# Flood risk analysis in the Kosi river basin, north Bihar using multi-parametric approach of Analytical Hierarchy Process (AHP)

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## Abstract

The Kosi river in north Bihar plains, eastern India presents a challenge in terms of long and recurring flood hazard. Despite a long history of flood control management in the basin for more than 5 decades, the river continues to bring a lot of misery through extensive flooding. This paper revisits the flooding problem in the Kosi river basin and presents an in-depth analysis of flood hydrology. We integrate the hydrological analysis with a GIS-based flood risk mapping in parts of the basin. Typical hydrological characteristics of the Kosi river include very high discharge variability, and high sediment flux from an uplifting hinterland. Annual peak discharges often exceed the mean annual flood and the low-lying tracts of the alluvial plains are extensively inundated year after year. Our flood risk analysis follows a multi-parametric approach using Analytical Hierarchy Process (AHP) and integrates geomorphological, land cover, topographic and social (population density) parameters to propose a Flood Risk Index (FRI). The flood risk map is validated with long-term inundation maps and offers a cost-effective solution for planning mitigation measures in flood-prone areas.

**Keywords:** Flood risk analysis, AHP, flood management, river basin, GIS.

## Introduction

The Kosi river in north Bihar plains, eastern India is a major tributary to the Ganga river system and has long been considered as a problematic river due to recurrent and extensive flooding and frequent changes in its course. During the last two centuries, for which records are available, the river has changed its course in a westerly direction and it has laterally moved nearly 150 kilometers (Gole and Chitale, 1966; Wells and Dorr, 1987). The movement of the river has not been gradual but of avulsive nature (sudden change in river course) originating from a nodal point (Wells and Dorr, 1987). The average avulsion frequency has been recorded as 24 years which is among the lowest in the world compared to 1400 years for the Mississippi river (Slingerland and Smith, 2004). A number of paleochannels on the satellite image of the Kosi basin testify the migratory behaviour of the river (Fig. 1). The river is typically braided in nature and has formed a very large alluvial fan due to a large sediment supply from the Himalaya and a generally

aggradational regime. Further complications arise due to (a) very high rainfall in the catchment (1200-2000 mm in most parts; Sinha and Friend, 1994), and (b) high seismicity in the hinterland causing landslides and large sediment production which eventually fill up the basin.

The Kosi river has laid waste large fertile tracts during frequent migrations and has caused extensive damage through overbank flooding and inundation. For this reason, it is often called "Sorrow of Bihar**"**. Initial suggestions for flood control for the Kosi river during late $19^{th}$ century included construction of marginal embankments, high dam at upstream section, river training in lower reaches and a series of barrages and canals. However, no consensus was reached and no definitive action could be taken until 1953. A very severe flood in 1953-54 and the subsequent social and political pressure led to the first serious attempts towards flood control in the Kosi basin and the formulation of the 'Kosi project' in 1954. This project was primarily aimed at flood control and to provide irrigation for increasing agricultural productivity. The project started in 1959 and the river was diverted through the barrage in 1963. The embankments on both sides have been designed to protect ~2800 $km^2$ of land in north Bihar and Nepal. Although the embankments have checked the lateral movements of the Kosi, the flooding problem continues in the Kosi basin and the objectives envisaged in the Kosi project have been only partially met. Several large floods and frequent breaches in the embankments have continued to occur in the region. In addition, several adverse effects of the Kosi project have been noted viz. drainage congestion and waterlogging, rise of river bed level, and reduction in crop productivity due to reduced silt flux on the floodplains (Ghani, 2001).

This paper investigates the hydrological characteristics and geomorphological controls of floods which may be important for long-term mitigation of floods in the basin. We have also carried out flood risk analysis of a part of the Kosi basin based on remote sensing and GIS techniques which may be of immense value for planning flood management strategies.

**The Kosi river basin**

The Kosi, known as Kaushiki in Sanskrit books, is one of the most ancient rivers of India. It rises in the Himalaya and drains the foothills to the east of Kathmandu in Nepal. Its

three tributaries within the Himalaya, the Sun-Kosi, Arun and Tamur, join together at a point ~10 km upstream of Barahkshetra and the combined channel debouches into the plains (Figure 1). One of the first geomorphological studies of the Kosi basin was done by Geddes (1960) who used the word 'cone' to describe the morphology of the Kosi system. Gole and Chitale (1966) described the Kosi system as an 'inland delta' built by large sediment flux which was also attributed to be the primary factor causing westward shifting of Kosi and extensive flooding. The dynamic nature of the Kosi River has attracted attention for over a century and a variety of mechanisms have been suggested ranging from tectonic tilting and nodal avulsions (Gole and Chitale, 1966; Arogyaswamy, 1971; Wells and Dorr, 1987; Agarwal and Bhoj, 1992) and discharge peakedness and autocyclic processes (Leier et al., 2005; Bridge and Karssenberg, 2005).

Figure 1 also shows the major geomorphological features in the Kosi plains based on digital mapping from IRS images (LISS III, 7 March, 2002). The braided channel of the Kosi river flows towards SW after debouching into the plains but takes a sharp turn towards SE and then flows parallel to the Ganga in its lowermost reaches before its final confluence with the Ganga. The river is embanked on both sides; the left embankment, running close to the river, is continuous but the right bank is discontinuous particularly in the lower reaches around the confluence with the Ganga. The vast plain, on which the Kosi megafan has formed, has a general slope from north to south and west to east, being steeper in the north (55-75 cm/km) and flatter in the south (6 cm/km). Thus, the entire fan surface is nearly flat, which is dissected by numerous 'dhars' (small channels) representing paleochannels of the Kosi river. Some of the paleochannels are vegetated and muddy due to monsoon water and dry season discharges**.** The entire alluvial plain is extensively cultivated. There are undulations and innumerable depressions called "chaurs", where water remains accumulated for most parts of the year. Some of these waterlogged patches in the lower reaches and close to the embankments are very large which may be related to seepage along the embankment but may partly represent accumulation of floodwater after overbank flooding.

**Flood hydrology**

For hydrological analysis, data obtained from Central Water Commission (CWC), Government of India has been used corresponding to three gauge/discharge stations along the Kosi River namely, and Barahkshetra, Birpur, and Baltara (see Fig.1). Data on

monthly average discharge and peak discharge are available for all three stations for different periods. The monthly average data was available for Baltara station only for a period of nearly 20 years (1980-2002). The inundation depth (water level above the danger level) data have also been used to study the trend and severity of floods.

**Figure 2** shows a typical monsoonal pattern of monthly discharge for the period 1985-2002 which generally starts to peak in the month of June with the maximum in the month of August/September. An increase in minimum monthly discharge in recent years (2000 onwards) is conspicuous. The average annual discharge ($Q_{av}$) of the Kosi at is 2236 $m^3/s$ (Table 1); the average monsoon discharge (5156 $m^3/s$) being almost 5 times higher than the non-monsoon discharge (1175 $m^3/s$). Such large difference between monsoonal and non-monsoonal discharge makes the river vulnerable to flooding as the shallow river sections can not accommodate the excess discharge. Further, the annual discharge at Baltara shows an overall increasing trend (Figure 2b) contrary to the decreasing trend reported in the mountainous catchments of Nepal attributed to decrease in snow covered areas and decrease in winter precipitation.

**Figure 3** shows variability of annual peak discharge for the Barahkhetra (1950-2001), Birpur (1981-92) and Baltara (1957-2001) stations. At Barahkshetra, extraordinarily high values of 24,000-25,000 $m^3/s$ in 1954 and 1968 correspond to two most severe flood events in the Kosi basin documented so far. Peak discharge variability at Birpur and Baltara is relatively lower.

