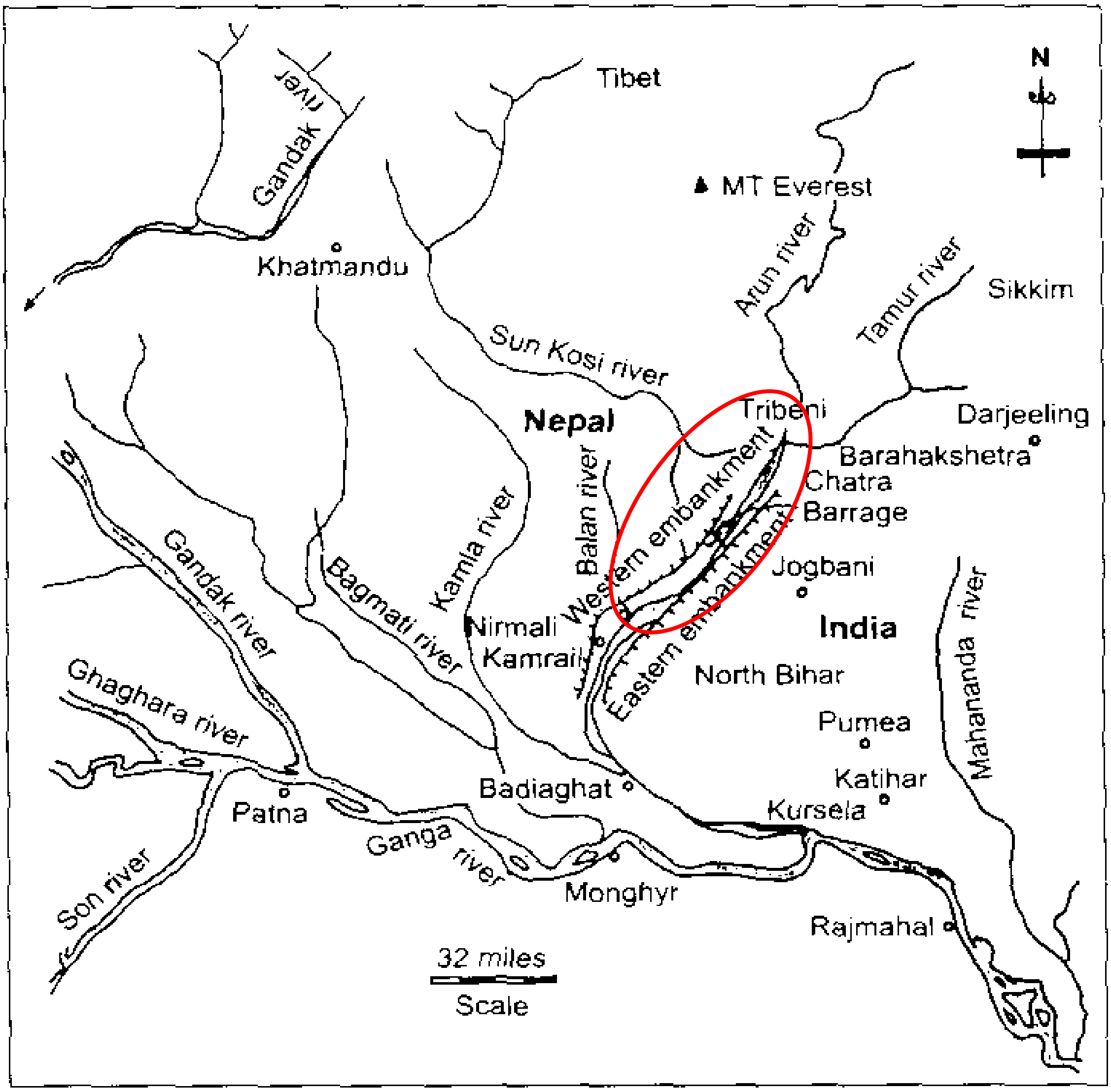


Figure 6.1 Plan showing study area (Gole and Chitale, 1966)

The data for river cross-sections post 2002 flood were used, at 1-km intervals for the study reach starting 41 km upstream to about 47 km downstream of Kosi Barrage. Fig. 6.2 shows the plan layout of the cross-sections while Figs. 6.3 and 6.4 show two typical cross-sections of the river at chainages 5 km upstream of barrage and 34 km downstream of barrage.

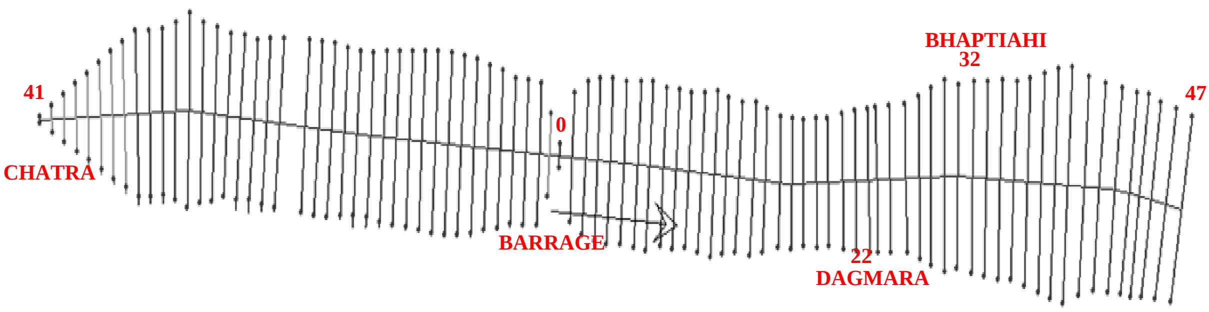


Figure 6.2 Plan showing cross-section

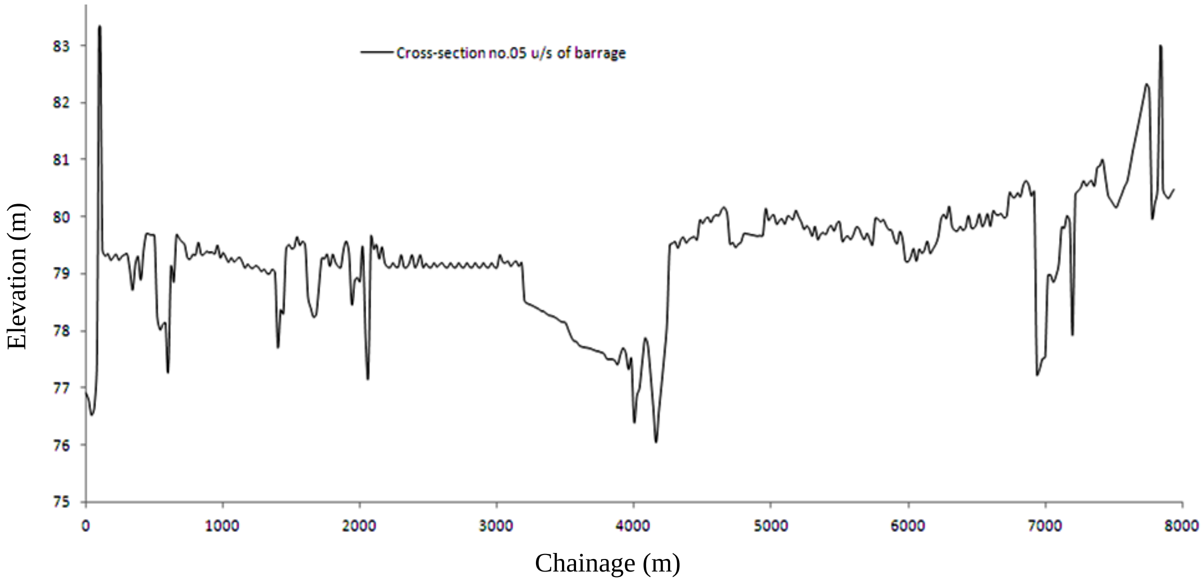


Figure 6.3 Typical Cross-section (c/s no. 05 u/s of barrage)

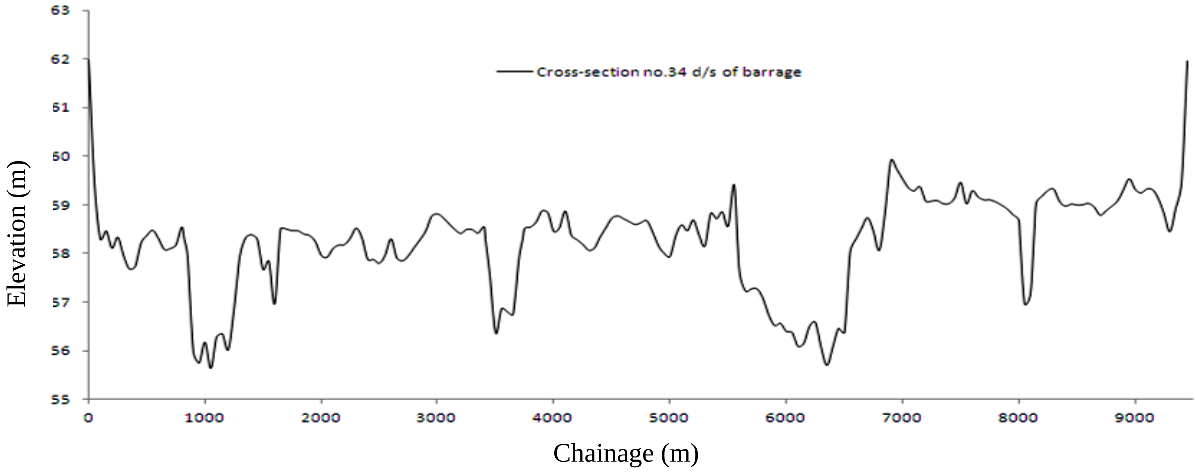


Figure 6.4 Typical Cross-section (c/s no. 34 d/s of barrage)

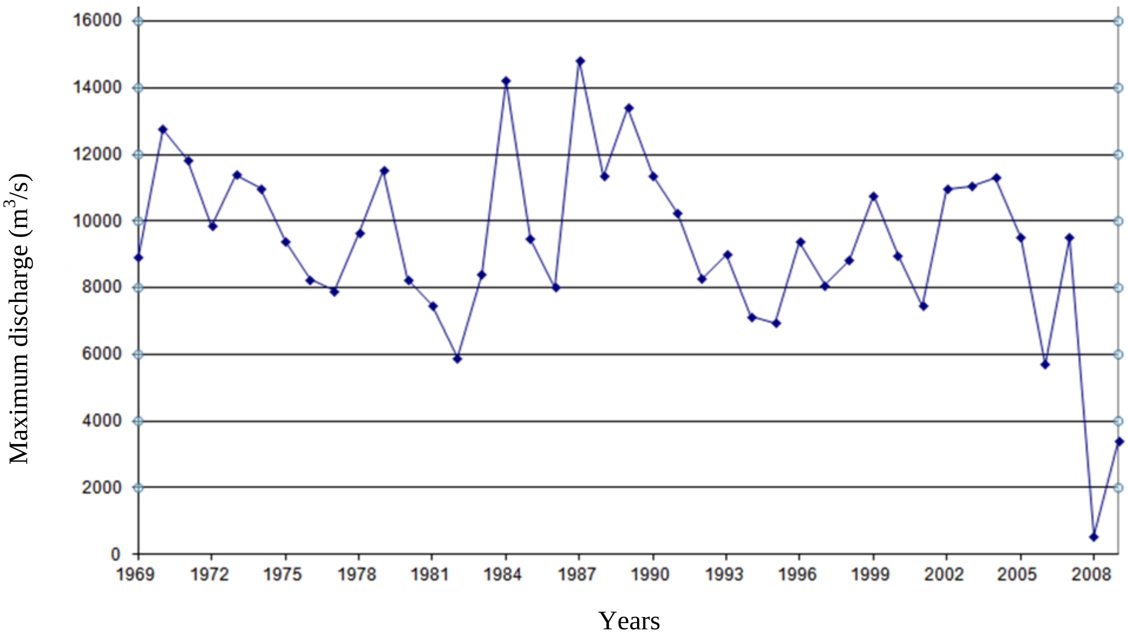


Figure 6.5 Annual peak flood discharge at Kosi barrage

Two gauges, one at Dagmara (22 km downstream of barrage) and another at Bhaptiahi (32 km downstream of barrage) were established in May 2002. The data of water level at these gauge sites were recorded at an interval of six hours during the period from June to December 2002. This data was used for fixation of Manning's "n" value in the model and for proving the mathematical model.

Figure 6.5 shows variation of maximum annual flood from 1969 to 2009. During last 40 years the annual flood frequency does not exceed 15,586 m^3/s (5, 50,000 cusecs), and the same is considered in this model study.

The riverbed material samples at three locations along the river width, including the deep channel portion and foot of Eastern and Western embankments, were collected in May 2002. The typical grain size distribution curve for a sample is shown in Fig. 6.6. It could be seen that the river bed material is composed of medium and fine sands with median diameter (d_{50}) of 0.23 mm. Sediment in the river can be classified as fine sand with no or little clay content and has a d_{50} of 0.23 mm. The discharge and sediment data were collected daily and recorded at the barrage for a period of June 2001 to April 2003. Similarly, inflow hydrograph at Kosi barrage for the period 01May 2002 to 1 January 2009 was available as shown in Fig. 6.7.

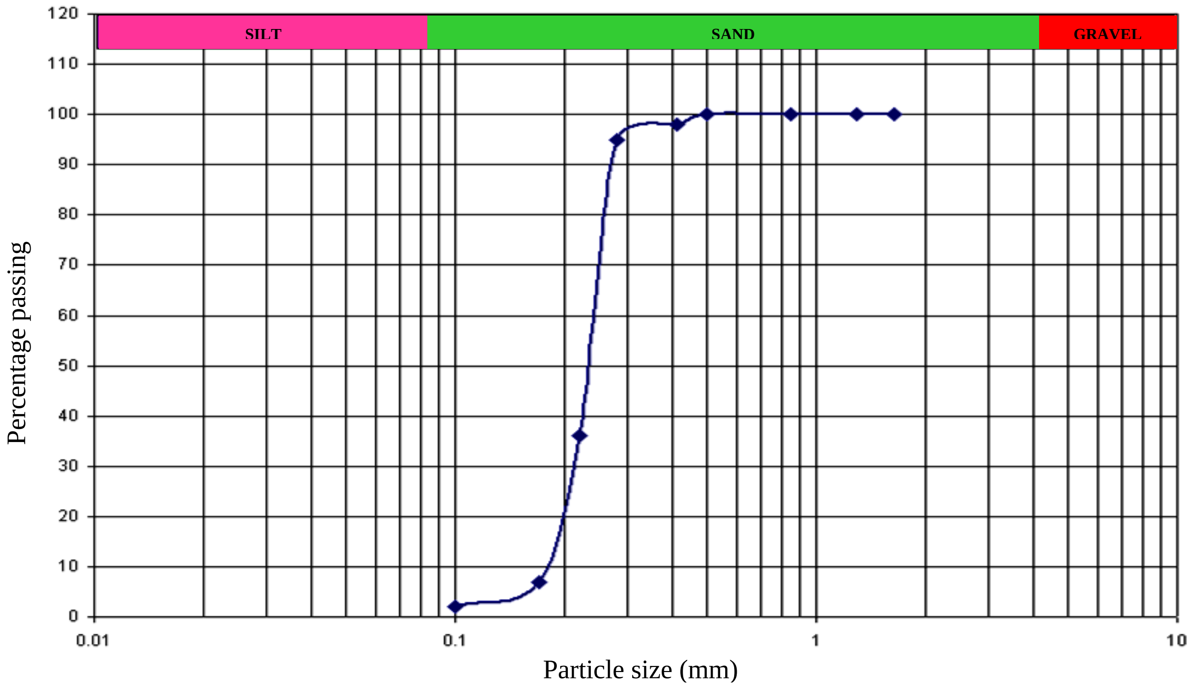


Figure 6.6 Grain size distribution curve

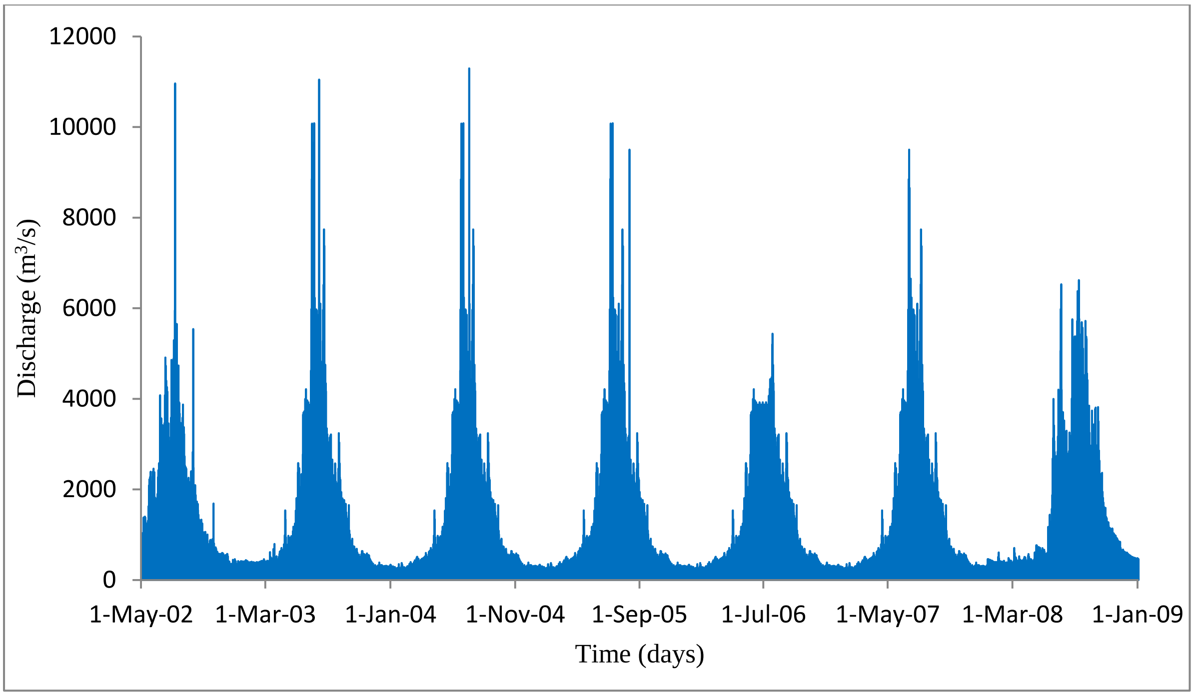


Figure 6.7 Inflow hydrograph at Kosi barrage

6.2.2 Numerical Model

6.2.2.1 Governing Equations

The numerical model (HEC RAS) solves the De Saint Venant equations describing unsteady flow in open channel and the continuity equation for the conservation of the sediment mass.

Continuity equation for water:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{6.2}$$

Momentum equation for water:

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{q^2}{h} + \frac{gh^2}{2}\right] + gh\frac{\partial z}{\partial x} + ghS_f = 0 \tag{6.3}$$

Continuity equation for sediment:

$$\frac{\partial}{\partial t}\left[(1-\rho)z + \frac{q_s h}{q}\right] + \frac{\partial q_s}{\partial x} = 0 \tag{6.4}$$

Evolution of the bed elevation and sediment erosion relationship

$$\frac{\partial z}{\partial t} = \frac{\varepsilon}{\rho_s} \qquad \varepsilon = \varepsilon_m \left\{\frac{\tau_b - \tau_{cr}}{\tau_{cr}}\right\}^{\alpha} \tag{6.5}$$

In the above equations, h is the flow depth; q the water discharge per unit width; z the bed elevation; q_s the unit sediment discharge; S_f the friction slope; x the distance along the channel; t the time; ρ the porosity of the bed; ρ_s the sediment density; τ_b the bottom shear stress; τ_{cr} the critical bottom shear stress; and ε_m, α are parameters.

The friction slope S_f is evaluated using the Chezy – Manning relation:

$$S_f = \frac{q^2 n^2}{h^2 R^{\frac{4}{3}}} \tag{6.6}$$

where R is the hydraulic radius and n the Manning roughness coefficient, which is evaluated by the Einstein's relation, taking into different roughness value on the wetted perimeter P:

$$n = \left(\frac{P_{sw} n_{sw}^{3/2} + P_b n_b^{3/2}}{P} \right)^{2/3} \tag{6.7}$$

$$\tau_b = \rho_w g R S_f \left\{ \frac{n_b}{n} \right\}^{3/2} \tag{6.8}$$

in which ρ_w is density of water.

6.2.3 Fixation of "n" value

Proving studies were carried out for verifying the conformity between mathematical model and observed data in respect of water surface profile in Kosi river by varying the value of Manning's 'n'. The discharge and water level data of Kosi river was recorded during monsoon of year 2002 were utilized for this purpose. The maximum discharge recorded at Kosi barrage during this period was 10,960 m^3/s. For this discharge at Kosi barrage, the corresponding water levels recorded at Dagmara and Bhaptiahi were 64.3 m and 60.2 m, respectively. The villages Dagmara and Bhaptiahi are situated at c/s no. 22 and 32 downstream of the barrage. For conforming the 'n' values, studies are carried out assuming model as a rigid and the upstream and downstream boundary condition as constant discharge and normal depth. The value of Manning's 'n' was varied for discharge of 10,960 m^3/s and the water levels computed by using mathematical model at Dagmara and Bhaptiahi were compared with the observed values. It was found that Manning's n value of 0.022 gives the best comparison and is used for further studies. The results of these proving studies are presented in Table-1

Table 6.1 Computed and observed gauge levels

Gauge site	Gauge levels		
	As observed during 2002 flood	Mathematical model result	
		n = 0.025	n = 0.022
Dagmara	64.30 m	64.79 m	64.67 m
Bhaptiahi	60.20 m	60.21 m	60.11 m

6.2.4 Calibration of model

While collecting the data cross-sections of the river in April/May 2002, water levels were also recorded along the cross-sections for the existing discharge of 2,000 m^3/s. The cross-section data as above with Manning's 'n' value as 0.022 and upstream and downstream boundary condition as constant discharge and normal depth. The mathematical model studies are carried out assuming a rigid model to get further confirming the use of Manning's 'n' value as 0.022. The water surface elevation all along the cross-sections and are compared with the recorded values in Fig. 6.8. The comparison is found to be satisfactory.

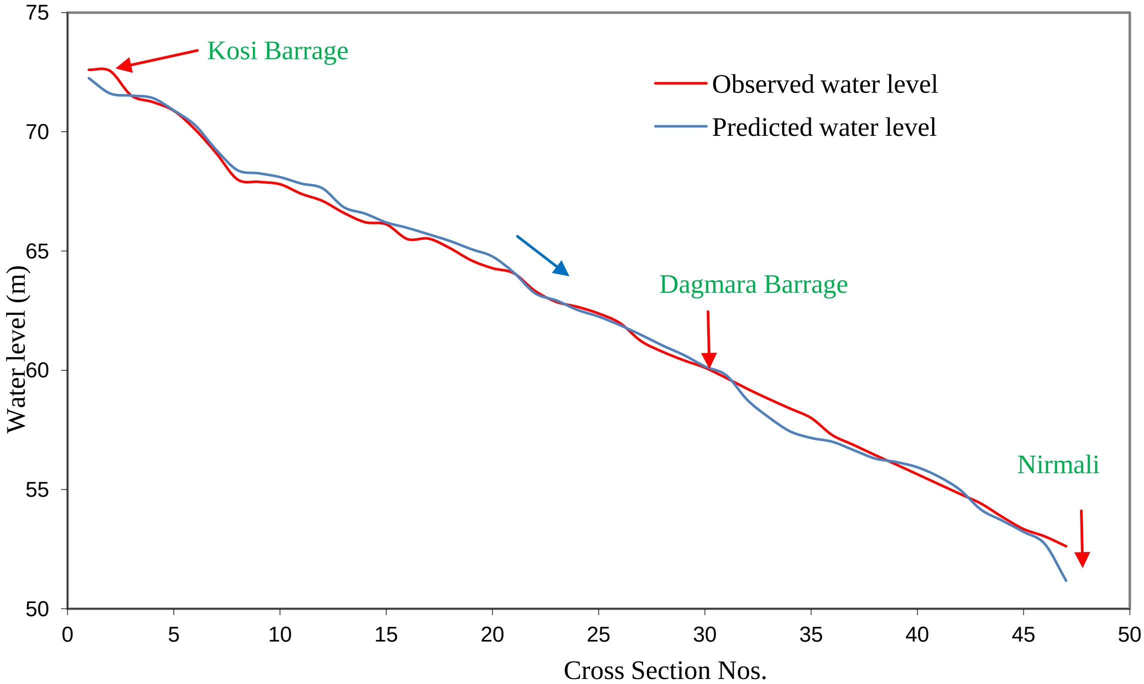


Figure 6.8 Comparison of prototype water surface profile with mathematical model results for Q = 2,000 m^3/s

6.3 CHANNELIZATION USING LEVEES

6.3.1 Model Analysis

The changes in river bed profile and the course occur due to several years of flows, necessitating long term simulations for predicting these changes. The topographical data in the form of river cross sections is required to simulate river flows. The water level and discharge data at boundaries and two to three locations within model reach are required for specifying the boundary conditions.

