Kosi: Rising Waters, Dynamic Channels and Human Disasters

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The recent Kosi floods have proved once again that inadequate control measures have been responsible for the recurring disasters. Typically flood control and riverine studies focus on hydrological information, whereas a much more integrated approach that pays attention to specific morphological factors is required. Since Kosi is a dynamic river with a unique morphology and because it is a river which has always carried high sediment loads, flood management strategies must be attuned to such specific parameters of the river, besides being much more than mere "river control" through embankments.

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Rivers play a critical role in human society and history as they are the major source of fresh water, transportation, and resources. However, this relationship is often "troubled" because changes in river discharge (floods or droughts) or position can play havoc with permanent settlements. Such changes can be caused by both natural forcing as well as human interventions or a combination of both. Natural processes may include short-term changes in sediment load, water volume or, long-term changes in relative sea level or climate change. Human interventions could impact in changes in sediment load or run-off through water resource management schemes such as dams, barrages and embankments. Human alterations of river systems can have many important consequences primarily because river systems are dynamic and highly integrated systems and any change in any part of the river can easily propagate and affect the whole system. The recent flood in the Kosi is certainly one of the biggest "human" disasters in recent years and it has sent out a strong signal that our flood management strategies are questionable and our preparedness to face such events is far too inadequate.

Further, there has been a paradigm shift in flood management globally from "river control" primarily involving an engineering approach addressing the "effect" at a local scale to "river management" which emphasises an integrated approach at a crossover of scales and addresses the cause rather than the effect. Even though India is a country drained by several large rivers, our river management strategies are rather rudimentary and our planners are yet to embrace modern approaches such as satellite-based monitoring and multi-criteria decision support system. This situation needs to be corrected to save a large population from repeated miseries of floods year after year.

The Kosi: A Dynamic System

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. The gently sloping alluvial surface of the Kosi has been described as "inland delta", "cone" and "megafan" by various researchers owing primarily to building up of a very large positive topography caused by deposition of enormous quantity of sediments carried by the river which it is unable to transport. During the last two centuries, for which records are available, the Kosi river has had a preferentially westward movement by nearly 150 kilometres across its fan surface. Many of the old courses of the river are clearly discernible on satellite images and some of them carry water during monsoon periods. These movements have been described as autocyclic and stochastic, typical in most of the alluvial fans across the world. However, the average frequency of movement of 24 years for the Kosi is among the lowest in the world compared to 1,400 years for the Mississippi river. In most cases, the movement involves a sudden change in course (called "avulsion") originating from a nodal point.

The dynamic nature of the Kosi river has attracted attention for over a century and a variety of mechanisms have been suggested:
(a) Tectonic tilting and nodal avulsions: It has been suggested that the entire plains of north Bihar is subsiding over a geological time period and this has created a westward tilt. Repeated earthquakes in this region are evidence of active tectonic movements in the area.
(b) Discharge peakedness and autocyclic processes: The Kosi river has extremely variable discharge (5-10 times between the average non-monsoonal and monsoonal discharge) and this creates channel instability and bank erosion. An added factor is the high sediment load of the river due to which the bed of the river has been continuously aggrading (the build-up of the river bed by deposit of sediment).

Most of the channel movements of the Kosi also cause extensive flooding, the fan surface being very gently sloping and the channels being shallow. If the river channel has aggraded enough, the monsoon floods may cause preferential drainage into any of the old, least aggraded lowest courses and can get stabilised. In an influential paper by Neil Wells at Kent State University, USA (Wells 1987), it was noted that the Kosi should shift west, one watershed at a time, till it meets another river moving east or its movement is restricted due to topographic barrier – this would cause the eastward sweep over its fan.

Why Do Rivers Aggrade or Degrade?