Further insight to flood frequency is provided by the return period analysis using Gumbel probability distribution (see Table 1 for results). $Q_{1.58}$ value is often taken as the bankfull discharge (Leopold, Wolman and Miller, 1964); $Q_{2.33}$ is a measure of mean annual flood ($Q_{maf}$) and $Q_{100}$ is generally used as ‘design flood’ for most engineering projects and flood management. It is observed that the upstream stations (Barahkshetra and Birpur) show higher peak discharges than that at the downstream station (Baltara) for the same return period (Table 1). The possible reasons for this are the diversion of water for irrigation (East Kosi Canal System and Chatra Canal System) and also the embanking of the river, which prevents the tributaries from joining the Kosi.

**Figure 3** shows that peak discharge has frequently exceeded the $Q_{maf}$ value at Barahkshetra and two floods in 1954 and 1968 are much higher than $Q_{100}$ value. High peak discharges in 1984-85 at Barahkhetra are perhaps local events caused by the massive breach of eastern embankment upstream of this station, and therefore, they are not reflected at downstream stations. The records at Birpur are much shorter and do not cover these years. The records at Baltara start from 1957 except for 1968 data which is missing. The 1987 flood is well-recorded at both Barahkshetra and Birpur but is not reflected at Baltara apparently due to attenuation of flood peaks downstream. Peak discharge at Baltara has however crossed the $Q_{maf}$ value a couple of times. In fact, the $Q_{maf}$ value at Baltara (7547 $m^3/s$) is much higher than the bankfull discharge (6615 $m^3/s$) at this station and this indicates that the river floods almost every year at this location.

To further assess the severity of floods, inundation depth (difference of maximum water level and danger level) at all the stations have been plotted in **Figure 4**. The danger level is normally taken as the 'bankfull level' for different stations. The graph clearly shows that the danger level has been exceeded every year for all the stations except for Birpur for some years, reflected in negative values. Inundation depths are much higher at Barakshetra in comparison to other stations.

A clear picture of flood intensity and variability emerges from **Figure 5** which plots the deviation of annual peak discharge from $Q_{maf}$ for all stations. Barring one or two years, there is a general correspondence of flooding history at all stations. The data clearly distinguishes several periods of flooding at all stations. While the period 1957-67 indicates no major flooding at all stations, the period 1968-75 has seen regular flooding at most stations. The period 1976-86 shows sporadic flooding at Barahkhestra. The worst period has been 1987-90 which records extensive flooding at all stations. In subsequent years, Barahkhestra and Birpur stations have not seen any major floods but Baltara has recorded two significantly large floods in 1998 and 1999.

Sediment load data for the Baltara station is available for the period 1980-97 in the form of average monthly suspended sediment concentration and tonnage which are normally measured in three size fractions, coarse (>0.2m m), medium (0.2-0.075 mm) and fine (<0.075). The coarse and medium fractions essentially represent the suspended bed load

component whereas the fine fraction represents 'wash' load derived from floodplains and bank erosion.

**Figure 6a** plots average monthly discharge vs. average monthly suspended sediment concentration (fine fraction) and shows that concentration increases with increasing discharge initially but at higher discharge values (close to bankfull discharge) the curve gets flatter. This trend supports the general belief that higher discharges do not associate with the highest suspended sediment concentration (Wolman and Leopold, 1957). The increase in sediment concentration in the Kosi river with the increase in discharge, particularly in terms of 'wash load' (fine fraction), shows that the basin is prone to bank erosion at the initial increase but at higher discharges, bank erosion decreases. In general, the Kosi River has lower concentration of suspended bed load (coarse and medium fractions).

Although a large part of the upper catchments of the Kosi is glaciated and a large amount of sediments are intercepted upstream of the Kosi barrage, the average annual sediment flux for the Kosi at Baltara (43 mt/year; Sinha and Friend, 1994) is still quite high which results in rapid and extensive aggradation within the channel as well as the floodplains. This in turn alters the channel-floodplain relationships and makes the river susceptible to avulsion and large scale flooding (Wells and Dorr, 1987; Sinha 1998; Sinha and Jain, 1998). For example, the highest flood level (HFL) of 36.4 m at Baltara in 1987 occurred at a flood discharge of ~14,000 $m^3/s$, which is much less than the discharge for 1954 and 1968 floods (~24,000 $m^3/s$). This suggests that significant siltation has occurred since 1968 (Agrawal and Narain, 1996) which led to severe reduction in channel capacity of the river and extensive flooding. This observation is further supported by the fact that the minimum monthly discharge of the Kosi River at Baltara has been increasing lately (Fig. 2).

Sediment budgeting for the Baltara station for the period 1980-97 indicates that the annual load for the Kosi is extremely variable over the years (**Figure 6b**). Major variability is in terms of wash load, and therefore, total load variability mimics the wash load curve (fine fraction). The coarse fraction also shows significant variability across the years. While the variations in wash load essentially reflect contributions from floodplain and bank erosion, the coarse fraction may reflect the channel bed aggradation and

degradation. A sharp decline in suspended load (all fractions) is noticeable after 1980 which suggests a significant reduction in bank erosion and channel bed aggradation of the reaches upstream of Baltara. The reduction in coarse fraction is particularly noticeable from 1980 to 1989 and this entire period is interpreted as aggradation period. There is a data gap between 1990 and 1992 and a sharp rise in suspended load between 1993 and 1995 is interpreted as a degradation phase which again returns to an aggradation phase after 1995.

**Flood risk mapping in Kosi basin using GIS**

Traditional methods of flood risk mapping are based on ground surveys and aerial observations, but when the phenomenon is widespread, such methods are time consuming and expensive. Furthermore, timely aerial observations may be impossible due to prohibitive weather conditions. We outline here a multi-parametric approach for delineating the flood-risk areas in the Kosi river basin, north Bihar, India in a GIS environment using one of the multi-criteria decision-making techniques, Analytical Hierarchical Process (AHP). The basic aim of this research is to create easily-readable and rapidly-accessible flood risk maps based on morphologic, topographic, and demographic data. A combination of different data sets such as remote sensing images (IRS LISS-III data), census data (1991), and topographic maps obtained from government agencies have been used to compute a composite index of flood risk based on multi-parametric analysis. Finally, all data have been integrated in a GIS environment to prepare a flood risk map which not only defines the susceptibility of each area to inundation but also provides means for assessment of flood risk in terms of loss of life and property.

The sequence of operations followed for this work is schematically shown in **Figure 7**. A digital elevation model (DEM) of the study area was generated using the spot heights on the 1:50,000 scale topographic sheets of Survey of India as very few contours are available in this extremely flat area. Geomorphic, land cover, and vegetation cover maps were derived from IRS LISS III digital satellite image for the Kosi basin. Demographic data such as population density was obtained from the census data for 1991 and was converted into spatial maps.

All data was integrated in a GIS environment using the Analytical Hierarchical Process (AHP) method which is a multi-criteria decision making technique based on a 9-point scale (Saaty, 1980; Siddique et al., 1996). This method involved a pair-wise comparison of the relative preferences of a small number of 'decision factors' for flood risk assessment after constructing a 'decision hierarchy' (Table 2). The next step involved the determination of Relative Importance Weight (RIW) for each hierarchy element by normalizing the eigen vector of the decision matrix (Saaty, 1980). Finally, a flood risk index (FRI) was computed using overlay analysis in Model Builder of ArcView 3.2 software as follows:

$$FRI = \sum_{i=1}^{N2} \left[ \left(RIW_i^{\,2}\right) * \left(RIW_{ij}^{\,3}\right) \right]$$

Where, FRI = Flood Risk Index, $N_2$ = the number of level 2 decision factor, $RIW_i^2$ = relative importance weight of level 2 decision factor i, $RIW_{ij}^{\,3}$ = relative importance weight of level 3 sub-factor j of level 2 decision factor i.