The required rivers cross sectional data are available for the month of May 2002. The cross sections of the river within the embankments are at a regular interval of 1.0 km, from 41 km upstream of Kosi barrage to 47 km downstream. Data pertaining to sediment and discharges recorded at the Kosi barrage for the period from 01 May 2002 to 01 January 2009, rating curve at cross-section number 38 downstream of barrage and normal depth are the boundary condition used for the present studies.

Mathematical model (HEC-RAS) was run with the input data as discussed above for a inflow hydrograph as shown in Fig. 6.7. The water way computed using Lacey's formulae $W = 4.83\sqrt{Q}$ for the 500 year return period discharge of Q = 26,900 m^3/s is 800 m. The waterway provided at the Kosi barrage is 1,100 m. The waterway of 800 m, 1,100 m, 2,000 m and without any constriction waterway (i.e. river flowing between the existing levees were computation along with a waterway of 2,000 m) computed for a period about 9 year discharge sediment data. The aggradation / degradation in the bed profile for various waterway widths are presented in Fig. 6.9.

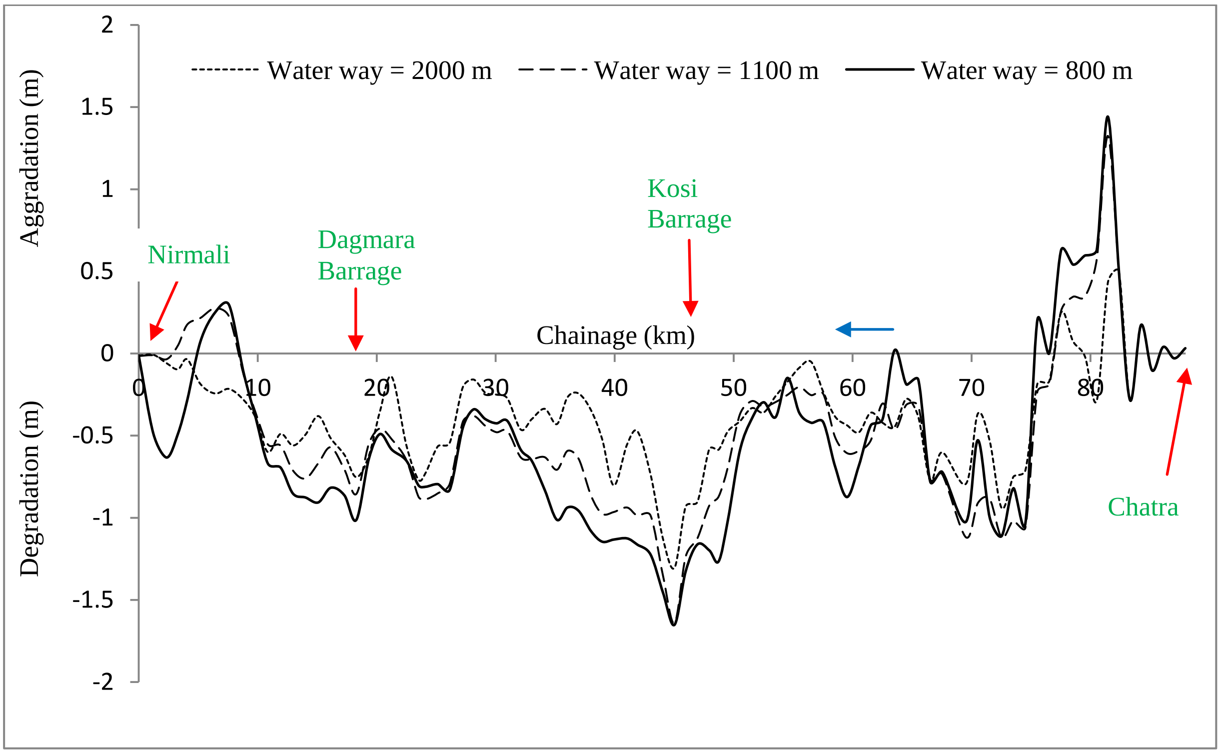


Figure 6.9 Morphological changes of bed level with respect to river bed level of year 2002

6.3.2 Results

It can be observed from Fig. 6.9 that the river bed is aggraded when the waterway is 2,000 m, and it is degrading when the waterway provided is 800 m, equivalent to Lacey's waterway. However, the river bed degradation is high in the initial year mathematical model run, afterward degradation is minimum when the waterway provided is 1,100 m and a regime channel is formed. The average velocities in the river without any constriction is about 1.5 m/s. However the average velocity were 2.2, 2,7 and 3.3 m/s for 2,000 m, 1,100 m and 800 m water way respectively, as shown in Fig. 6.10. In the proto site, it is also observed that in the vicinity of Kosi barrage, the sedimentation near the spillway portion has not affected the operation of the barrage over nearly 50 years. The barrage has a waterway of 1,100 m. The river Kosi reach constricted to 1,100 m width would result in a regime channel, which will not be in either degradation or aggradation stage.

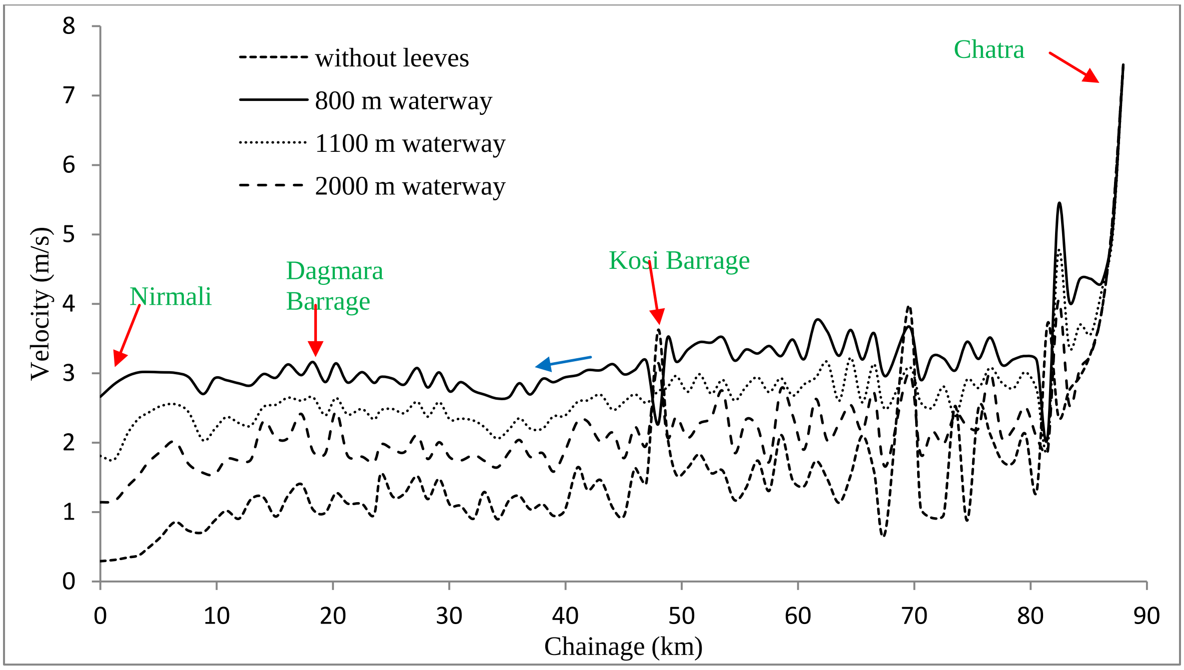


Figure 6.10 Velocity distribution longitudinally for various channelization width

After taking the run of mathematical model for a 9 years hydrograph with a constricted waterway to 1,100 m, effects on the bed level is discussed below by considering one cross-section agradation and another cross-section degradation. Figure 6.11 shows a typical cross-section 5 km upstream of Kosi barrage and Fig. 6.12 shows details of change in bed level in constricted area. Volume of sediment per unit length at cross-section no. 05(u/s) are shown in Fig. 6.13 which indicates that by constricting the waterway, bed level variation in the initial year is high than in the later years. Similar is the case with Cross-section no. 34(d/s) as shown in Fig. 6.14. Figures 6.15 and 6.16 indicate that, by constricting the waterway, bed level variation in the initial year is high than in the later years. From the above discussion we can conclude that in the intitial year there is tremondous change in bed level, as the time lapses, it reduces and becomes negligible, which helps in formation of a regime channel. Fig 6.17 show that, because of constriction, the water bed level is rose up which helps in generating the scouring velocity. It is seen from Fig. 6.18, that many a places level of water overtops embankments, if one of the either bank consider as leeves then top level of that bank is to be raised and also has to be strengthen or a new leeve has to be constucted. Also Figure 6.18 shows the afflux for waterway of 1,100 m for a various discharges, which, indicates that lot of portion embankment level will be high as compare to old embankment.

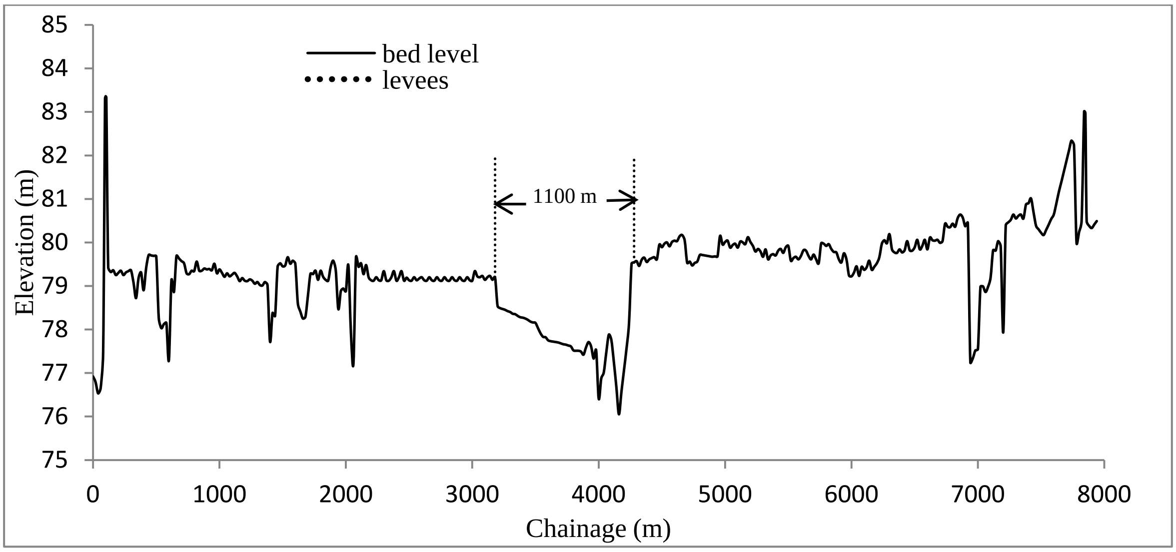


Figure 6.11 Cross-section no. 05(u/s) showing position of leeves

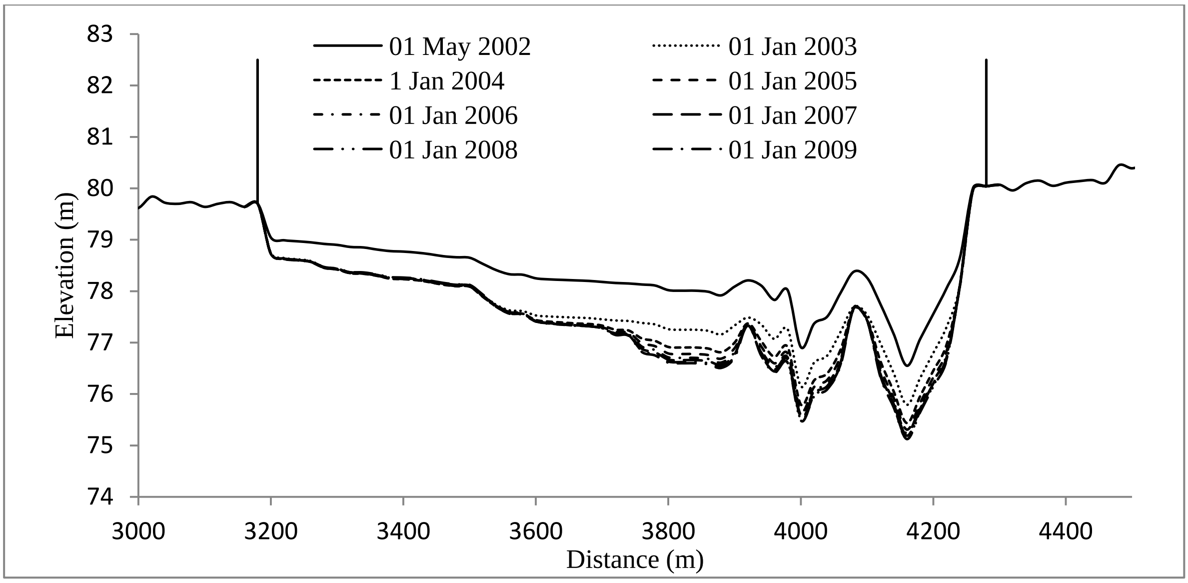


Figure 6.12 Cross-section no. 05(u/s) showing temporal changes in bed level for constricted waterway = 1,100 m

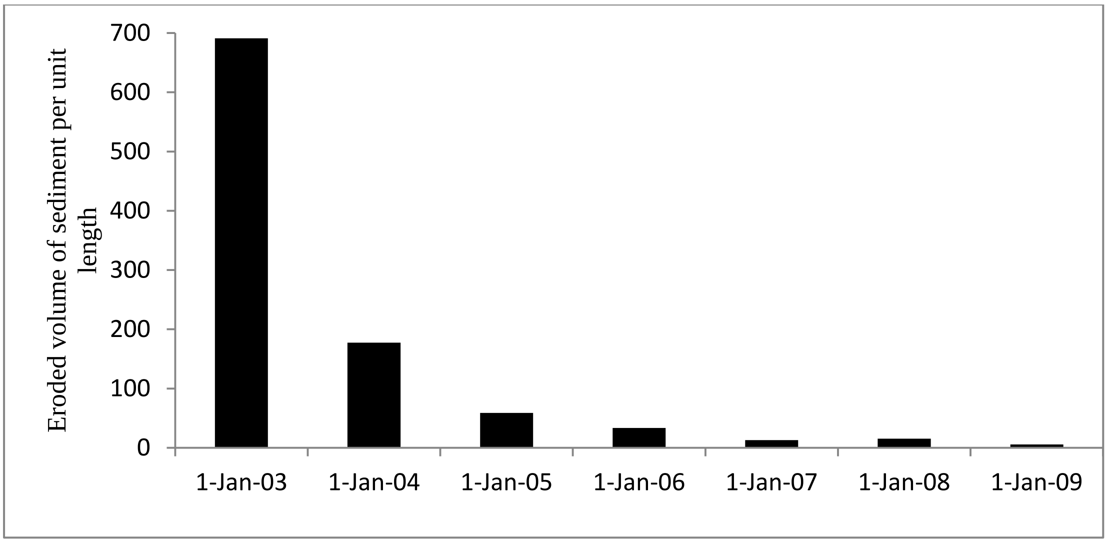


Figure 6.13 Temporal variation of eroded volume of sediment per unit length at cross-section no. 05(u/s)

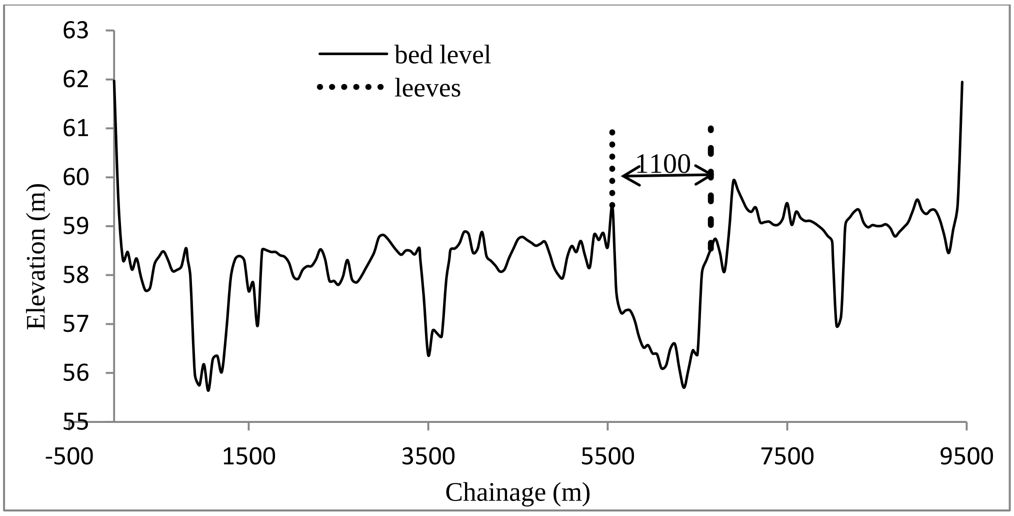


Figure 6.14 Cross-section no. 34(d/s) showing position of leeves

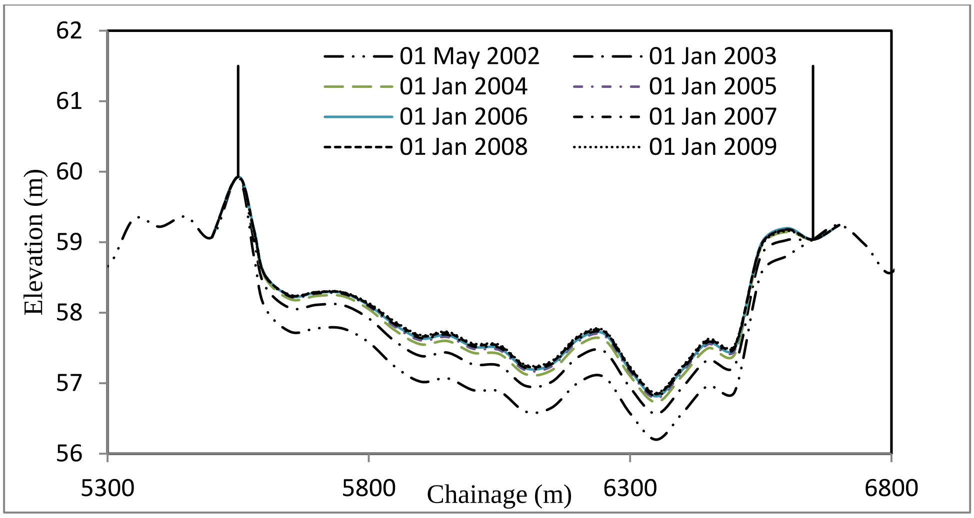


Figure 6.15 Cross-section no. 34(d/s) showing change in bed level due to constriction of waterway to 1,100 m

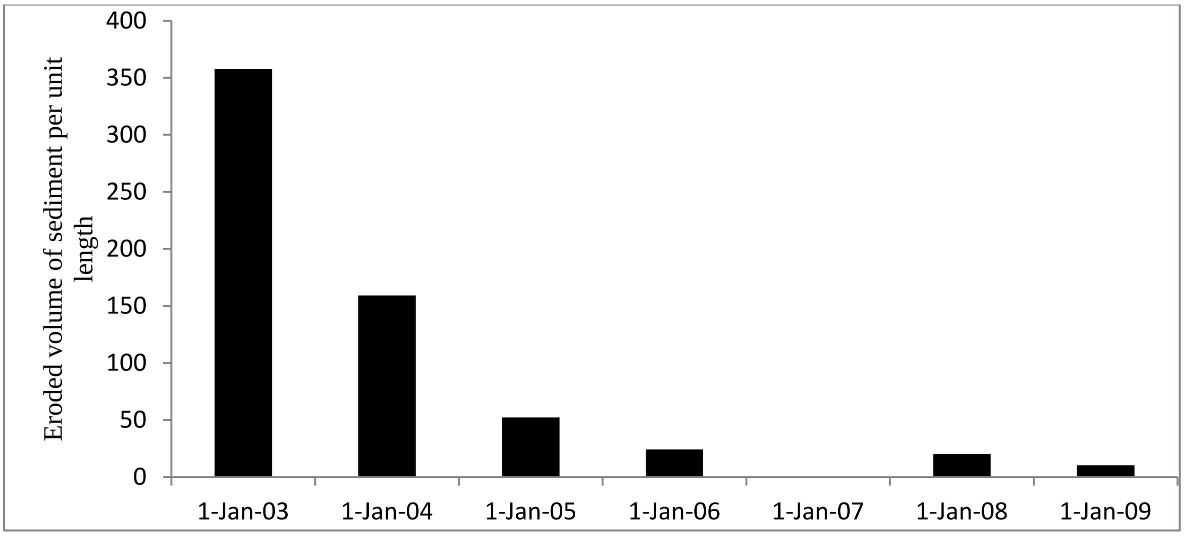


Figure 6.16 Temporal variation of eroded volume of sediment per unit length at cross-section no. 34(d/s)

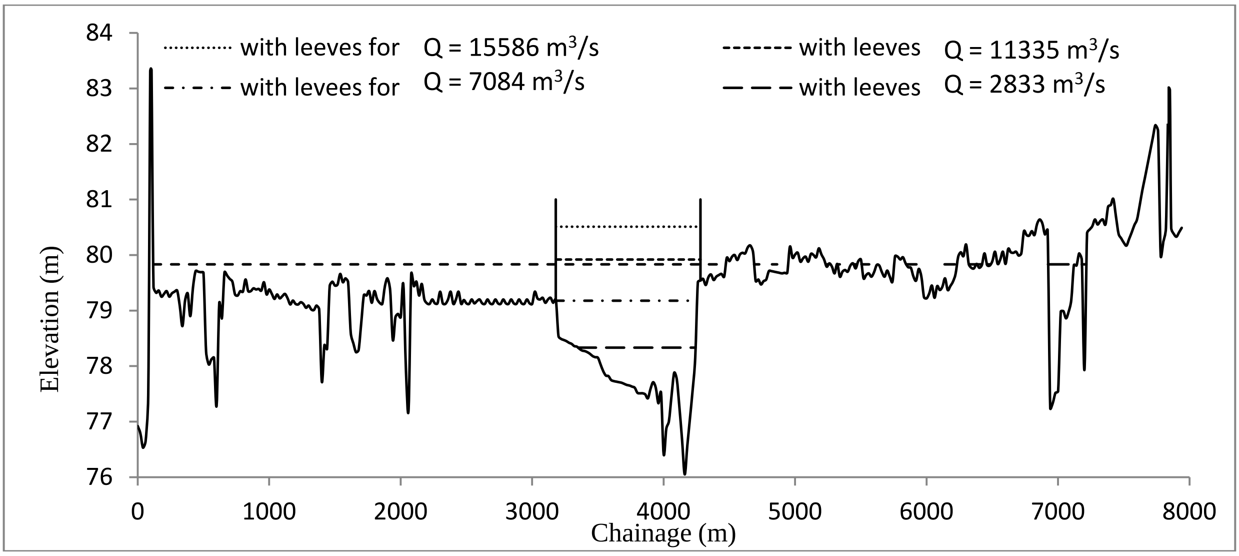


Figure 6.17 Typical cross-section showing watel level for 1,100 m waterway

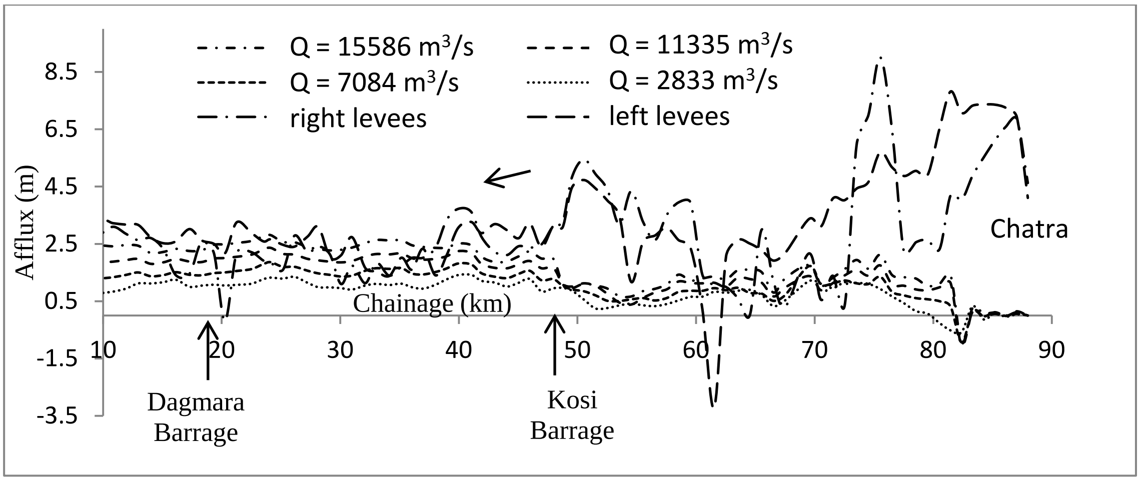


Figure 6.18 Afflux for waterway of 1,100m

6.3.3 Discussion

The conceptual views by mathematical model studies were conducted for the channelization of river Kosi. Various waterways were considered including the Lacey's waterway. The study indicates that the river did not aggrade/degrade for a waterway of 1,100 m, which is also the waterway provided at the Kosi barrage. The Kosi barrage has not been affected by the sediment for the last 50 years, and it is seen that there is no aggradations / degradation in the vicinity of the barrage. This along with the mathematical model studies indicate that the River Kosi would be in regime without aggradations or degradation with the waterway of 1,100 m.

