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Status Report

Large River Systems of India

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The Indian sub-continent is host to several large rivers, which are distinctive in terms of their hydrology and sediment transport characteristics due to monsoonal climate and tectonic setting. Many of these rivers have attracted international attention for the last several decades and continue to do so. This paper highlights the major research contributions on various aspects of large rivers of India made during the last 5-6 years. Some of the important themes covered in this paper include glacier-river interactions, erosional history and sediment dynamics, river processes including flood hazards, alluvial stratigraphic development and river management. A couple of large-scale initiatives on the Ganga River attest to the change in the mindset of the policy makers. The use of modern techniques such as remote sensing and GIS, digital elevation models, high-precision measurements such as kinematic GPS, Total Station and ADCP in river surveys is being realized by researchers as well as river managers. We emphasize the emergence of River Science as a discipline that aims to study the integration of hydrological, geological, chemical, and ecological processes and their interactions, and suggest that the Indian researchers and river managers promote this new approach which links river management to river health.

Key Words: Himalayan Rivers, river science, river health, river dynamics, Ganga River basin

1. Introduction

Large river systems constitute one of the most important continental geomorphic systems that have sustained civilizations for more than 5000 years. Large rivers are generally defined by one or more of the following criteria: drainage area (A) = 800000 km^2, river length (Lr) = 2500 km, average discharge (Q) = 7500 m^3/s, and suspended and dissolved load = 100 mt/yr (Potter, 1978; Hovius, 1998; Gupta, 2007). The subject of large rivers can be approached from different perspectives. A modern perspective emphasizes the hydrological, sediment transport and network organization of large rivers. This perspective also includes the process-based understanding of the rivers and river management in the backdrop of future sustenance of human civilizations. From a geological or stratigraphic perspective, the reconstruction of ancient large river systems through the methods of sedimentary basin analysis and long-term development of alluvial architecture has been highlighted. Potter (1978) suggested that most large rivers 'have large, long-lived deltas which have played a major role in both deep and shallow waters'. Alluvial stratigraphic records preserved in most large rivers and their valleys have enabled an understanding of the development of large rivers on different time scales – century, millennial, tens of thousands of years, million and tens of millions of years.

Tandon and Sinha (2007) reviewed the origin and evolution of large rivers across the globe in a variety of tectono-climatic settings and assessed geological criteria for the definition of large rivers. Maps of the distribution of modern large rivers in different tectonic settings and climatic regimes were used to throw light on their genesis and sustenance. The authors discussed the hydrological and sediment dispersal aspects of the large rivers in the light of climatic variations and source area characteristics. A direct manifestation of sediment dispersal by large river systems is the sedimentary architecture developing below the alluvial plains, and not surprisingly, the large rivers display a strong variability in terms of their alluvial architecture. Many of the large rivers originate in active mountain belts and terminate in open oceans after draining through large alluvial plains. These systems are influenced by sea level changes, tectonics and climate change in different parts of their catchments but the extent of these controls and their coupling are not well understood. Fig. 1 shows the large rivers in the Asian region along with rivers in India with lengths more than 1000 km. The Indian sub-continent hosts three large rivers, the Ganga, Brahmaputra and Godavari. All these three rivers have high sediment yield; the Ganga and Brahmaputra are essentially Himalayan drainages with high sediment production in active tectonic settings whereas high sediment yield of the Godavari in spite of its cratonic

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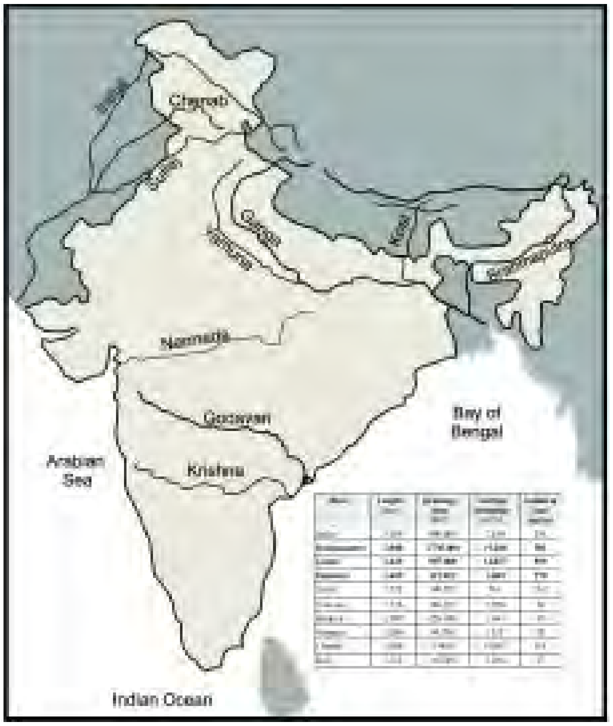

Fig. 1: Rivers of India with length >1000 km. Out of these, three rivers namely, the Ganga, Brahmaputra and Godavari fall in the category of Large Rivers

setting is a reflection of tropical weathering of Deccan Basalts and therefore higher sediment production (Tandon and Sinha, 2007).

Large river systems constitute the lifeline for the future of human populations, and therefore, it is important to understand them with the aim of securing their futures and thereby our own futures. Large rivers have supported civilizations in the south Asian region for more than 5000 years, leading up to a population hotspot that hosts almost a fourth of the globe's human population. It is postulated that comparative climatic extremities have strongly influenced human habitation and at times negative impact of such systems on continental drainages have led to the collapse of major river bank civilizations (Ponton *et al*. 2012). The close relationship between large rivers and human habitation has in turn led to significant human interventions and impacts on the freshwater systems of the region. Future rise in human population is likely to result in an unprecedented impact on freshwater availability in many parts of the world including India. Therefore, the understanding of water problems and water security in this region has to be based on holistic approaches that should focus on dynamic strategies for the management of natural freshwater systems.

2. Cryosphere and Large River Interactions

Freshwater supply from the Himalayan ice-fields and glaciers is a critical resource for a large population in India because they sustain dry-period low flows for major rivers, such as the Indus, Ganges and Brahmaputra Rivers, in the south western Himalaya. The Indus and Ganges Rivers currently have little outflow to the sea during the dry season owing to large extractions and human interventions. The realistic quantitative estimates of hydrological impacts of glacial retreat on the water resources of these rivers are still fragmentary. Some data for the Chenab, Parbati and Basapa basins have been published (Kulkarni *et al*., 2007; Kulkarni, 2010). Data on glacial retreat for 1868 glaciers in 11 basins distributed across the Indian Himalaya for the period 1962-2001/2004 (Kulkarni, 2010) show that the overall glacial area has decreased from 6332 km^2 to 5329 km^2 which amounts to an average loss of ~16%. A comprehensive report on the Asia Glacier Melt vulnerability has been produced by Malone (2010) through USAID. Venkatesh *et al*. (2011) developed a model for glacial retreat and suggested that glacier slope and changes in equilibrium line altitude are the two most important controlling parameters for glacier retreat.