The FRI values thus obtained for the parts of the Kosi river basins were plotted as histogram and, based on the threshold values, the flood risk map covering 17 developmental blocks was classified into 'low', 'medium', 'high' and 'very high' risk zones (**Fig. 8a**). A first order validation of the flood risk map obtained by our analysis has been done with the MODIS-derived inundation map for the period 1988-2006 (Brakenridge et al., 2006). Figure 8b has been extracted from the MODIS flood inundation map of 2006 which shows the years of the latest inundation of the areas covered in our study. The western parts of the study area have been flooded almost every year and the areas inundated in recent years are shown (the subsequent inundation areas mask the previous inundation). The area in the middle was inundated in 2003 and some small patches were inundated in 1998. A large area in the eastern part has not been inundated since 1988. Although the MODIS map does not include population data, we can make some general observations and validate the results of our risk analysis.

Figure 9 presents the data on the percentage of area of each block falling under different risk zones. In three blocks namely Alauli, Hasanpur and Kusheshwar West, more than 50% of the area falls under very high risk zone, and out of these two blocks, Hasanpur

and Kusheshwar blocks also have more than 50% of their area classified as high risk zones. Three additional blocks namely, Gourabouram, Alinagar, and Biarul also have more than 50% of their area falling in high risk zone. As many as five blocks namely, Kiratpur, Kusheshwar East, Mahisi, Nau atta and Salukha have more than 50% of their area falling in moderate risk zone. The remaining six blocks fall in low risk zone and all of them are located in the eastern part of the study area.

**Discussion**

Floods are natural phenomenon and they play a vital role in maintaining the river form and overbank flows should be expected with a reasonable degree of regularity (Leopold and Maddock, 1955). It is the very mechanics of river formation which demands that highest discharges would not be confined within the channel and overbank flooding will occur. The risk from flooding becomes greater because of the increase in population pressure as more and more floodplain is occupied thereby necessitating the efforts to reduce the flood risk to be stepped up. However, it is very rarely possible to provide complete protection against floods, and therefore, all flood management programmes have to be designed in such a way that it does not give a false sense of security to the people living in the region, as is normally the case in India. Any flood management plan has to conform to local conditions and has to be cost-effective apart from minimizing the adverse effects of flood control measures such as modifications in river sections, waterlogging and increased development in floodplains to avoid greater damages during flooding.

The basis for selection of an appropriate method has to be based on a careful analysis of hydrological data to understand the processes involved and then to extrapolate the changes in the hydraulic regime after applying the flood control measures. The Kosi river in eastern India has defied all flood control measures so far, and therefore, a major policy shift is required for flood management in the region. A proper floodplain zoning and identification of flood risk is essential before planning any further flood control measures.

Our hydrological data analysis shows that the Kosi river displays very high discharge variability and difference between monsoonal and non-monsoonal discharges is as high as 5 times. This results in an enormously excess discharge during monsoon months which

the river cannot carry in its shallow alluvial channels and overbank flooding occurs. This is clearly manifested in the peak discharge variability which frequently exceeds the mean annual flood ($Q_{maf}$). Further, the average inundation depths for Barahkhestra, Birpur and Baltara are 2.55, 0.5 and 1.3 meters respectively, but the highest values have been recorded as 7.5, 2.5 and 1 meters respectively. These values are reasonably high in such a flat terrain where the total elevation difference from Birpur to confluence is about 30 meters and in the alluvial fan area, it is just above 10 meters (35-47m). Another important aspect is the very high sediment flux in the Kosi river which is a reflection of the tectonically active hinterland and very high rainfall in the entire catchment (Sinha and Friend, 1994; Sinha et al., 2005).

It implies therefore that the embankment strategy for taming the floods in the Kosi river basin must be reviewed. The fluctuating discharge and high sediment flux tend to fill up the channel raising the bed level as is reflected from our data and this reduces the available section to carry the excess water even further. The aggradation of the river bed is also confirmed by volume changes in river bed as reported in government memorandums on floods in Bihar (Agrawal and Narain, 1996). Field visits around Baltara also reveal that the river water level within the embankment is flowing at a much higher level than the surrounding ground level. Many of the smaller tributaries joining the Kosi along the right bank have also been obstructed/deflected due to embankment construction and this has resulted in drainage congestion and waterlogging along the embankment. Many of the paleochannels of the Kosi also get rejuvenated during the monsoon and their flow into the present channel of the Kosi is also obstructed due to the embankments along the left bank. In fact, the embankment along the left bank is too close to the active channel and the river has no place to spread its overbank flows. Moreover, there are people living right on the embankment which not only deteriorates the structure but also increases the risk of loss of life and property in case of a breach. The most appropriate strategy for flood management should therefore be a proper floodplain zoning after a careful evaluation of flood risk.

Our GIS-based flood risk analysis incorporates a variety of hydrological, geomorphological and human parameters. The western parts of the study area namely Alauli, Hasanpur and Kusheshwar west blocks are mapped as ‘very high’ risk zone (Fig. 8a). More than 50% of the area of these three blocks fall in very high zone (Fig. 9). Three

other blocks namely, Bilaul, Gourabouram, and Alinagar have more than 50% of their area falling in 'high' risk zone (Fig. 8a, 9) and many of them have patches of very high risk zones. The main factors which have contributed to their classification as very high and high risk zones are very low elevation, proximity to active channels and a moderate population density. It may be noted that although population density has been given a high weightage, the data available is only district-wise, and therefore, does not seem to influence the zoning in a major way. A high resolution data (say block-wise) may provide further insight. This area is frequently inundated due to contributions from the Kamla-Balan and Baghmati system into the Kosi (Sinha, 1998; Jain and Sinha, 2003). Due to poor drainage and low elevation, a number of marshes and swamps have developed in this area as seen on the satellite image (Fig. 1). It is therefore obvious that frequent flooding in this region is caused more by the smaller tributaries rather than the Kosi itself. The MODIS-derived map (Fig. 8b) also shows that these areas have been inundated in all recent years (2004-06). The hydrological data also support our interpretation. The Baltara station falls in this region where flood peaks often cross the mean annual flood ($Q_{maf}$) value (Fig. 3c). Further, the Baltara station also shows very high concentrations of wash load which is mainly contributed by bank erosion and sheet wash from the floodplains. Such high sediment load also tends to raise the bed level and encourage overbank flooding (discussed earlier).

The central part of the study area mainly covering Nau atta, Mahisi and Salukha blocks has been classified as moderate risk zone but has frequent patches of high risk zone. Of particular attention is a large patch of high risk zone at the SE corner (Salukha block) of the study area which happens to have the lowest elevation in the entire window. Although there is no major tributary joining the Kosi from the eastern side, several paleochannels of the Kosi seem to be converging in this region which is causing drainage congestion and inundation. The MODIS-derived map shows that Salukha block has been inundated in 2004 and 2005 and this validates our zoning. The Nau atta and Mahisi blocks falling in the moderate risk zone are probably flooded less frequently; the last inundation happened in 2003 and some small patches were inundated in 1998.

The eastern parts of the study area covering Kahara, Madhepura, Singeshwar, Supaul, Sour Bazar and Simri Bakhtiyarpur blocks fall under 'low' risk zone with parts of Supaul and Simri Bakhtiyarpur falling in moderate risk zone. Supaul and Simri Bakhtiyarpur are

also the two blocks the western edges of which have been flooded in 2005 and 2003 although most of these areas have not been inundated for more than 10 years (Fig. 8b). This is perhaps a manifestation of gradual migration of the Kosi river towards the west during the last 200 years and a sloping sandy bed which does not allow any drainage congestion. These area also have the highest elevations (40-47 meters) in the study window due to positive build-up of the Kosi plains and the population density is also low.