HEC-RAS being a 1D mathematical model, it is not possible to reproduce the structures like spur, guide bunds of barrage, etc. Attempt has been made for channelizing river Kosi considering limited hydraulic aspects. Further, detailed studies need to be carried out using physical and 2D mathematical models with additional field data.

6.4 CHANNELIZATION USING LOWERING THE RIVER BED THROUGH MANUAL EXCAVATION (DR. S. V. CHITALE'S RECOMMENDATION)

6.4.1 Model Analysis

As per Report no. 1 of Kosi Judicial Enquiry Commission: - regarding Kusaha breach of 2008 under the Chairmanship of Honorable Justice Rajesh Balia (former Chief Justice, Patna High Court), Dr. S.V. Chitale recommended that by lowering the riverbed by 0.44 m, shifting of the river may reduce and erosive nature may disappear. In view of this, mathematical model studies were conducted for a reach from Chatra to Kosi barrage using the data of River cross-section post 2002 flood and sediment-discharge relationship as an upstream boundary condition and normal depth as a downstream condition. The required river cross sectional data was available for the month of May 2002. The cross sections of the river within the embankments were at a regular interval of 1.0 km, from 41 km upstream of Kosi barrage. Data pertaining to sediment and discharges recorded at the Kosi barrage were also used for this study.

6.4.2 Results

Mathematical model (HEC-RAS) was run with the input data as a discharge variation of nine year hydrograph on mobile bed model. The mathematical model study indicated that by deepening the cross-section bed surface by 0.44 m helps in increasing the velocity of flow along the channel. The increased velocity helps in deepening the channel, due to transportation of sediment by increased velocity reducing shifting behaviour of river (Fig. 6.20). Figure 6.19 shows the changes in bed level for a typical cross-section at 5 km upstream of barrage. It is seen that deepening the original bed level by 0.44 m helps in further deepening of bed level after the run due to increase in velocity of flow along the channel. The average velocity in the river was 2.2, 2.7 and 2.8 for original bed level, constricted waterway of 1,100 m and 0.44 m deepened bed surface. It is seen from the Figure 6.21 that the velocity of the constricted waterway is almost same with deepening of bed level by 0.44 m, which facilitates increase in transportation of sediment.

6.4.3 Discussion

Dr. S. V. Chitale recommendation of 0.44 m re-gradation of bed level, helps in generating scouring velocity, transport the sediment from the flow along the channel, which helps in further deepening of the channel.

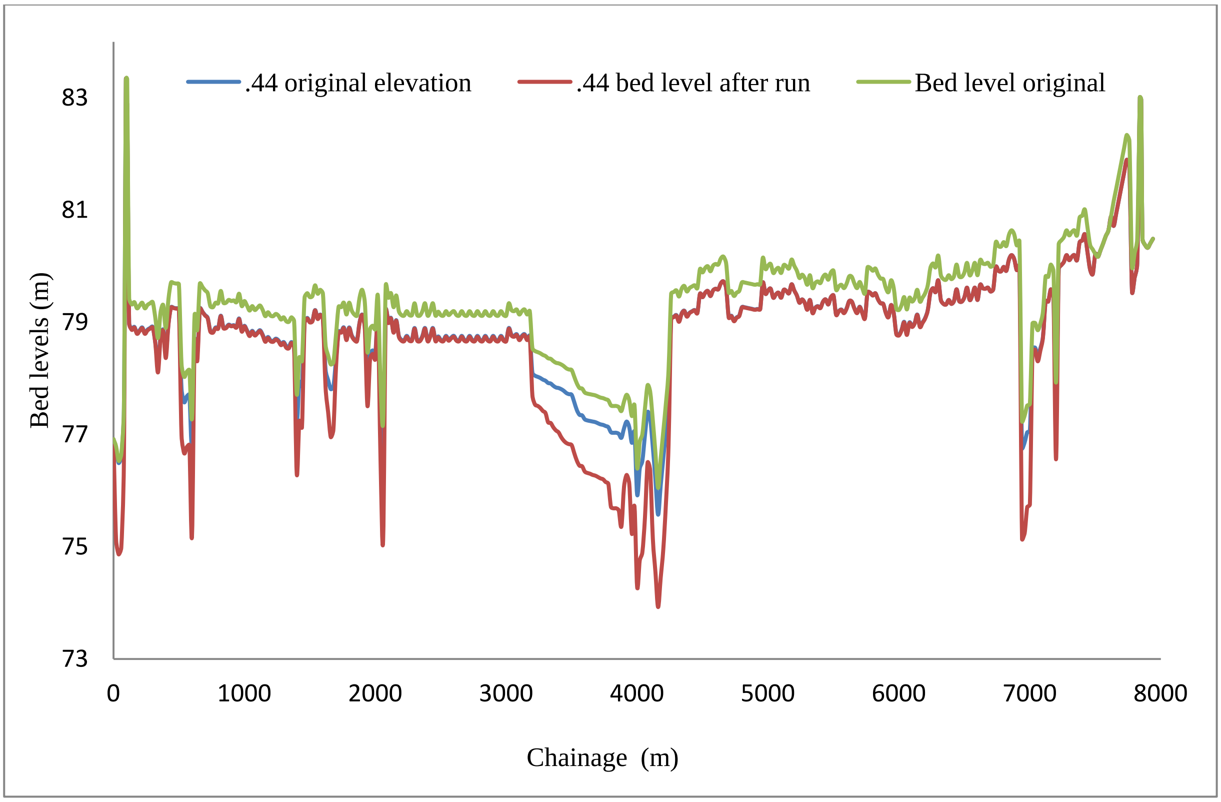


Figure 6.19 Typical cross-section at 5 km upstream of barrage, showing changes in bed deformation

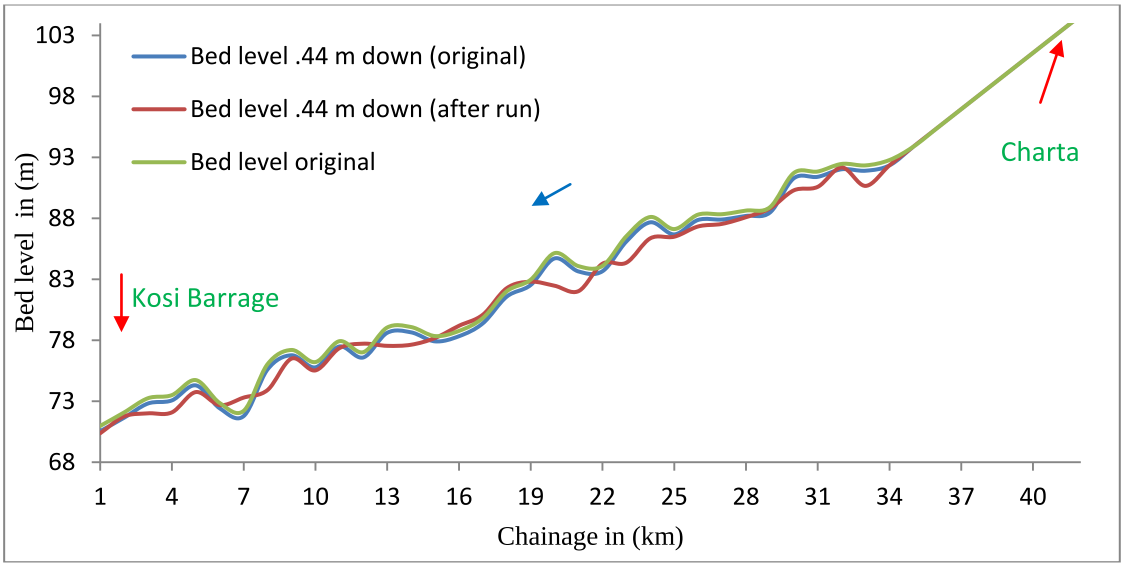


Figure 6.20 Bed level changes along the river

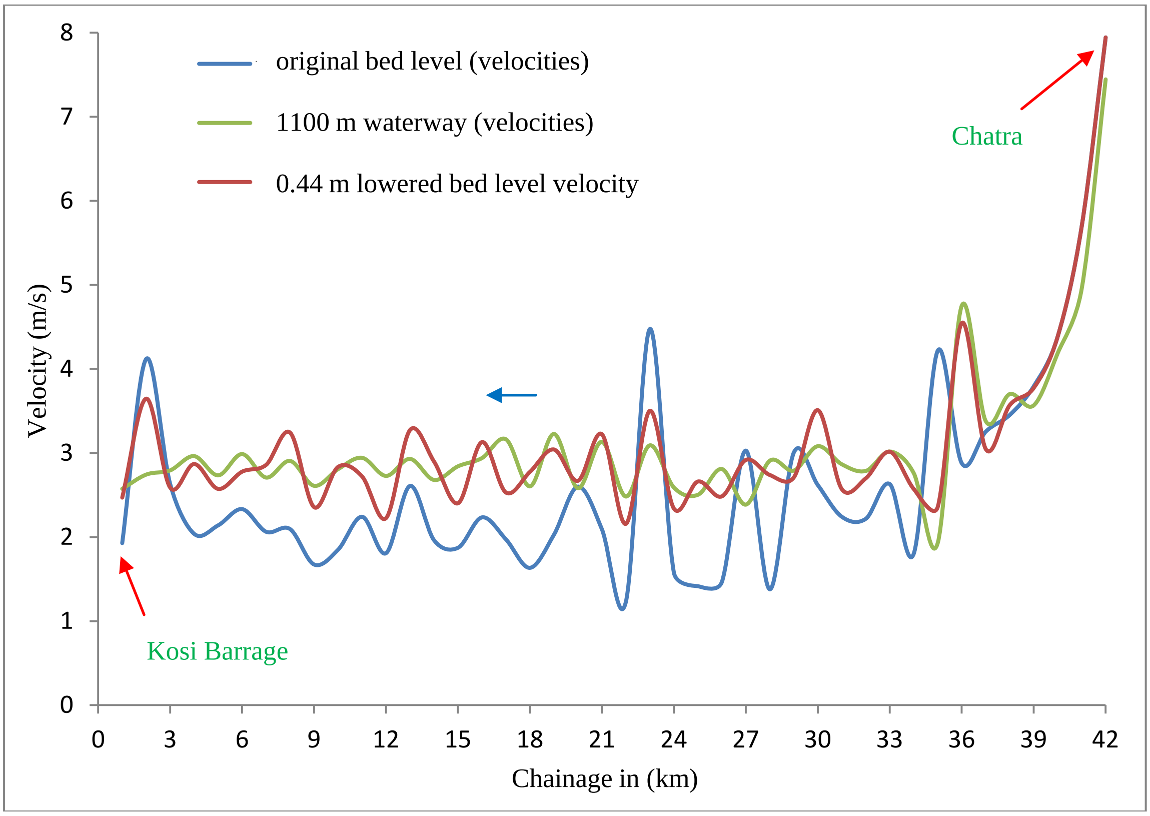


Figure 6.21 longitudinal velocity distribution for various channelization width

Chapter 7

PHYSICAL MODELLING FOR CHANNELIZATION

7.1 INTRODUCTION

Channelization of a stream may be undertaken for making it more suitable for navigation and to restrict water to a certain width to reclaim lands for other important purposes. Another reason is to avoid inundation and spread of flood water over large stretches of flood plains, which is also associated with sedimentation and related complications. The river Kosi has been provided with levees along the banks at a width ranging from 6 km to 16 km to avoid notorious shifting of the river. The bed level in many places has risen by 0.1 to 3 m due to insufficient velocities in the river required to carry the sediment. It is estimated that out of about 187 million tonnes of sediment brought from Himalaya every year by the river Kosi, only about 30% is transported to river Ganga and the rest is settled in the Kosi river belt. Due to heavy inflow of sediment, major reaches of the River Kosi are braided and at several places it is perched also. River engineers are apprehensive of increased attack of the river on the embankments (levees) requiring higher maintenance cost. In view of this, channelization of river Kosi is thought to be one of the methods by which the velocities in the river could be increased, thereby increasing the sediment carrying capacity of the river. This would avoid settlement of sediment in the river course and maintain the regime channel. Physical model studies conducted to investigate the various options for channelizing the stretch of river Kosi from Chatra to Nirmali are presented in this chapter.

7.2 DATA

The same data as used in the mathematical model studies were used in the physical model studies also. This is described in the following.

7.2.1 Survey data

In order to reproduce the prototype of the river in the model, the bed configuration of river Kosi and the formation of deep channels, the survey data from 40 km upstream to about 47 km downstream of Kosi Barrage (i.e. Upto Nirmali) collected during April and May 2002 has been used. The cross sections of the river within the embankments, available at a regular interval of 1.0 km are also used. The location and alignment of these cross sections and the formation of deep channels are shown in the survey plan of Fig. 7.1

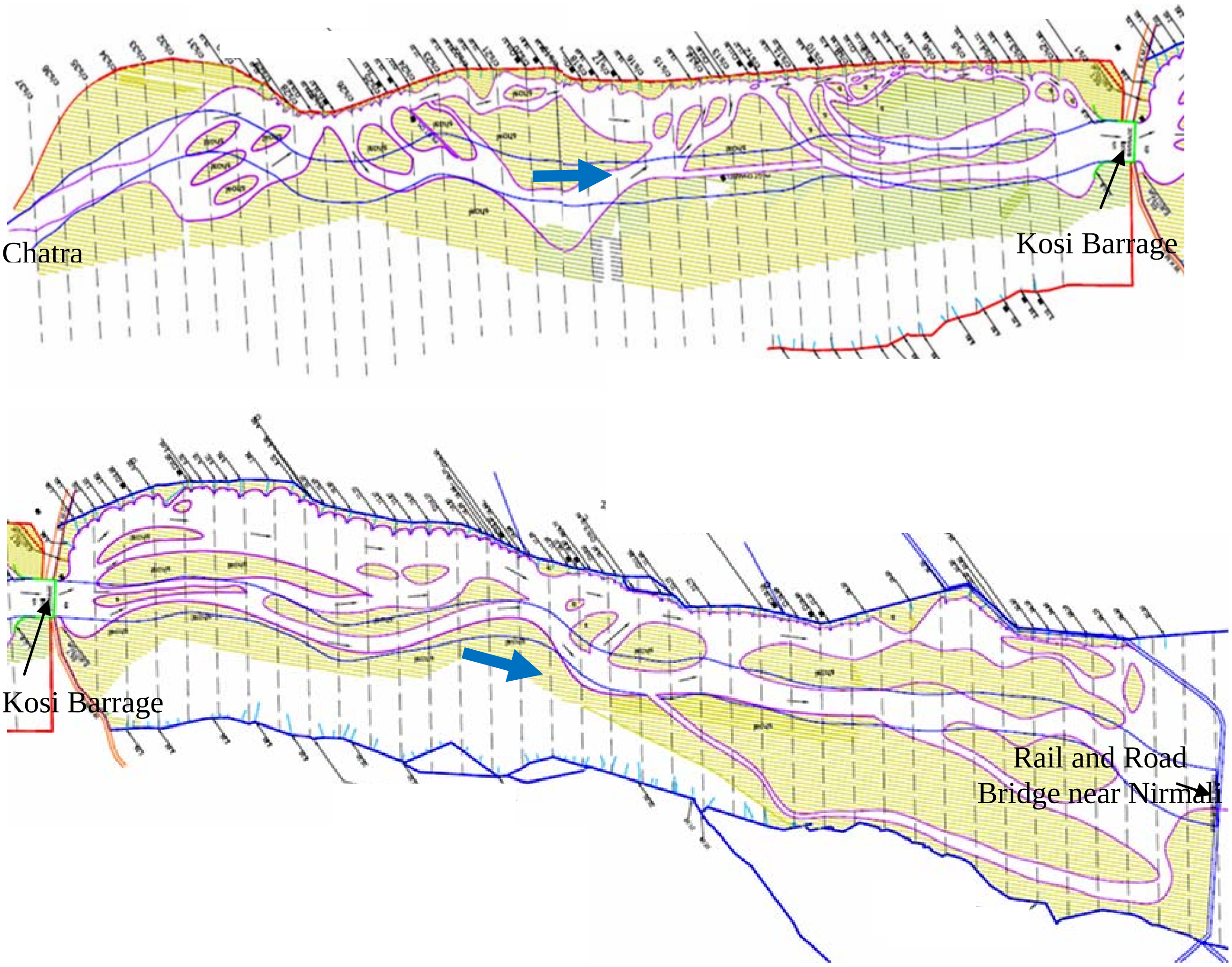


Figure 7.1 Plan of river Kosi from Chatra to rail-cum-road Bridge

7.2.2 Hydraulic Data

As mentioned before, there was no gauge site along a 40 km reach of river from Kosi barrage to Nirmali. As such no water level data of river Kosi in this reach were available. The data recorded at two new gauge sites established in May 2002 one at Bhaptiahi (chainage 35.75 km), and another at Dagmara (chainage 21 km) were therefore used.. Figures 7.2 and 7.3 show the view of the gauge sites at Dagmara and Bhaptiahi, respectively. The water levels at these gauge sites were recorded every six hours during the period from June to December 2002. Data regarding water levels and discharges, recorded at the Kosi barrage during the period from June to October 2002 were also available. The highest discharge, recorded at the Kosi barrage during this period, was of the order of 10,960 m^3/s (3, 87,000 cusecs). This data was analyzed to develop the gauge discharge relationship for calibrating the physical model.

Figure 7.2 Gauge site at Dagmara **Figure 7.3** Gauge site at Bhaptiahi

7.3 ANALYSIS OF HYDRAULIC DATA

7.3.1 Gauge Discharge Relationship

The discharges recorded at the Kosi barrage and corresponding water levels observed at Dagmara and Bhaptiahi are shown plotted in Figs. 7.4 and 7.5, respectively. The discharges exceeding 5,660 m^3/s (2,00,000 cusecs) only have been considered for evolving the relationship between gauge and discharge at Dagmara and Bhaptiahi. The statistical analysis of Gauge-Discharge data gave the following relationships:

Dagmara: $$H = 57.116\, Q^{0.013} \qquad (7.1)$$

and Bhaptiahi: $$H = 52.44\, Q^{0.0149} \qquad (7.2)$$

Where H = Gauge in m and Q = Discharge in m^3/s

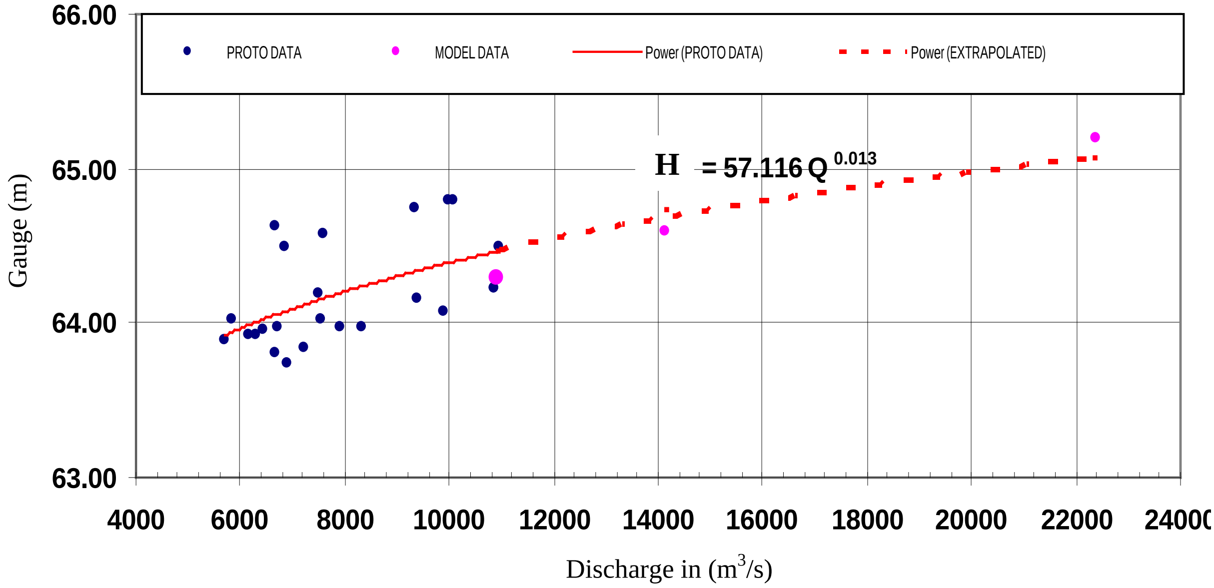


Figure 7.4 Gauge-Discharge relationships at Dagmara

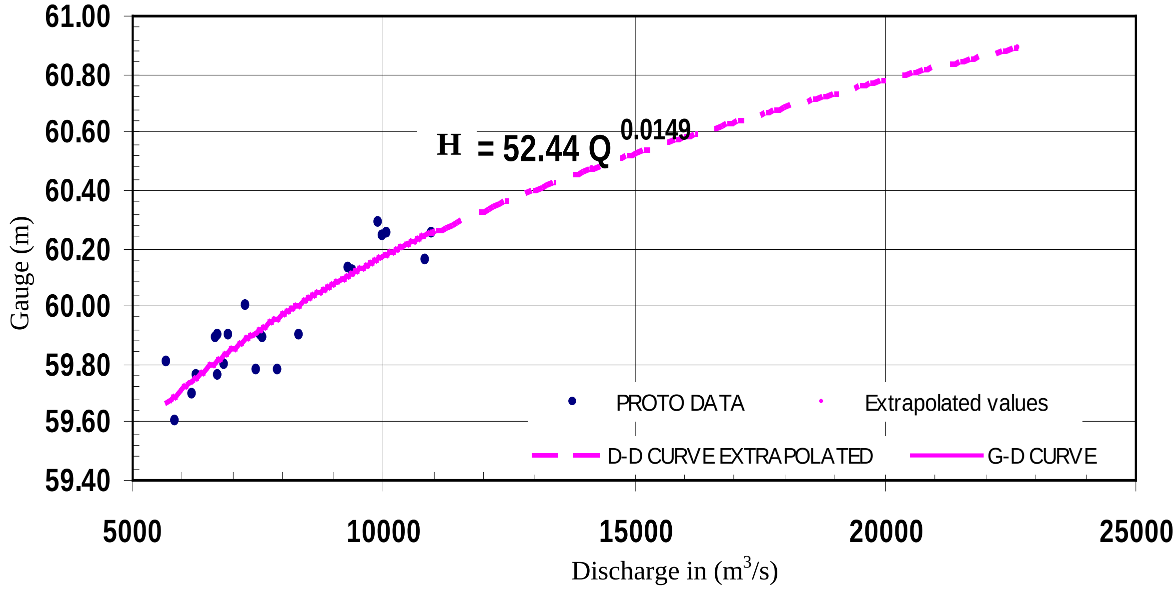


Figure 7.5 Gauge-Discharge relationships at Bhaptiahi

7.3.2 Design discharge

The highest known discharge at Kosi barrage is 22,375 m^3/s during the year 1968. But, the analysis of annual peak flood discharges, recorded at the Kosi barrage during the years 1969 to 2009 shown in Fig. 7.6 indicates the maximum discharge has been fluctuating around 14,330 m^3/s (5, 00,000 cusecs) only. Thus the enveloping discharge of 15,586 m^3/s (5, 50,000 cusecs) is considered in the present study.