Glacial retreat will strongly influence the hydrology of large river systems, and the available data suggests that the impacts may vary from basin to basin. In the western Himalaya, the glacial melt has a significant contribution in the annual discharge of the Indus and Sutlej Rivers (> 50%), while it decreases in eastern region (~ 30% in Tsangpo River) and becomes insignificant (<20%) in other river basins in the central Himalaya such as the Karnali River basin (Bookhagen and Burbank, 2010) (Fig. 2). Snowmelt contribution is significant during pre- and early monsoon season (April to June) and is most pronounced in the western catchments (Bookhagen and Burbank, 2010). The spatial variability supports the earlier studies which suggests ~60% glacial melt contribution in the Sutlej river at Bhakra Dam (Singh and Jain, 2002) and 35% in Beas River at Pandoh (Kumar *et al*., 2007). Jain (2008) has also concluded insignificant contribution of glacial melt form the Gangotri glacier to the Ganga River on the basis of hydrological analysis of the Ganga River and its major tributaries. Similarly, in the Bhagirathi basin, field measurements highlight the inter-annual runoff variation in lower order tributaries which is governed by precipitation rather than mass balance changes of the Dokriani glacier (Thayyen and Gergan, 2009). Hence, enhanced glacial melting will have more significant effect on the Indus River in comparison with the Ganga River. Limited analysis of sediment characteristics of melt water from the Gangotri Glacier suggest increase in interconnected sub-glacial drainage system with increase in glacial melting and

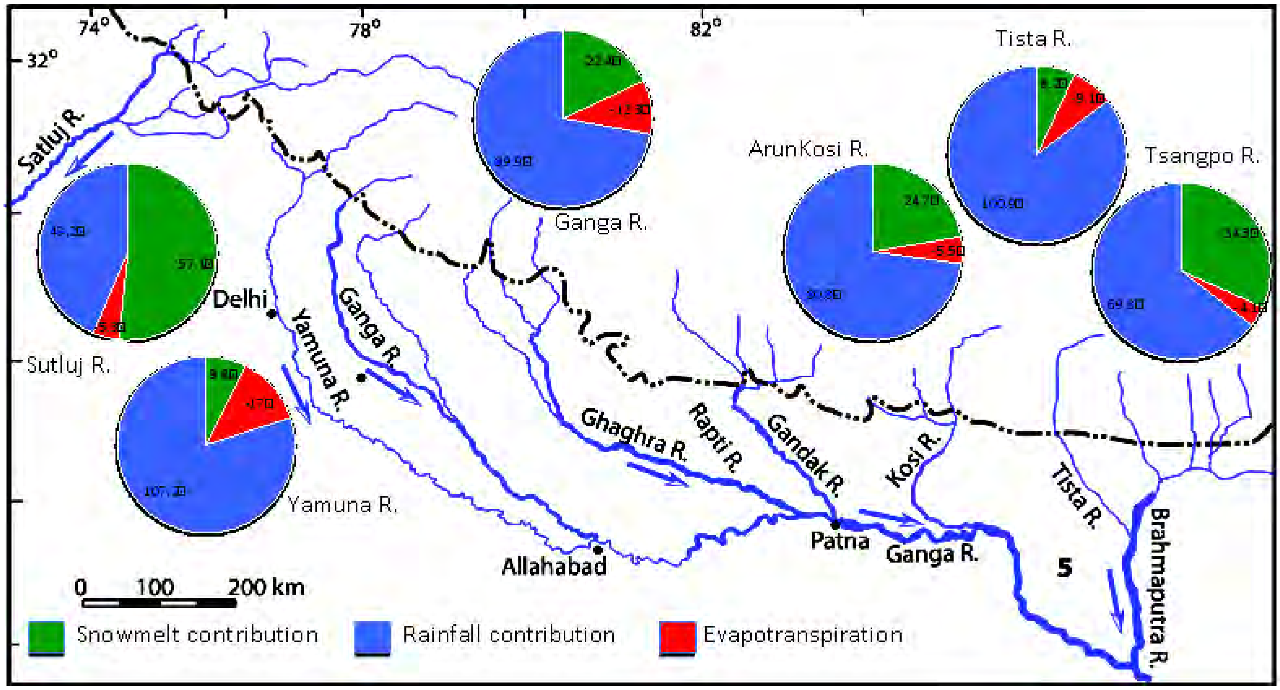

Fig. 2: Spatial distribution in snowmelt contribution to annual discharge of the Himalayan Rivers (after Bookhagen and Burbank, 2010)

complex behaviour of the glacial system as a source of sediment supply (Haritashya *et al*., 2010).

3. Erosional History and Sediment Dynamics of Large Rivers

The erosional history and sediment dynamics of large rivers and its quantification at different spatio-temporal scales is one of the fundamental aspects aimed towards process-based understanding of rivers. Sr and εNd data of modern sediment load have provided information about dominant sources within the Himalaya as these litho-tectonic provinces are characterized by a specific range of isotopic values (Singh *et al*., 2008; Wasson *et al*., 2008; Jain *et al*., 2008). In general, the Higher Himalaya (mostly in larger river basins) (Krishnaswami and Singh, 2005; Singh, 2006; Singh *et al*., 2008, Wasson *et al*., 2008) and the Sub Himalaya (in smaller river basins) (Tripathi *et al*., 2004; Jain *et al*., 2008) are the main sources of sediment supply. Measured suspended load data for the Ganga River at Devprayag for 3 years period also suggest very high rate of physical weathering in Alaknanda (~3.25 mm/yr) and Bhagirathi (~3.42 mm/yr) sub-basins (Chakrapani and Saini, 2009).

Isotope data has also been used to determine the rate of chemical weathering in different parts of the landscape. In the Brahmaputra River basin, major ion composition of water, and $\delta^{13}C$ of dissolved organic carbon suggest that the Eastern Syntaxis of the Himalayan Zone is characterized by the highest rate of chemical erosion (~ 300 t km^{-2} y^{-1}) while the chemical erosion rate in Tibet was much slower (~ 40 t km^{-2} y^{-1}) (Singh *et al*., 2005). The higher rate of chemical weathering in the Eastern Syntaxis was attributed to high precipitation, rapid tectonic uplift, steep channel slopes and high stream power, which together are also responsible for the significant consumption of CO_2 (Hren *et al*., 2007). These sediments are mostly derived through weathering of silicates and carbonates of the Himalayan and the Trans-Himalayan regions with more contribution from carbonates during the monsoon season (Singh, *et al*., 2006; Rai and Singh, 2007).