Before going any further, it may be prudent to examine the factors responsible for aggradation (silting) and degradation (downcutting) in river systems. The well-known balance model suggests that hydrological (stream power) and sediment transport characteristics (sediment supply) are two main fluvial parameters affecting the aggradation-degradation behaviour of the river systems (Figure 1). Specific stream power, defined as (γ.Q.s/w), where γ is the specific weight of water, Q is discharge, s is the slope and w is the channel width, can be considered to represent the sum total of hydrological parameters. It must be emphasised that a right combination of these three parameters would give rise to the requisite specific stream power to erode the river bed and produce incised channels. Research on the rivers draining the Ganga plains at Indian Institute of Technology (IIT) Kanpur by our group has shown that the specific stream power of the rivers draining the western Ganga plains (WGP) rivers (e g, Ganga at Haridwar, Kanpur and Allahabad and Yamuna at Delhi) is significantly higher (40-43 w/m^2) than that of the eastern Ganga plains (EGP) rivers (e g, Kosi, Gandak, Baghmati, and Kamla-Balan) (6-20 w/m^2). Our analysis also shows that for comparable values of discharge and width of channels in EGP and WGP, slope values are distinctly different. This happens because as a river gets bigger, the increase in discharge is largely or partly cancelled by increase in channel width and hence slope becomes the controlling factor for specific stream power.

We have also examined the data on sediment yield of different rivers of the EGP and WGP (Figure 2) which indicates that the sediment supply from the upstream Himalayan catchment is variable from west (Uttar Pradesh plains) to east (Bihar plains). The Ganga (at Haridwar) and Yamuna (Allahabad) are characterised by low sediment yield of 150-350 t/km^2/yr, while Kosi (Barakshetra) and Gandak (Triveni) rivers are characterised by much higher sediment yield of 1,500-2,000 t/km^2/yr. Similarly, the Ramganga river in the WGP has much less sediment yield in comparison to the Baghmati and Kamla-Balan rivers in the EGP. High sediment yields of the mountain-fed rivers in Bihar plains are primarily attributed to the exceptionally high topographic relief in their source areas and high rainfall in their catchments. The foothills- and plains-fed rivers of Bihar plains such as the Baghmati and Burhi Gandak respectively show even higher sediment yields and this indicates that the sediments are remobilised vigorously by the smaller rivers. Lower sediment yields of the rivers draining the UP plains is clearly a function of, apart from the distance from the source areas, difference in rainfall in their catchments and fluvial processes operating in the plains. Further, active tectonics in the mountainous catchment area directly affects the erosion rates and sediment production. A higher uplift rate would eventually mean availability of a larger amount of sediments in the catchment which would ultimately be brought down by the rivers into the plains.

Figure 1
River Aggradation or Degradation Is Controlled by the 'Balance' between Stream Power (Power to Erode and Transport Sediments) and Sediment Supply (Function of Delivery from the Mountains)

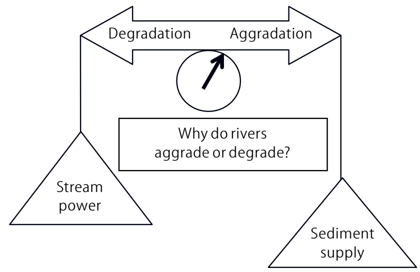
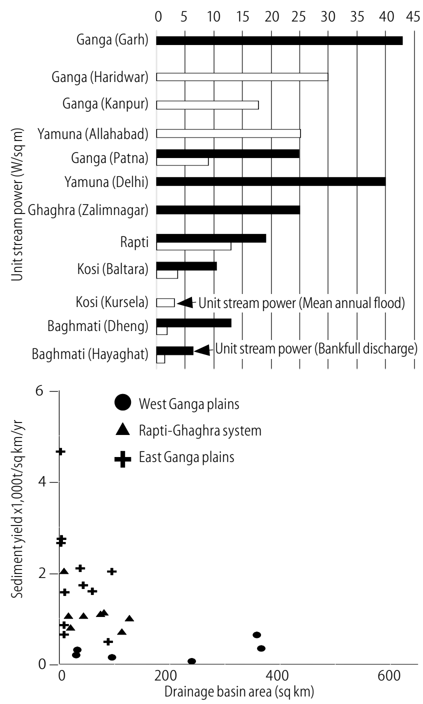


Figure 2
A Significant Variability Is Observed in Stream Power and Sediment Supply of the Rivers Draining the Western and Eastern Ganga Plains. The Plains of North Bihar Have Characteristically Low Stream Power and High Sediment Supply and therefore a Highly Aggradational Regime Is Characteristics of this Region



Tectonically stable catchments would contribute significantly less quantities of sediment to the river systems. Similar to the rainfall distribution, spatial variation in the uplift rate along an east-west transect has also been observed. Research by several workers has shown that the eastern parts of the Himalaya are characterised by higher uplift rate (15-20 mm/yr) along the mountain front in Nepal, based on the analysis of deformation of terraces along Baghmati river system.

