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Geomorphology of the Ganges fluvial system in the Himalayan foreland: an update

Geomorfologia do Sistema Fluvial do Rio Ganges no Antepaís do Himalalia: Uma Revisão Atualizada

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Abstract

The Ganges is one of the largest fluvial systems in the world rising from the loftiest Himalaya and draining into the Bay of Bengal. Together with the Brahmaputra, it also constitutes the largest delta in the world before finally meeting the sea. The Ganges system passes through a variety of terrain from the rugged mountains through the flat alluvial plains and the sea margin, and also transects variable climatic zones. As a result, the processes, landforms and stratigraphy are strikingly different in different zones of the system. This paper attempts to provide an update on our understanding of this very large and diverse system. A global effort has been made in the last few decades, and the research has focused on a variety of themes. The mountainous catchments have attracted attention in view of the extent of glaciation and extensive erosional processes. The alluvial plains of the Ganges symbolizes the life line of one of the world's largest population. Consequently, a number of studies have been carried out on the morphology, hydrology including flooding history and sediment transport behaviour of the river system. The alluvial stratigraphy of the large valleys and the interfluves in the plains has provided insight about the sedimentation pattern and response to climate change. The deltaic plain is the final destination of this huge sediment dispersal system before it drains into the sea, and it also records the influence of sea level changes apart from the upstream catchment controls over a period of time.

Key words: Ganges River, Gangetic Plain, Fluvial Geomorphology, India

Resumo

O rio Ganges é um dos maiores sistemas fluviais do mundo estendendo-se das alturas do Himalaia até a baía de Bengala e, juntamente com o sistema do rio Brhamaputra, constitui também o maior delta do planeta. O sistema do rio Ganges atravessa diferentes relevos (montanhas, planícies interiores e litorâneas) e zonas climáticas que produzem uma variedade de processos, formas e depósitos. O presente trabalho é uma tentativa de sintetizar e atualizar os dados referentes a esse sistema imenso e diverso. Nas cabeceiras montanhosas predominam os processos de erosão glacial ao passo que as planícies sustentam uma das maiores populações do mundo. Conseqüentemente, um grande número de estudos tem sido desenvolvido no tocante a morfologia, hidrologia, paleohidrologia, e transporte de sedimento desse sistema fluvial. A estratigrafia aluvial dos amplos vales e interflúvios têm fornecido informações sobre o padrão de sedimentação e sua resposta às mudanças climáticas. A planície deltaica, que é o destino final dessa imensa quantidade de sedimento, registra informações sobre as oscilações do nível do mar e reflete os controles da bacia a montante sobre um amplo intervalo temporal.

Palavras chaves: Rio Ganges, Planície fluvial, Geomorfologia fluvial e Índia.

1. Introduction

The study of large rivers has gained enormous importance during the last two decades. The geological perspective of such studies has been to develop understanding of the process-form relationships and to use them for interpreting ancient fluvial sequences. Geomorphology has increasingly played an important role in multi-disciplinary research of river systems and there has also been a growing realization of a close coordination between geomorphologists, river engineers and policy makers to work in tandem to understand the process-form relationships and to account for the fluvial dynamics.

The Ganges is one of the several large rivers that originate in the Himalaya-Tibetan uplift and is joined by a number of major Himalayan tributaries such as Yamuna, Ramganga, Ghaghra, Gandak, Kosi, and Tista before meeting the sea in the Bay of Bangal (Fig.1). The mighty Brahmaputra also meets the Ganges and forms a major deltaic depocenter in the Bangal basin. Apart from the Himalayan tributaries, there are also a number of tributaries joining the Ganges system from the Indian craton and Deccan Basalt terrain such as the Chambal (through Yamuna), Son, and Punpun. Given the enormity of the system, the information available so far is still very fragmentary and somewhat flawed keeping view the recent global developments in fluvial geomorphology and sedimentology. This paper attempts to review some of the major aspects of the studies of the Ganges fluvial system and evaluates their relevance in terms of our increased understanding of the fluvial systems across the world. The paper presents a holistic view of the Ganges fluvial system starting from the mountainous catchments to the deltaic plain through the vast alluvial plains.

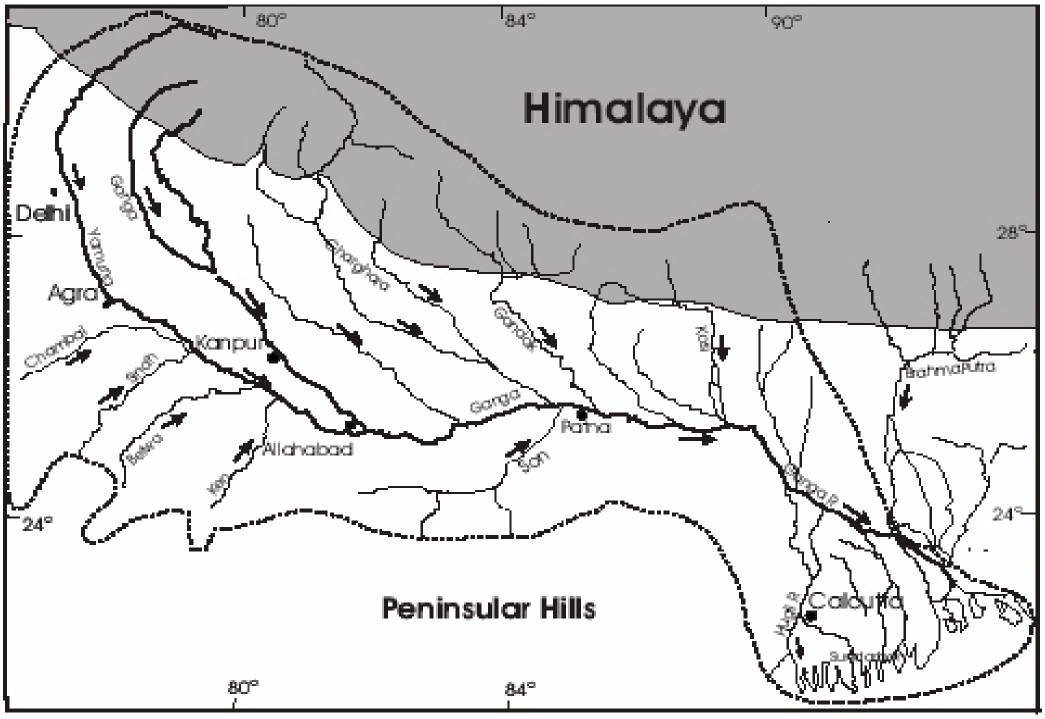

Figure.1. The Ganges fluvial system; The Ganges originates in the Himalaya and drains a large alluvial plains of India and finally meets the sea in the Bay of Bengal forming the largest delta system together with the Brahmaputra river.