Another line of research has been to analyse the isotopic composition of the detrital and carbonate fractions from stratigraphic sequences to document temporal variation in sediment source areas, which change in response to tectonic/climatic or anthropogenic controls. A recent work by Singh *et al*. (2008) based on Sr and Nd isotopes of river sediments highlights a major contrast in contemporary sediment flux and catchment erosion rates between the Kosi and the Gandak; the computed sediment flux and erosion rates for the Gandak (450-510 mt/yr and 6 mm/yr) is significantly higher than that of the Kosi (60-130 mt/yr and 1 mm/yr). Rahaman *et al*. (2009) demonstrated that monsoon-driven changes in the hydrological regime of the hinterland generated a signal in terms of shifts in the sediment provenance as far as the distal Ganga plains. Both $^{87}Sr/^{86}Sr$ and εNd values for one of the cores in the interfluve (~12 kms west of the Ganga around Kanpur) showed major incursions at 70 ka and 20 ka coinciding with lower monsoon intensities and maximum glacial cover thereby limiting the sediment supply from the Higher Himalaya (Rahaman *et al*., 2009). Another paper in the same region focused on the evolution of $^{87}Sr/^{86}Sr$ ratio of the Ganga water during the past ~100 ka (Rahaman *et al*., 2011). The $^{87}Sr/^{86}Sr$ ratio in carbonate nodules from different depths of two sediment cores from the Ganga plains showed distinctly lower values compared to contemporary Ganga river water at Kanpur as well as groundwater samples from adjacent areas. The sudden rise of $^{87}Sr/^{86}Sr$ ratio of the Ganga is attributed to an increase in the relative proportion of Sr from the Lesser Himalaya containing silicates and carbonates with higher $^{87}Sr/^{86}Sr$ ratio. The cause for the recent increase in Sr contribution from the Lesser Himalaya is not clear but it is possible that intense agricultural activities and deforestation and/or climatic variability during recent times have resulted in enhanced erosion of the Lesser Himalayan rocks. More recent work involving detailed chemical budgeting of suspended sediments in the Ganga river has also demonstrated that the floodplain is the dominant location of silicate weathering for Na, K and H_2O^+ (Lupker *et al*., 2012). Using an extensive data set from the source to sink, the authors have also shown that sediments become significantly depleted in mobile elements during their transit through the floodplain. By comparing sediments sampled at the Himalayan front with sediments from the Ganga mainstream in Bangladesh, weathering in the floodplain was budgeted which showed that sediments undergo a significant depletion in Na, K, Ca and Mg that is correlated to a gain in hydration during floodplain transfer.

Erosion history in the Alaknanda basin for the last ~ 7 ka, based on Nd analysis of sediments, has shown significant temporal variation in the source areas (Wasson *et al*., 2008). Lesser Himalaya was the dominant sediment source area during 1970 flood event and 800±100 yr event, while sediments deposited during 400±40 and 2700±700 annum witnessed a major contribution from the Higher Himalaya. Higher contribution from the Lesser Himalaya in the 1970 flood event was attributed to deforestation in the basin area (Wasson *et al*., 2008).

Further, grain size variability of the bed load, its control and nature of sediment transport has also been analysed in the different rivers. Generally, the peninsular rivers are bed load-dominated rivers, where maximum sediment transport occurs during monsoon period (Kale and Hire, 2007). The grain size distribution of bed material in the peninsular rivers is governed by relative weathering of mafic and felsic minerals. Geochemical study in the Cauvery River shows that less weathered felsic minerals form the coarse bed load and geochemical signatures of sediments are grain size dependent (Rajamani *et al*., 2009). Grain size distribution in the Ganga river basin suggests that bed load is characterized by an exponential decrease in grain size with distance, and is strongly influenced by lateral sediment inputs by the tributaries and channel slope (Singh, *et al*., 2007). Tripathi *et al*. (2007) used a geochemical approach to unravel the weathering history and large-scale sediment recycling in the Ganga alluvial plains. Given the diverse litho-tectonic units of the Himalayan source, the nature and properties of the sedimentary fill in the alluvial plains are quite varied in response to the prevailing tectonic and climatic conditions during the orogeny. The chemical index of alteration (CIA) and A–CN–K diagrams indicated that the sediments in the Ganga plains are derived from moderately weathered source area and that the sediments were not subjected to any significant post-depositional chemical weathering. This was attributed to higher rates of erosion in the catchment (Galy and France-Lanord, 2001) and the dynamic situation of the Ganga plains with repeated cycles of aggradations and degradation (Gibling *et al*., 2005).

4. River Processes, Dynamics and Flood Hazards

Two new approaches have been pursued in recent years to develop a process-based understanding of the large river systems in India. One of them is to utilize the stream power distribution to understand the large-scale landscape evolution and geomorphic diversity. The earlier work on the hydrological controls on the geomorphic diversity of the rivers in the Ganga plains indicated the importance of upstream controls on river processes and geomorphology of the Ganga Plains and stream power and sediment supply were used as important attributes to characterize those controls (Sinha *et al*., 2005a). This work was further developed by Tandon *et al*. (2008) who proposed five major classes for the rivers draining the Ganga, based on hinterland type and dynamics in the Ganga foreland basin setting, incorporating the major forcing factors of the system, like along-strike rainfall variability, hinterland-basin connectivity, and sea level influence. These are (1) Himalayan hinterland extending from source to mountain exit, (2) cratonic hinterland comprising the Aravalli, Bundelkhand, and Singhbhum belts, (3) northern alluvial plains north of the Ganga and the Yamuna from the mountain front to the Rajmahal-Garo gap; divisible into a western part consisting of tributaries with high stream power and incised valleys (3A) and eastern part consisting of tributaries with low stream power and aggradational valleys (3B), (4) southern alluvial plains south of the Ganga and the Yamuna consisting of tributaries to the Ganga and Yamuna sourced in the cratonic hinterland, this area is divisible into western (4A) and eastern (4B) based on variable degree of incision, and (5) lower Ganga Plains and delta south and east of the Rajmahal-Garo gap (Fig. 3). Such an approach centered on dynamics has not only helped to understand the relative stages of landscape development in different domains of the Ganga Plains but has also allowed for the assessment of inter-connections between components using a systems approach.

Another modern approach is the connectivity concept to understand the network properties and flow characteristics. A large river system consists of a number of compartments or landforms, which may be connected in a hierarchical order. However, geomorphic connectivity between these landforms will be governed by temporal scale. A review of sediment residence time in the Ganga Plains suggest that source to sink connectivity may vary from millennia to million years time scales (Fig. 4) i.e. the geomorphic landforms in the large river system will be disconnected at smaller time scales (Jain and Tandon, 2010). Based on functional connectivity (defined through material transfer across the landform) and structural connectivity (defined through physical connectedness between different landforms), four different types of connectivity were defined namely, (a) active connected system, (b) inactive connected system, (c) partially active connected system, and (d) disconnected system Jain and Tandon (2010).