The present models on Himalayan seismotectonics predict westward decrease in uplift rate along the Himalayan front in Dehradun (~7 mm/yr). Therefore, not just that sediment production is low in their catchments, there is obviously no remobilisation of sediments due to incised nature of the river channels.

It appears therefore that high sediment supply from upstream area coupled with low stream power in EGP rivers has resulted in aggradation of channels, frequent floods and rendering channels prone to avulsion. To the contrary, in WGP, high unit stream power and lower sediment supply to the WGP rivers may be responsible for degradation and incision of river channel. Such hydrological differences triggered by climatic and tectonic variations may have existed for a fairly long time and this has produced marked geomorphic diversity across the plains. This means that every river has its own peculiarities and therefore needs to be dealt with carefully in terms of its management. Unfortunately, these factors are yet to become a part of river management in India.

History of Flood Management

Keeping in view the hydrological and geomorphological perspectives outlined above, let us now briefly examine the flood management strategies in Bihar plains with particular reference to the Kosi. Initial suggestions for flood control for the Kosi river during late 19th century included construction of marginal embankments, high dam at upstream section, river training in lower reaches and a series of barrages and canals. The famous Calcutta Conference (1896-97) concluded against any major flood control measures except for short embankments. The Patna Flood Conference in 1937 also voted against the embankment strategy and G F Hall, chief engineer noted that "embankments merely transferred trouble from one area to another and that they give rise to false sense of security". A later investigation by C C Inglis also highlighted that the cause of movement of the Kosi river is the building up of the submontaneous delta (fan) due to very large influx of sand from the hinterland and suggested detailed investigations in terms of river discharge, silt load, ground elevations and subsoil water levels before finalising any scheme. No such investigations ever followed and no definitive action could be taken until 1953. The debate on "embankment or no embankment" continued and a certain section of engineers kept pushing the embankment strategy on the grounds that constraining the river between the embankments would increase the waterway of the river through increase in velocity and erosive power. The arguments against the embankment strategy that these would affect the natural flow of water and trap the sediments apart from creating problems of waterlogging prevailed until this time.

A very severe flood in 1953-54 and the subsequent social and political pressure led to the formulation of the "Kosi project" in 1954. The project consisted of (a) a barrage at Bhimnagar and afflux bund, (b) embankment downstream of barrage on both sides, (c) eastern and western canal system, (d) hydroelectric power station in eastern canal, and (e) a high dam at Barahkshetra. 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. Barring the high dam at Barahkshetra, most of the components of the project have been completed or are still in progress. Apart from the huge irrigation potential of the project, the embankments on both sides of the river formed a very important component – designed to protect about 2,800 sq km of land in north Bihar and Nepal from floods. While the success of the entire project is debatable, it has certainly not served the objective of flood control. 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. These issues have been discussed in great detail in a recent book titled *Trapped! Between the Devil and Deep Waters* (Mishra 2008) and have also been reported in the pages of EPW (Mishra 2008). The bottom line however is that flooding problems have been further aggravated by the construction of embankments on both sides and the barrage in the upstream reach. This is not surprising if one recalls the statement of F C Hirst in 1908 that

> …it is more than probable that the heavy floods which in every recent year have devastated several of the North Bihar districts are mainly, if not entirely, due to prevalence of embankments…..An embankment, with little or no waterway through it for carrying off the floodwaters, is a glove thrown in Nature's face – an insult which she has yet not been known to leave unavenged.

Lessons of 18 August

The Kusaha breach on 18 August 2008 was not totally unexpected but the disaster that followed was unprecedented. The breach occurred at a discharge of 144,000 cusecs in the river and more than 80-85% of the flow of the river passed through a new course east of the original course. On 24 August, the river was flowing as an approximately 22 km wide channel and swelled to about 35 km wide in later weeks. Till today the river flows through this new course and has inundated large areas in more than 1,000 villages affecting nearly 350,000 people in the region. This breach was different from all previous breaches which have kept occurring repeatedly along the western or eastern embankment along the Kosi during the last 4-5 decades. During the Kusaha breach, two unusual events occurred: (a) the river moved east of the modern course – unlike the westward migration trend over the last 200 years, and (b) the total movement was of the order of about 120 km – an order of magnitude higher than any single movement recorded in historical times.