2. Mountainous catchments

The mountainous catchment of the Ganges system manifests a complex interaction among glacial processes, tectonic uplift, erosional unloading, bedrock incision and mass wasting processes. The mountainous topography obviously indicates that there is an imbalance between uplift and denudation and there is a growing realization that quantification of these parameters may be necessary to constrain the relationship between landforms and processes. Active tectonic belts such as the Himalaya have lately become the focus of such studies. The Alakananda river draining the Garhwal Himalaya, Uttar Pradesh (India) is one of the major sources of the Ganges system. Rising at the Mana Pass, the Alaknanda joins the Bhagirathi River, originating from Gaumukh in the Gangotri glacier, at Devprayag to become the Ganges. The Alaknanda has shifted its course abandoning its old channel, and is now flowing through a gorge (Fig. 2a) leaving behind conspicuous terraces (Fig. 2b) representing different phases of Quaternary sedimentation. Several abandoned channels, abrupt swings in channel courses, entrenched meanders, valley floors dropping as much as 1000 m below MSL and the terraces standing several meters above the present river level provide eloquent testimony of rapid uplift (~ 5 mm/yr) and variable fluvial incision (2-12 mm/yr). Most of the geomorphic rejuvenation and evolution present-day landforms in this region have taken place in mid Holocene times.

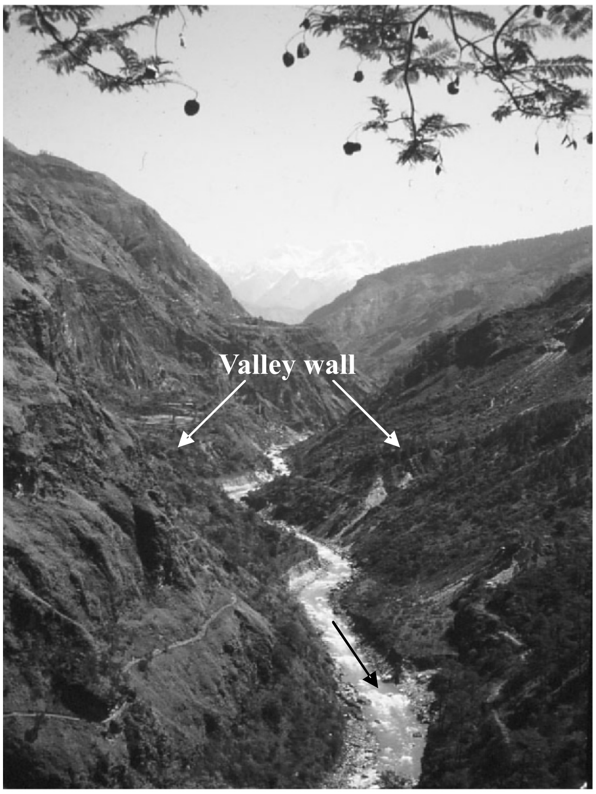

Figure. 2a. A view of the narrow gorge of the Alaknanda river, near Gauriganga, Garhwal Himalaya, India

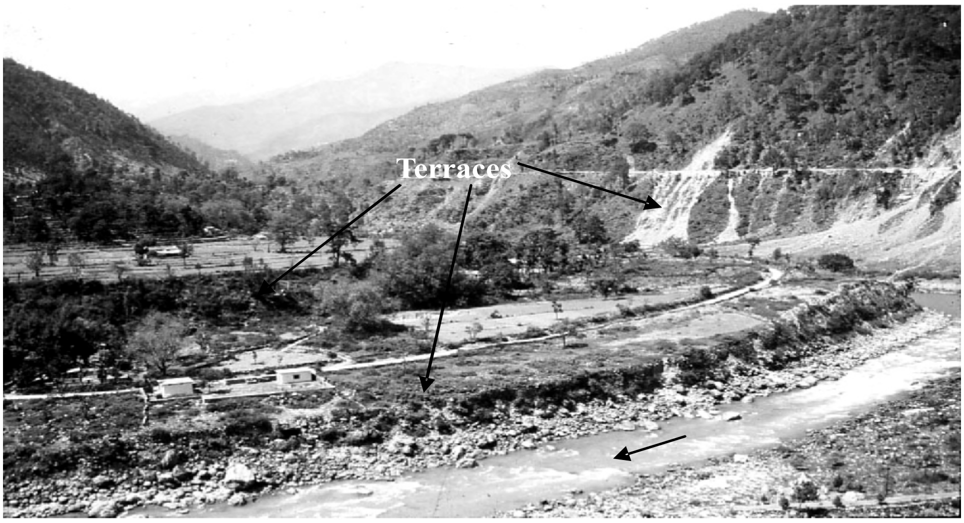

Figure. 2b. River terraces formed in the Alaknanda valley near Karnprayag, Garhwal Himalaya, India

2.1 Glacial landforms

An important line of research in the glaciated catchments of the Himalaya has been to ce examine the extent of major glacial advance through the mapping of glacial landforms. In general, uncertainties exist on the extent of the former glaciation in many regions throughout the

Himalaya essentially due to misinterpretation of glacial landforms and uncertainties in the chronological data base. In the Bhagirathi (one of the main tributaries of the Ganges system) valley, NW Garhwal Himalaya, Sharma and Owen (1996) recognized a major glacial advance (~40km from the contemporary glaciers) during ~63 ka (MIS 4). They suggested that the valley glaciers existed until ~5ka after which there were two minor advances at ~5ka and ~200-300 years BP. In a more recent review, Owen et al. (2002) have shown that most glaciers in the Himalayan region advanced during LGM within ~10km of their present extent but there can be significant spatial variation due to local parameters such as aspect, topographic constraints and valley direction (Sharma and Owen, 1996). Even though the Himalayan glaciers form a very small component of the total glaciated surface on earth, they significantly influence climate change, landscape evolution and fluvial processes operating in the mountainous terrain and alluvial plains. The Ganges and other river systems in the Indian subcontinent are glacier-fed and a major proportion of the total volume of water discharge and sediment transport is contributed from these glaciers.

2.2 Catchment erosion and sediment production

The mountainous catchment of the Ganges system falls in the Garhwal Himalaya which forms the western end of the Central Himalaya in northern India and is situated in a seismic gap along the Main Central Thrust (MCT) that separates the Lesser Himalaya to the south from the Greater Himalaya to the north (Valdiya, 1980). A number of high magnitude earthquakes have occurred in recent past e.g. October 20, 1991 ($M_b = 7.1$) and March 28, 1991 (Ms = 6.6). The entire region is has been undergoing rapid uplift and intense fluvial and glacial incision manifested in steep gullies and deep valleys and large scale erosion. For example, the western Himalayan zone (including the Garhwal Himalaya) faces an erosion rate of about 40 tonnes/ha/yr, which is the highest in the Indian sub-continent (Singh and Venkataramanan, 1991). Erosion and mass movement are also accentuated by the monsoonal climate with a heavy rainfall and cause severe problems including filling up of reservoirs, reduction in water quality, loss of soil cover among a host of others. Apart from the geological and geomorphological factors, the authorities are also to blame for their inability to practice forest management, and their support for indiscriminate developmental activities. Indiscriminate felling of trees for fuel and fodder for cattle has resulted in massive deforestation of the slopes. Many engineering projects meet untimely demise because of increased sediment yield in the catchment due to excessive erosion.