The Kosi River in north Bihar has continued to attract attention because of its dynamic behavior that resulted in yet another major avulsive event followed by large-scale inundation in August 2008. A series of papers have focused on various aspects of the Kosi river including flood risk evaluation (Sinha *et al*., 2008), the August 2008 event itself (Sinha, 2008, 2009) and the reconstruction of historical changes in channel courses (Chakraborty *et al*., 2011). Sinha (2008, 2009) documented the August 2008 avulsion of the Kosi which occurred as a result of a major breach of the eastern embankment at Kusaha (Nepal), 12 km upstream of the Kosi barrage. The breach occurred at a discharge of 1, 44,000 cusecs in the river, radically lower than the design capacity of the Kosi barrage (9, 80,000 cusecs). The river shifted by ~120 km at its maximum near Madhepura in the mid-fan region (Sinha, 2009). The avulsion belt reoccupied

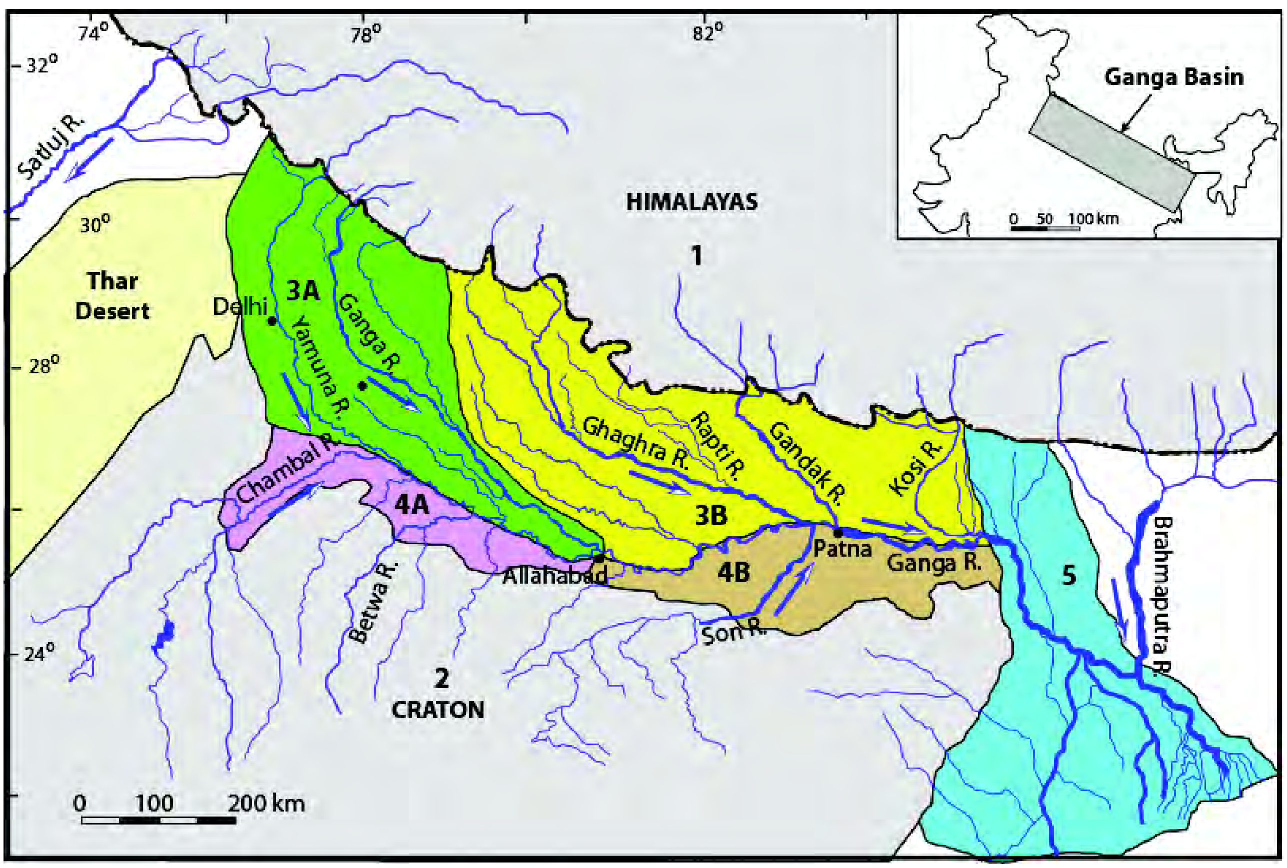

Fig. 3: Genetic classification of the Ganga plains based on hinterland type and dynamics, along-strike rainfall variability, hinterland-basin connectivity, and sea level influence (1 - Himalayan hinterland; 2 - Cratonic hinterland; 3 - Northern plains; 3A. Western; 3B. Eastern; 4 - Southern plains ; 3A. Western; 3B. Eastern; 5 - Lower Ganga plains and delta) (modified after Tandon et al., 2008)

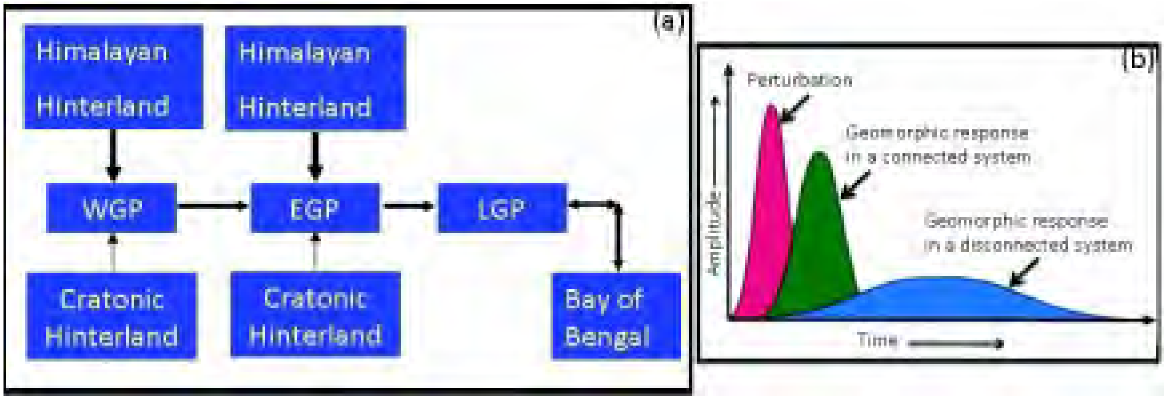

Fig. 4: **(a) Connectivity structure of the Ganga river basin. High energy Himalayan hinterland is well connected with the Ganga Plains (WGP and EGP) in comparison to the low energy Cratonic Hinterland (modified after Jain and Tandon, 2010). (b) Different geomorphic response to the similar perturbation highlights the significance of geomorphic connectivity (modified after Metivier and Gaudemer, 1999)**