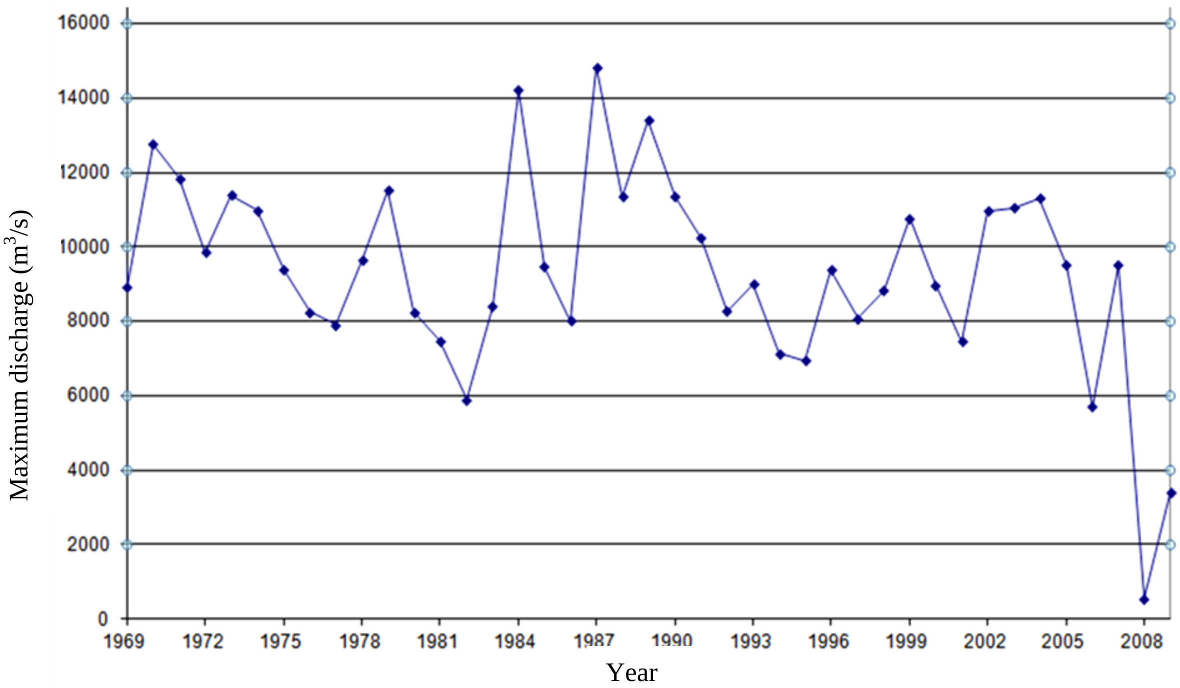


Figure 7.6 Annual peak flood discharges

7.4 MODEL CONSTRUCTION ACTIVITY

The selection of the model scale has to be made keeping the above data in mind. The ranges of the scale used for the study of spillways and such large structures vary from 1:30 to 1:100. Spillway model should be such that the normal heads over the crest should not be less than 10 cm. Reducing these dimensions would not only pose difficulties of observations, but also would vitiate the similitude requirements. Further, the size of the model is also dictated by the capability of the instruments for measuring the particular parameter. For example, current-meters for measurement of velocities in a model would have a minimum threshold value below which they would not respond to the flow.

Hydraulic models are limited towards the upper end by the existing laboratory facilities, viz. Space, head, discharge, etc., and towards the lower end by the similarity conditions. One lower limit is given by the proper scaling of viscous forces. The requirement is that the Reynolds number in the model must always remain large enough to ensure turbulent flow conditions in the model, when the flow in the prototype is turbulent. Another limitation is the influence of surface tension. The Weber number in prototype is usually so large that the influence of surface tension can be neglected. But this is not true in the small scale model. As a matter of experience, a lower limit of 3 cm of depth is usually maintained in the model to avoid the scale effects. Weber number also influences the phenomenon of air entrainment in the model. Large scale models are required to study this phenomenon. For models of large water bodies, smaller scaling number for vertical depths are required than for horizontal dimensions, resulting in distorted model scale. A severe limitation of model similarity is always reached whenever cavitation effects are observed. This phenomenon cannot be studied in Freudian model. In the Kosi river model, the width of the river varies from 6 to 16 km and depth of flow is about 9 to 12 m. Therefore, keeping this in mind, scale of the model is decided. Length scale of 1/500 and a depth scale of 1/70 is adopted. Figure 7.7 a) shows the construction of datum at the bank of river in the model. Figure 7.7 b) shows laying of reduced cross-section using depth rod. Figure 7.7 c) shows fixing the peg given for cross section using cement mortar. Figure 7.8 a) and 7.8 b) show side and top view of sediment injector used in the model. At the bottom of the Hopper an adjustable slit is provided for injecting the required sediment in the model.

The sediment feeding setup was set to supply a constant sediment quantity of 0.25 m^3/hr. This was mainly introduced at Chatra, where the river width is 330 m. Downstream of Chatra, river width increases. Sediment was supplied to simulate the sediment motion and its distribution from the gorge area the downstream plains between Chatra and Nirmali. Figure 7.9 shows the standing wave flume from where the required discharge is taken into the model.

Figure 7.7 a

Figure 7.7 b

Figure 7.7 c

Figure 7.8 a) Silt injector (Front view)

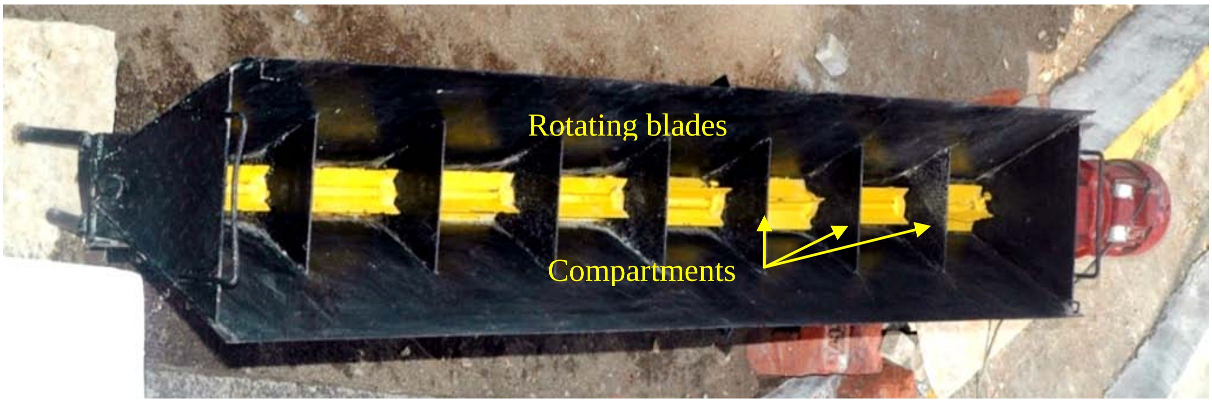


Figure 7.8 b) Silt injector **(**Top view)

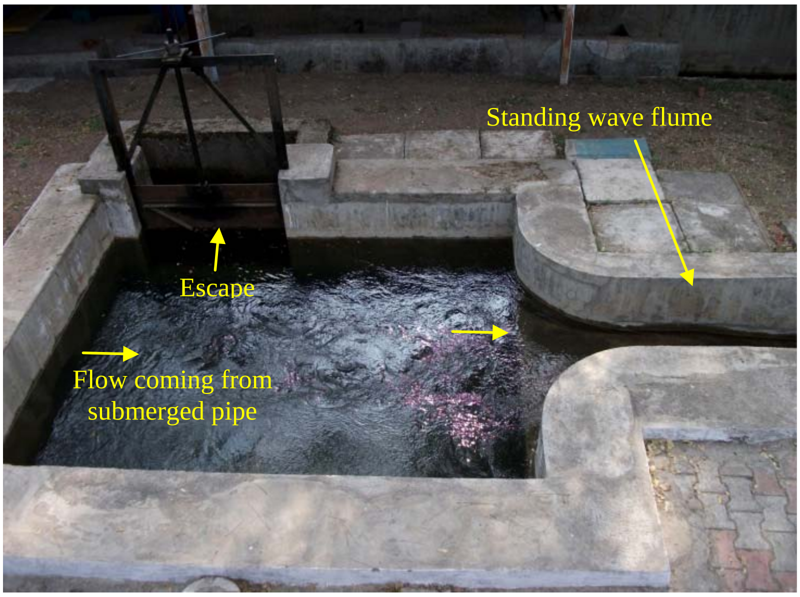


Figure 7.9 Shows standing wave flume from where the measured discharge is taken in to model

7.5 MODEL

Three-dimensional physical model of river Kosi, covering the reach from 40 km upstream to about 47 km downstream (Nirmali) of Kosi Barrage, was constructed to a horizontal scale of 1/500 and the vertical is a scale of 1/70. Figure 7.10 shows full view of model from Chatra to Nirmali with channel configuration, while Fig. 7.11 shows a view of the model from Kosi barrage to Nirmali with channel configuration. The bed configuration of the river, including deep channels, shoals and spill portion etc. are reproduced in the model as per the survey data (post flood 2002). Figure 7.12 shows a downstream view of the model. Figure 7.13 shows the structures provided in the model viz. a) Kosi barrage, b) Dagmara barrage, and c) Rail-cum-road bridge. The grain size distribution of the material used in the bed of the model is presented in Fig. 7.14 with d_{50} = 0.26 mm. The derived scales for velocity and discharge are 1/8.36 and 1/292831, respectively.

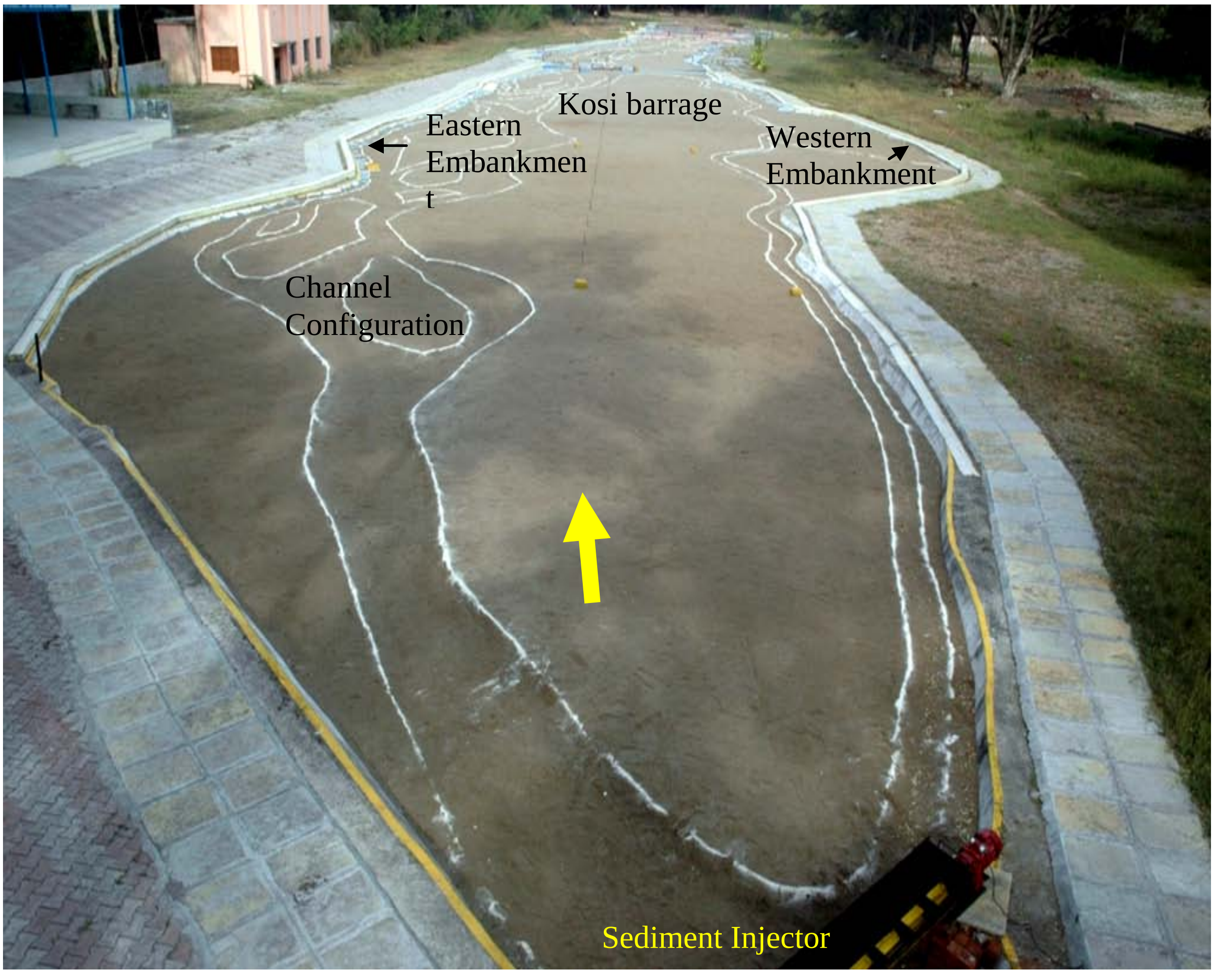


Figure 7.10 Full view of the model

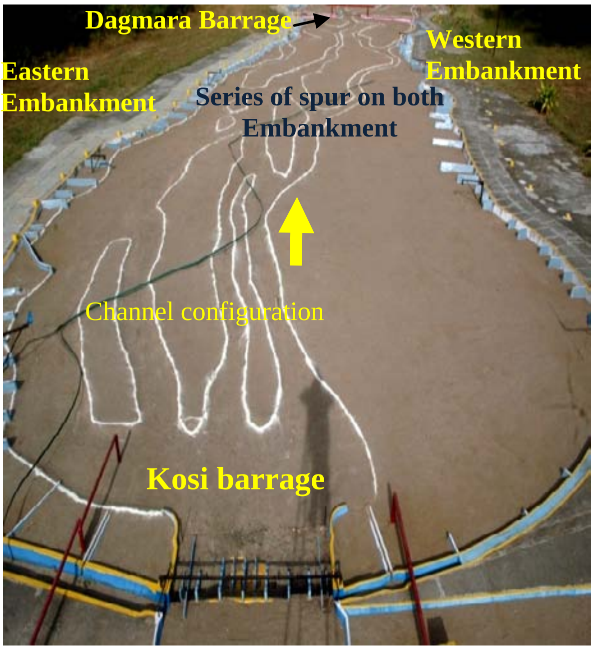


Figure 7.11 View from upstream end and from Kosi barrage to Nirmali

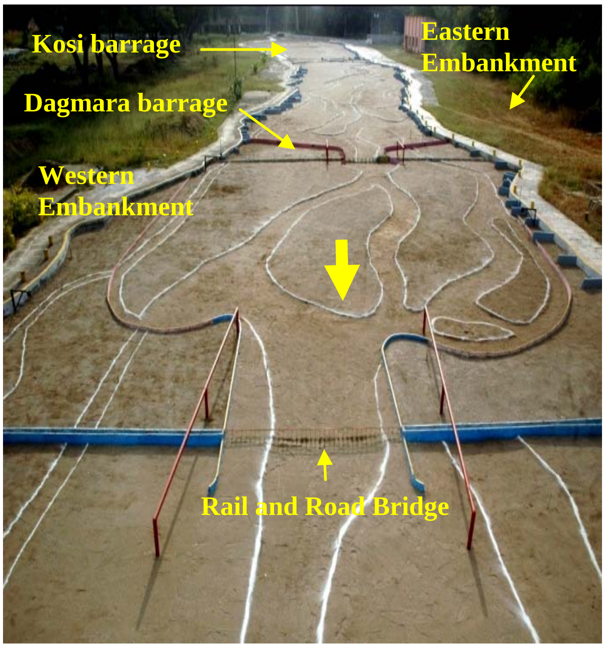


Figure 7.12 View from downstream end of the model

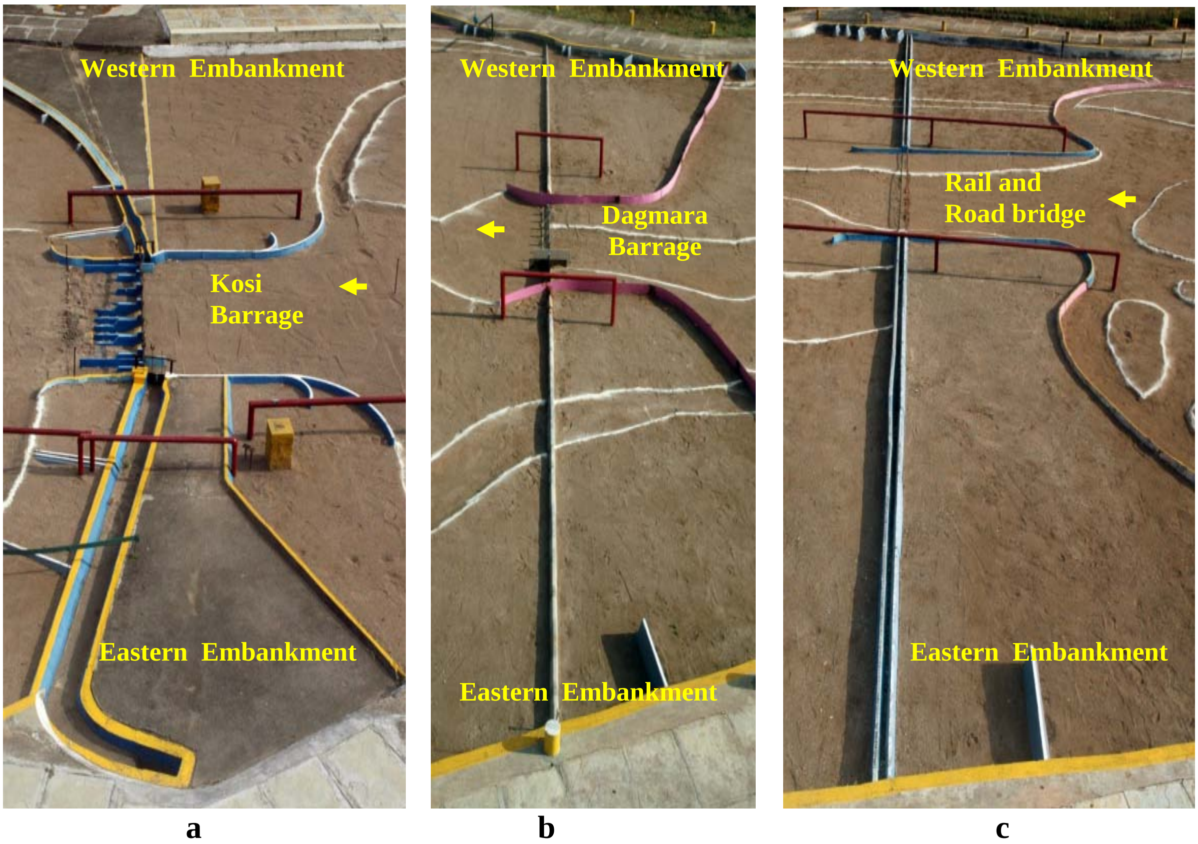


Figure 7.13 a), b), and **c)** Structure provided in model

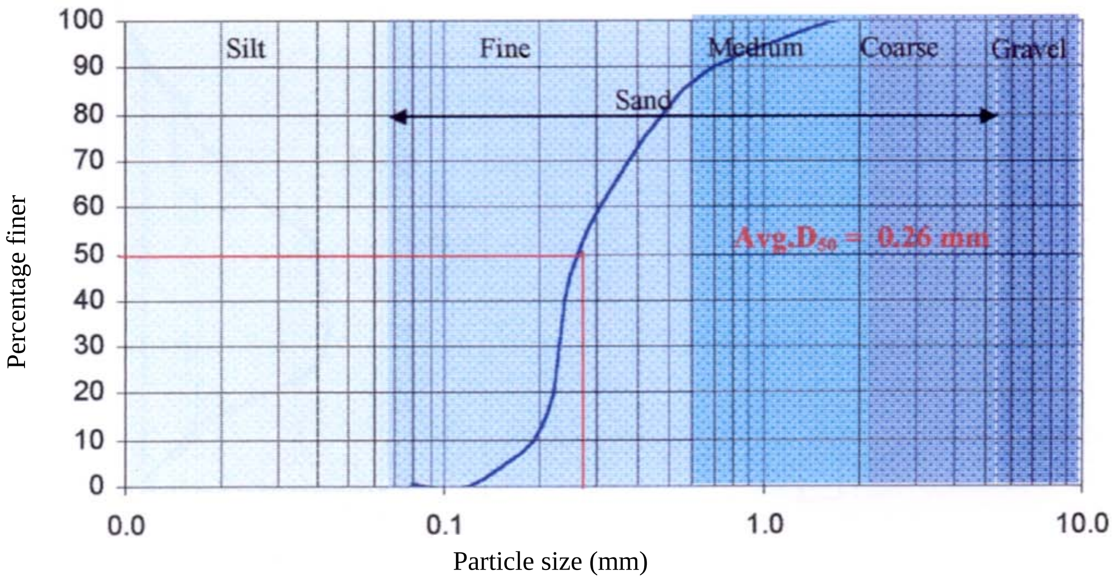


Figure 7.14 Grain size distribution curve of bed material used in the model

7.6 MODEL PROVING STUDIES

Proving studies were carried out for verifying the conformity between model and prototype data in respect of water levels, and water surface profile in Kosi river. The discharge and water level data of the Kosi river, available for the monsoon of the year 2002, were utilized for this purpose. The maximum discharge recorded at the Kosi barrage during this period was 10,960 m^3/s (3, 87,000 cusecs), equivalent of which was run on the model. The corresponding water levels recorded at Dagmara and Bhaptiahi were of the order of 64.30 m and 60.20, m respectively. The gauge at Bhaptiahi in the model was controlled accordingly and corresponding water level at Dagmara was measured. It may be seen from Fig. 7.15 that the water level observed in the model compares fairly well with the prototype data recorded during the flood of year 2002. In view of this close agreement between the model and the prototype data, the model was considered as proved.

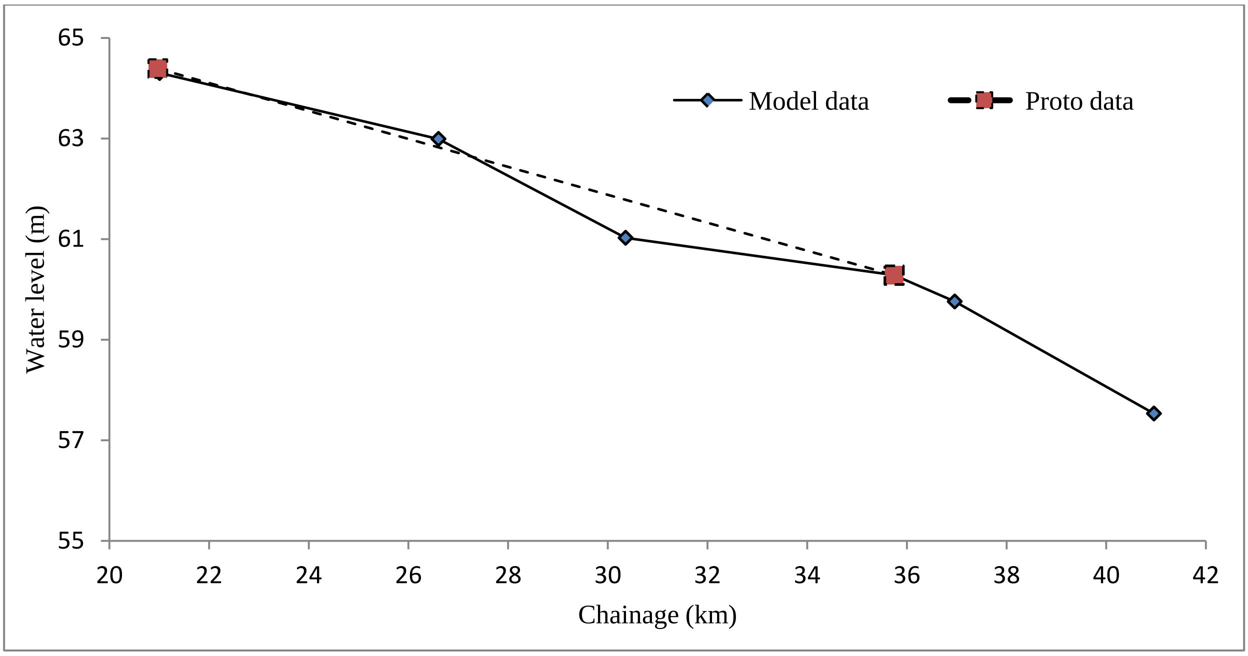


Figure 7.15 Comparison between observed and recorded water level for Q = 10,960 m^3/s

7.7 MODEL STUDIES UNDER PRE-STUCTURE CONDITION (no constriction)

7.7.1 Water surface profiles

Studies were carried out for estimation of water levels at various locations and water surface profile in river Kosi between Dagmara and Nirmali for the design discharge of 15,586 m^3/s (5, 50,000 cusecs). As per the Gauge-Discharge relationship given in Fig. 7.5, the water level at Bhaptiahi for the design discharge of 15,586 m^3/s (5,50,000 cusecs), will be of the order of 60.55 m. The gauge at Bhaptiahi in the model was controlled accordingly and water levels were observed at each cross-section, the same are shown in Fig. 7.16., which indicates that at many a places the river overtops. This is because of sediment deposition (i.e. low carrying capacity of sediment by the flow).