Erosion and denudation in the mountainous catchment of the Ganges system have attracted much attention in recent years and several workers have emphasized the natural and human controls of these mass wasting processes in this region (Valdiya, 1985; Pachauri and Pant, 1992; Owen et al, 1995; Valdiya, 1998; Pachauri et al, 1998; Barnard et al, 2001). The estimates of sediment yield for Asia reveal a rate of 380 tonnes/km^2/yr, compared to 28 and 35 tonnes/km2/yr respectively for Australia and Africa, which are the lowest (Berner and Berner, 1987). The primary factor cited for the above difference in sediment yield is the relief of the drainage basin; Asia having the highest mean elevation of 0.96 km has the highest sediment yield. Similarly, the rivers originating in Himalayas carry more sediment than the peninsular rivers. According to estimates for India, about 5000 metric tons of soil gets detached annually of which about 30% goes to the sea (Narayana and Babu, 1983). About 10% of this gets deposited in the reservoirs resulting in an annual loss of capacity of the order of 2% (Singh and Venkataramanan, 1991). Data show that the Ganges and the Brahmaputra together transport 3% of the total dissolved load of the world. Together, the sediment yield of these two is the largest in the world amounting to 1670 tonnes/yr (Milliman and Meade, 1983).

Several attempts have been made to map the erosion intensity and sediment sources in the Himlayan catchment of the Ganges and the approaches have varied from field based methods (Narayan et al., 1983) to the use of satellite images and GIS (Sinha et al., 2002a; Vaidyanathan et al., 2002). Satellite remote sensing data coupled with published maps and supported by field investigation offer an advantage over field-based methods due to inaccessibility of many parts of the mountainous terrain. Based on scale and extent, two classes of sediments sources are identified by Sinha et al. (2002a) viz. *primary sources including landslide zones, gullies, and terraces and secondary sources including alluvial fan, channel bars, point bars and side bars. The major controlling factors considered in their study are slope, lithology, lineament density, landforms, vegetation, and drainage density. The information extracted from different sources was analyzed in a GIS environment using multi-criteria decision-making technique, Analytical Hierarchical Process (AHP) to produce erosion intensity maps.*

The extensive erosion in these catchments produces a significant impact on landscape evolution. In addition to consistent erosional activities, high-energy events such as landslides (Fig. 3) and earthquakes play a very significant role as formative processes in shaping the landscape. Owen et al. (1995) carried out an extensive mapping of mass movements in the upper catchments of the Alaknanda valley in response to the October 20, 1991 earthquake. Measurements of the amount of debris involved in the mass movement showed that the equivalent landscape lowering due to earthquake and rainfall-induced mass movements was ~0.007 and ~0.02

mm respectively. A similar study was followed up after the March 28, 1999 earthquake in Chamoli area and the total volume of landslide debris in ~226km^2 area mapped was estimated to be 1.3 million m3 (Barnard et al., 2001). The denudation produced by the active landsliding within the study area is equivalent to a maximum landscape lowering of 5.7mm (Barnard et al., 2001).

Figure. 3. The Kaliasaur landslide zone along the Alaknanda valley, Srinagar-Karnprayag section, Garhwal Himalaya, India

An important conclusion of this study was that about two-thirds of the landslides was influenced by human activities and therefore the denudation rates have certainly been accelerated by human interference in the Himalaya (Valdiya, 1985).

The impact of erosion in the Himalaya has been profound and of far-reaching consequences. The loss of vegetal cover has reduced the capacity of mountain slopes to absorb and infiltrate rainwater. This has led to drying up of springs and consequent dwindling of the water resources on one hand; on the other hand it has led to excessive run-off flowing downstream. In addition, a short term but deep impact of these phenomenon has been the loss of innumerable lives, injuries to many, loss of live-stock, destruction of property, burial of natural resources, permanent shut-down of hydro-electric projects, expenditure on road repairs and debris clearing. A very recent example is the August 1998 Malpa tragedy, which took a toll of more than 600 people (Valdiya, 1998). The landslides and rock falls buried the entire village of Malpa along with its people and pilgrims in transit. The mountain region is being fast denuded of its soil cover as a result of quickened pace of erosion in the catchment of rivers and streams. The rivers are carrying incredibly large amount of sediments, generated by widespread and frequently devastating landslides, rock falls and slumping.

3. Alluvial plains

The alluvial plains formed by the Ganges system is one of the largest in the world and forms a major proportion of total agricultural land of India for a large population of about 250 million people. Running roughly east-west, these plains are drained by a large number of rivers most of which form the tributaries of the Ganga river. The following sections describe the morphology, hydrology and dynamics of these rivers and attempt to present a brief account of the alluvial stratigraphy.

3.1 Morphology and hydrological characteristics

One of the first geomorphological mapping of the flat alluvial terrain of the Ganges was done by Geddes (1960) who divided them into fan and interfan areas. This was followed up by detailed morphological and sedimentologic studies of the fans such as the Kosi and Gandak in north Bihar plains (Gole and Chitale, 1966; Gohain and Parkash, 1990; Mohindra et al. 1992; Singh et al., 1993; Singh and Ghosh, 1994). Sinha and Friend (1994) recognized the primacy of source area distinction of the river systems using examples from north Bihar and distinguished 'mountain fed' (e.g. Kosi and Gandak), 'foothills fed' (e.g. Baghmati) and 'plains-fed' (e.g. Burhi Gandak) river systems. The characterization of the

Ganges river systems in the classical straight-braided-meandering types has often posed problems due to the frequent transitions between single-channel and braided morphologies. Friend and Sinha (1993) provided revised definitions of the braiding and sinuosity parameters which allow measurements readily from topographical maps, aerial photographs and satellite image and also has the advantage that the channel length is unlikely to change in a major way with changes of river water level. It was also suggested that the availability of bed load sediment relative to suspended load sediments has much stronger influence on the braiding, contrary to the general belief that slope and discharge are better discriminators of sinuous and braided rivers.

The Ganga and the Yamuna rivers form the major drainage axes of the Ganges system (Fig. 1) and both have multi-channel system with pronounced braiding (Fig. 4a). Although the sinuosity values of the Ganga and Yamuna rivers are comparable, they differ significantly in terms of braid-channel ratios, the Ganga showing much higher values (Sinha et al., in press-a). Most reaches of the Ganga and Yamuna have low sinuosity (<1.5) whereas the interfluve rivers show low to moderate sinuosity (1.5 to 2.5) (Babu, 2003). Field examination of the river channels reveals that most of these rivers are incised by about 15-30 m in the major rivers and 8-10 m in the minor channels (Fig. 4b). In contrast, the rivers of the Ganges system in the eastern plains such as Gandak and Kosi do not

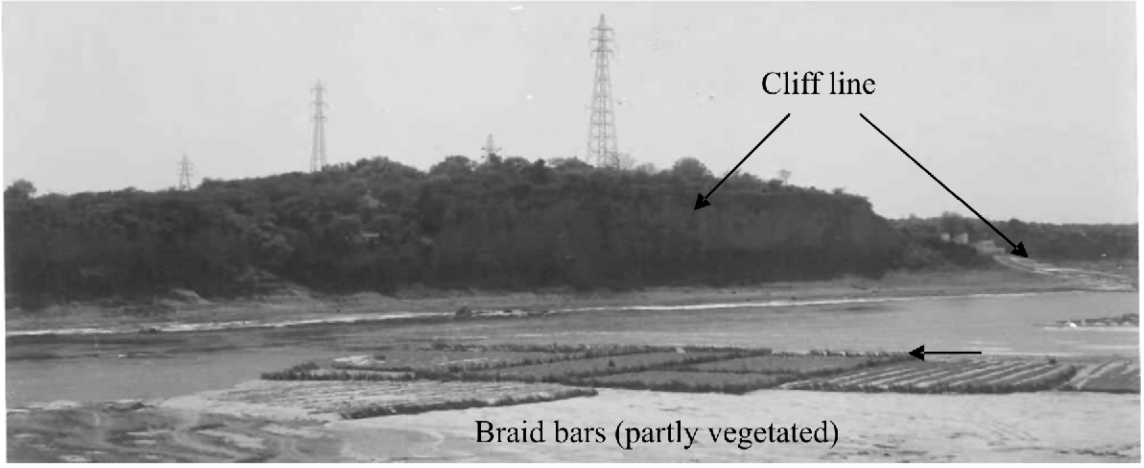

Figure. 4a. Braided Ganga river around Kanpur; Cliff line (~20m) along the southern bank have formed due to incision