Reports available suggest that the eastern embankment around Kusaha has been under pressure for some time. The repetitive satellite images show that the river has been moving towards the eastern embankment at least since 1979. A breach in the embankment at Kusaha was detected as early as 5 August 2008 and perhaps a timely action could have averted such a disaster. However, the fact remains that embankments have not produced the desirable results and that they have already outlived their effective lifespan.

The human intervention with a river like Kosi had perhaps reached a threshold and the lateral movehave occurred sooner or later. The basic principles of earth surface processes govern that large changes happen after a threshold is exceeded. The eastward shift of the river and that too by about 120 km suggests that the river may have reached the threshold of its westward movement and the natural fan building processes would demand an eastward sweep. Most analysts agree that the confinement of the Kosi within the embankment further worsened the situation and has caused significant aggradation within the channel belt. The river was possibly flowing at a higher elevation than the surrounding areas outside the embankment. There have been reports about the rising bed level of the Kosi from many parts in the plains in downstream reaches as evidenced from siltation of canals and sediment budgeting at downstream stations. In the upstream reaches, the Kosi barrage has also accentuated the aggradation. In a study carried out by IIT Delhi for a stretch of 167 km from Chatra to Koparia suggested that all reaches changed from a "degrading" to "aggrading" in the post-embankment period with rates as high as 150 mm/year creating a volume change of the order of 20-30 MCM/year.

Therefore, unlike the previous movements and flooding history, this disaster seems to have a strong human component in terms of our intervention and ill-planned, outdated flood management strategies. Time has come to realise that a long-term solution to floods does not lie in "controlling" the river through embankments but in "managing" the rivers through integrated planning and understanding of riverine processes. This event has once again raised doubts about the embankment strategy although we already had the deplorable results from Chinese rivers and from Damodar embankments. It is time to develop a process-based understanding of rivers and encompass all physical attributes of the earth's surface involved in water cycle for flood management. It calls for a national policy for flood management to reduce risks to the people and to the developed and natural environment from flooding.

What Next?

If there is any lesson to be learnt from the Kosi disaster – unless this event passes off as yet another natural disaster – it is that we need to move towards a strategy which emphasises on "river management" rather than "river control". The embankment strategy has been questioned at the international level citing the failure in Mississippi and three major Chinese rivers and alternative methods such as small-scale irrigation strategies are now favoured flood control measures in many flood-prone countries such as Bangladesh. Our experience shows that there has been no appreciable flood moderation in the Kosi and other rivers of north Bihar even after the construction of embankments and dam and there will be very little effect on the river stage.

It is time to adopt an integrated river basin management which requires a rigorous understanding of the physical processes by which river channels are formed and maintained. An understanding of the historical and site-specific conditions is critical for successful river management including floods. To achieve this, there is a strong need to include the geomorphological parameters of the river basin in flood analysis, as these parameters govern the hydrological response of river basin. In a traditional approach of rainfall-runoff analysis the effect of geomorphology is not considered. However, some recent works have focused on incorporating drainage network parameters and river morphology in flood analysis. More work on this aspect particularly on the Indian rivers is needed for better understanding of flooding processes and their causative factors.

A proper integration of fluvial geomorphology and river engineering aided by high resolution aerial and satellite data is the need of the hour to understand the flooding behaviour of the rivers such as those draining the north Bihar plains. Complete understanding of related fluvial processes such as lateral shifting by avulsion and cut-offs would be extremely desirable to plan the flood control strategy in north Bihar plains. The detailed geomorphological investigations must be coupled with long-term hydrological data to develop a better understanding of the causative factors of floods in the area. The flood mitigation procedures must take into account the geomorphological factors to derive long-term benefits. An associated problem in flooding is the extensive erosion in the hilly catchment area which contributes excessive sediment load to the Himalayan rivers thereby influencing the flow parameters. A better understanding of the sediment supply in the upper catchments of the rivers is necessary particularly in relation to developing long-term solutions to flood mitigation as afforestation and landuse changes. This is where an "integrated management" of river basin becomes crucial.

Another aspect is to develop basin-scale flood risk maps and to improve the decision support systems. 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 need a multi-parametric approach for delineating the flood risk areas in a geographic information systems (GIS) environment. In a recent research with students at IIT Kanpur, we attempted to produce flood risk map in parts of the Kosi river basin, north Bihar using one of the multi-criteria decision-making techniques, Analytical Hierarchical Process (AHP). The basic aim of this research was 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 was used to compute a composite index of flood risk based on multi-parametric analysis. Finally, all data was integrated in a GIS environment to prepare a flood risk map which not only defined the susceptibility of each area to inundation but also provided means for assessment of flood risk in terms of loss of life and property.