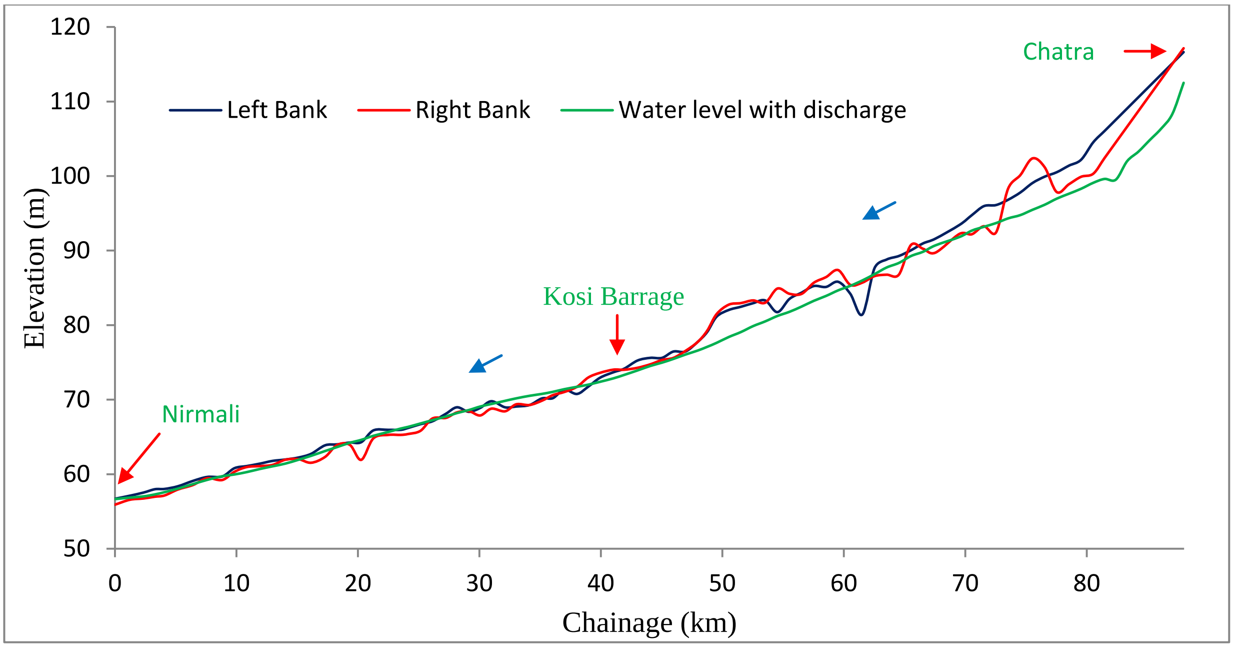


Figure 7.16 Observed water surface profile for Q =15,586 m^3/s (5, 50,000 cumecs)

7.7.2 Tail Water Rating Curve

As there is no gauge site available on river Kosi on the downstream, it is considered necessary to evolve a tail water rating curve on the basis of water level observations in the model. For this purpose, water levels in cross section no. 40 downstream of barrage in the model under existing conditions for discharge of 10,960 m^3/s and 14,150 m^3/s after controlling the gauge at Bhaptiahi as per Gauge-Discharge relationship given in Fig. 7.5 were measured. A tail water-rating curve, evolved on the basis of the above observations is given in Fig. 7.17

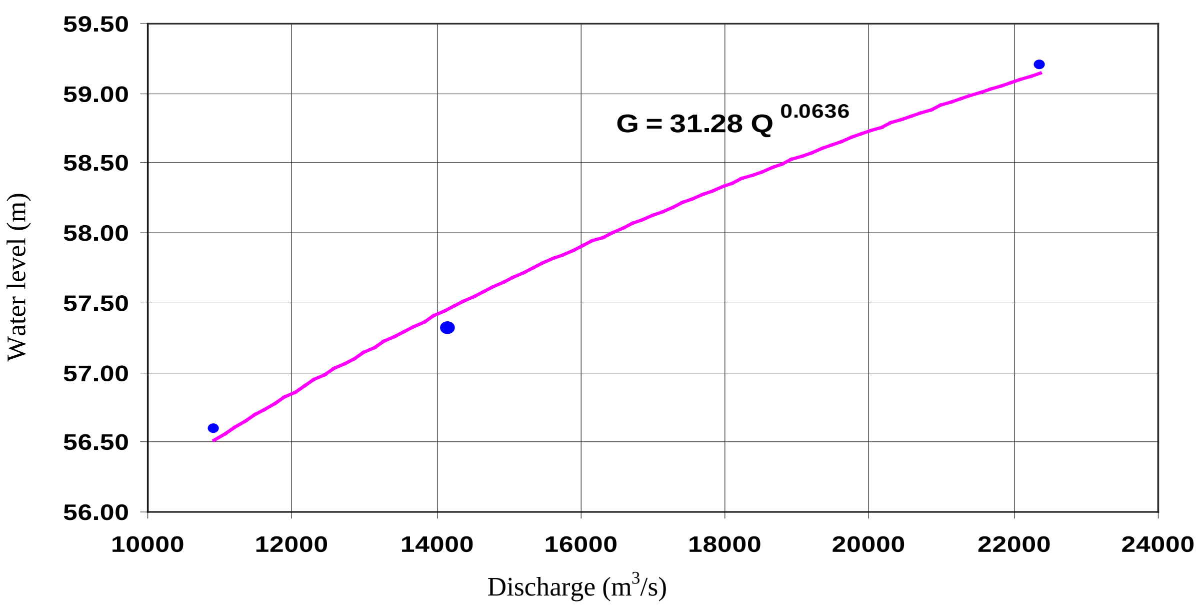


Figure 7.17 Tail water rating curve simulated on the model

7.7.3 Flow pattern

The study was initially conducted under existing site condition, i.e. with spurs, structures and embankments. A discharge of 0.053 m^3/s, which corresponds to a discharge of 15,586 m^3/s on the prototype was taken as upstream boundary condition and water level = RL 57.79 m was taken as downstream boundary condition near rail-cum-road bridge at Nirmali. The model was run and the velocity at different locations and the flow pattern in the river were observed. In the upper reach (i.e., upstream of barrage), the flow was hugging the left bank, whereas in the downstream reach (i.e., downstream of barrage), the river was seen to spread widely over the reach from Chatra to Kosi Barrage (Fig. 7.18 a), b).

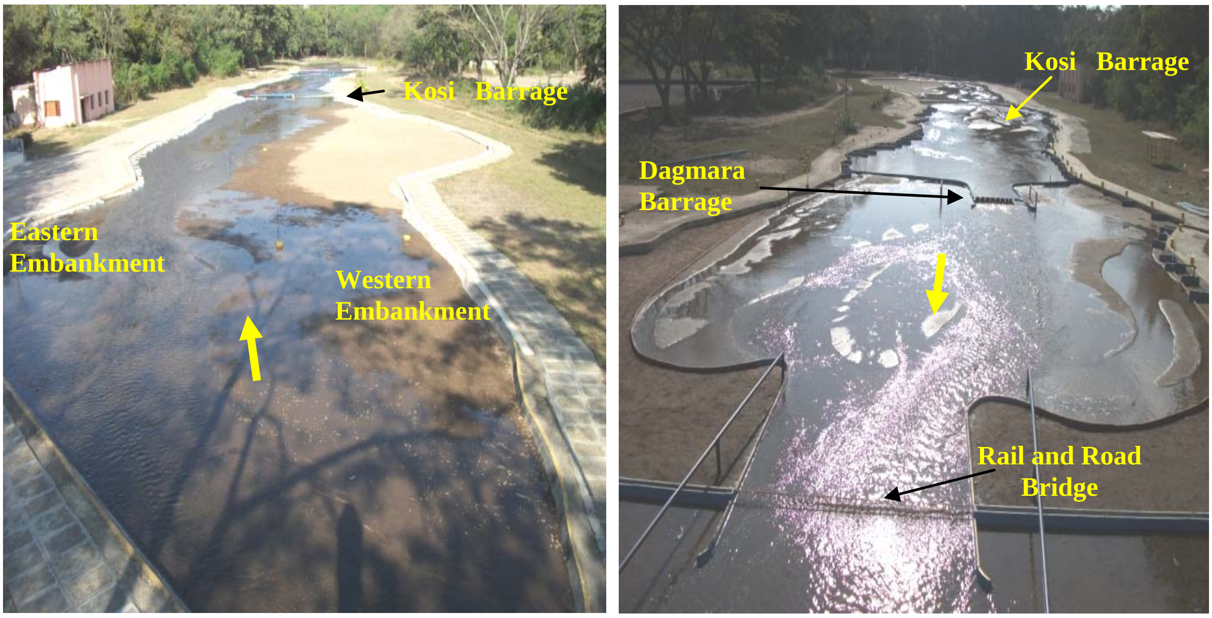


Figure 7.18 a) A upstream View **b)** A downstream View of the model (Q = 15,586 m^3/s)

It was further observed that the shoals present along the river deflect the flow and make the flow oblique, which start hitting the flood embankments (Fig. 7.18c). From the past studies conducted at CWPRS, Pune, it was found that at low discharge, the river flows through the braided channels, and the braided channel gets merged and the river start flowing haphazardly as the discharge increases. When the flood recedes, the sediment present in the flow gets deposited, which results in the formation of shoals. The flow thus starts attacking the existing flood embankments. To avoid this hitting, a series of sedimenting type of spurs were provided on both the embankments, the safety and maintenance of which is also difficult task. Further, extension of old spurs and constructions of new spurs were required from year to year due to changing morphology of the river. In view of this situation, it is required that the flow of the river should be straight as far as possible. The following measures of channelization are undertaken in this study.

(i) Providing T-shape groynes along both the banks
(ii) Providing levees to have a waterway of 1,100 m
(iii) Providing hockey stick shape spurs along both the banks

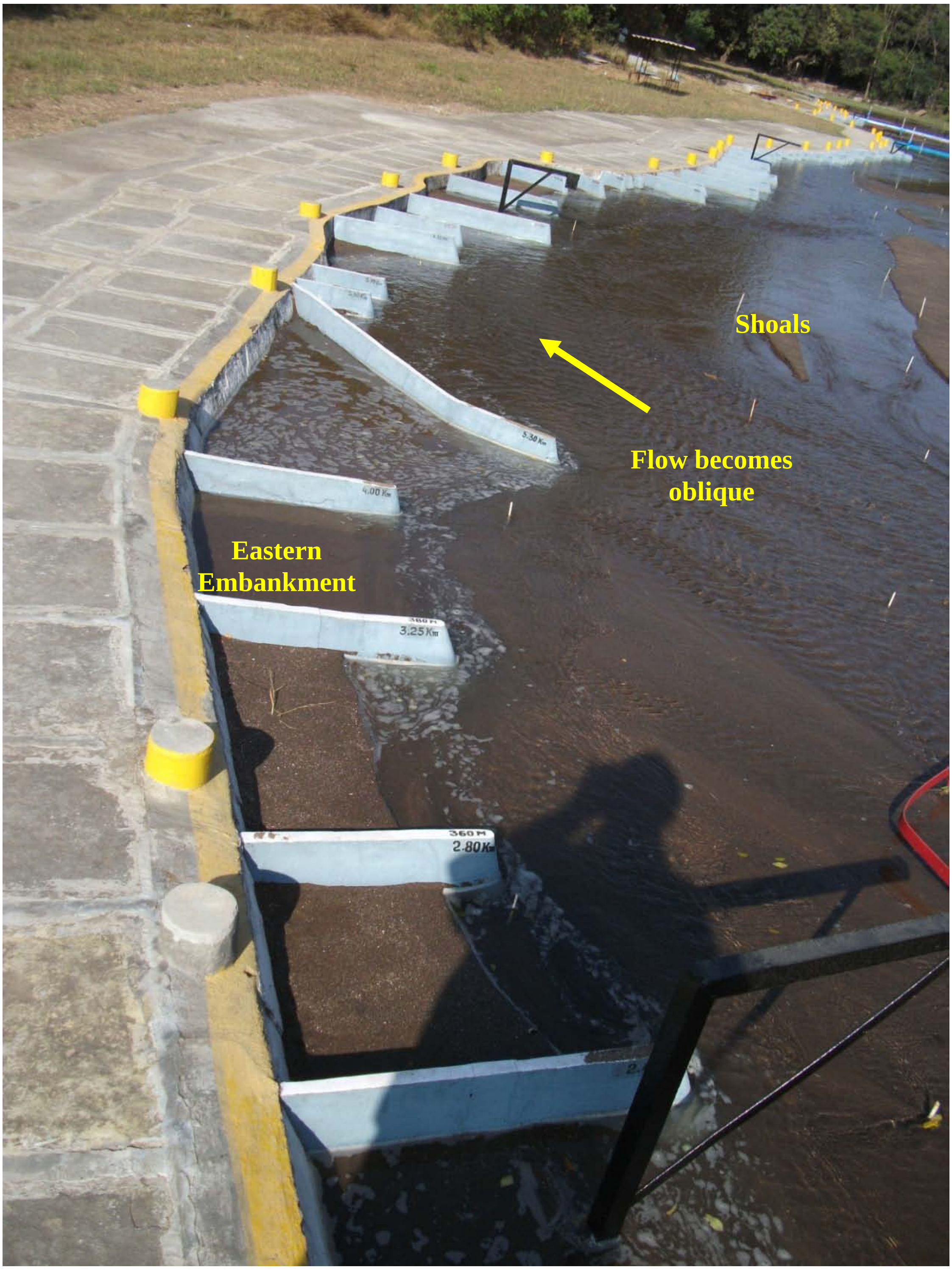


Figure 7.18 c) Close view of flood embankment (Q = 15,586 m^3/s)

7.8 CHANNELIZATION USING T-SHAPE GROYNES

The movable bed model of river Kosi extending from Chatra to Nirmali, built to a distorted scale of Vertical 1:70 and Horizontal 1:500 is shown in Fig.7.19. The movable bed model has been reproduced using silt having d_{50}=0.26 mm. The scales and sediment used are as per the requirements of the movable bed model laws. The various structures like, the Kosi barrage and its guide bunds; rail-cum-road bridge; eastern and western embankments along with the spurs have been reproduced in the model. A standing wave flume on upstream and a rectangular weir on the downstream of the model were provided for discharge measurement and verification. For downstream boundary condition, Gauge-Discharge curve available at the downstream of rail-cum-road bridge was used (tail water rating curves). The sediment feeding facility also exists to study the qualitative effects of sediment being brought by the river along with the water on the plan form changes in the flow of the river.

As discussed in Chapter 5 under the heading of Morphological Studies, the river's channel configurations are not rigid, and they are changing as the time lapses. For providing artificial control point in the river, T-spur as a tool for channelization of the river is used.

T-shape groynes are provided in the model to channelize the river in four ways as described in the following and the reach considered in this study was from Chatra to Kosi barrage.

i) T-shape groynes having wing length of 2,000 m were first provided with a spacing 4,000 m on both the banks to have a waterway of 3,000 m as shown in the model in Figs. 7.19, 7.20 a), 7.20 b), and Film A in the enclosed CD.

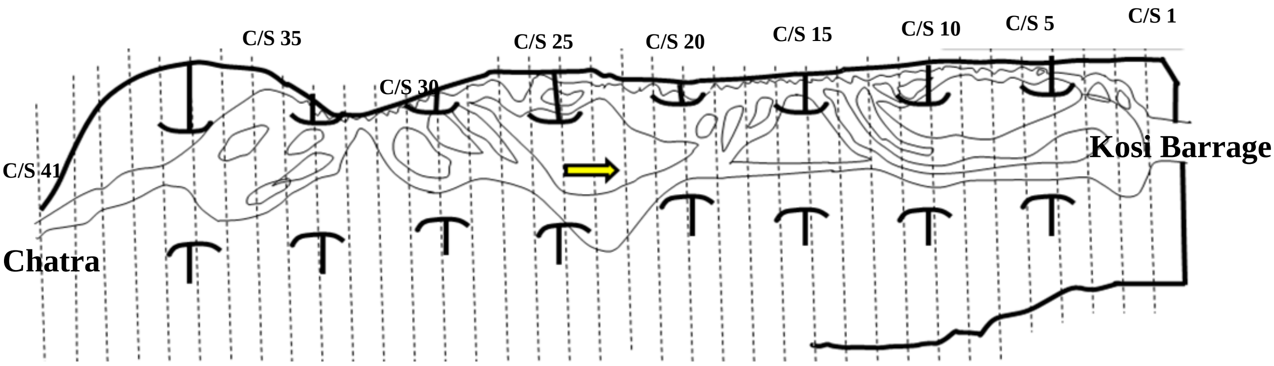


Figure 7.19 Plan showing layout of T-shape spurs provided for a reach from Chatra to Kosi barrage (Waterway = 3,000 m, spacing = 4,000 m, length of guide bund – u/s = 1,000 m & d/s = 1,000 m)

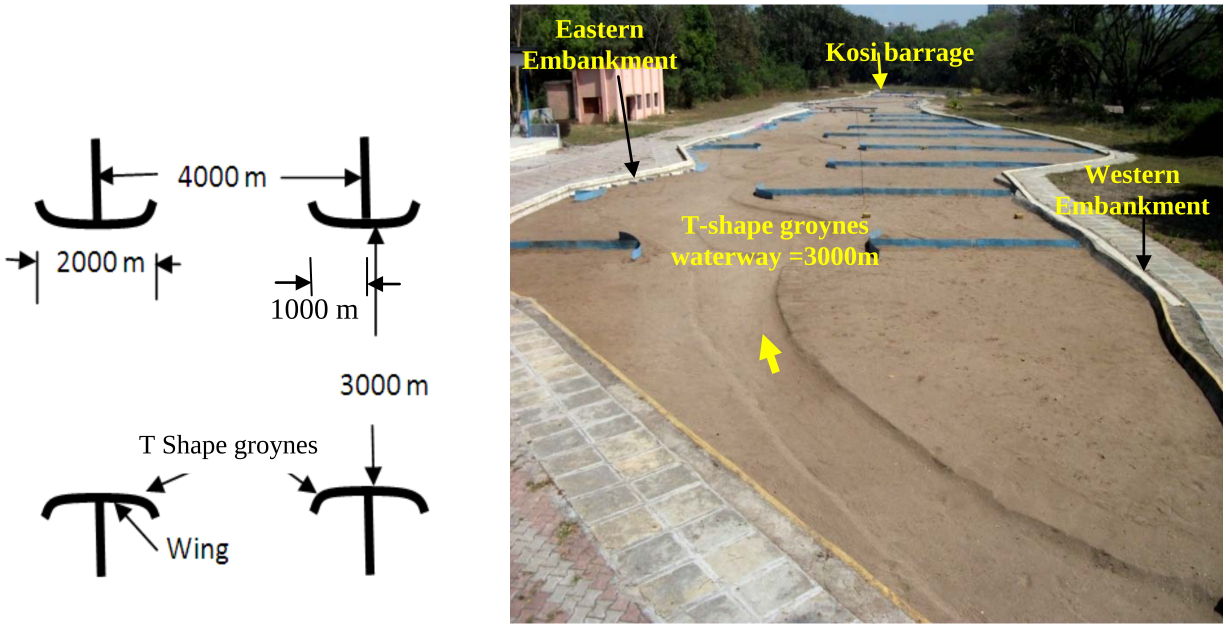


Figure 7.20 a) Details of T-shape groynes provided for water way of 3,000 m in the model

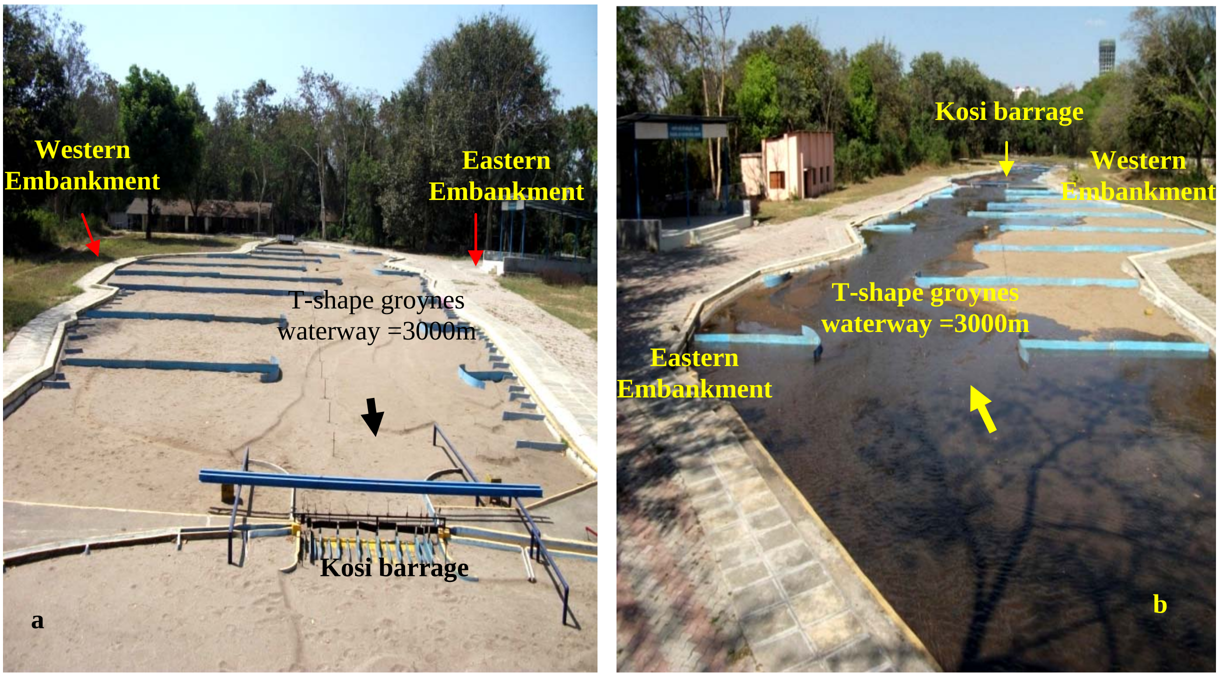


Figure 7.20 b) Downstream and **Figure 7.21** Upstream view with T-shape groynes for water way of 3,000 m in the model with Discharge of 15,586 m^3/s

Using the observed maximum discharge of 15,586 m^3/s for the past 40 years in the model, the flow of water was not seen to touch the wings of the T- shape groynes in most cases as seen from Fig. 7.21and Film B in the enclosed CD. The sediment, which was introduced from upstream side from Chatra is not flushed completely and is seen to settle at many places. Similarly, there is no effect on the shoal present in the channels. The measured velocities at salient locations of spur are given in Table 7.1. Underline value of velocities from the table indicates that, the flow of water does not touch the face of the wings, which are more. At a few places, oblique flow was also observed, as shown in Film C in the enclosed CD. In view of above it was decided to constrict the waterway to 2,000 m, in the further studies.

Table 7.1 Velocities (m/s) along wings for waterway of 3,000 m with spacing of 4,000 m

Cross section	Velocity (m/s)					
	Left Wing			Right Wing		
	U/S Nose	Centre	D/S Nose	U/S Nose	Centre	D/S Nose
4	2.84	3.80	3.30	2.99	3.78	3.20
8	3.42	2.84	3.33	2.22	2.84	3.04
12	2.80	3.83	3.11	2.22	2.75	1.98
16	--	--	--	3.3	2.99	2.65
20	2.80	1.98	1.84	3.27	1.65	2.13
24	1.94	2.94	3.37	1.84	1.65	2.99
28	3.88	3.13	1.55	3.27	3.80	2.75
32	3.37	2.15	--	2.12	2.13	--

ii) Studies were next conducted using T-shape groynes of wing length of 2,000 m and spacing of 4,000 m on both the banks to have a waterway of 2,000 m and the arrangement of T-shape groynes is shown in Figs. 7.22 and 7.23. The flow of water was seen to touch the wings except a few cases as shown in Fig.7.24 a) and Fig. 7.24 b) and Film D in the enclosed CD. But the scouring velocity required for flushing the introduced sediment and shoal was not generated. The measured velocities at salient locations of spur are given in Table 7.2. After running the model, no changes in the bed was noticed as shown in Fig. 7.25 and Film E in the enclosed CD. Therefore it was decided to further constrict the waterway to 1,100 m.

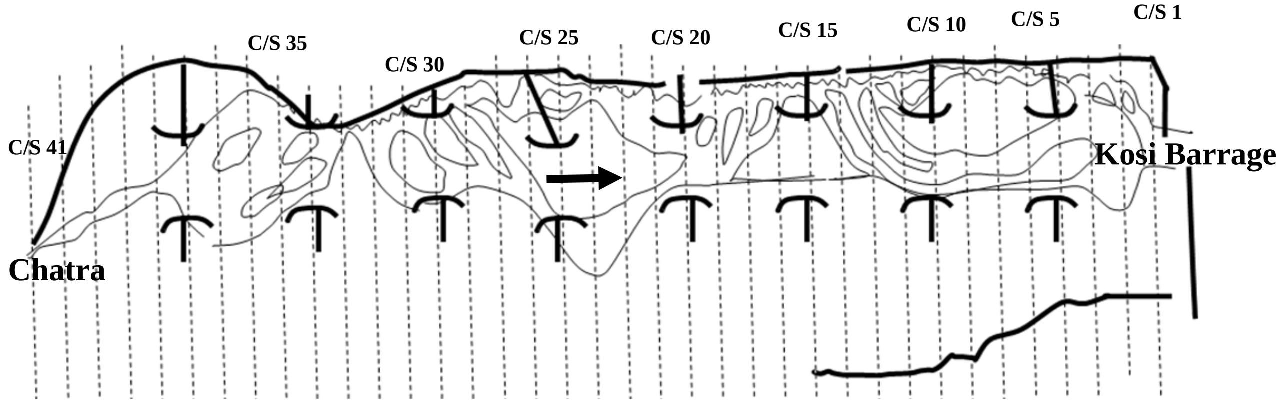


Figure 7.22 Plan showing layout of T-shape spur provided for a reach from Chatra to Kosi barrage (Waterway = 2,000 m, Interval = 4,000 m, length of guide bund – u/s = 1,000 m & d/s = 1,000 m)

Figure 7.23 Upstream view of model showing position of T-shape groynes

Figure 7.24 a) Flow touching the wings of T-shape groynes, but no shoal flushed and sediment motion

Figure 7.24 b) Closer view - Flow touching the wings of T-shape groynes, but no shoal flushed or sediment motion.