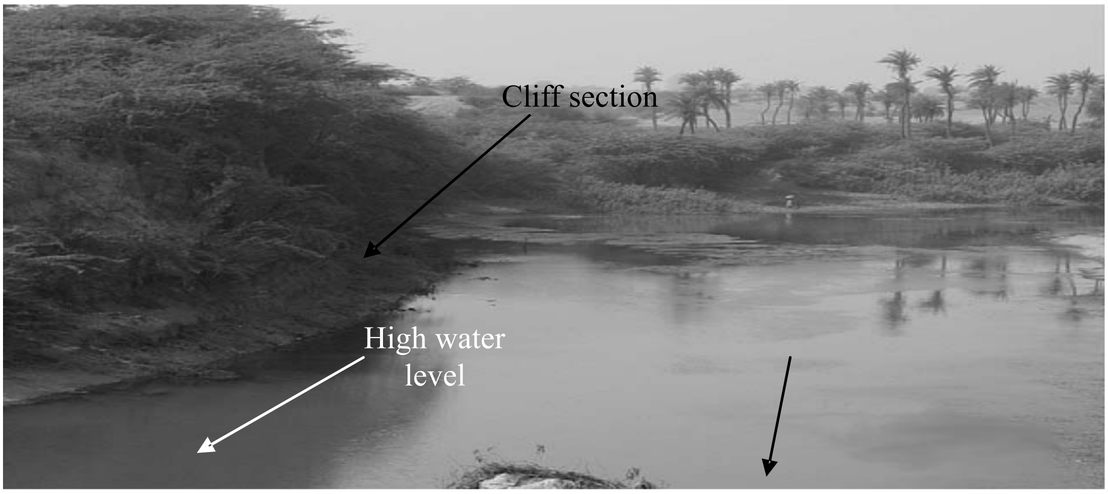

Figure. 4b. An incised section of the Sengar river in the Ganga-Yamuna interfluve. The river is single channel and has a line of cliff formed due to incision

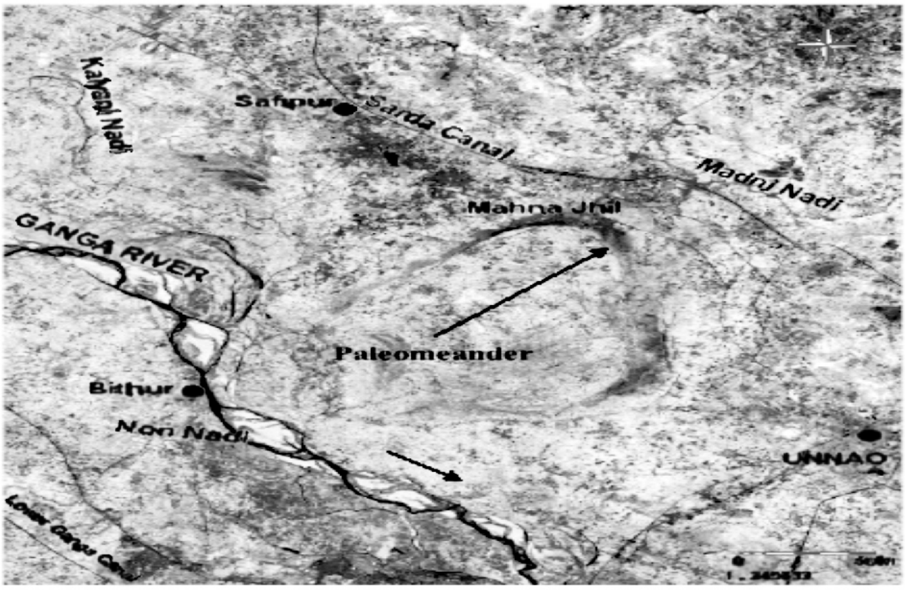

Figure. 4c. Satellite image showing the present-day Ganga river near Bithur (Kanpur) and a large paleomeander located NE of the present-day course

show any incision and most rivers flow at bankfull except in low flow periods and overbank spilling is common. The major rivers namely, are braided and the interfluve rivers consist of single channels with variable sinuosity. Sinha et al. (2002b) described a large paleomeander of the Ganga river around Kanpur (Fig. 4c) and attributed the metamorphosis of channel form to decrease in water budget and increase in sediment load.

Many river system in the Indo-Gangetic plains are anabranching which has been identified as a separate class with distinct morphological and hydrological properties in recent literature (Brice,1964; Rust, 1978; Schumm, 1985 a, b; Nanson and Crook, 1992; Knighton and Nanson, 1993). Chandra (1993) described the anabranching-avulsive Rapti river in the Gandak and Ghaghra interfluve. The avulsive behavior of the Rapti river is characterised by a dominant channel and an underfit secondary channel such as the Ami river (Richards et al., 1993). In north Bihar plains, the anabranching reach of the Baghmati river has increased in length by 25 km in a period of 75 years (1924-2000) and the actual point of bifurcation of channels has moved upstream through repetitive avulsions (Jain and Sinha, 2003a, 2004).

Table 1 shows the discharge and sediment load characteristics of the Ganges river systems. The mountain-fed rivers such as the Yamuna, Ganga (up to Allahabad), the Ghaghra, and the Gandak and Kosi have large catchment areas with average annual discharge varying from 1500-3000 m^3/sec. The foothills-fed systems such as the Ramganga, Rapti, Baghamti and Kamla-Balan have lower discharges (70-500 m3/sec) and smaller catchment areas whereas the plains-fed systems such as the Gomati and Burhi-Gandak drain even smaller areas with average annual discharges of 70-500 m3/sec. Data on sediment yield of the rivers are also presented in Table 1. High sediment yields of the mountain-fed rivers in the eastern tributaries of the Ganges system are due to the exceptionally high topographic relief in their source areas and high rainfall. However, the foothills- and plains-fed rivers show even higher sediment yields and this indicates that the sediments are remobilized vigorously through overbank flooding, bank erosion and channel movements by these rivers. The lower sediment yields of the western tributaries of the Ganges system rivers is clearly a function of, apart from the distance from the source areas, the difference in rainfall in their catchments and fluvial processes operating in the plains. Sediment production is low in their catchments, and the rivers are incised in the plains restricting remobilization of sediments in the western plains. In most rivers, there a downstream decrease in sediment yield is observed due to accommodation of sediments through deposition. Any departure from this trend is generally a function of the exact location of the hydrological station and sediment influx from major tributaries e.g. the Ganga River (Table 1). The Burhi Gandak river in the eastern plains is another exception showing a downstream increase in sediment yield (Table 1), which has attributed to a marked increase in wash load component due to local bank erosion processes (Sinha and Friend, 1994).