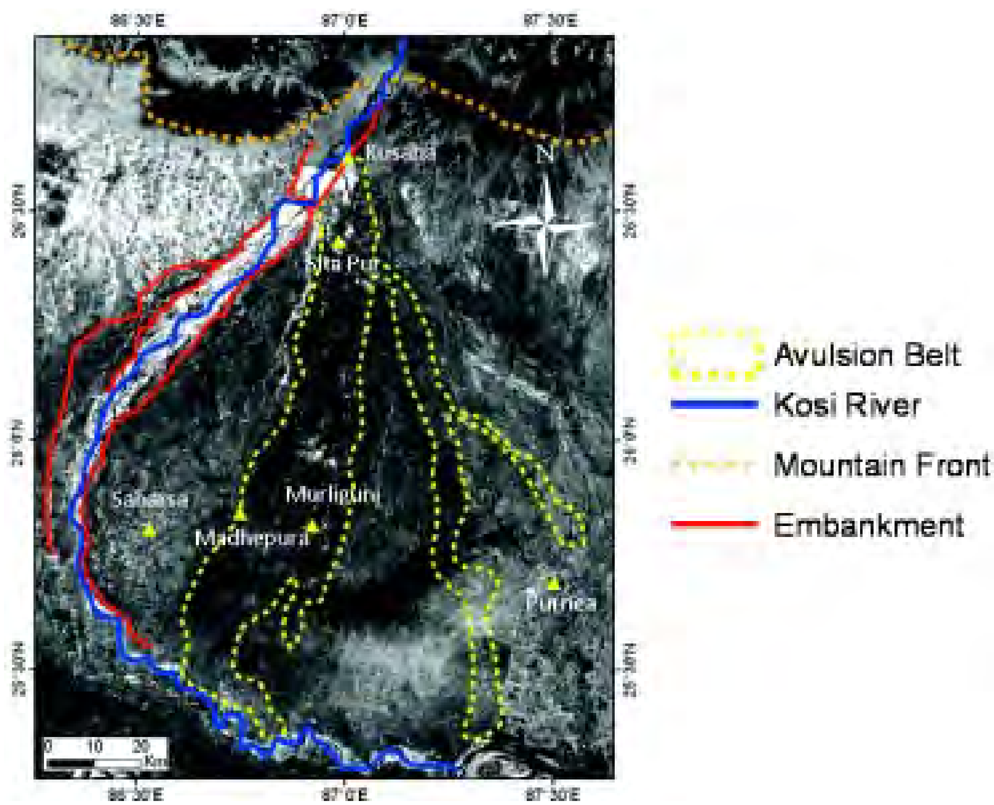

Fig. 5: **The August 2008 avulsion of the Kosi River caused by the breach of the eastern embankment at Kusaha in Nepal. The avulsion belt reoccupied one of the paleochannels of the Kosi and 80-85% of the total flow found its way into this course**

one of the paleochannels of the Kosi (Fig. 5), and 80-85% of the total flow found its way into this course. Soon after the breach event, a sheet of water, 15-20 km wide and 150 km long, with a velocity of 1 m/sec flowed in the avulsion belt. The author described this as a human-induced mega-avulsion event. Kale (2011a) also analysed the mega flood of the Kosi after the August 2008 breach and concluded that the embankments have not served the desired purpose of 'flood control' and systematic flood-risk zoning and avulsion hazard mapping must be taken up urgently. Chakraborty *et al*. (2011) revisited the historical records of the Kosi River in order to understand the hypothesis of unidirectional westward migration of the Kosi River over the last two centuries. The available records on the contrary show that the Kosi channels were occupying a narrow zone in the east-central part of the megafan. The channel position did, however, shift randomly within this zone. Based on the examination of the upper 2-3 m of succession in the north-central part of the megafan, Chakraborty *et al*. (2011) showed that there is an overwhelming dominance of meandering stream deposits across the fan surface and not that of a sweeping braided river. The authors emphasize that both from theoretical considerations as well from the results of numerical simulations (c.f., Karssenberg and Bridge, 2008) such unidirectional shift of the trunk channel in a megafan setting is a near impossibility. Most of these papers reiterated the inefficacy of the engineering solutions of large rivers through high embankments and large dams and argue that these measures have enhanced the avulsive tendency of the river by bed aggradation. Further work on the Kosi has focused on the computation of avulsion threshold using the slope data and flow accumulation analysis using satellite images and SRTM-based DEM (Sinha *et al*., 2010a). Computation of avulsion threshold for the 20-km long stretch of the Kosi suggested that apart from Kusaha where the August 2008 breach occurred, there are several other points both upstream and downstream of the barrage which are at threshold for avulsion.

Rudra (2010) documented the drainage reconstruction of the Ganga River between Rajmahal and Jalangi for the period 1764-2007 and discussed the science-policy interaction of river migration. The author commented that the river migration in this area is not just a major engineering problem but is a serious social issue impacting land reallocation, population displacement and border dispute. Sinha and Ghosh (2012) followed up this work and attempted to understand the natural as well as anthropogenic factors which have influenced large-scale dynamics of the river during the last 234 years. Morphological changes in the Ganga River reconstructed from repetitive satellite images and toposheets show that serious problems of aggradation both upstream and downstream of the barrage had started much earlier than the commissioning of the Farakka barrage in 1975. After the construction of the Farakka barrage, the channel upstream of the barrage has moved towards the east but channel shifting downstream of the barrage has been erratic. The authors argued that sedimentological readjustments due to aggradation and bar growth due to Farakka barrage have further accentuated the river dynamics in this region.

Another important aspect in river dynamics studies has been the integration of reach-scale processes such as migration of river confluences with the basin-scale processes such as sediment flux. A recent study on the Ganga-Ramganga and Ganga-Garra confluences by Roy and Sinha (2005, 2007) indicated that these confluences have moved both upstream and downstream and the next movement of the confluence points during the period of ~100 years is as large as ~20 km although no definite trend was observed. The authors suggested that apart from major avulsions, river capture, cut-offs, junction angle and bed aggradation are the major factors which have influenced the confluence dynamics. This study was supplemented with the analysis of channel morphology, hydrology and sediment budgeting between two stations upstream and downstream of the confluence area for the study period. These analyses showed that the periods of confluence dynamics coincided with increased sediment budget and growth of channel bars.

Sahu *et al*. (2010) investigated one of the important southern tributaries of the Ganga, the Son River, and parts of the Ganga-Son confluence and reported a classical example of tilt-induced avulsion and channel migration during the Holocene. Nine avulsion events in the Son River were attributed to high lateral tilt related to its proximity to one of the important faults, the East Patna Fault (EPF). The Ganga River, located in the lowered part of the tilted block away from the line of uplift, has migrated in the down-tilt direction. The authors concluded that the rate of lateral tilt controlled the style of channel movement, with gradual migration occurring at low tilt rates, and avulsion at higher rates. impact on river channels was also analysed through hydrological data. Kale and Hire (2007) calculated unit stream power and estimated total energy expenditure in large floods to analyse its impact on large rivers of Indian Peninsular namely the Godavari, Tapi and Narmada rivers. The analysis showed that unit stream power values were significantly higher than the critical stream power value to entrain cobbles and boulders, and hence caused significant geomorphic input on the large rivers. Further, the pattern of extreme floods in larger rivers of South Asia were statistically analysed and their relationship with above-normal monsoon rainfall periods was estimated (Kale, 2011b). In general, most of the extreme floods have clustered around ˜ 840 and 2000 AD and show a significant link with above-normal rainfall during the same time. Temporally, the magnitude and frequency of the large floods have increased from past (late Holocene) to the present. The modern floods in Peninsular Rivers have recorded higher flood magnitude in comparison to the late Holocene floods. The frequency of large floods has also increased and is mostly clustered in three decades namely 1940s, 1950s and 1980s (Kale, 2011b).

5. Quaternary Fluvial Stratigraphy of the Ganga-Brahmaputra System

5.1 Himalayan fronts and mountain exits of rivers

Singh and Tandon (2008, 2010) examined the Sutlej exit point. These two studies although mainly focus on the evolution of the Pinjor intermontane basin, reveal the important role of tectonics in controlling the mountain front geomorphology and deflection of the river courses. In a detailed study of the landforms and structures of the recessed mountain front and the associated intermontane basin, an integrated model was developed by the authors and they concluded that the mountain-front geomorphology and courses of rivers basically result from the interaction of orogen-parallel thrust fault and transverse tear fault in this region. Although the role of growing anticline on relocation of the river courses and sediment conduits has been theoretically postulated and numerically modeled for a long time (Gupta, 1997; Van der Beek, 2002) this is possibly the only documented case study of interaction of thrust-related growing anticlines, river courses and mountain-front fans in the Indian part of the Himalaya. In this case study, Singh and Tandon (2008, 2010) documented field evidence of different faults and modeled them to explain the origin of different geomorphic features. Further, through these analyses they have shown that incipient fault-related anticlines, forming in the Indo-Gangetic alluvial plain, far south of the outermost Siwalik Hills, deflect all the rivers northwestward.