**Concluding remarks**

The Kosi river in north Bihar plains, eastern India shows extreme variability in terms of flood magnitude and frequency both spatially as well as temporally. Data from all three stations, Barahkshetra, Birpur and Baltara, show that the river is extremely prone to flooding and the flood magnitude is generally higher at the upstream station, Barahkshetra. Discharge-sediment relationships conform to the flooding characteristics of the river. Data reflects a large sediment flux in the Kosi river, particularly in the wash load component which is generally a function of local overland flow and severe bank erosion.

A flood risk map has been developed using a multi-parametric approach using hydrological, geomorphological as well as demographic data. Although our map broadly matches with the MODIS-derived map, it is distinctly different in terms of risk assessment. High and low risk zones correspond well with the river migration histories and hydrological characteristics. Such efforts should be a part of non-structural measures of flood management to reduce short term and long-term damages and to bring awareness among the scientific community on the potential need of this research.

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## FIGURE CAPTIONS

1. (a) Location map of the Kosi Basin. The Kosi river has built a very large fan in the alluvial plains and has migrated for more than 150 kms during the last 200 years. Hydrological stations along the river are also marked. Box represents the area for which flood hazard zonation has been carried out; (b) Detailed geomorphological map of the area shown in the box in (a).

2. (a) Average monthly discharge at Baltara station from 1980-2002 (with some data gaps) illustrate the monsoonal climate. Peak discharge normally occurs in the month of August/September. Thick arrow indicates the increase in minimum discharge since 2000 due to rise in bed level; (b) Temporal variation of average annual discharge at Bltara.

3. Peak discharge variation in Kosi River (a) at Barahkshetra (1950-2001); (b) at Birpur (1981-92) and (c) at Baltara (1957-2001). Two large peaks at Barahkshetra station correspond to severe flood years of 1954 and 1968. Peak discharges corresponding to mean annual flood ($Q_{maf}$) and 100-year flood ($Q_{100}$) are also marked.

4. Inundation depth data for Barahkshetra and Birpur stations since 1975; the danger level has been exceeded for all stations since 1993.

5. Deviation of annual peak discharge from mean annual flood ($Q_{maf}$). Data for Birpur is available for the period 1981-1992 only and data for Baltara is not available for 1968 and 1990-94.

6. Sediment transport characteristics of the Kosi River (Baltara station); (a) Fine sediment concentration – discharge Relationship shows that high wash load is not associated with highest discharges. (b) Annual sediment load variation reflects aggradation and degradation phases at Baltara station.

7. Strategy and methodology for flood risk analysis in a GIS environment.

8. (a) Classified flood risk map for parts of the Kosi basin based on AHP; (b) Inundation map derived from MODIS data (modified after Dartmouth Flood Observatory, 2004) validates the GIS-based flood risk map.

9. Flood risk evaluation at development block level in the Kosi basin.

## LIST OF TABLES

1. Discharge and sediment transport parameters of the Kosi River

2. Decision hierarchy and Relative Importance Weightage (RIW) for Level 2 and 3 factors

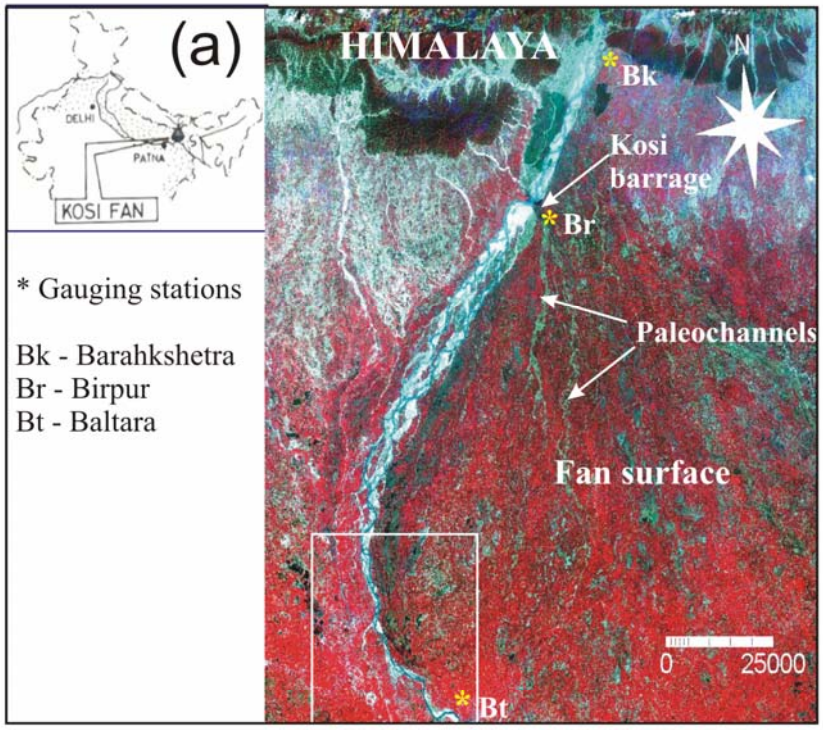
**Table 1: Discharge and sediment transport parameters of the Kosi River**

| **Discharge Parameter** | **Barahkshetra ($m^3/s$)** | **Birpur ($m^3/s$)** | **Baltara ($m^3/s$)** |
|---|---|---|---|
| Average annual discharge (Qav) | N A | N A | 2236 |
| Average monsoonal discharge | NA | NA | 5156 |
| Average non-monsoonal discharge | NA | NA | 1175 |
| Max. observed discharge ($Q_{obs}$) | 25838 (Oct. 1968) | 14833 | 12043 |
| Bankfull discharge ($Q_b/Q_{1.58}$) | 8023 | 7458 | 6615 |
| Mean annual flood discharge ($Q_{maf}/Q_{2.33}$) | 9925 | 9183 | 7547 |
| 100-year flood ($Q_{100}$) | 23085 | 21118 | 13992 |
| Average sediment load (mt/yr) | NA | NA | 43 |

**Table 2 : Decision hierarchy and Relative Importance Weightage (RIW) for Level 2 and 3 factors**

| **Flood Risk Index (Level 1)** | | | | | | |
|---|---|---|---|---|---|---|
| **Decision factors (Level 2)** | | | | | | |
| **Decision factors** | Population density | Distance to active channels | Elevation | Land cover | Agriculture | Geomorphic features |
| **RIW[2]** | 0.49 | 0.23 | 0.15 | 0.07 | 0.04 | 0.02 |
| **Sub- factors (Level 3)** | | | | | | |
| **Classes** | **Cell attribute** | **RIW[3]** | **Classes** | **Cell attribute** | **$RIW_3$** | |
| **Population density (no.)** | | | **Distance to active channels (m)** | | | |
| A | > 1001 | 0.77 | A | 0 – 6.5 | 0.51 | |
| B | 701 - 1000 | 0.17 | B | 6.5 – 13 | 0.26 | |
| C | 401 - 700 | 0.05 | C | 13 – 20 | 0.13 | |
| | | | D | 20 – 27 | 0.06 | |
| | | | E | 27 – 34 | 0.03 | |
| **Geomorphic features** | | | **Elevation (m)** | | | |
| A | Active Channels | 0.34 | A | 33 – 35 | 0.35 | |
| B | Channel Bars | 0.26 | B | 35 – 37 | 0.23 | |
| C | Inactive Channels | 0.15 | C | 37 – 39 | 0.15 | |
| D | Crevasse Deposits | 0.11 | D | 39 – 41 | 0.10 | |
| E | Water-logged areas | 0.06 | E | 41 – 43 | 0.07 | |
| F | Oxbow-lakes | 0.05 | F | 43 – 45 | 0.05 | |
| G | Sand Patches | 0.02 | G | 45 – 47 | 0.03 | |
| H | Flood Plain | 0.01 | H | 47 – 49 | 0.02 | |
| **Land Cover** | | | **Agriculture** | | | |
| A | Running Water | 0.52 | A | Dense | 0.62 | |
| B | Fresh Sand | 0.27 | B | Moderate | 0.24 | |
| C | Moist Sand | 0.13 | C | Less | 0.08 | |
| D | Water-logged areas | 0.05 | D | Barren | 0.05 | |
| E | Agriculture | 0.02 | | | | |