3.2 River dynamics

Channel movements through avulsion and cut-offs have been recognized in most of the rivers of the Ganges system albeit with a difference in

Table 1: Hydrological characteristics of the rivers of Gangetic plains

River	**Station**	**Total Basin area (10^3 km^2)**	**Total length (km)**	Av. Annual Discharge (m^3/sec)	**Average Sediment load (mt/yr)**	**Sediment Yield (mt/yr/km^2)**
Brahmaputra	Bangladesh	938	2900	20000	-	-
Ganga	Hardwar	95,500		757	14	0.147
Ganga	Kannauj	240,000		1252	14.5	0.06
Ganga	Allahabad	358,000		4820		
Ganga	Farakka	648,000		14555	729	1.125
Ganga	Bangladesh	1073	2700	15000	1670	1.56
Yamuna	Allahabad	366,000		2949		
Ghaghra	India	127	1550	2128	18	0.68
Rapti	Berdighat	21	782	1730	22	0.78
Kosi	Baltara	101	1216	2036	43	0.43
Gandak	Dumariaghat	46	630	1529	79	1.73
Baghmati	Hayaghat	8,440		189	7	0.854
Burhi Gandak	Rosera	9,580	579	273	15	1.573
Kamla-Balan	Jhanjharpur	9	240	66	10	1.11

(Sources: Sinha and Friend, 1994; Kale, 1997; Kale and Gupta, 2001; Chandra, 1993; GFCC, 1991)

scale and frequency. The early work on the migration of the Kosi river in north Bihar plains by Geddes (1960) and Mookerjea (1961) was followed by several studies (Gole and Chitale, 1966; Arogyaswamy, 1971; Wells and Dorr, 1987; Agarwal and Bhoj, 1992). Mohindra and Parkash (1994) described the migration of the Gandak over its megafan from west to east over a distance of about 105 km in the period of 5000 years. Phillip et al. (1989), Phillip and Gupta (1993) and Sinha (1996) reported migration of several smaller rivers such as Burhi Gandak, Baghmati, and Kamla-Balan in the Gandak-Kosi interfluve. Jain and Sinha (2003a, 2004) have presented one of the most comprehensive data on the 'hyperavulsive' Baghmati river over a period of ~250 years and attributed this to neotectonic perturbences and sedimentological readjustments.

The rivers of the Ganges system draining the UP plains are not as dynamic as the north Bihar rivers, but they do show some channel movement over a long time period. In the area between Bithur and Kanpur Railway Bridge, the main channel of the Ganga river has recorded major movements in the historical period (1857-present between its left and right bank (Hegde et al., 1989) attributed to the highly irregular shape of the valley in the area. The Ghaghra river in the UP plains has also shifted by ~5 km at certain places, on either side of the active channel over a 7-year period of (1975-1982) which has been related with the neotectonics in the area (Tangri 1986). Chandra (1993) noted an avulsion of Rapti river near Baharaich due to aggradation process in the old channel, which caused the SW diversion of the Rapti river. The Sarda river is characterised by several westward lateral shifts in different reaches (Tangri, 1992). Tangri (1992) also suggested an upstream migration of the confluence of the major rivers such as Ghaghra, Gandak, Ganga, Son and Punpun rivers perhaps in response to the change in water budget of source area catchment (Himalaya).

3.3 Flooding history

Flooding is one of the most disastrous natural phenomena in alluvial plains of the Ganges system particularly in the eastern parts which are presently regarded as one of the worst flood-affected regions in the world (Agrawal and Narain, 1996). The plains of north Bihar have the dubious distinction of recording the highest number of floods in India in the last 30 years (Kale, 1997). An excess of 2700 billions of rupees have been spent on the flood protection measures in India but the flood damages and flood-affected areas are still on rise. The flood protection measures have largely failed and one of the important reasons for this has been that floods have long been considered as purely hydrological phenomenon. A geomorphic understanding of floods is lacking. Our recent work has emphasized the role of basin geomorphology on floods (Sinha, 1998; Sinha and Jain, 1998; Jain and Sinha, 2003b, c, d). The overall hydrological response of the basin depends upon, apart from the rainfall intensity and duration, the geomorphometric characteristics, neotectonics and fluvial processes. The dynamic behaviour of river channels and frequent avulsions caused by sedimentological readjustments or otherwise often divert the flow into a newly formed channel with low bankfull capacity causing extensive flooding. Often, people are not prepared for flooding along such newly formed channels and the flood damage is quite severe in such cases.

One of the most important geomorphic considerations in understanding the flooding behaviour of the rivers is the channel-floodplain relationship. In areas of modern sedimentation with continuous subsidence, such as the north Bihar plains, the frequency and extent of overbank flooding is considerable, and most of the rivers carry a very high suspended load and a simultaneous aggradation of the channel bed and the floodplain surface encourages flooding.

The most favored flood protection strategy in the Gangetic plains is to build embankments along the rivers. In most cases, thus measure has proved to be a very short-term solution, and has merely transferred the problem from one region to the other. Apart from interfering with the natural fluvial processes in the region, these embanked areas have developed severe water-logging problems. Large fertile areas have been destroyed due to drainage congestion and increased soil salinity. Jain and Sinha (2003c) suggested that upstream catchment controls such as afforestation, small check dams and regular channel maintenance are better solutions for management of the ravaging floods in the region.

3.4 Alluvial stratigraphy

The alluvial plains formed by the Ganges river system form two distinct depositional regimes. The major rivers form narrow valleys or large megafans separated by wide interfluves. The megafan deposits are characterised by very narrow zone of gravel restricted to the reaches close to mountain front (~10-20km) but are dominated by sandy facies in the plains (braided rivers) with increasing mud component downstream corresponding to meandering channel zone (see Gohain and Parkash, 1990; Singh and Bhardwaj, 1991). The 3D architecture of megafan deposits is composed of multi-storied sand-sheets (generally gravel in upper reaches), typically 8-10 m thick and 16-20m in case of multistoried bodies (Singh et al., 1993) interbedded with overbank muddy layers.

The interfluve stratigraphy in the alluvial plains of the Ganges around Kanpur is characterized by thick (~25-30m) mud deposits are exposed as cliff lines along the rivers (Fig. 5) which are moderately pedogenised with well-developed calcrete horizons (Sinha et al., 2002a, 2005a). In some cases, major depositional discontinuities have also been recorded manifested as swampy and eolian facies (Gibling et al., in press) or as low relief degradational surfaces with gully fills of mud, sand and reqorked gravels (Sinha et al., in press-b). These discontinuity-bound sequences reflect repetitive phases of floodplain aggradation and degradation in response to regional climatic fluctuations during the last 30-40 ka (Gibling et al., in press). The chronological data for these sections suggest that such repetitive floodplain aggradation and degradation dominated the Gangetic plains during Marine Isotope Stage 3-5 (35-100 Ka). This phase was followed by marked changes in sedimentation pattern through the LGM period (Stage 2) and most rivers started incising in early Stage 1. Our work so far has shown that these events show a reasonable correlation with monsoonal precipitation record set out by Prell and Kutzbach (1987). Our work strongly refutes any influence of sea level fluctuations on the stratal architecture of the Ganges alluvium and the effects of tectonics have been minimal. The Gandak-Kosi interfluve in the eastern plains consists of muddy sequences in the top 2-3 meters of along with narrow sand bodies defining former channel positions and very minor sandy layers defining crevasses (Sinha, 1995; Sinha et al., 1996, 2005b). In Sharda-Gandak interfluve, the top 10-20 meters of sediments are characterised by muddy sequences averaging thick medium sand layers (Chandra, 1993). The coarse sand layer was interpreted as possible marker of the Rapti palaeochannel with high-energy fluvial regime.