Srivastava *et al*. (2009) has studied the Brahmaputra River exit in the Pasighat area, eastern Himalaya. The authors identified three major geomorphic surfaces, belonging to high angle mountain-front fans and river terraces in this area and dated them using OSL techniques, to have formed between 15 and 3 Ka. Based on the sedimentology of the terrace deposits, OSL chronometry and their geomorphic relationship, Srivastava *et al*. (2009) related the terrace formation to a combination of climatic and tectonic features. In a very similar study, Srivastava and Mishra (2008) identified four river terraces in the exit of the Kameng River, one of the major tributaries of Brahmaputra. At the Kameng exit, the terraces are strath terraces with 6-15 m of gravelly alluvium, dated to have formed between 14-6 Ka, overlying 10 to 45 meters of Siwalik bedrock. Based on a number of calculated geomorphic instability indices, Srivastava & Mishra (2008) showed that tectonically induced frontal belt uplift varied from 7.5 mm to 11 mm per annum. They related the major phases of alluvial aggradation to the strengthening of the Indian monsoon after the LGM that brought in huge sediment load available in the upstream during 15-12 Ka. As the monsoon intensity reached its peak around 12-9 Ka, the decreasing sediment to water ratio resulted in the major phases of incision. It should be noted that in both the cases the extant terraces only reveal late Quaternary history at the mountain-front and do not reflect the control of the river exit *per se*.

Similarly, some information exists on the mountain exit of the Tista River (Chakraborty, *et al*., 2010; Chakraborty and Ghosh, 2010; Chakraborty *et al.*, 2008; Kar, 2007; Mukul, 2000; Mukul *et al*., 2007). These authors have documented the simultaneous existence of a megafan along the Tista valley and a number of small alluvial fans along the mountain-front. Three major terraces have been dated by OSL method and range in age between 30-0.5 ka. The authors argue that the Tista Valley alluvium is significantly younger than the Ganga basin alluvium. It appears that the formation of alluvial fans and the Tista megafan is controlled by the tectono-geomorphic setting in the hinterland, while three major terraces formed in response to climate events. Mukul *et al*. (2007) documented that the MFT in this region was emplaced around 40 Ka but out-of-sequence thrusting continued since then forming strath terraces, forcing river migration and causing 48m of incision by the Tista River.

In the eastern Himalaya, Goswami *et al*. (2012) studied the smaller alluvial fans in the Chalsa area and the drainages associated with them. Based on total station survey and terrain analysis, the authors demonstrated that the deformation associated with blind thrusts within the Quaternary sediments affected the evolution and drainage pattern in this area.

Sinha *et al*. (2010) published new data for the Ganga exit and terrace systems overlying Lesser Himalayan or Siwalik rocks. Geomorphic correlation, stratigraphic documentation and sedimentologic analysis suggest a coupling of climate and tectonics in the development of these terraces. Four levels of terraces (T_1 to T_4) have been documented ranging in age from 11 ka and 0.5 ka separated by distinct incision events during 11 ka (T_4-T_3), 9.7 ka (T_3-T_2) and 6.9 ka (T_2-T_1) out of which 11 ka and 6 ka events are consistent with widespread incision events in the Ganga plains (Gibling *et al*., 2005; Tandon *et al*., 2006; Sinha and Sarkar, 2009) driven by monsoonal intensification. In addition, a significant tectonic influence on these incision events was also interpreted by the authors due to movements along the HFT based on the marked variation in their distribution across HFT.

Dutta *et al*. (2011) have documented five levels of terraces (T1 to T5) in the Yamuna exit in the frontal Himalaya, cutting across numerous tectonic planes, deposited by both glacier-fed perennial and piedmont-fed ephemeral streams over a time period of ~30 ka. Contrary to the assumed dominance of the tectonic processes in the formation of such terraces, the authors have argued that climate played an important role in their genesis. Based on the OSL age data, the authors interpreted the abandonment of these terraces during major climatic transitions from arid to humid or vice versa. However, they noted the abrupt termination of the lower terraces (T1 to T3) at the mountain front and decrease in valley width with staircase of terraces suggesting tectonic uplift along the Himalayan Frontal Thrust which could have amplified the incision.

5.2 Ganga Basin

The Ganga basin is one of the largest foreland basins in the world and has accumulated thick alluvial sediments. The Ganga basin has attracted a lot of attention not just because of its sheer size and large sediment flux but also due to complexity and diversity in sedimentation history (Tandon *et al*., 2006; Sinha *et al*., 2005a,b,c, 2007a,b; Sanyal and Sinha, 2010). Fig. 6 shows the spatial variation and major controls in valley generation and Late Quaternary stratigraphic development across the Ganga Plains in terms of tectonics, climate and glacioeustasy. Tandon *et al*. (2006) suggested that tilting and uplift are important factors in incision near the Himalayan front whereas climate has been an important factor near the craton margin in the western plains, where tectonic activity is minor and subsidence rates are moderate. Tectonics has also governed long-term subsidence and accumulation within the foreland basin, depending on the distance from the thrust front and the complex topography of the underlying Indian Craton, while active faults affect river courses in places. Similarly, a near-synchronous period of incision and alluvial valley formation affected Himalayan and cratonic rivers in both foreland and extensional basins across northern India and Nepal between 15 ka and 5 ka which correlate with the

Fig. 6: Geomorphic diversity across the Ganga plains and the controlling factors (after Tandon *et al*., 2006)

period of post-glacial monsoonal intensification. This study also showed that valleys may vary from prominent to subtle to non-existent across large alluvial plains, and may vary in relief through time, especially where precipitation changes is a strong driver.