Figure 7.25 Flow touching the wings of T-shape groynes, but no sediment motion took place

Table 7.2 Velocities (m/s) along wings for waterway of 2,000 m with spacing of 4,000 m

Cross section	Velocity (m/s)					
	Left Wing			Right Wing		
	U/S Nose	Centre	D/S Nose	U/S Nose	Centre	D/S Nose
4	1.17	1.36	2.51	3.18	3.4	2.32
8	2.65	2.61	1.55	3.32	1.98	3.18
12	3.2	3.1	3.0	2.61	2.46	2.75
16	--	--	--	3.9	3.6	2.08
20	3.51	2.08	1.27	1.32	3.11	2.99
24	1.51	3.34	2.75	1.89	2.51	2.75
28	1.22	1.36	2.18	3.22	2.94	--
32	1.51	3.23	2.75	1.89	2.51	2.75

iii) Studies were conducted using T-shape groynes of wing length 2,000 m and spacing of 4,000 m on both the banks to have a waterway of 1,100 m as per the arrangement of T-shape groynes shown in Figs. 7.26 a) and 7.26 b) and Film F in the enclosed CD.

Figure 7.27 a) and Film G in the enclosed CD, show that the flow is touching the wings of T-shape groynes and the sediment introduced and shoal present has been flushed. Same can be visualized in the Fig 7.27 b) and Film H in the enclosed CD. After running the model, it is clearly visualized from the bed formation that a regime bed was formed. Fig. 7.28 a) and b) shows the close-up shot at the start and the end of the run. The measured velocities at salient locations of spur are given in Table 7.3. In this case there is no underline value of velocities in the table, which indicates that, the flow of water touch the face of the wings.

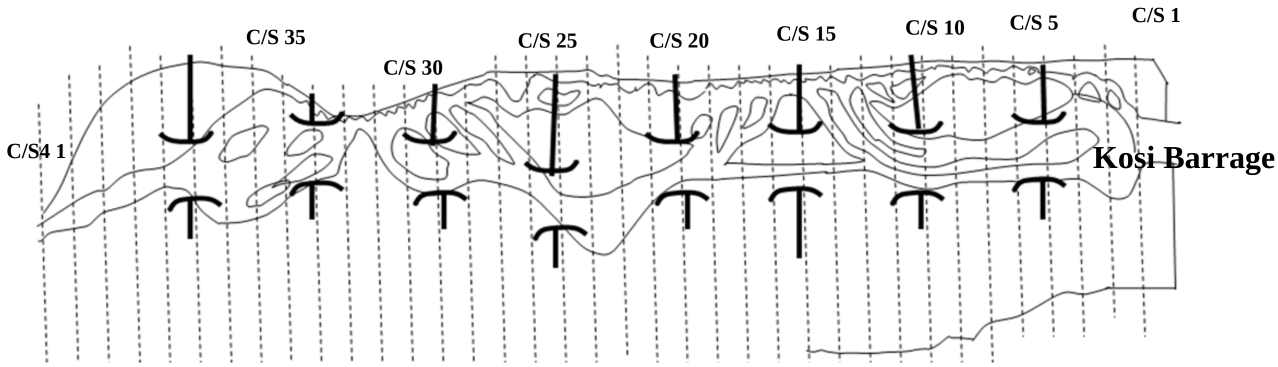


Figure 7.26 a) Plan showing layout of T-shape spur provided for a reach from Chatra to Kosi barrage (Waterway = 1,100 m, Interval = 4,000 m, length of guide bund – u/s = 1,000 m & d/s = 1,000 m)

Figure 7.26 b) Model showing channel configuration **7.27 a)** Discharge of 15,586 m^3/s given in the model **7.27 b)** After discharge, bed formation

Figure 7.28 a) Closer view showing formation of regime channel in the model

Figure 7.28 b) Closer view showing formation of regime channel in the model

Table 7.3 Velocities (m/s) along wings for waterway 1,100 m with spacing 4,000 m

Cross section	Velocity (m/s)					
	Left Wing			Right Wing		
	U/S Nose	Centre	D/S Nose	U/S Nose	Centre	D/S Nose
4	3.08	2.89	2.94	3.04	3.74	4.05
8	3.37	3.27	3.74	2.64	3.23	3.41
12	3.44	3.27	3.2	2.70	3.08	2.89
16	2.51	1.65	2.41	3.90	3.97	3.40
20	1.84	2.46	2.99	2.08	3.18	3.37
24	3.31	2.94	2.37	2.37	2.89	2.75
28	3.56	3.66	3.32	3.18	2.70	1.89
32	1.65	2.08	2.75	2.03	2.37	3.42

iv) To examine the possibility of further optimising the above, another trial was made by increasing the spacing between T-shape groynes from 4,000 m to 8,000 m. Figures 7.29, 7.30 and Film I in the enclosed CD show the channel configuration and location and alignment of

T-shape groynes. Figure 7.31 and Film J in the enclosed CD show the discharge taken in the model, flow touching the wings of T-shape groynes. The sediment introduced and shoal present are not flushing from the channel, only the shoal present between the wings gets flushed. The flow is flowing haphazardly and at many a places it becomes oblique also. The measured velocities at salient locations of spur are given in Table 7.4. Thus increasing the spacing between T-shape groynes was not found feasible.

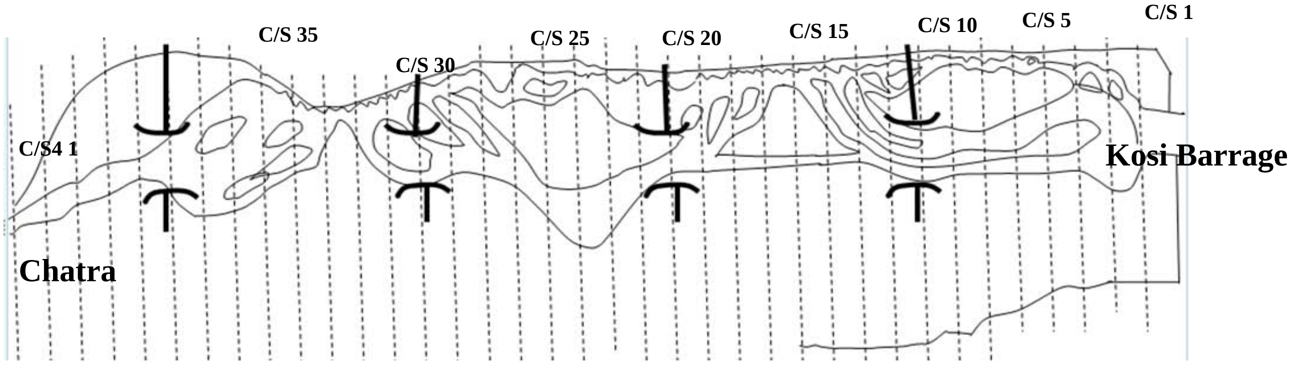


Figure 7.29 Plan showing layout of guide bund for a reach from Chatra to Kosi barrage (Waterway = 1,100 m, Interval = 8,000 m, length of guide bund – u/s = 1,000 m & d/s = 1,000 m)

Figure 7.30 Channel configuration and position of T-shape groynes

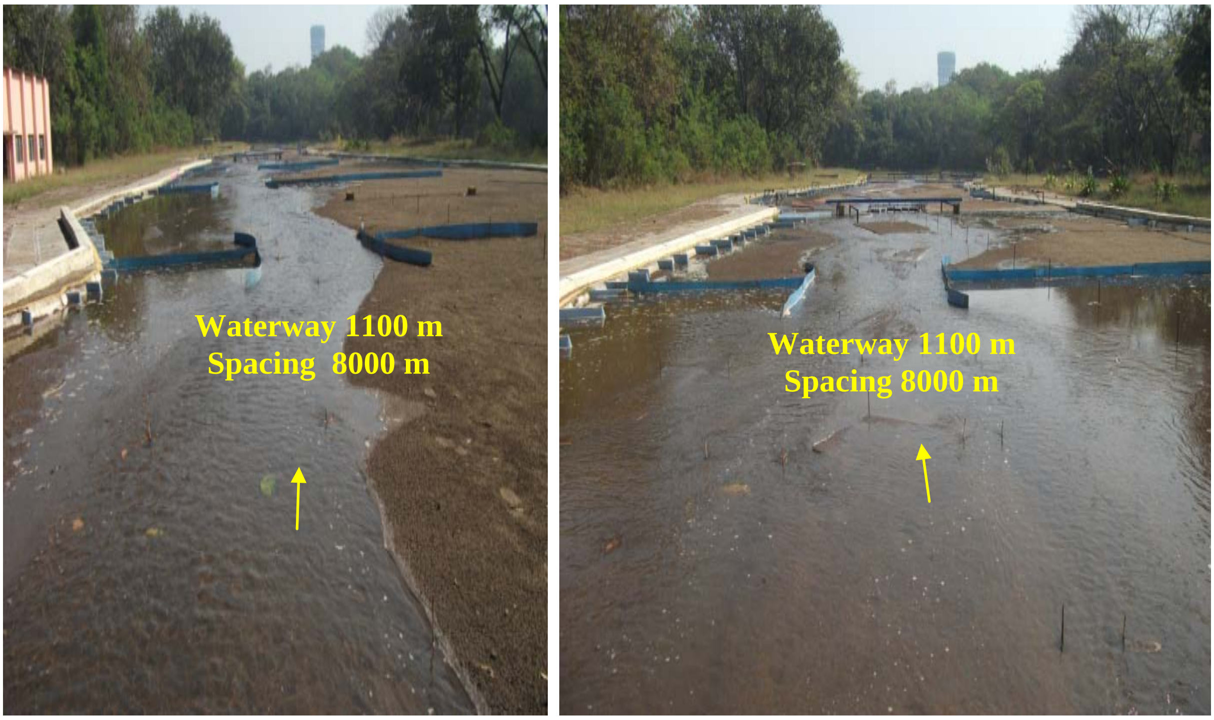


Figure 7.31 Closer view showing water is flowing haphazardly

Table 7.4 Velocities (m/s), along wings for waterway 1,100 m with spacing 8,000 m

Cross section	**Velocity (m/s)**					
	Left Wing			**Right Wing**		
	U/S Nose	**Centre**	**D/S Nose**	**U/S Nose**	**Centre**	**D/S Nose**
8	3.16	3.13	3.66	3.88	3.64	3.70
16	3.61	3.03	3.03	3.27	3.78	3.94
24	3.84	3.13	3.89	3.08	3.56	3.31
32	2.43	2.46	3.08	2.65	2.61	2.85

Note: - Underline a value, flow of water does not touch the face of the wings

7.9 CHANNELIZATION USING LEEVES

The satisfactory results of mathematical model for waterway of 1,100 m with levees along both the banks were also tested by the physical model studies. The physical model studies were conducted in two phases, from Chatra to Kosi barrage in the first phase and for the complete reach from Chatra to Nirmali in the second phase.

a) **First Phase**: - Figure 7.32 show the alignment and location of levees in plan for the reach from Chatra to Kosi barrage. For the ease of construction, the alignment of levees is located on the shoal to the maximum possible. The alignment of levees on the physical model is shown in

Fig. 7.33 a) and running of the model with a discharge of 15,586 m^3/s is shown in Fig. 7.33 b). Providing the levees to restrict the waterway to 1,100 m has helped to flush out the shoals and the sediment introduced at Chatra as seen from Fig. 7.34 a). The flow velocities were found to be adequate to wash out shoal and a regime/stable channel was established. However, due to decrease in velocity as a result of sudden widening of river on the downstream side, the sediment was deposited over the reach on the downstream of the barrage as shown in Figs.7.34 b). The average velocity on the upstream reach was observed to be 3 m/s, which is quite similar to that obtained from the mathematical model study. The measured velocity along the reach under study is shown in Fig. 7.35.

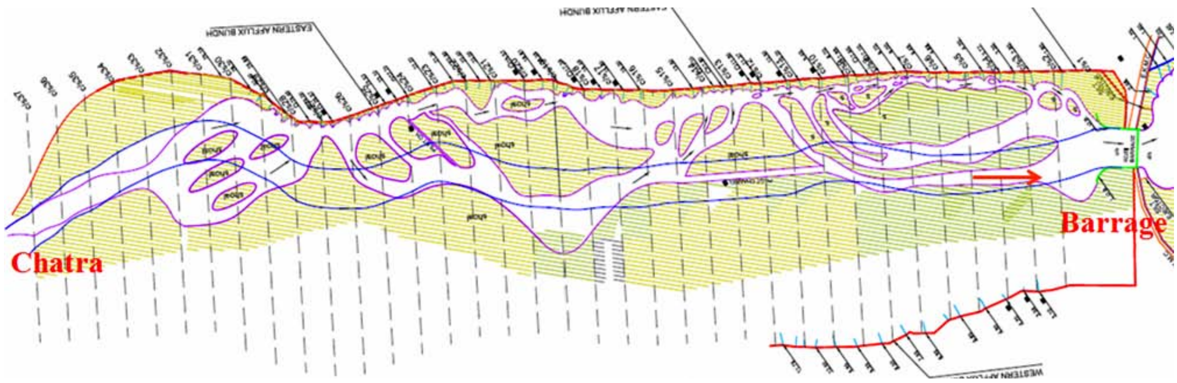


Figure 7.32 Plan showing layout of embankments for a reach from Chatra to Kosi barrage (Waterway = 1,100 m,)

Figure 7.33 a) Channel configuration showing position of levees from Chatra to Barrage **b)** View of model with discharge of 15,586 m^3/s

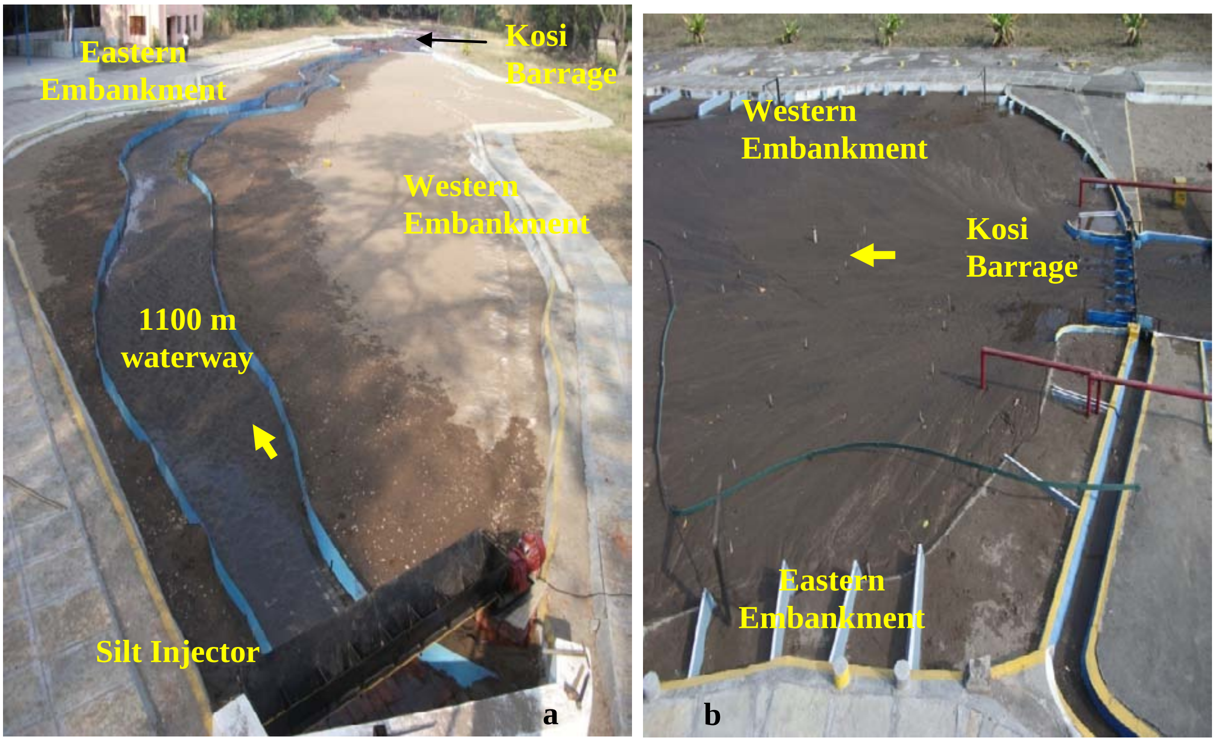


Figure 7.34 a) Upstream view of the model showing bed formation after a discharge of 15,586 m. b) View of model downstream of barrage showing bed formation

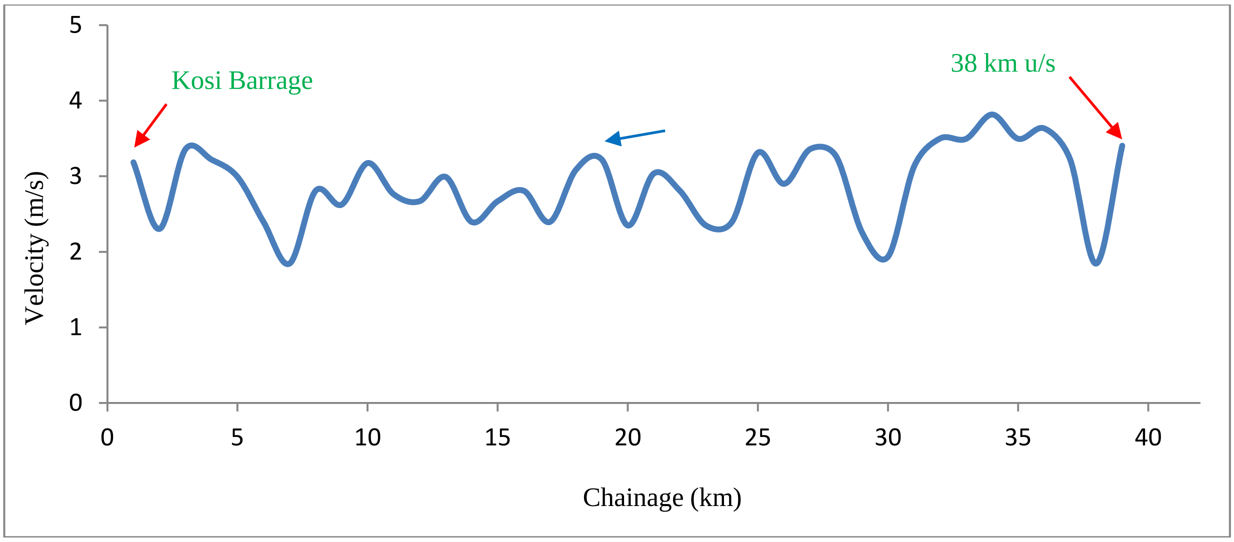


Figure 7.35 Velocity along the river Kosi for Q = 15,586 m^3/s

As may be seen from Fig. 7.33 b) and also from Film K in the enclosed CD, the flow of water was touching the constricted embankment and the shoal present in the channel was flushed out and a regime bed was formed. Figure 7.36 shows the change in bed level, before and after the run which indicates that sediment introduced from Chatra and shoal present in the channel are flushed out. Typical plots of original cross-sections and corresponding change in shape of constricted cross-sections after taking a discharge of 15,586 m^3/s are shown in Fig. 7.37 a), b) & c).

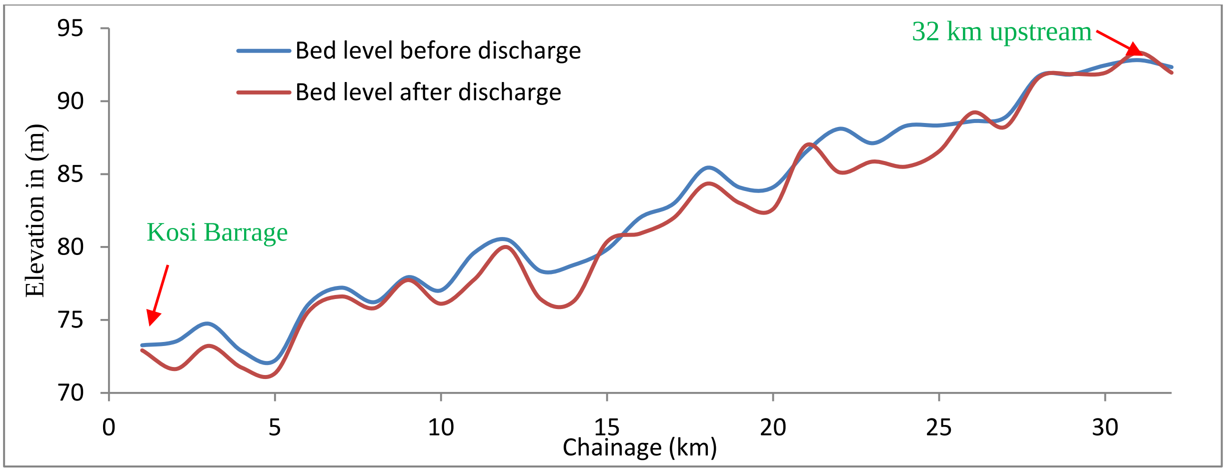


Figure 7.36 Change in Bed level for Q = 15,586 m^3/s

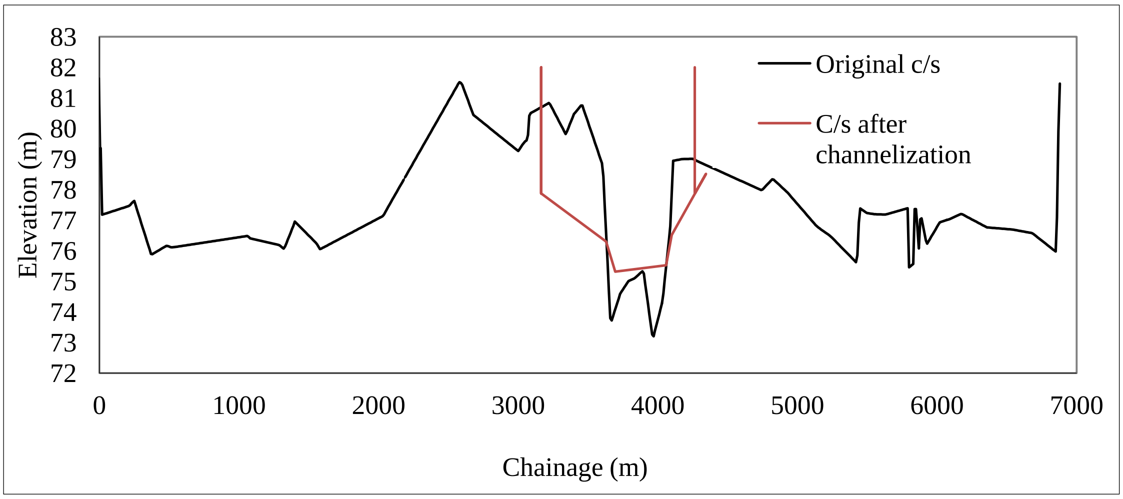


Figure 7.37 a) Cross-section showing change in bed due to levees at three km upstream of barrage

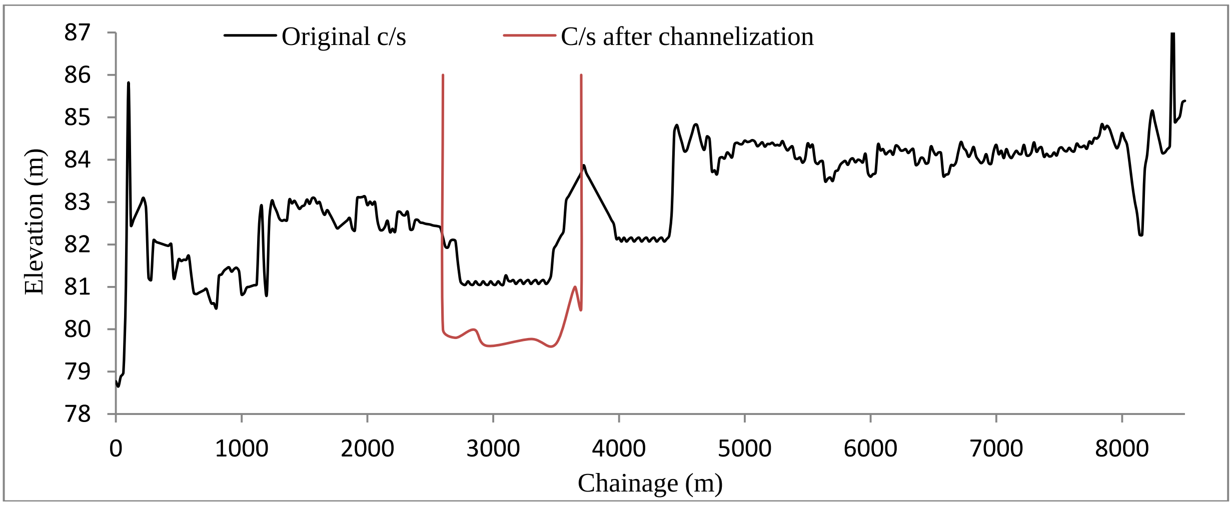


Figure 7.37 b) Cross-section showing change in bed due to levees at eleven km upstream of barrage

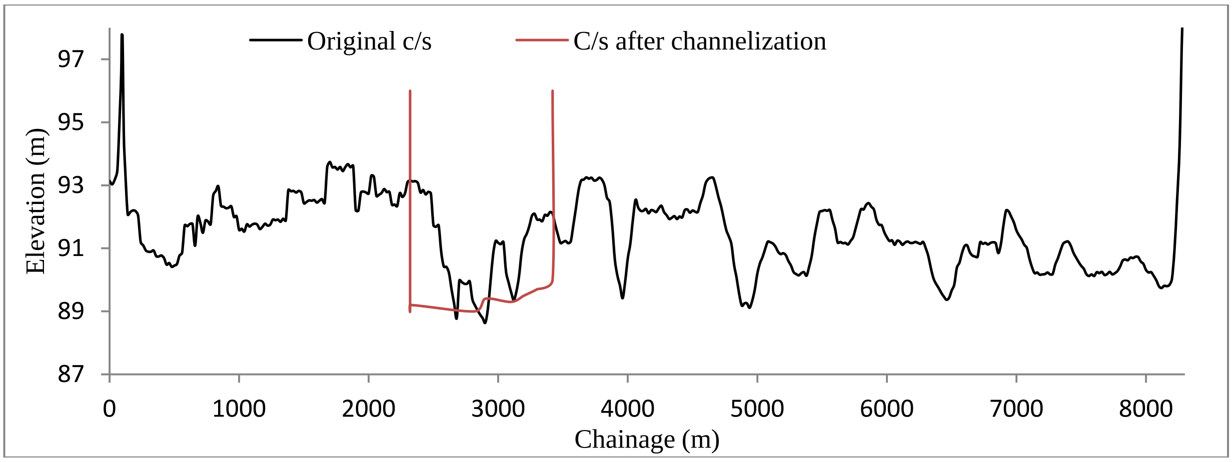


Figure 7.37 c) Cross-section showing change in bed due to levees at twenty-six km upstream of barrage

A typical cross-section on the downstream side, which was not constricted in the first phase of the study, is shown in Fig. 7.38. The deposition of sediment seen in this figure, has not resulted in any observable change in the flow condition and velocities on the channelized upstream reach. In the second phase of the study, when the entire reach upto Nirmali was constricted to 1,100 m using levees, the regime was formed over the complete reach as described in the following.