4. The ganges mouth and deltaic plain

After draining to alluvial plains of UP and Bihar, the Ganga river enters the lower plains area and delta region and finally meets the sea in the Bay of Bengal. The Brahmaputra river draining from NE joins the Ganga and together they constitute the largest delta in the world. The Ganges Brahmaputra together transport ~1x10^{9} t/yr sediments and this puts them among world's largest sediment load carrying system. The Bengal Basin acts as a large sink of this huge sediments disposal system, about 80 % of which is delivered during the monsoon (Goodbred & Kuehl, 2000).

One of the major interests in this region has been to estimate sediment discharge being delivered through the Ganges- Brahmaputra system and to understand its fluctuations in time in response to climate change. It is believed the Ganges- Brahmaputra delta started developing about ~11ka ago when the rising level trapped most of the river discharge on the inner margin (Goodbred and Kuehl, 2000). It has been suggested that there has been significant variation in the sediment discharge under different climatic regimes since ~11ka. Goodbred and Kuehl (2000) estimated a mean load of 2.3x10^{6} ^{t}/yr for the period 11Ka-7ka which is almost twice the present day load of ~1x10 9 t/yr. Such variations have been considered to have resulted due to strengthening of

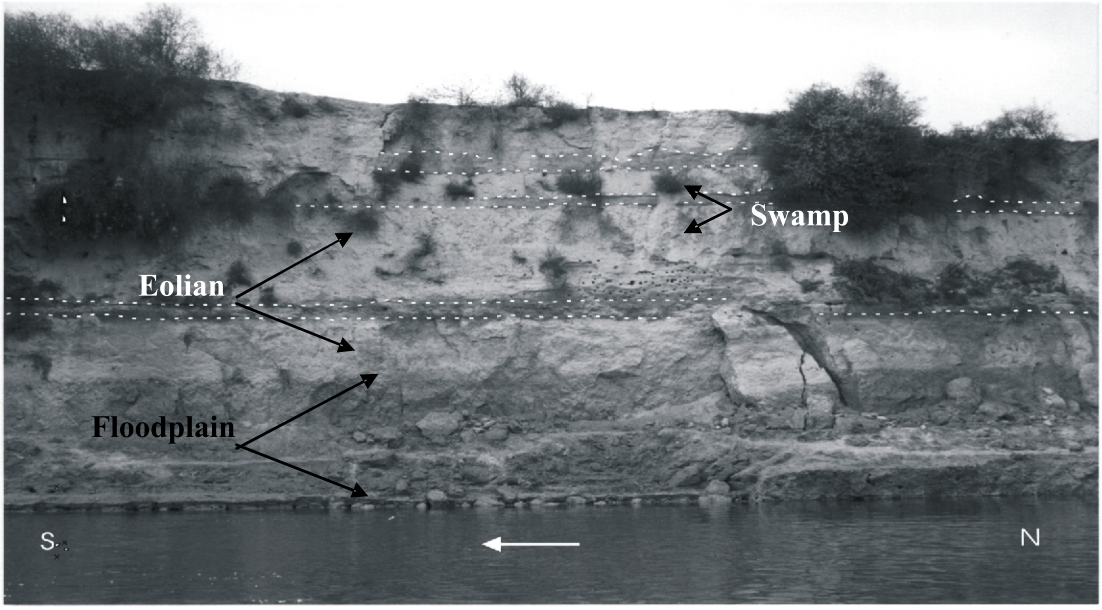

Figure. 5. A typical cliff section along the Ganga river at Bithur (see Fig. 4c for location) displaying the alluvial stratigraphy in the plains. Different stratigraphic units have bee.

monsoon during early Holocene. Goodbred (2003) has presented a mere comprehensive analysis of the response of the Ganges disposal system to climate change and has argued that this system has responded to multi-millenial scale climate change in a system- wide and contemporaneous manner, right from the source to sink. Although this work is based on a rather limited dataset, it drives an important point that sediment signals in the Ganges system are transported very rapidly from source to sink with little apparent attenuation. However, the implication that the entire system responded to climatic changes during the past 60ka synchronously seems to be somewhat generalized keeping in view sharp geomorphic diversity in the Ganges system ~ from source catchment area to the lower delta plain.

In the deltaic region, stratigraphic development has been controlled by, apart from sediment supply, active tectonics and the interplay between the two has resulted in unique and differing stratigraphies within the delta system (Goodbred et al., 2002). Areas of active tectonism have preferentially stored fine-grained sediments whereas high energy conditions have favoured the preservation of coarse-grained sediments. Additional controls are applied by riverine processes such as avulsions and episodic earthquakes. A long history of delta switching in the Bengal basin has been related to channel avulsion of the Ganges and Brahmaputra rivers. Heroy et al. (2002) established a sequence of river switching in the delta sequence using clay mineralogy and heavy mineralogy. The major diagnostic difference between the ganges and Brahmaputra sand fractions turns out to be a low (<1) epidote to garnet (E/G) ratio and relative abundance of smectite in the Ganges alluvium.

5. Concluding Remarks

The Ganges system exhibits unique fluvial processes operating in its three zones viz. source area, alluvial plains and deltaic plain. There are several issues in each of these domains which are continuously being debated and our understanding has improved dramatically in the past decade owing to enormous data generated by researchers all over the globe. Except for the deltaic plain, the upstream controls have played a dominant role in shaping the landforms and in the stratigraphic development of the alluvial plains rather than downstream control such as sea level changes advocated by earlier workers (Kumar and Singh, 1978; Singh et al., 1990; Singh, 1996). The landward limit of sea level changes and its influence on fluvial incision and aggradation has been long debated since Fisk's (1944) estimate of > 1000 km upstream from the modern shorelines but there is now a general agreement that for a low-gradient, high sediment supply systems such as the Ganges, it may not be more than 300-400 km (Schumm, 1993 a,b; Saucier, 1994; Shanley and McCabe, 1994). The western and eastern Gangetic Plains are located ~1500 km and ~800 km respectively from the sea, and therefore, any influence of sea-level related changes in both the regions is ruled out.

Further, even within a zone such as the alluvial plains, recent workers have recorded marked spatial inhomogeneity (Jain and Sinha, 2003e; Gibling et al., in press; Sinha et al.,in press-a) which is a significant departure from previous work where spatial homogeneity in geomorphic development, manifested as regional geomorphic surfaces, has been emphasized over vast regions of the Gangetic Plains. There is a significant implication of such spatial inhomogeneity in geomorphic development in understanding fluvial response to climate change. Spatial or geographical differences in fluvial response due to global change in circulation resulting in simultaneous changes in discharge regimes are expected (Blum and Tornqvist, 2000\) but recent understanding suggests that significant inhomogeneities may also occur in areas separated by less than 1000 km due to spatial differences in sediment supply governed by rainfall and tectonics which in turn would result in 'differential sensitivity' to climate change.