Figure 1


(a)
DELHI
PATNA
KOSI FAN
* Gauging stations
Bk - Barahkshetra
Br - Birpur
Bt - Baltara
HIMALAYA
Bk
N
Kosi
barrage
Br
Paleochannels
Fan surface
0
25000
Bt

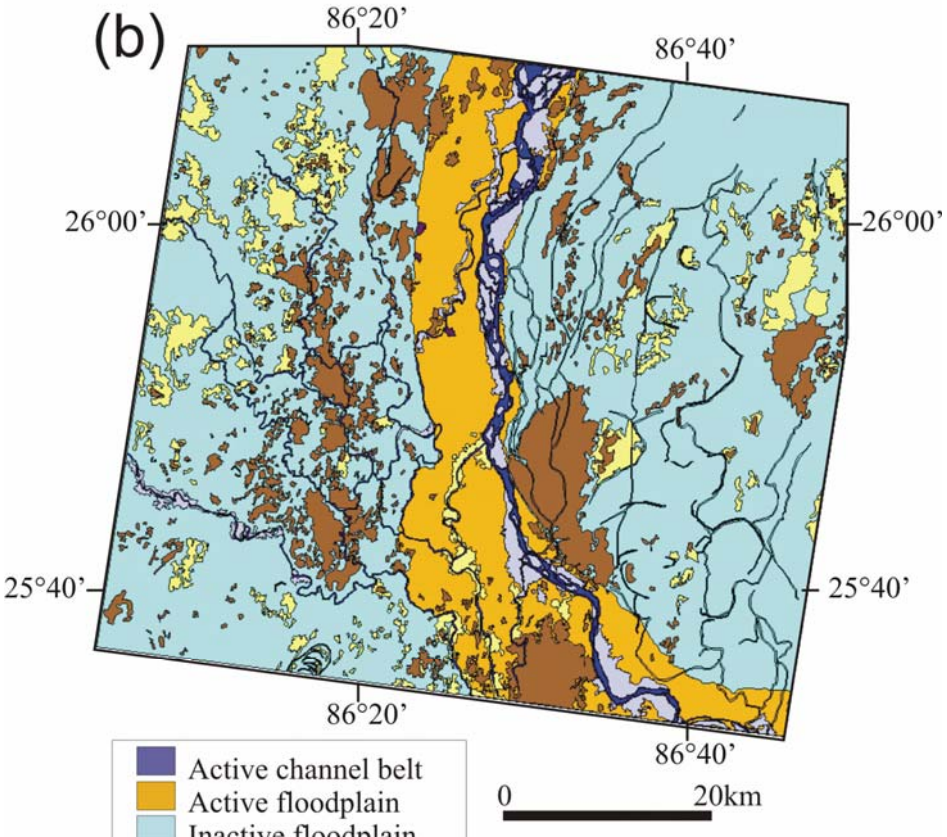

(b)
86°20'
86°40'
26°00'
25°40'
0
20km
Active channel belt
Active floodplain
Inactive floodplain
Channel bars
Sand patches
Waterlogged areas
Paleochannels
Meander scars

Figure 2

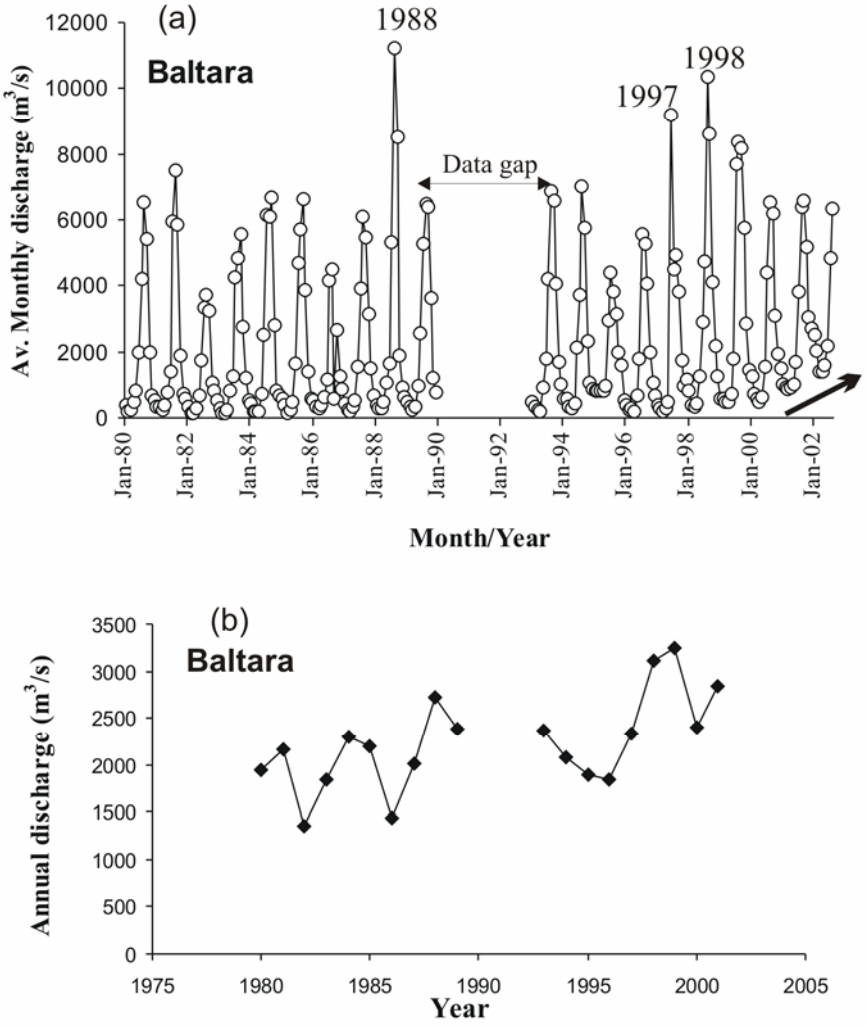

(a)
Baltara
1988
1997
1998
Data gap
Av. Monthly discharge (m3/s)
12000
10000
8000
6000
4000
2000
0
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Month/Year
(b)
Baltara
Annual discharge (m3/s)
3500
3000
2500
2000
1500
1000
500
0
1975
1980
1985
1990
1995
2000
2005
Year