For most parts of the Ganga basin, stratigraphic studies have remained constrained due to lack of exposed sections (Sinha *et al*., 2010b). However, there has been a tremendous development in the last few years in examining the subsurface using a combination of resistivity surveys and sediment coring (Sinha *et al*., 2009; Yadav *et al*., 2010; Srivastava *et al*., 2010; Pal *et al*., 2011, Roy *et al*., 2011). The river valleys in the Western Ganga plains (WGP) are deeply incised in places and provide continuous cliff sections for several kilometers (Fig. 7). The initial work on the Ganga-Yamuna interfluve focused on geomorphic mapping using aerial photos, and stratigraphy of cliff sections. More recent work on the sedimentology and magnetic mineralogy of drill cores of the Ganga valley fills and the adjoining interfluve near Kanpur (Sinha *et al*., 2007a) suggested that the Ganga has been near its present location since at least ~30 ka. The cores indicated renewed fluvial activity following the LGM, as well as meander cutoff and southward migration since ~6 ka. The valley margin records a major discontinuity that marks a period of reduced discharge in the Ganga River during the LGM, when monsoonal precipitation was greatly reduced and lakes and eolian dunes occupied areas distant from the main channel. Stable isotopic work on calcretes from the Ganga plains (Sinha *et al*., 2006) suggested little variation in precipitation and vegetation types for the sampled interval of ~60 ka which was surprising because climate models suggest that Asia experienced radical fluctuations in monsoon intensity and precipitation during this period. Some of the apparent lack of variation was explained by preferential preservation of aggradational strata that represent relatively active monsoonal periods, as well as by the mixing of drier floodplain (C_4) and riparian (C_3) vegetation. A modest up-section increase in C_4 plants was interpreted to be due to increased aridity and lower atmospheric CO_2. More recent work by Agrawal et al. (2012), using samples from several drill cores from the Ganga plains and based on $\delta^{18}O$ values of soil carbonates, has recorded three periods of monsoonal intensification at 100, 40 and 25 ka and ~20% decrease in rainfall during LGM. Based on the $\delta^{13}C$ values of soil carbonates and soil organic matter, the authors also concluded that relative abundances of C_3 and C_4 vegetations during the time period 84-18 ka were mainly driven by variations in monsoonal rainfall.

The Ganga and Yamuna valley cores have contributed significantly to our understanding of Ganga plains history since ~100 ka. Sinha *et al*. (2007b) suggest that the Ganga

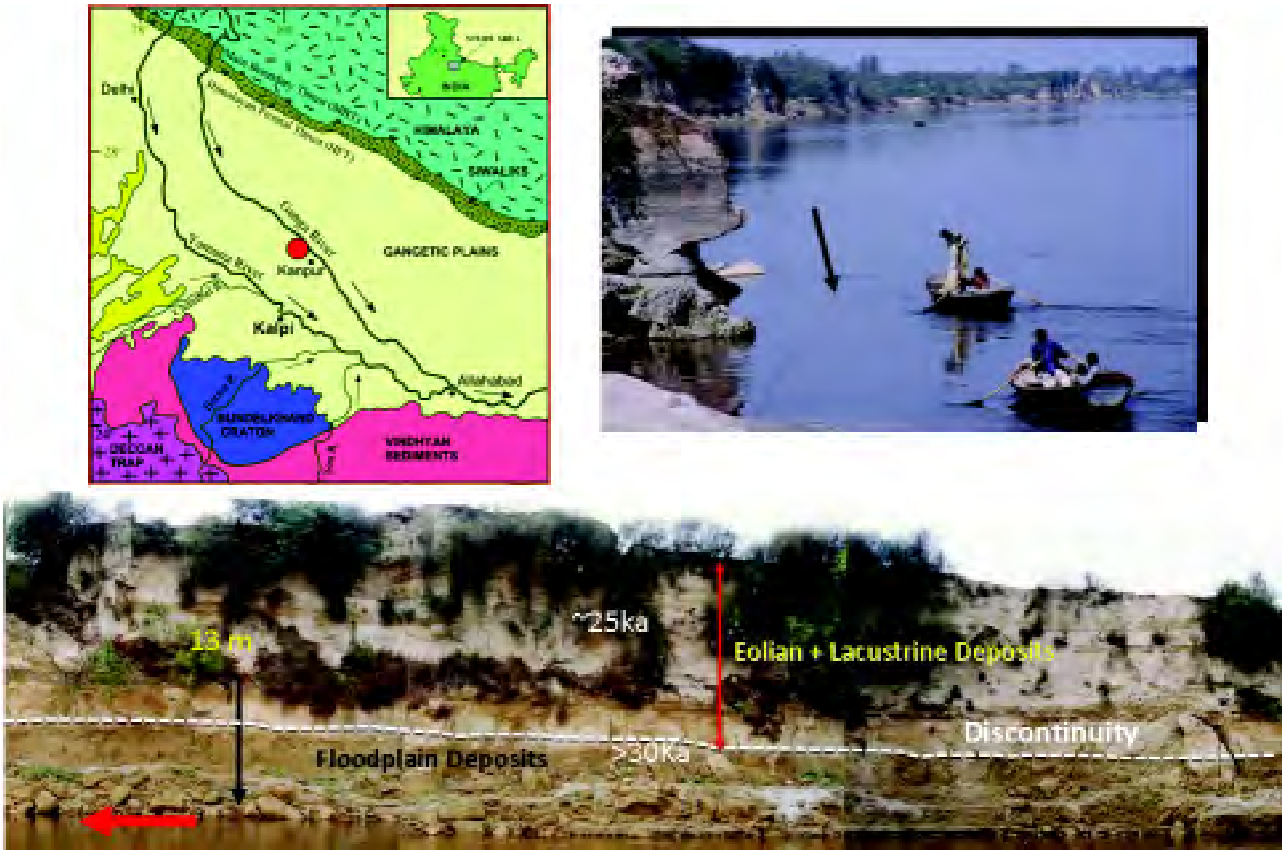

Fig. 7: Discontinuity-bound stratigraphic sequences from the Ganga plains (a) Location of cliff section at Bithur along the Ganga River around Kanpur (b) Exposure of the cliff section along the right bank of the river; (c) a major discontinuity separates the lowermost floodplain deposits from the upper eolian and lacustrine sequences (modified after Gibling *et al*., 2005)

valley and the interfluve to the south have existed for at least tens of thousands of years. The interfluve cores penetrated floodplain deposits with only one small channel body, and do not show any subsurface evidence for major Himalayan rivers since ~100 ka. Further, these cores were also studied for sand petrography to establish their provenance and to understand the competition between the Himalayan and cratonic sources to build the interfluve over a period of 100 ka (Sinha *et al*. 2009). Drill core data from the Ganga-Yamuna interfluve between Kanpur and Kalpi showed that thick wedges of red feldspathic sand and gravel underlie much of the southern foreland basin at shallow depth (>30 m), where the uppermost red feldspathic strata have yielded a date of 119.2 ± 12 ka B.P. (Gibling *et al*., 2005). Similar red sediments, petrographically akin to modern sands of the cratonic rivers such as the Betwa, extend to deeper levels (>540 m) to about one-third of the distance across the foreland basin (Sinha *et al*., 2009). The apparent vitality of cratonic rivers during this period may reflect strong monsoonal activity in central India, or factors such as river capture and changes in the course of Himalayan rivers, changing the relative dominance of cratonic and Himalayan rivers.

Roy *et al*. (2011) presented stratigraphic data from the Ganga valley fills and the interfluve based on a series of drill cores and exposed cliff sections covering a time span of ~100 ka as indicated by luminescence dating. A comparison of the stratigraphic data with the available proxy data suggested widespread fluvial activity during MIS 5 with minor discontinuities. MIS 3 also recorded several periods of aggradations preceded by incision resulting in composite channel sand complexes separated by thin floodplain muds. The authors recorded a reasonable correlation between the valley filling episodes and valley margin sequences between MIS 5 and 3. In line with previous studies in the adjoining parts (Sinha *et al*., 2007a), modest accumulation of floodplain, lacustrine and aeolian deposits, punctuated by discontinuities, were recorded through to early MIS 2 after which the interfluve was apparently not inundated by the Ganga and underwent degradation through gully erosion. No fluvial activity was recorded during the LGM period and it was suggested that the Ganga River may have been underfit during this period. One of the major conclusions of Roy *et al*. (2011) is that the periods of valley aggradation correspond to times of declining monsoonal strength whereas the timing of incision events corresponds broadly with periods of monsoonal intensification.