References

Agarwal, R.P. and Bhoj, R., 1992. Evolution of Kosi river fan, India: Structural implication and geomorphic significance. International Journal on Remote Sensing, 13(10): 1891-1901.

Agarwal, A. and Narain, S. (1996) Floods, Floodplains and Environmental Myths. *State of India's Environment: A Citizen Report, Centre for Science and* E*nvironment, New Delhi, pp167.*

Arogyaswamy, R.N.P., 1971. Some geological factors influencing the behaviour of the Kosi. *Records* of Geological Survey of India, 96 (2): 42-52.

Babu, G.P. 2003. Geomorphic characterization and evolution of the Ganga-Yamuna interfluve: a remote sensing approach. Umpublished Master's these, III Kanpur, India.

Barnard, P.L., Owen, L.A., Sharma, M.C. and Finkel, R.C., 2001. Natural and human-induced landsliding in the Garhwal Himalaya of northern India. Gemorphology, 40: 21-35.

Berner, E.K. and Berner, R.A., 1987. Lakes, The Global Water Cycle, Geochemistry and Environment, pp. 241-286.

Blum, M.D. and Tornqvist, T.E., 2000. Fluvial responses to climate and sea-level change: a review and look forward. Sedimentology, 47(Suppl.1): 2-48.

Brice, J. C., 1964. Channel patterns and terraces of the Loup rivers in Nebraska. United States Geological Survey Professional Paper, 422-D, D1-D41.

Chandra, S., 1993. Fluvial landforms and sediments in the north-cnetral Gangetic Plain, India. Ph.D. Thesis (unpublished), Darwin College, Univeristy of Cambridge, UK.

Fisk, H.N., 1944. Geological investigation of the alluvial valley of the Lower Mississippi River, Vicksburg, Mississippi.

Friend, P.F. and Sinha, R., 1993. Braiding and meandering parameters. In: J.L. Best and C.S. Bristow (Editors), Braided Rivers, pp. 105-111.

Geddes, A., 1960. The alluvial morphology of the Indo-Gangetic Plain: Its mapping and geographical significance. Institute of British Geographers, 28: 253-277.

Gibling, M.R. Tandon, S.K., Sinha, R. and Jain, M., in press. Modern interfluves and their expression in the late Quaternary record of the southern Gangetic plains. Journal of Sedimentary Research.

Gohain, K. and Parkash, B., 1990. Morphology of the Kosi megafan. In: A.H. Rachocki and M. Church (Editors), Alluvial Fans: A Field Approach. John Wiley and Sons Ltd., pp. 151-178.

Gole, C.V. and Chitale, S.V., 1966. Inland delta building activity of Kosi river. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 92(HY2): 111-126.

Goodbred, J.S.L., 2003. Response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstade. Sedimentary Geology, 162: 83-104.

Goodbred, S.L. and Kuehl, S.A., 2000. Enormous Ganges-Brahmaputra sediment discharge during strengthened early Holocene monsoon. Geology, 28(12): 1083-1086.

Goodbred, S.L., Kuehl, S.A., Steckler, M.S. and Sarker, M.H., 2002. Controls on facies distribution and stratigraphic preservation in the Ganges-Brahmaputra delta sequence. Sedimentary Geology, 3066: 1-92.

Hegde, M., Mathur, V. K. and Mandal, P. S., 1989. Erratic meander shift of the river Ganga at Kanpur. 3rd Int. Workshop on Alluvial River Problems (TIWARP), University of Roorkee, Roorkee; Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, 239-246.

Heroy, D.C., Kuehl, S.A. and Goodbred, S.L., 2002. Mineralogy of the Ganges and Brahmaputra rivers: Implications for river switching and Late Quaternary climate change. Sedimentary Geology, 3068: 1-17.

Jain V. and Sinha, R., 2003a. Hyperavulsive-anabranching Baghmati river system, north Bihar plains, eastern India, Zeitschrift für Geomorphologie (Annals of Geomorphology), 47/1:101-116.

Jain, V. and Sinha, R., 2003b. Geomorphological controls on hydrological response and its significance in flood management: a case study from a 5th order Himalayan river system. Water Resources Management, 17: 355-375.

Jain, V. and Sinha, R., 2003c. Geomorphological manifestations of the flood hazard: a remote sensing based approach. Geocarto International, 18 (4): 51-60.

Jain V. and Sinha, R., 2003d. Evaluation of

Geomorphic control on flood hazard through GIUH. Current Science, v. 85 (11): 1596-1600.

Jain, V. and Sinha, R., 2003e. River systems in the Gangetic plains and their comparison with the Siwaliks: A review. Current Science, 84(8): 1025-1033.

Jain, V. and Sinha, R., 2004. Fluvial dynamics of an anabranching river system in Himalayan foreland basin, north Bihar plains, India, Geomorphology, 60/1-2: 147-170.

Kale, V.S., 1997. Flood studies in India: A brief review. *Journal of the Geological Society of India, 49: 359-370.*

Kale, V.S. and Gupta, A., 2001. Introduction to Geomorphology, Orient Longman, Calcutta, India, 274pp.

Knighton, A.D. and Nanson, G.C., 1993. Anastomosis and the continuum of channel pattern. Earth Surface Processes and Landforms, 18: 613-625.

Kumar, S. and Singh, I.B., 1978. Sedimentological study of Gomti river sediments, Uttar Pradesh, India. Example of a river in alluvial plain. Senckenbergiana marit, 10(4/6): 145-211.

Milliman, J.D. and Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. The Journal of Geology, 91(1): 1-21.

Mohindra, P.S. and Parkash, B., 1994. Geomorphology and neotectonic activity of the Gandak megafan and adjoining areas, middle Gangetic plains. Journal of the Geological Society of India, 43: 149-157.

Mohindra, R., Parkash, B. and Prasad, J., 1992. Historical geomorphology and pedology of the Gandak megafan,middle Gangetic plains,India. Earth Surface Processes and Landforms, 17: 643-652.

Mookerjea, D., 1961. The Kosi-A Challenge in river control. Journal of Institution of Engineers,Calcutta, 125.

Nanson, G.C. and Croke, J.C., 1992. A genetic classification of floodplains. Geomorphology, 4: 459-486.

Narayan, D., Tandon, S.K. and Joshi, D.D., 1983. Erosion intensity in a mountain watershed in the Himalayan region. Geological Society of India, 24: 533-539.

Narayana, D.V.V. and Babu, R., 1983. Estimation of soil erosion in India. Journal of Irrigation and Drainage Engineering, 109(4): 419-443.

Owen, L.A., Sharma, M.C., and Bigwood, R., 1995. Mass movement hazard in the Garhwal Himalaya: the effects of the 20 October 1991 Garhwal earthquake and the July-August Monsoon season. In: McGregor, D.F.M. and Thompson, D.A. (eds), Geomorphology and Land Management in a Changing Environment, pp.69-88. John Wiley.

Owen, L.A., Finkel, R.C. and Caffee, M.W., 2002. A note on the extent of glaciation throughout the Himalaya during the global Late Glacial Maximum. Quaternary Science Reviews, 21: 147-157.

Pachauri, A.K., Gupta, P.V. and Chander, R., 1998. Landslide zoning in a part of the Garhwal Himalayas. Environmental Geology, 36: 325-334.

Pachauri, A.K. and Pant, M., 1992. Landslide hazard mapping based on geological attributes. Engineering Geology, 32: 81-100.