Figure 3

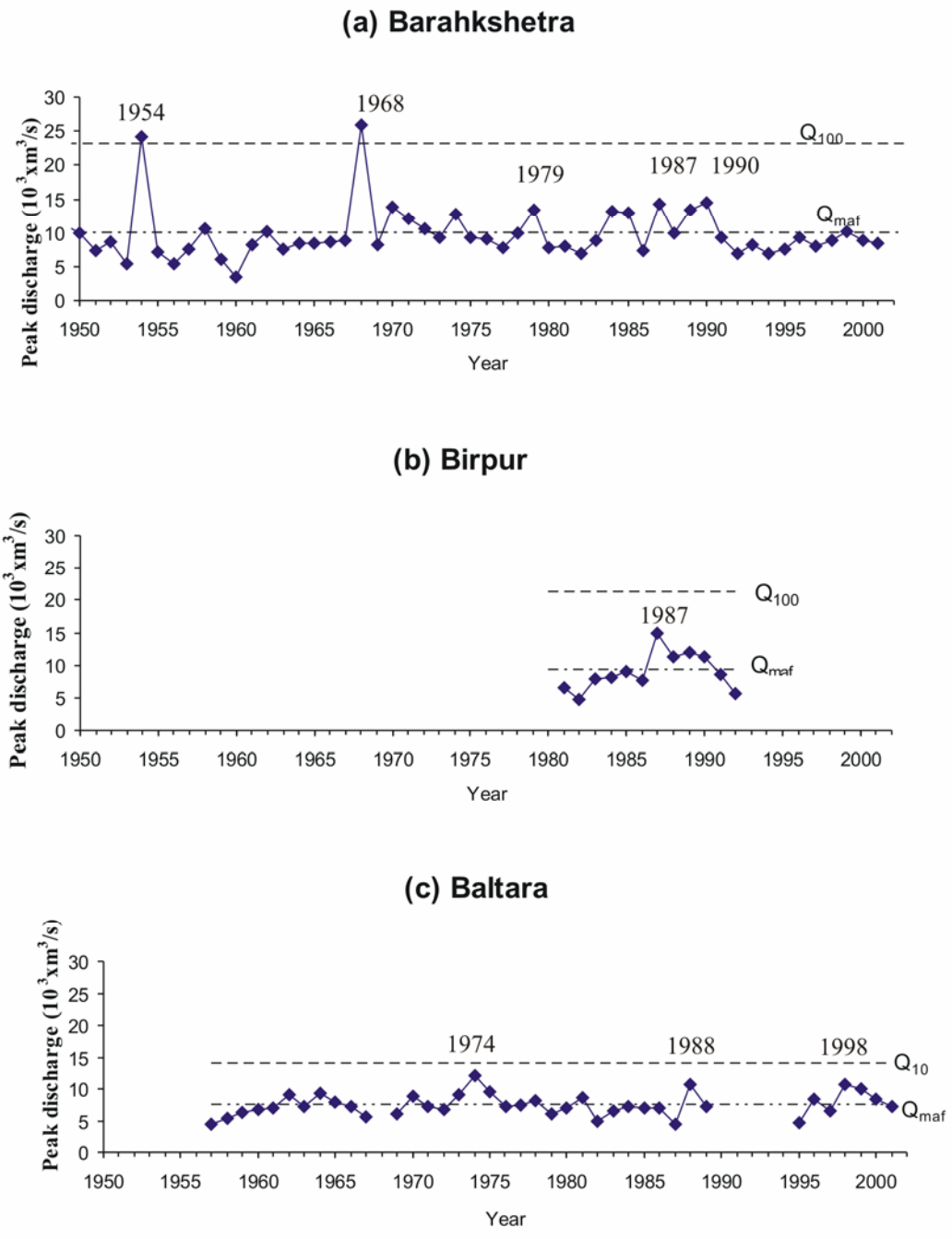

(a) Barahkshetra
Peak discharge ($10^3$xm$^3$/s)
1954
1968
1979
1987
1990
$Q_{100}$
$Q_{maf}$
Year
(b) Birpur
Peak discharge ($10^3$xm$^3$/s)
1987
$Q_{100}$
$Q_{maf}$
Year
(c) Baltara
Peak discharge ($10^3$xm$^3$/s)
1974
1988
1998
$Q_{10}$
$Q_{maf}$
Year

Figure 4

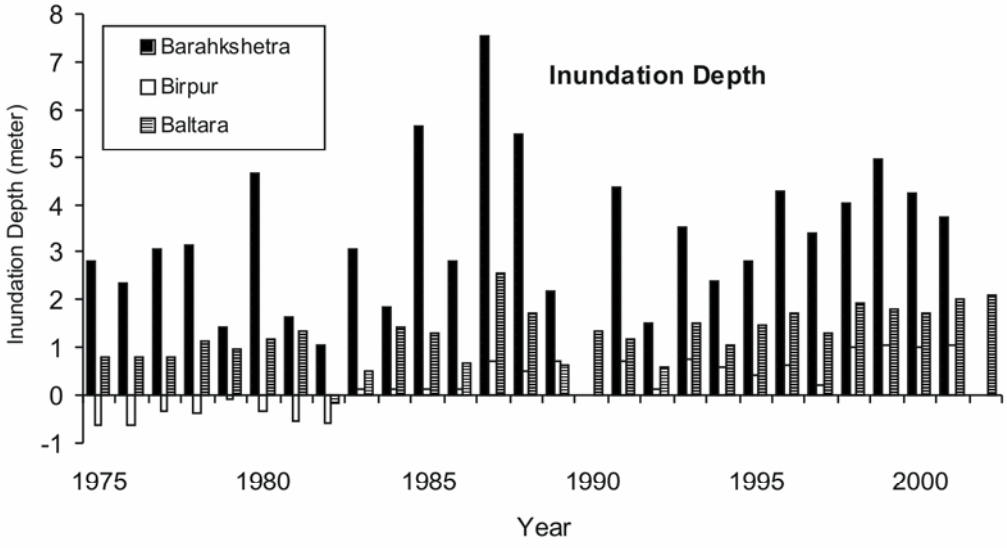



Figure 5

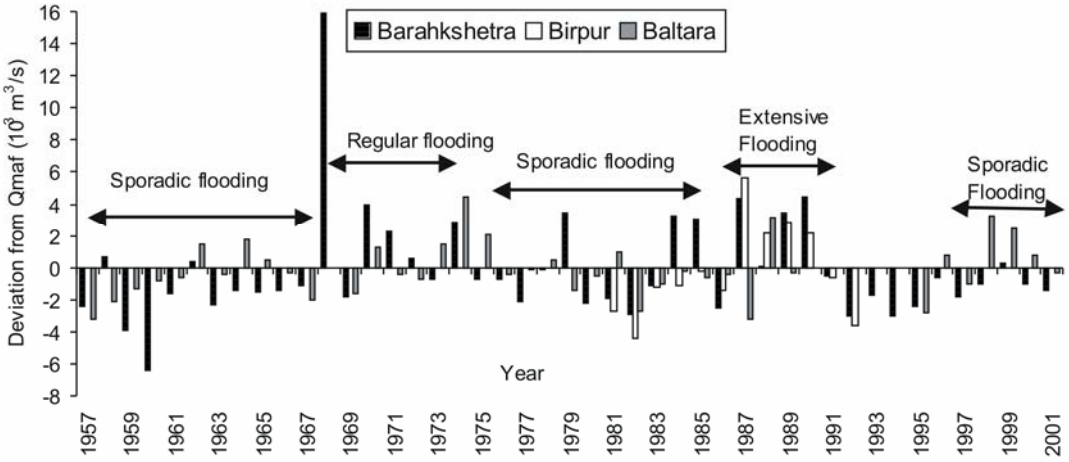
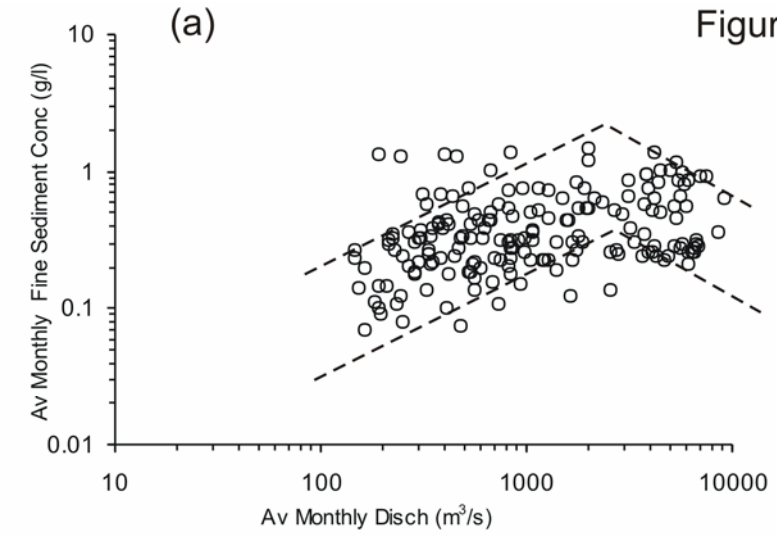