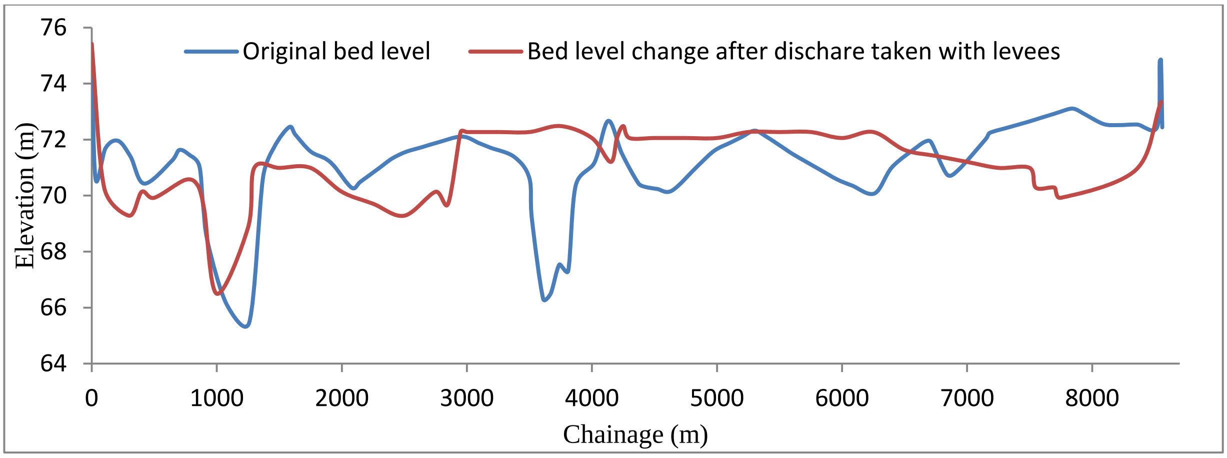


Figure 7.38 Cross-section showing change in bed level downstream of barrage at 4 km

b) Second phase: - To show that the channelization can also improve the situation on the downstream of the barrage, physical model studies were conducted using levees to have 1,100 m waterway from Chatra to Nirmali. Figure 7.39 and Film L in enclosed CD show alignment and location of embankment for the reach from Chatra to Nirmali. Figure 7.40, 7.41 and 7.42 show different views of the physical model with location and alignment of levees. After taking the discharge in the model, it was observed that discharge flowing along the constricted bank is uniform as shown in Figs. 7.43, 7.44, 7.45 and Film M in the enclosed CD. Figure.7.46 and

Film N in the enclosed CD clearly shows that flow of water was touching the constricted embankments and the shoal present in the channel was flushed out and a regime bed was formed. Figure 7.47 shows that the average velocity over the complete reach from Chatra to Nirmali has become 3 m/s, which is very close to the results of the mathematical model.

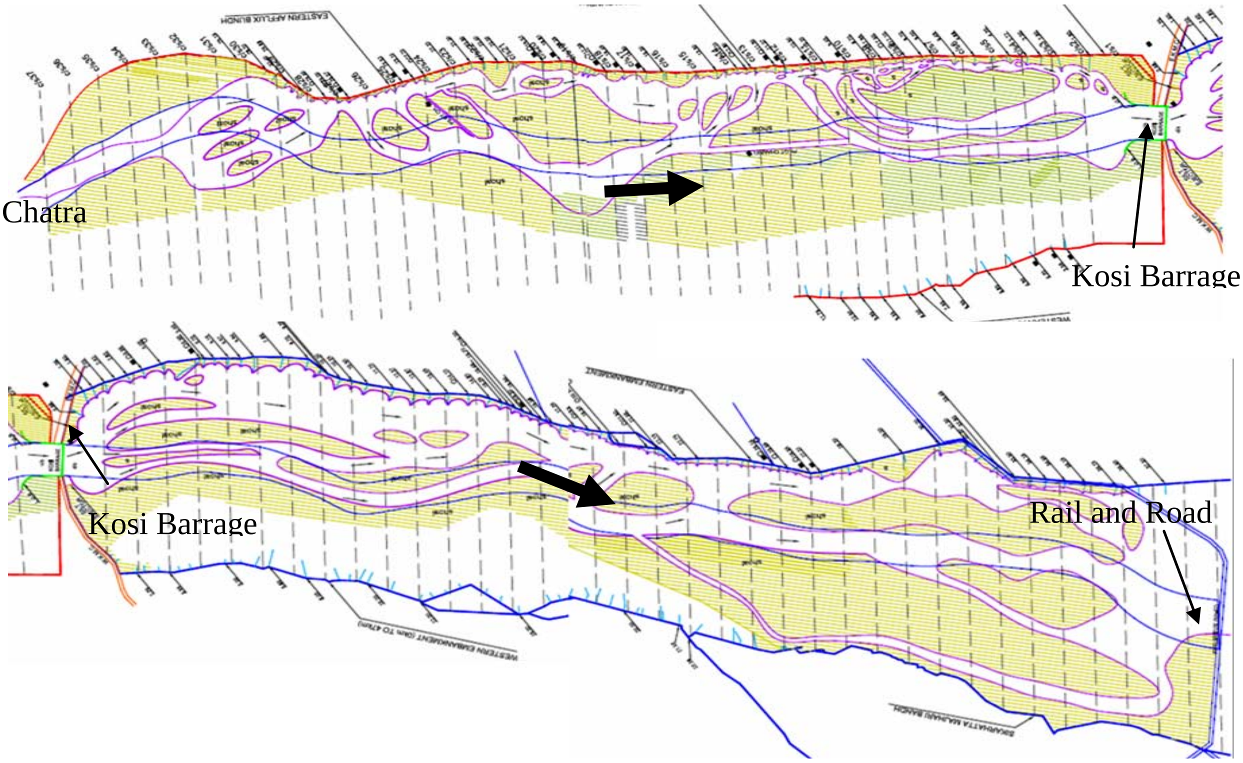


Figure 7.39 Plan showing layout of embankment for a reach from Chatra to rail-cum-road bridge (Waterway = 1,100 m)

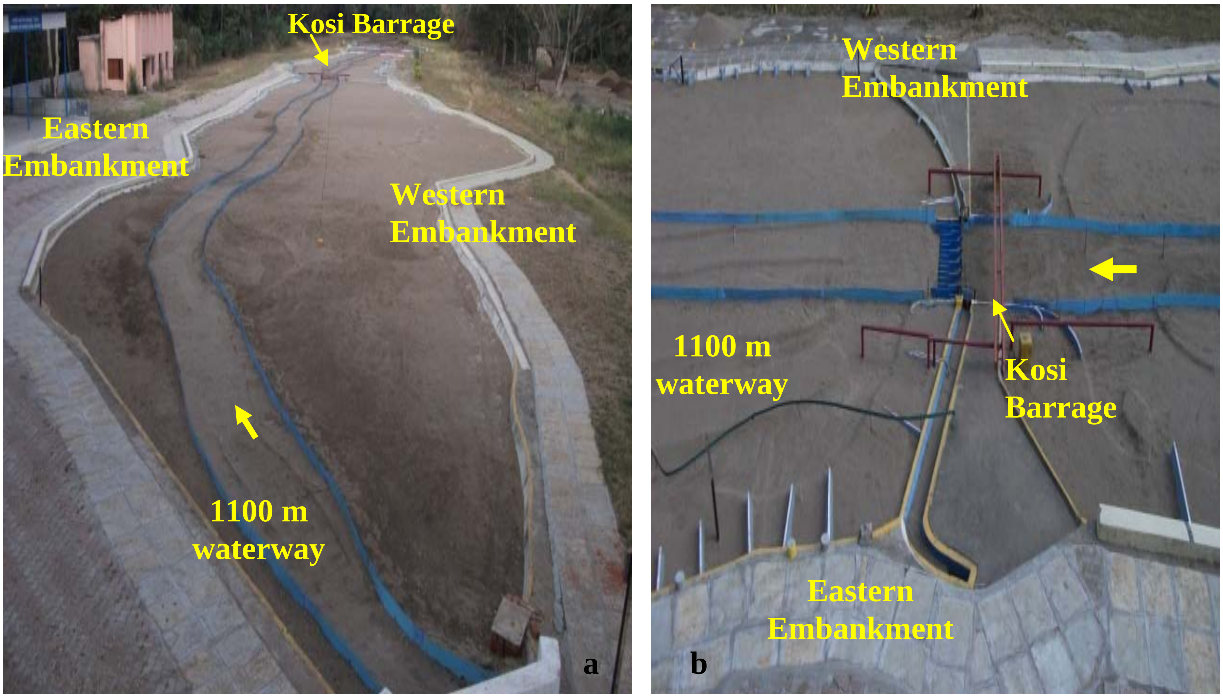


Figure 7.40 a) Upstream view showing position of embankment from Chatra to rail-cum-road bridge b) View of model showing channel configuration at Kosi barrage

Figure 7.41 a) Channel configuration showing position of embankment from kosi Barrage to rail-cum-road bridge b) View of model showing channel configuration at Dagmara barrage

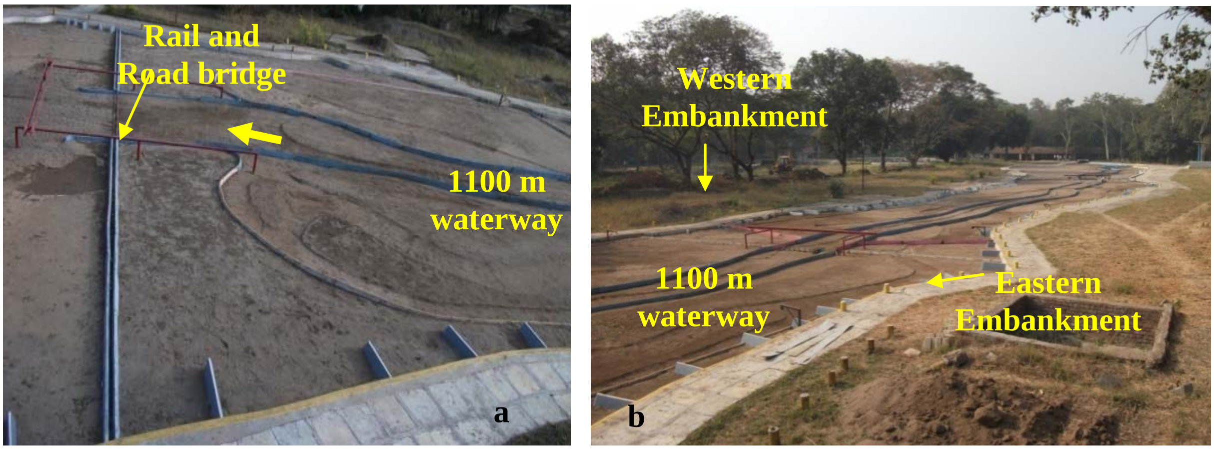


Figure 7.42 a) Channel view of model showing channel configuration at rail-cum-road bridge b) View of model showing channel configuration downstream of Kosi barrage

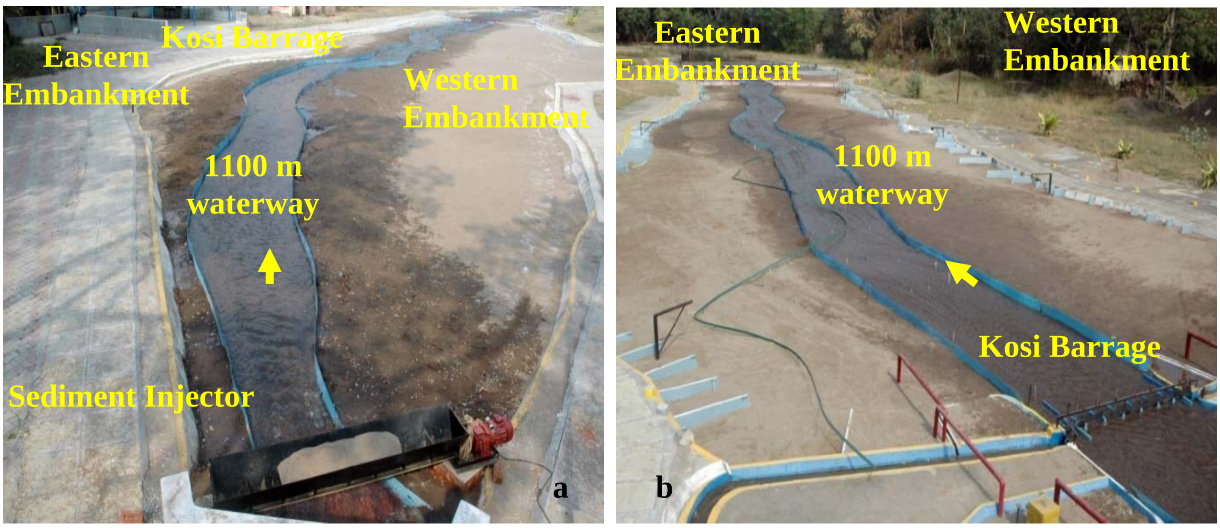


Figure 7.43 a) upstream view of model with Discharge of 15586 m^3/s from Chatra to Barrage **b)** Upstream view of model from Kosi barrage to rail-cum-road bridge for a discharge of 15586 m^3/s

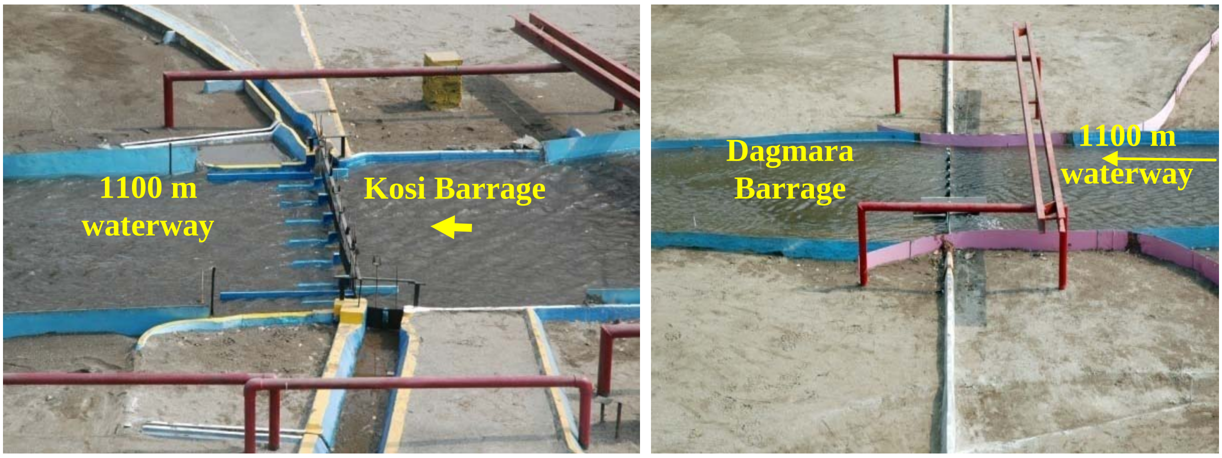


Figure 7.44 a) Views of model showing flow pattern at Kosi barrage and at Dagmara barrage for a discharge of 15,586 m^3/s

Figure 7.45 Views of model showing flow pattern at rail-cum-road for a Discharge of 15,586 m^3/s

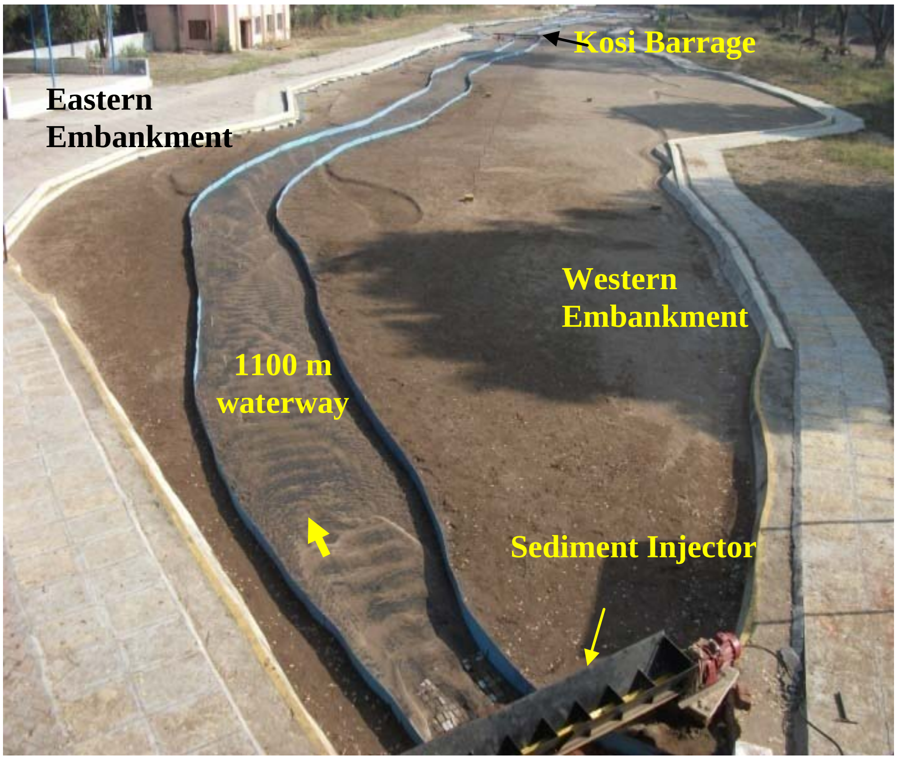


Figure 7.46 Upstream view of model showing bed formation, after a discharge of 15,586 m^3/s

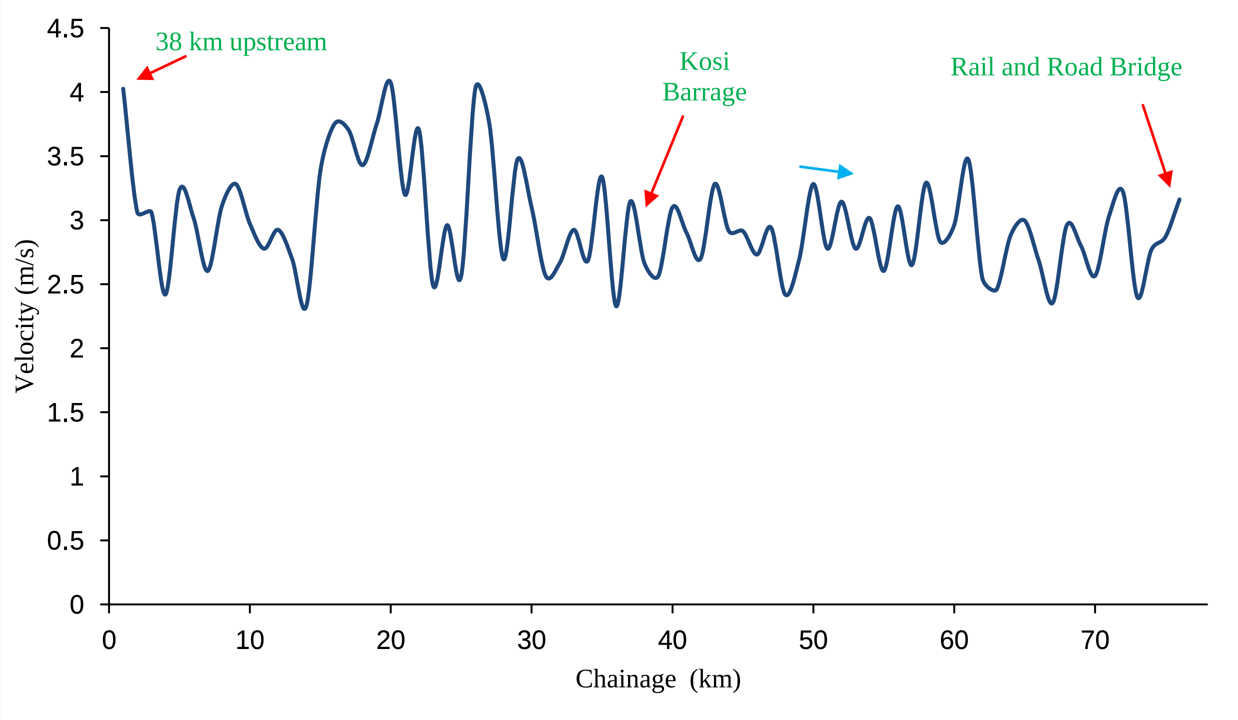


Figure 7.47 Velocity along the river Kosi for a reach from Chatra to Nirmali for Q = 15,586 m^3/s

7.10 CHANNELIZATION USING HOCKEY STICK SHAPE SPURS

Hockey-stick shape spurs were provided with a spacing of 1,500 m on both the banks to achieve a waterway of 1,100 m, for a reach from Chatra to Kosi barrage as shown in Figs. 7.48, 7.49 and 7.50. Figures 7.51 and 7.52 and Films O and P in the enclosed CD show that how the channel is formed. It was observed that the sediment introduced and shoal present in the channel are flushed downstream of Kosi barrage. For the maximum observed discharge of 15,5865 m^3/s, it was seen that the hockey-stick shape spurs guide the flow of water with an average velocity 3 m/s and form the bed regime as shown in Fig. 7.53.