Phillip, G. and Gupta, R.P., 1993. Channel pattern transformation of the Burhi Gandak River, Bihar, India: A study based on multi-date sets. Geocarto International, 3: 47-51.

Phillip, G., Gupta, R.P. and Bhattacharya, A.B., 1989. Channel migration studies in the middle Ganga basin, India using remote sensing. International Journal of Remote Sensing, 10(6): 1141-1149.

Prell, W.L., and Kutzbach, J.E., 1987, Monsoon variability over the past 150,000 years: Journal of Geophysical Research, v. 92, p. 8411-8425.

Richards, K., Chandra, S. and Friend, P., 1993. Avulsive channel systems: Characteristics and examples. In: "Braided Rivers", J. L. Best, C. S. Bristow (eds.). Geological Society Special Publication, 75: 195-203.

Rust, B.R., 1978. A classification of alluvial channel systems. In: A.D. Miall (Editor), Fluvial Sedimentology, pp. 187-198.

Saucier, R.T., 1994. Geomorphology and Quaternary geologic history of the Lower Mississippi Valley, Mississippi river Commission, U.S.Army Corps of Engineers., Vicksburg,U.S.A.

Schumm, S. A., 1985. Patterns of alluvial river. Annual Review of Earth and Planetary Sciences, 13, 5-27.

Schumm, S.A., 1993. River response to baselevel change: Implications for sequence stratigraphy. The Journal of Geology, 101: 279-294.

Schumm, S.A., 1993. River response to baselevel change: Implications for sequence stratigraphy. The Journal of Geology 101, 279-294.

Shanley, K.W. and McCabe, P.J., 1994. Perspectives on the sequence stratigraphy of continental strata. American Association of Petroleum Geologists Bulletin., 74: 544-568.

Sharma, M.C. and Owen, L.A., 1996. Quaternary glacial history of NW Garhwal, Central Himalayas. Quaternary Science Reviews, 15: 335-365.

Singh, A. and Bhardwaj, B.D., 1991. Fluvial facies model of the Ganga River sediments, India. Sedimentary Geology, 72: 135-146.

Singh, G. and Venkatarmanan, C., 1991. Soil Erosion in different Agroclimatic Zones of India. Jalvigyan Sameeksha, V: 1-6.

Singh, H., Parkash, B. and Gohain, K., 1993.

Facies analysis of the Kosi megafan deposits. Sedimentary Geology, 85: 87-113.

Singh, I.B., 1996. Geological evolution of Ganga Plain-an overview. Journal of the Palaeontological Society of India, 41: 99-137.

Singh, I.B., Bajpai, V.N., Kumar, A. and Singh, M., 1990. Changes in the channel characteristics of Ganga River during Late-Pleistocene-Holocene. Geological Society of India, 36: 67-73.

Singh, I.B. and Ghosh, D.K., 1994. Geomorphology and neotectonic features of Indo-Gangetic plain. In: K.R. Dikshit, V.S. Kale and M.N. Kaul (Eds.), Geomorphological Diversity. Rawat Publications, Jaipur, pp. 270-286.

Sinha, R., 1995. Sedimentalogy of Quaternary alluvial deposits of the Gandak- Kosi interfan, north Bihar plains. Geological Society of India, 46: 521-532.

Sinha, R., 1996. Channel avulsion and floodplain structure in the Gandak-Kosi interfan, north Bihar plains, India. Z. Geomorph. N.F., Suppl.-Bd. 103: 249-268.

Sinha, R. (1998) On the controls of fluvial hazards in the north Bihar plains, eastern India, In: Maund, J.G. & Eddleston, M. (Eds) Geohazards in Engineering Geology, Geological Society of London, Engineering Geology Spl. Publication 15:35-40.

Sinha, R. and Friend, P.F., 1994. River systems and their sediment flux, Indo-Gangetic plains, northern Bihar, India. Sedimentology, 41: 825-845.

Sinha, R., Friend, P.F. and Switsur, V.R., 1996. Radiocarbon dating and sedimentation rates in the Holocene alluvial sediments of the northern Bihar plains, India. Geological Magazine, 133(1): 85-90.

Sinha, R. and Jain, V., 1998. Flood hazards of north Bihar rivers, Indo-Gangetic plains. Memoir Geological Society of India, 41: 27-52.

Sinha, R., Das, S. and Dikshit, O., 2002a. GIS-assisted mapping of catchment-scale erosion and sediment sources, Garhwal Himalaya, India. Z. Geomorph N.E., 46(2): 145-165.

Sinha, R., Khanna, M., Jain, V. and S.K.Tandon, 2002b. Mega-geomorphology and sedimentation history of parts of the Ganga-Yamuna plains. Current Science, 82(5): 562-566.

Sinha, R., Tandon, S.K., Gibling M.R., Bhattacharjee, P.S. and Dasgupta, A.S. (2005a) Late Quaternary geology and alluvial stratigraphy of the Ganga basin, Himalayan Geology, 26(1), 223-240.

Sinha, R., Gibling, M.R., Jain, V. and Tandon, S.K. (2005b) Floodplain processes and sedimentation in a hyperavulsive anabranching river system in the Himalayan foreland basin, India. In: Fluvial Sedimentology (eds. Blum, M. and Marriott, S.), Special publication of the International Association of Sedimentologists, 35, 181-196.

Sinha R., Jain V., Prasad Babu G., and Ghosh S. (in press-a) Geomorphic characterization and diversity of the rivers of the Gangetic plains: morphology, processes and controls. Geomorphology.

Sinha, R., Gibling, M.R., Tandon, S.K., Jain, V. & Dasgupta, A. S. (in press-b) Quaternary stratigraphy and sedimentology of the Kotra section on the Betwa river, Southern Gangetic plains, Uttar Pradesh. Jour. Geological Society of India

Tangri, A.K., 1986. Understanding the dynamics of Ghaghra river system in Uttar Pradesh, India, using satellite remote sensing, Proceedings of the seventh Asian conference on remote sensing. Korean Society of Remote Sensing, Asian Association on Remote Sensing, Seoul, Korea. Actes: 1 - 6.

Tangri, A. K. (1992) Satellite remote sensing as a tool in deciphering the fluvial dynamics and applied aspects of Ganga plain. In: Singh, I.B. (ed.) Gangetic Plain: Terra Incognita; Department of Geology, Lucknow University, 73-84.

Vaidyanathan, N.S., Sharma, G., Sinha , R. and Dikshit, O., 2002. Mapping of erosion intensity in the Garhwal Himalaya. Int.J.Remote Sensing, 23(20): 4125-4129.

Valdiya, K.S., 1980. Geology of the Kumaun Lesser Himalaya. Wadia Institute of Himalayan Geology, Dehradun:.9-158.

Valdiya, K.S., 1985. Accelerated erosion and landslide-prone zones in the central Himalayan region, Environment regeneration in Himalayas: Concept and strategies. The Central Himalayan Environment Association and Gyanoday Prakashan, Nainital, 12-57.

Valdiya, K. S., 1998. Catastrophic Landslides in Uttaranchal, Central imalaya, Journal of the Geological Society of India, 52 (4): 483-486.

Wells, N.A. and Dorr, J.N., 1987. Shifting of the Kosi river, northern India. Geology, 15: 204-207.