Figure 6


(a)
Av Monthly Fine Sediment Conc (g/l)
10
1
0.1
0.01
10
100
1000
10000
Av Monthly Disch (m3/s)

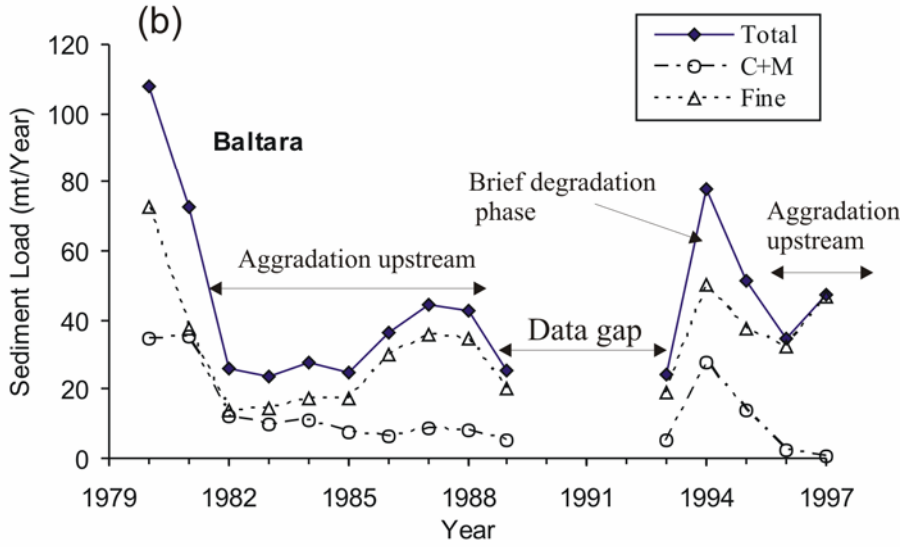

(b)
Total
C+M
Fine
Baltara
Brief degradation phase
Aggradation upstream
Aggradation upstream
Data gap
Sediment Load (mt/Year)
120
100
80
60
40
20
0
1979
1982
1985
1988
1991
1994
1997
Year

Figure 7

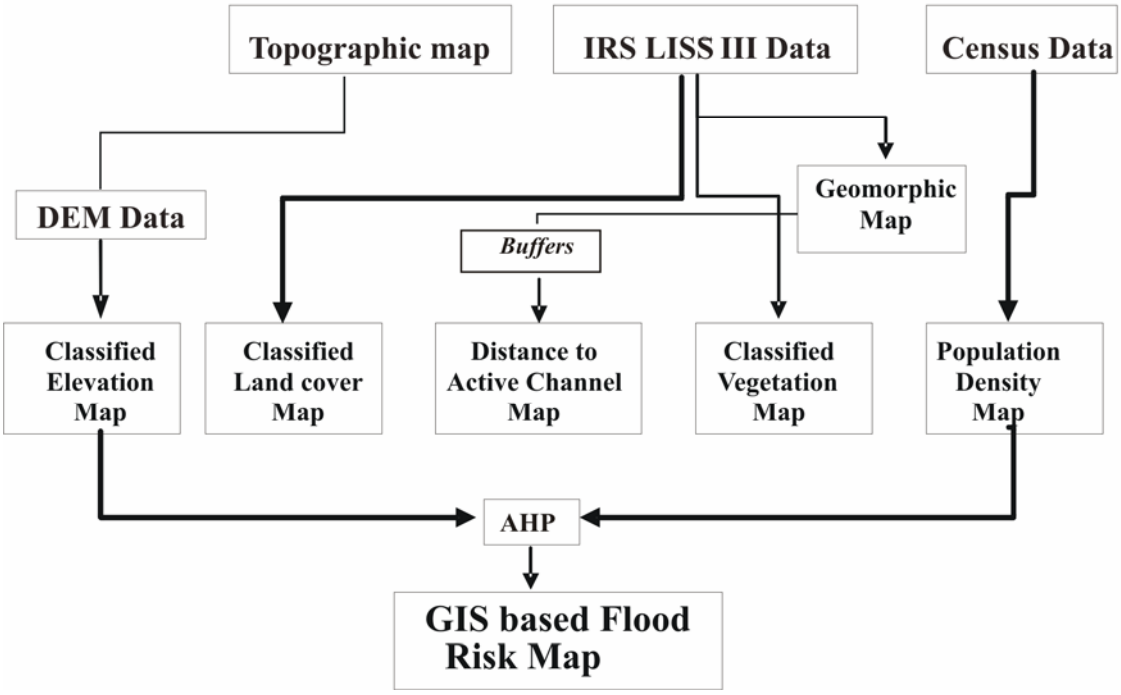

Topographic map
IRS LISS III Data
Census Data
DEM Data
Geomorphic Map
Buffers
Classified Elevation Map
Classified Land cover Map
Distance to Active Channel Map
Classified Vegetation Map
Population Density Map
AHP
GIS based Flood Risk Map