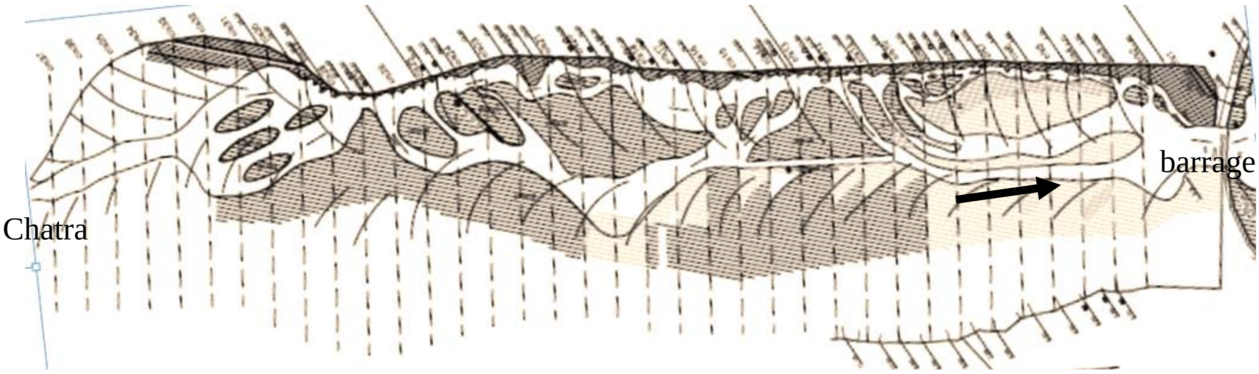


Figure 7.48 Plan showing layout of embankment and showing position of hockey stick shape groynes for a reach from Chatra to Kosi barrage (Waterway = 1,100 m,)

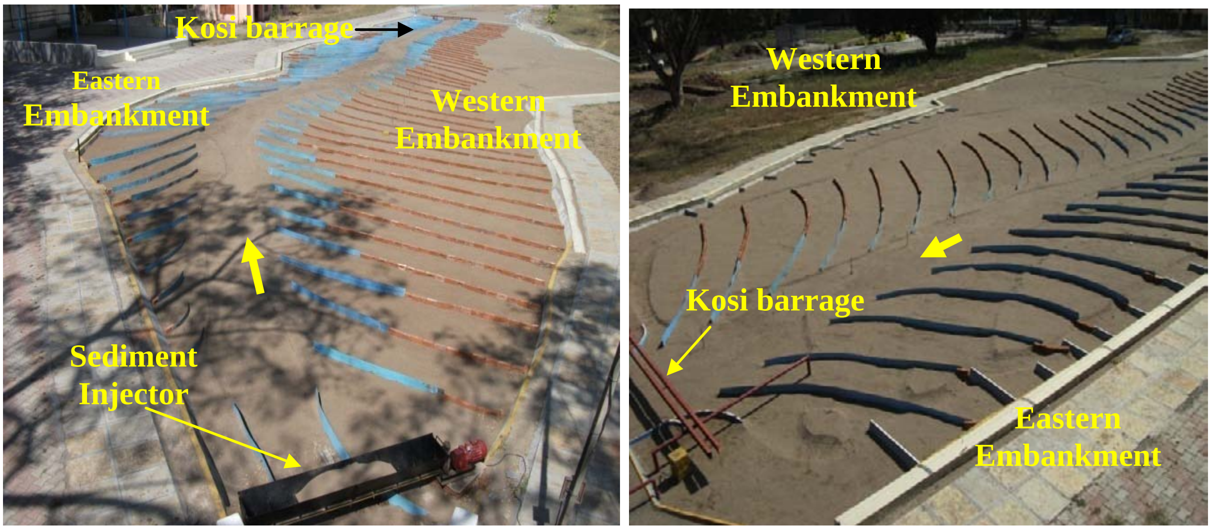


Figure 7.49 a) Channel configuration showing position of hockey stick shape groynes from Chatra to Barrage **b)** Upstream view of model showing position of hockey stick shape groynes near barrage

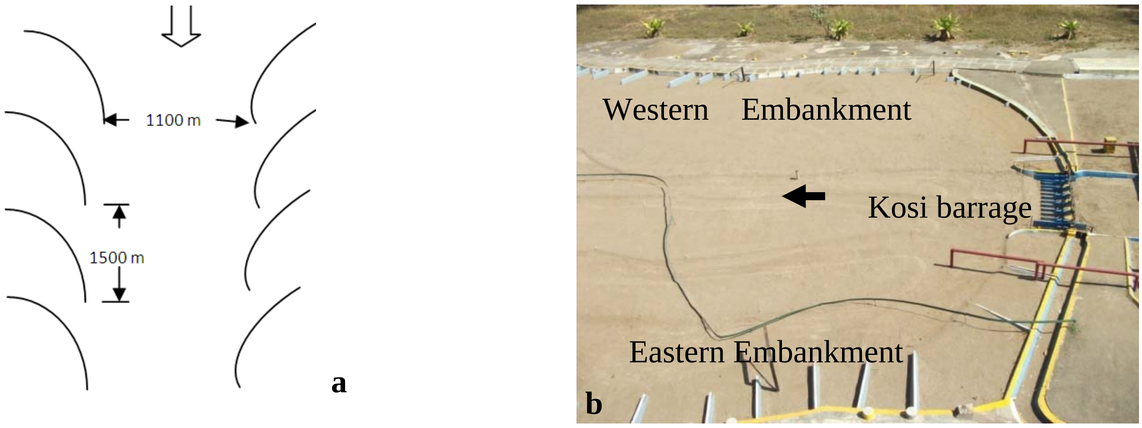


Figure 7.50 a) Detail of hockey stick shape groynes provided in the model **b)** View of model near barrage showing channel configuration

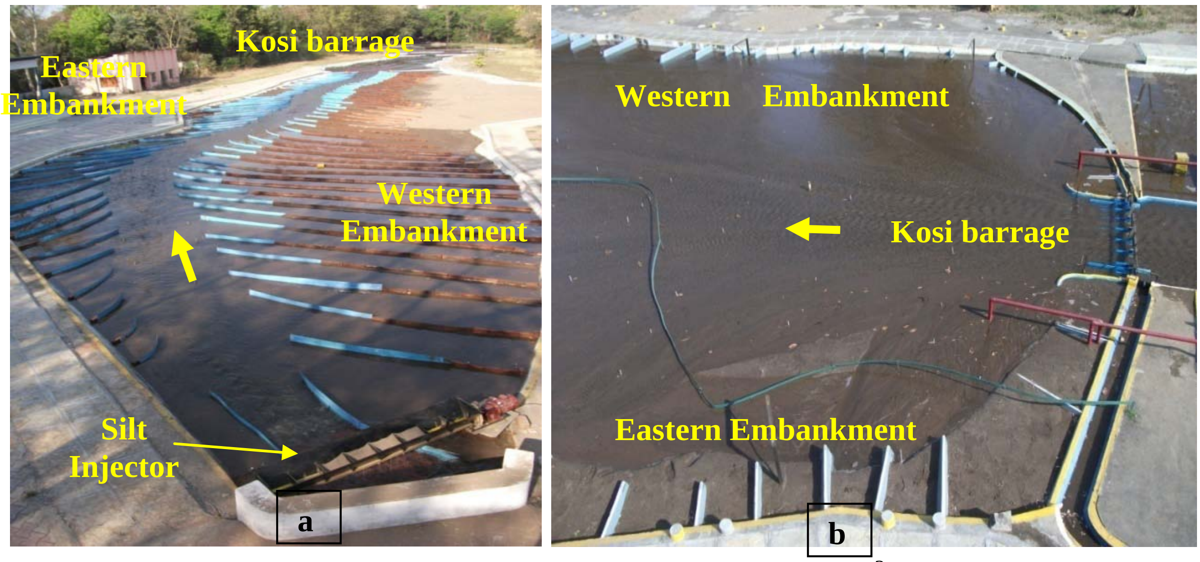


Figure 7.51 a) Upstream view of model with a discharge of 15586 m^3/s for a reach from Chatra to Barrage b) Side view of model near barrage showing flow pattern for discharge of 15586 m^3/s

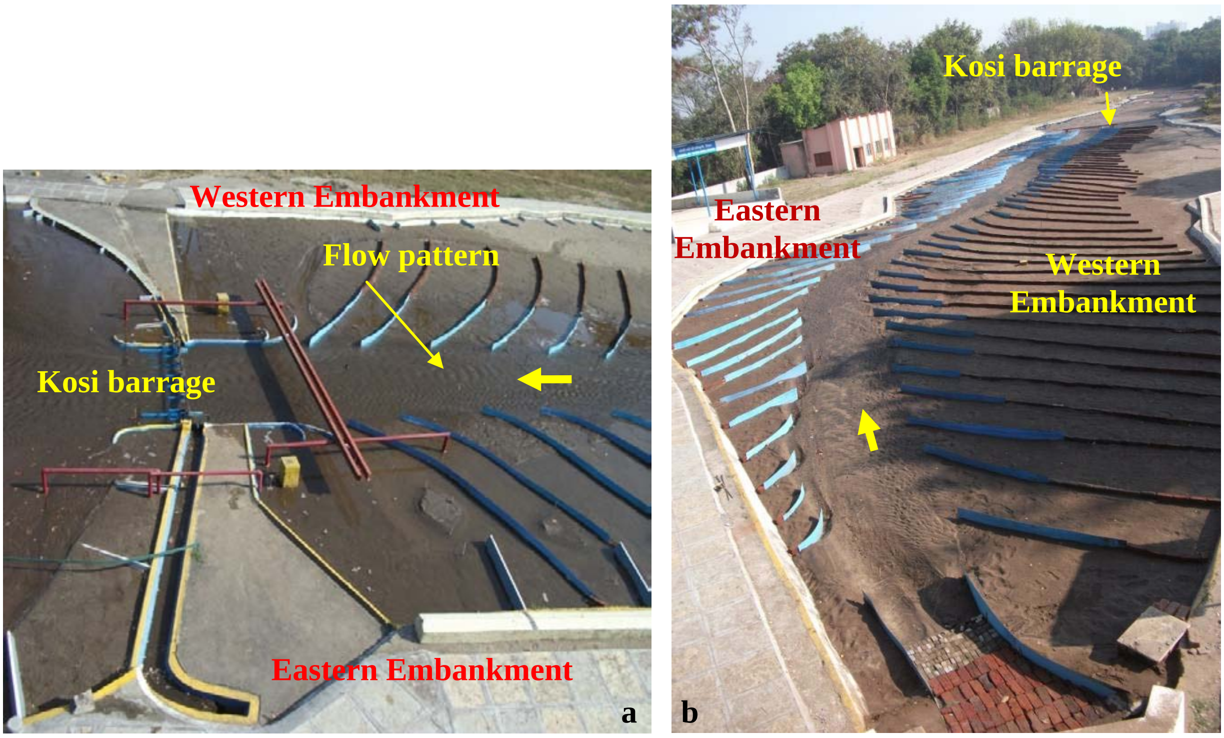


Figure 7.52 a) Side view of model with a discharge of 15586 m^3/s at Barrage b) Upstream view of model showing bed formation after a discharge of 15586 m^3/s

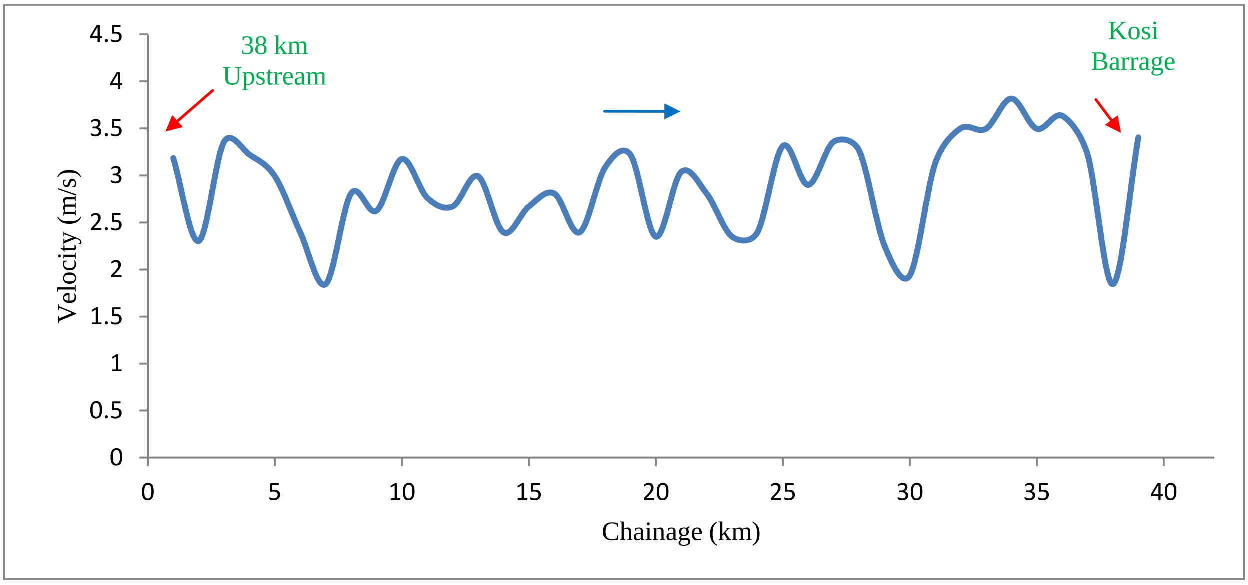


Figure 7.53 Velocity along the river for Q = 15,586 m^3/s

7.11 CONCLUSIONS

Three methods were used for channelization of river Kosi by using three dimensional physical models, which are accomplished as follows:-

(i) Providing T-shape groynes along both the banks

(ii) Providing levees to have a waterway of 1,100 m

(iii) Providing hockey stick shape spurs along both the banks

Extensive measurement of various Hydraulic parameters has been carried out for T-Shape groynes along both the banks

- Three different waterways of 3,000 m, 2,000 m and 1,100 m were investigate using T-shape groynes with wing length 2,000 m and spacing of 4,000 m on both the banks. The maximum discharge of 15,586 m^3/s with sediment injection at the upstream end was used in the model study. It was found that flushing of sediment introduced and the shoals present took place only for the case of waterway constricted to a width of 1,100 m. the average velocity generated for this case was observed to be 3.0 m/s, which is sufficient for sediment transportation. These observations are similar to those made from the mathematical model study with levees on both banks to constrict the waterway to 1,100 m. thus, T-shape groynes can be considered to exhibit the same effect as shown by the levees, which was further confirmed by the physical model studies.

- The satisfactory results of mathematical model for a waterway of 1,100 m with levees provided formed the best for the physical model study, conducted in two phases. In the first phase reach consider was from Chatra to Kosi barrage and from Kosi barrage to Nirmali in the second phase. In both the phases, the average velocity of 3 m/s was achieved which helps in carrying the sediment downstream. The sediment flushed from the first stretch flow was seen to deposit downstream of barrage, but it was flushed further downstream when the levees were extended upto rail-cum-Road bridge at Nirmali. Thus, providing levees is seen to be an effective method for channelization of river Kosi.

- Hockey-stick shape spurs were provided from Chatra to Kosi barrage with a spacing of 1,500 m on both the banks to achieve a waterway of 1,100 m. in this case also the sediment introduced and the shoals present in the channel were seen to be flushed downstream of Kosi barrage. For the maximum observed discharge of 15,586 m^3/s, it was seen that the hockey-stick shape spurs guide the flow of water with an average velocity of 3 m/s and helps to form bed regime. Thus this method was also found to be an effective way for channelization of river Kosi on technical grounds.

Chapter 8

CONCLUSIONS AND SCOPE OF FUTURE RESEARCH

8.1 BACKGROUND

The present study has been focused on a part of river Kosi from Chatra to Nirmali. This river has its practical importance as it has shifting tendency, flowing in a braided pattern with high sediment inflows, and sediment carrying capacity of this river is inadequate. Percentage of sediment settlement between the banks is very high resulting in increase in bed level, and seepage into country side. Rainwater, stream flow and seepage water cause huge water logging along the country side of the embankments. Therefore, investigation is warranted for sediment management by adopting modelling technique.

In this context, the studies like channelization of river Kosi is being focused to aim towards an in-depth study of the complex hydro-dynamics of river Kosi. This chapter presents the summary, conclusions and scope of future research work.

8.2 SUMMARY

1) Kosi river brings about 187 million metric tonnes of sediment every year from the Himalayas, about 70 percent of the sediment settles between the embankments, so, river Kosi meander between Eastern and Western embankments. The width between the two embankments varies from 6 km to 16 km. Distance between the two embankments is extensive that’s why river has a tendency to deposit sediment and then meander. Deposition of sediment and formation of shoals, make the river flow oblique and endanger the embankments, therefore, series of spurs has been provided on both the embankments. So, proposing any type of structure on such type of river is a challenging task for engineer. For conducting model studies on mathematical model and physical model required precise data, and thus generating input data like stage-discharge and sediment-discharge required help of ANN tool. An ANN tool reduces the time lag, as the regression and curve fitting techniques are not adequate in view of the complexities involved in hydrological process. An inherent problem in the rating curve technique is the high degree of scatter, which may be reduced but not eliminated. The prediction of daily discharge and suspended sediment concentration based on the performing ANN models for both the gauging sites (Barahakshetra and Kosi

Barrage) yielded good results with an accuracy of more than 94% and 98% respectively at the two sites.

2) Morphological study is required to know the braiding process of the Kosi. The braiding process in the river Kosi starts from downstream of Belka hills, where interlacing channels are spread over width of about 5 to 6 km. To identify the relative extent of braiding in different reaches, the braiding indicator Plan Form Index (PFI) developed by Sharma (2004) and old cross-sectional data have been compared.

   When the cross-sectional data were plotted, it was observed that yearly sediment was depositing in the river bed and therefore, the bed level has gone up over a period from 1977 to 2009. It is further observed that, the channel configurations are not fixed, it is changing between embankments and the river is flowing in multichannel mode, this is because of non-cohesive material, no rigid boundary and flat slope. Further it can be observed that in the year 1992, the river was flowing (hugging) along the eastern side with a low braided pattern, but as the time lapses the braided pattern of river increases. At the downstream of barrage reach, it is observed that the river was flowing along the western side, but later river shifted towards eastern side. It can be easily figured out that maximum values are predominant in the year 1992, whereas in 2005-12 minimum values are predominant in the upstream of barrage. While at the downstream of barrage, irrespective of the time, the six discrete reaches show moderate changes in braiding intensity and pattern.

3) The conceptual view by using mathematical model studies was analysed for the channelization of river Kosi. Reach considered for channelization is from Chatra to Nirmali. The values of Manning's 'n' were varied for discharge of 10,960 m^3/s and the water level computed by using mathematical model at Dagmara and Bhaptiahi which were compared with the actual observed values. It was found that Manning's n value of 0.022 gives better comparison and is used for further studies. The cross-section data with Manning's 'n' value as 0.022 were used as input data for the mathematical model. The results of this study were compared with the water surface elevation recorded all along the cross-sections. The comparison is found to be satisfactory; hence the use of Manning's 'n' value as 0.022 was considered as justified.

   Various waterways were considered including the Lacey's waterway. The study indicates that the river aggrade/degrade in the initial years afterward there was no effect for a waterway of 1,100 m which is incidentally also the equivalent waterway provided at the Kosi barrage. The Kosi barrage has not been affected by the sediment for the last 50 years and it is seen that there is no aggradations / degradation in the immediate vicinity of the barrage portion. This along with the mathematical model studies indicate that the River Kosi would be in regime without significant aggradations or degradation with the waterway of 1,100 m within the prevailing range of fluvial variables.

4) Huge quantity of sediment is coming from the Himalayas, when it comes in plain the river flows with a flatter slope and wide spacing between the existing stop banks/levees on river Kosi at upstream and downstream of the barrage; thus evidently the river channels are in a state of instability and have developed highly braided configuration. This results in shoal formation. Shoals make the flow oblique, and therefore, flow of water attack the embankments. To avoid this problem, it is necessary to channelize the river for stabilizing the river course along a centralized channel. For conducting physical model studies, reach considered for channelizing the river Kosi, using T-shape groynes, levees and hockey stick shape spurs as device extends from Chatra to Kosi barrage. Further levees have been extended upto rail-cum-road bridge. Using the established gauge reading at Dagmara and Bhaptiahi, Gauge-discharge relationships were developed and then model was proved. Similarly, same data were used for developing a tail rating curve which was generated at the downstream of rail-cum-road bridge at Nirmali.

5) Extensive measurements of various hydraulic parameters have been carried out for T-Shape groynes along both the banks in three stages. Waterway between wings was given 3,000 m, it was fixed to the banks with an interval of 4,000 m, and the wing length provided was 2,000 m. Discharge of 15,586 m^3/s was passed to operate the model. Here the flow of water did not touch the wings face and similarly flow of water never affected the sediment and shoal in the model runs. Hence the waterway was further constricted to 2,000 m and there was no change in remaining parameter. Here flow of water touched the face of wings; but there was no change in bed. Therefore the waterway was further finally constricted to 1,100 m. Here flow of water touched the face of wings and motion of sediment was noticed. For optimising the same, trial was made by increasing the interval of T-shape groynes. Here flow of water touched the wing’s face, only shoals present in the vicinity of wings were flushed out and elsewhere discharge was flowing haphazardly.

6) The satisfactory results obtained from the mathematical modeling for a waterway of 1,100 m with the levees were also observed in the case of the physical modeling. Utmost care has been taken such that alignment of levees should be through the channels. Studies were conducted in two phases: - In the first phase reach considered was from Chatra to Kosi barrage. Here the discharge was flowing with an average velocity of 3 m/s, which helped in carrying forward the sediment. The transported sediment got deposited downstream of the barrage, so, levees length was further increased upto rail-cum-Road bridge, at Nirmali. Here the shoals present in the river were flushed out and relatively regime bed configuration was formed. Both the experiments yielded satisfactory results.

7) Hockey-stick shape spurs were provided with a spacing of 1,500 m on both the banks to achieve a waterway of 1,100 m. Here the sediment introduced and shoals present in the channel have been flushed downstream of Kosi barrage. For the dominant discharge of 15,586 m^3/s, it was seen that the hockey-stick shape spurs efficiently guided the flow of water with an average velocity of 3 m/s and formed desired stream bed regime.

8.3 CONCLUSIONS

1) The prediction of daily stage-discharge relationship based on the best performing ANN model for the gauging station at Barahakshetra site and sediment-discharge for gauging station at Kosi barrage yielded good results with an accuracy of more than 94% and 97% respectively.
2) The plots of cross-sections, upstream and downstream of barrage concluded that, yearly sediment was depositing in the river bed and therefore, the bed level has gone up over a period from 1977 to 2009. Further the channel configuration is changing between the embankments, because of non-cohesive material, no rigid boundary and flat stream bed slope.

   From the imageries of discrete years 1992, 2005 and 2012 when compared, it can be concluded that, maximum values of Plan Form Index (PFI) developed by Sharma (2004) are predominant in the year 1992, whereas in 2005-12 period its lower values signifying higher degree of braiding are found to be predominant in the upstream of barrage. While at the downstream of barrage, reach shows relatively little changes in braiding intensity and pattern.
3) In mathematical model runs, average velocities in the river without any constriction is found to be about 1.5 m/s. For waterways of 2,000 m, 1,100 m and 800 m , the average velocities are indicated as 2.2, 2.7 and 3.3 m/s respectively. It can be concluded from mathematical modelling that, for a waterway of 1,100 m at the dominant discharge, the desired scouring velocity of 2.7 m/s was achieved for channelization of the shifting water courses of the river Kosi.
4) Physical model studies were carried out using T-shaped spur as a river training device to achieve desired river channelization investigated for multiple waterways 3,000 m,

2,000 m and 1,100 m. It can be concluded from the physical modelling results that for a channelized waterway of 1,100 m, discharge was flowing with an average velocity of 3 m/s at dominant flow which is somewhat higher than that of mathematical model's scouring velocity of 2.7m/s, and thereby flushing out the braid forming shoals present in the stream bed.

5) Nearly identical mathematical modelling results obtained for the channelized waterway of 1,100m with dykes, could be satisfactorily corroborated from the physical model runs with identical similar levees spacing and similar channelized waterway. Here, discharge is flowing with an average velocity 3 m/s at discharge of 15,586m^3/s, which has enabled desired carrying of the sediment albeit sediment deposition could be seen in the physical model downstream of barrage. Sediment deposit downstream of barrage has caused rise in bed level. To counter such an eventually levees length was further increased upto rail-cum-road bridge. In this case of model runs, the shoals deposit downstream of barrage were flushed out and the desired channelized regime bed could be achieved. Thus both the experiments yielded give satisfactory results with mutual corroboration.

6) Physical model studies were conducted using Hockey-stick shape spurs, which were provided with a spacing of 1,500 m on both the banks to achieve a waterway of 1,100 m. Here the sediment introduced in the model and shoals deposit in the channel have been flushed out downstream of Kosi barrage.

7) The modelling results of the present reseach endeavoured for desired channelization of the Kosi river have amply brought out that the following three river training measures have emerged to be equally efficacious from technical standpoint
   (i) Providing T-shaped groynes along both the banks
   (ii) Providing levees to have a waterway of 1,100 m
   (iii) Providing hockey stick shaped spurs along both the banks

8.4 SCOPE OF FUTURE RESEARCH

a) HEC-RAS is a 1D mathematical model, in which the effect of the structures like spur, guide bunds of barrage etc. cannot be reproduced. Thus, attempt has been made for channelizing river Kosi considering limited hydraulic aspects. Further, detailed studies need to be carried out using 2D mathematical and physical models with additional field data.

b) The effect of variation of non-uniform size, especially upstream of Kosi barrage should be incorporated in future studies for evaluation of complex channel progress.

c) Considering the complexity of Kosi river channelization, further studies may explore efficacy of using other river training structure, such as RCC jack jetty, submerged vanes, permeable spur and trial dyke system, either conjunctive or isolated.
d) Model studies are required to be conducted on present structures like Kosi barrage and rail-cum-road bridge, because constricted waterway will definitely increase the water level.

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