Although this map was validated with inundation maps of the National Aeronautics and Space Administration (NASA) for the last few years, it did not show the areas flooded during the recent floods as high risk zones primarily because the August 18 event was not a simple overbank flooding but was caused by an unprecedented shift of the river due to a breach in the embankment. Our model can be improved if such information on long-term migration history of the river can be incorporated along with large volumes of nearly inaccessible hydrological data, repetitive satellite images and anthropogenic factors such as deforestation, history of embankment breaches and other engineering structures. There is an urgent need for the preparation of reliable flood risk maps which should involve (a) a physical flooding system, (b) a historical database on the performance of the system, (c) the distribution of flood risk, (d) options for intervention in flooding system, and finally (e) an efficient decision support system.

Most of our current flood risk management rests on a systemic response to one or a handful of "design events" rather than temporal interactions. Given the complexity of river systems and multiplicity of possible antecedent conditions, it is important to consider as to how the flooding system would perform in a very wide range of conditions. For example, the current floods in the Kosi inundated the areas that are supposedly less flood-prone as these have not experienced floods in the last few years. As a result, a large population has been living there under a false sense of security. If only we had a longer data set and a better understanding of river migration behaviour, we could have developed a more reliable flood risk maps to help flood management procedures.

It is also important to spread awareness about floods amongst the local population. Apart from the misery that floods bring, the beneficial effects of flood have to be understood and the age-old concept of "living with the floods" needs to be reiterated. The river-specific and site-specific knowledge base has to be compiled in the form of guidance documents for planners as well as local population.

Two important issues are currently being debated in various circles: (a) whether or not it is feasible and desirable to bring the Kosi back to its course before the Kusaha breach, and (b) what are the long-term solutions for flood management given that embankments do exist along the Kosi? While several suggestions are floating in the media and informal newsgroups, it may not be easy to comment without a detailed evaluation. A good possibility is to use the new channel as a diversion channel for the excess water during floods and follow the age-old practice of controlled flooding. Perhaps a few other paleochannels of the Kosi can be surveyed and a system of channel networks can be developed as a long-term effort. The course of the Kosi through the barrage and within the embankment would need significant channel improvement perhaps through dredging in selected reaches. Many of the embankments have probably outlived their time span and it may not be advisable to raise them to accommodate additional discharge. However, proper maintenance and continuous monitoring of the embankments are vital to avert such disasters. Apart from this, alternative schemes of flood management (e g, rainwater harvesting, artificial recharge, canal system, dredging, river training, interlinking, etc) and drainage improvement must be seriously examined after detailed studies are undertaken involving academia.

A Wake-up Call

Floods have long been considered as a purely hydrological phenomenon, and flood management has remained the domain of the engineers in this country. Therefore, flood management programmes have essentially focused on hydrological variations and river control. This has been one of the major reasons for the failure of flood management efforts across the globe including India. Hydrological response of a basin is governed by the basin geomorphology and hence, an integrated approach to flood studies should involve the geomorphological understanding of the river basin. Historical data reveal that even after continuous efforts to control the floods, flood damages and flood affected areas in India have increased with time. At present, floods are among the most disastrous natural hazards in India and especially in the north Bihar plains. Repeated failure of flood control measures in different parts of the country calls for an urgent need of an integrated flood analysis including the hydrological, geomorphological and geological understanding of the river basin. The UNDP flood policy study also called for greatly increased research on river morphology, river training, mathematical modelling, and land and water management. A "system" approach to river engineering must become an essential part of flood management.

The Kosi disaster should provoke a critical evaluation of the flood control measures to be immediately undertaken and a document needs to be prepared containing the historical performance of the flood control strategies, impacts of the existing flood control measures, knowledge gaps, and reports from the specific sites in the Kosi basin as well as the surrounding areas. It is important to adopt an integrated river basin management and scientists and engineers should be encouraged to take up detailed studies, to suggest alternative schemes for flood mitigation and to identify the areas in order of priority. A networking of academic, research and governmental institutions undertaking studies on floods, and a multidisciplinary approach can benefit flood management immensely. At the same time, the media should play a proactive role in awareness building among the public.

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