Figure 8a

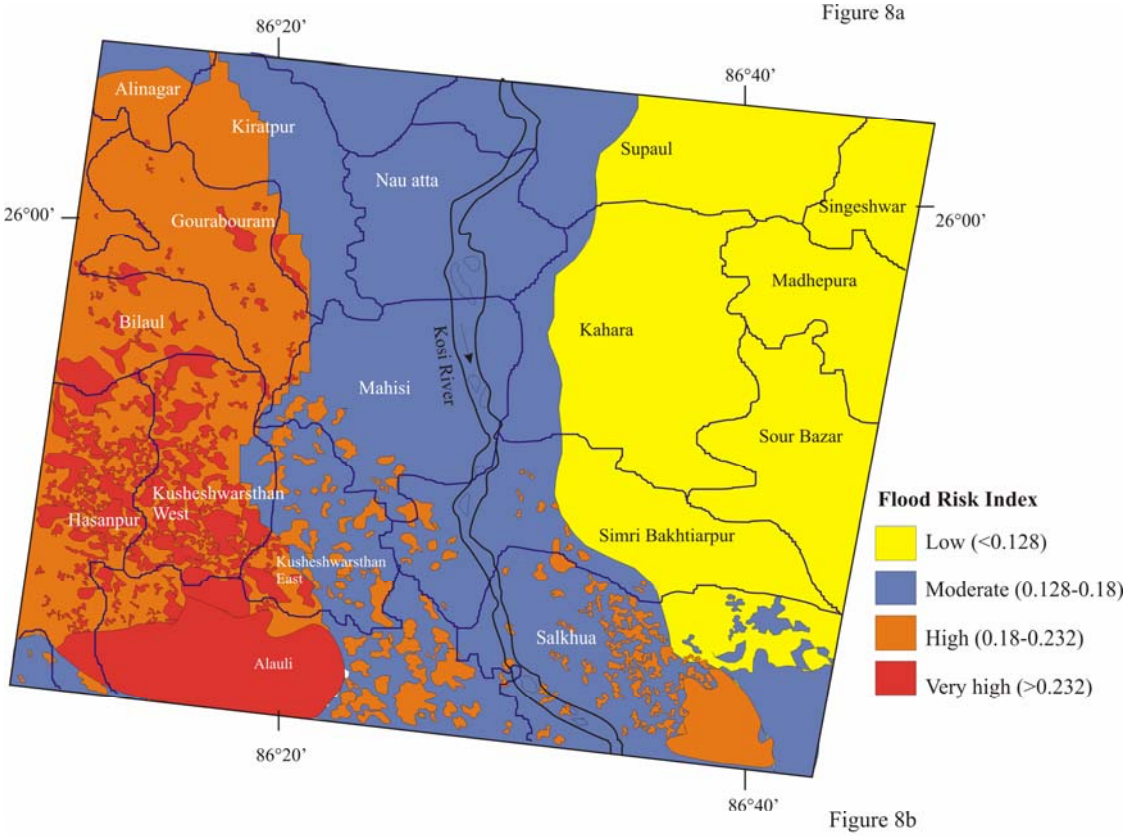



Figure 8b

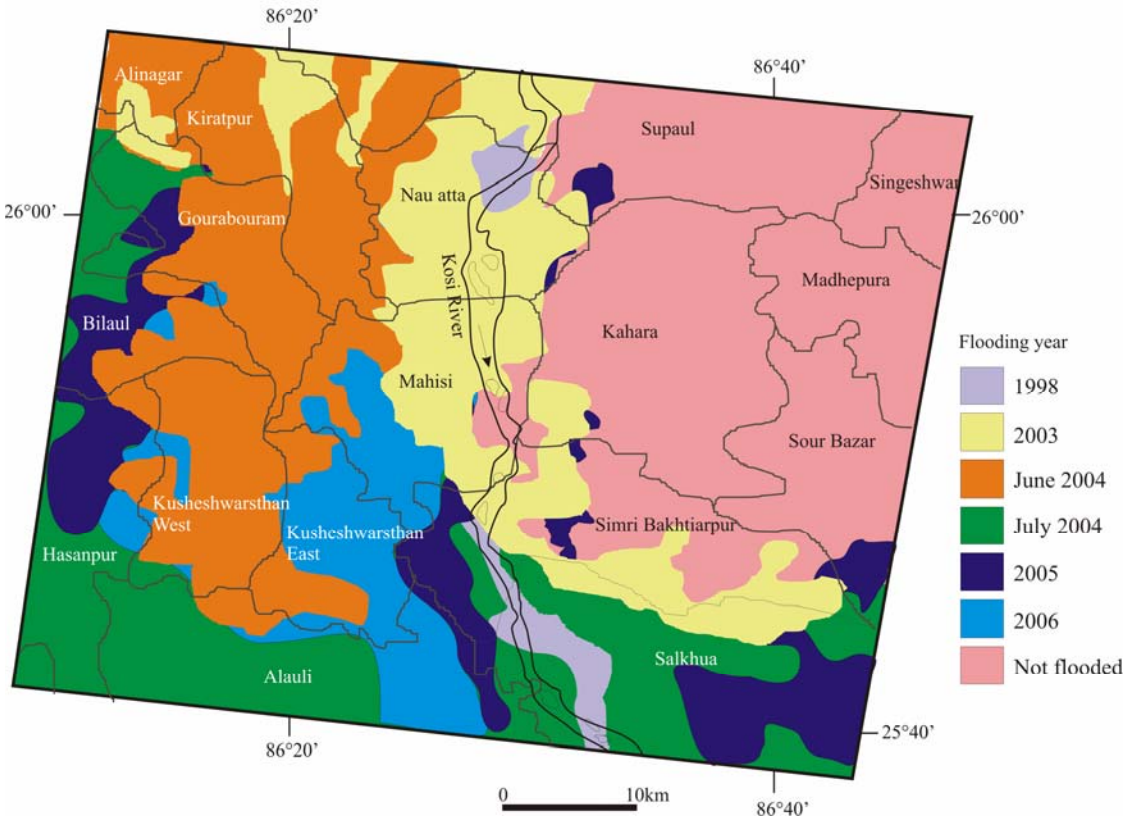
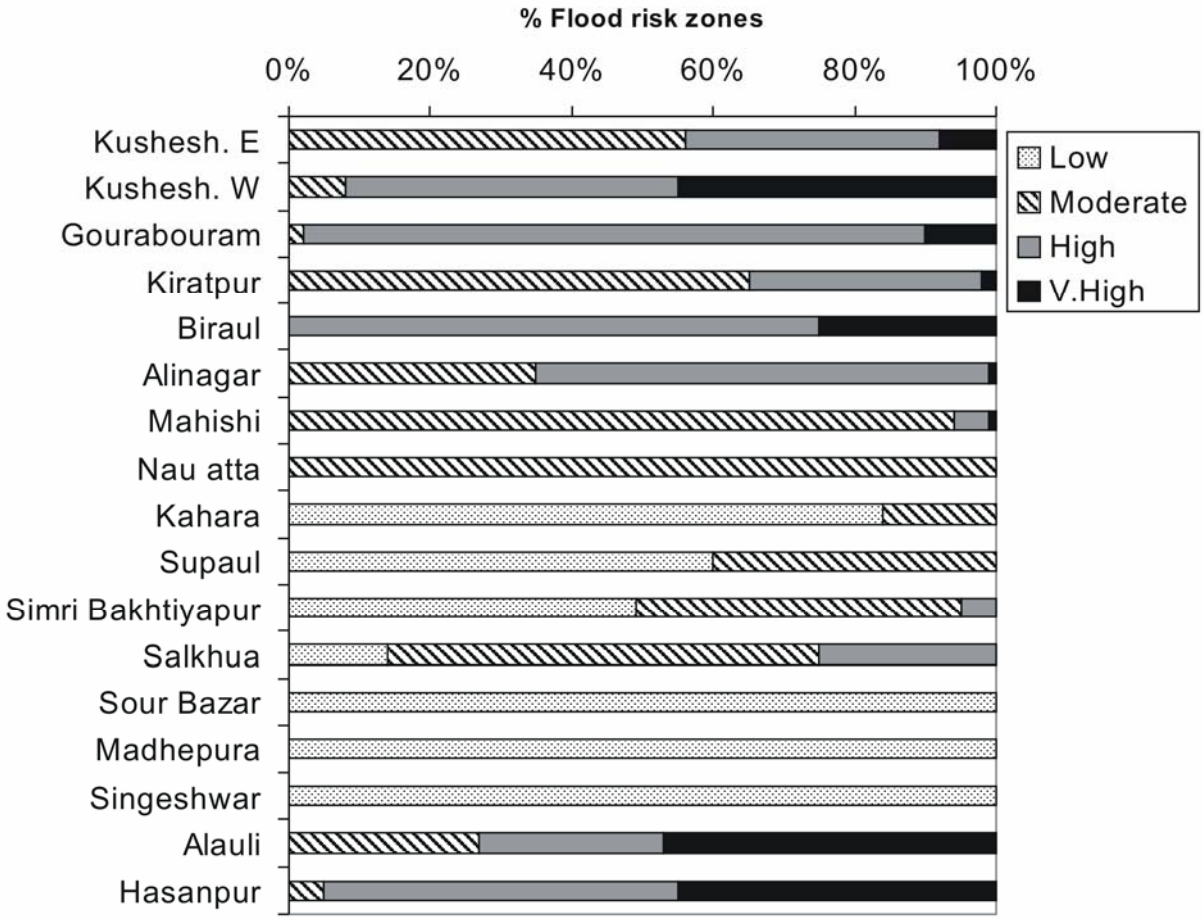


Figure 9


% Flood risk zones
0%
20%
40%
60%
80%
100%
Kushesh. E
Kushesh. W
Gourabouram
Kiratpur
Biraul
Alinagar
Mahishi
Nau atta
Kahara
Supaul
Simri Bakhtiyapur
Salkhua
Sour Bazar
Madhepura
Singeshwar
Alauli
Hasanpur
Low
Moderate
High
V.High