The southern tributaries of the Ganga River have received much less attention all through. One clear exception is the Middle Pleistocene to Holocene fluvial succession in the Belan and Son which have evoked significant interest due to the presence of artefacts, ranging from early Acheulian through Middle and Upper Palaeolithic to Mesolithic and Neolithic, and due to the presence of an ash bed, attributed to the eruption at 73 ± 4 ka of the volcano Toba in Indonesia (Williams and Clarke, 1984). Gibling *et al.* (2008) provided new insights into the Belan River section at Deoghat which starts with channel-base calcretes above the Vindhyan Unconformity (Marine Isotopic Stage 5 or older) overlain by fluvial sediments (~85 to 16 ka, Marine Isotopic Stage 5 to 2). The record for ~70 ka period of fluvial activity consisting predominantly of muddy floodplain deposits with some meandering-river channel bodies is in accord with generally high precipitation levels during Marine Isotopic Stage 3 to 5 (Gibling *et al*. 2008).

5.3 Ganga-Brahmaputra Delta

In an important study of subsurface sediments in the lower Hoogly delta plain, Sarkar *et al*. (2009) summarized the evolutionary history of the Indian part of the Ganga-Brahmaputra delta. Eight bore holes located from >100 km inland to the present day coast, coupled with OSL and ^{14}C dates and stable carbon and oxygen isotope data reveal that a major unconformity and incised valley, dated to be older than 23 Ka, marks the delta succession. The type 1 unconformity has been correlated with the low stand during LGM. Lowstand fluvial deposits filled up the incised valley in a later stage. Further, a transgression around 9 Ka inundated the coastline and pushed back the coastline and mangrove forest about 100 km inland. From ~7 Ka onward, intensification of southeast Asian monsoon and the arrival of pulses of enhanced sediment supply (4-8 times than that of the present) resulted in progradation of the coastline to its present position. Stable isotope data reveal that at the beginning of the progradation C3 plants dominated the delta plain and during late Holocene the C4 plants appeared and subsequently reached their dominance. The study further reveals that the Hugli River, now a narrow distributary, was one of the main conduits of sediment supply during early Holocene progradation. It further reveals that the transgression in the Ganga-Brahmaputra delta started from ~7 Ka, at least 2000 years earlier than thought previously. The authors also argue that late Quaternary perturbations in climate, depositional environment and basin configuration was more responsible for a convoluted evolutionary path from C3 to C4 vegetation, rather than a unidirectional pathway of changes related to the pCO_2, as postulated by some the workers (Galy *et al*., 2008).

Panda *et al*. (2011) studied the sediment transport data from 133 gauge stations covering all the major peninsular Indian Rivers over a period spanning from 1986 to 2006. They showed that 88% of the gauging stations show a decline of sediment load over this period. According to Panda et al. (2011) as the rainfall in this area is characterized by non-significant decreasing trend, this sediment reduction is attributable to dams constructed upstream. Based on their study, they predicted increased coastal erosion due to rising sea level and decreasing sediment load of the main drainages in the east coast. A similar conclusion was earlier drawn by Gamage and Smakthin (2009) in a study of the Krishna delta.

6. River Science and River Management

Multidisciplinary approaches for river studies and complexity of interaction among fluvial forms and processes at different spatial and temporal scales have led to the emergence of the discipline of River Science (Fig. 8). It can be defined as "*the study of how hydrological, geological, chemical, and ecological processes interact to influence the form and dynamics of riverine systems and how riverine ecosystems in turn influence these processes across multiple spatial and temporal scales*" (NAS, 2007). This new approach considers the linkages between river related processes and patterns at multiple scales, from small streams to large rivers, from pristine to heavily urbanized watersheds, and from daily-to century-scale dynamics. Sinha *et al*. (2012) have emphasized an urgent need to initiate an integrated effort to develop a process-based understanding of the large river systems in India in the overall framework of River Science. An integrated effort should be made towards developing a core of River Science that includes hydrology, hydraulics, fluvial and hill slope geomorphology, geochemistry, ecology, glaciology, climate change and interaction of these disciplines at different scales through physical and mathematical modeling. It is also important to respect the inherent diversity, complexity, and variability of large river systems, and this cannot be done in a reductionist discipline-specific mode (Sinha *et al*., 2012). The issue of 'demand and supply', of water must be accompanied by the realization and effort to maintain the 'river health' and 'environmental flow' which are significantly influenced by geomorphic characteristics and biotic associations of the river. Increased demands for fresh water have resulted in extensive anthropogenic modifications on the Himalayan river systems, and any efforts towards maintaining sustainable flow and river rehabilitation must address the issues of ecological health of the rivers to derive a long-term benefit.

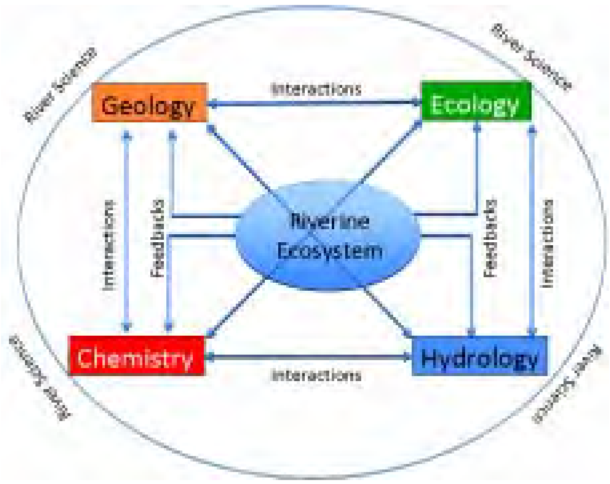

Fig. 8: Conceptual framework of River Science showing the integration of hydrological, geological, chemical, and ecological processes

The ‘ecosystem based’ approach is a cross-disciplinary, holistic approach applied at catchment scale - a probabilistic approach which recognizes uncertainty and complexity in the system (Brierley and Fryirs, 2005, 2008). Geomorphic characterization is an important parameter in an ‘ecosystem based’ approach because the physical template of a river system provides the basic structure to analyse the suitability of biosystem and livelihood. This approach requires to bring hydrogeomorphic and ecological understanding at similar spatial and temporal scale and to analyze the data through a common framework of hierarchy, connectivity and non-linearity aspects of river system (Sinha *et al*., 2012). Some efforts have been made in this direction and a recent study on parts of the Ganga River integrated the hydrological, morphological, ecological, sociological and hydraulic data integration for assessment of environment flow (e-flow) at different reaches (WWF, 2011) and for a geomorphic assessment of habitat suitability (Sinha *et al*., 2010c). E-flows are defined as the flows required for the maintenance of the ecological integrity of rivers, their associated ecosystems and the goods and services provided by them (WWF, 2011). The e-flow assessment for the selected reaches of the Ganga was based on the flow stage requirement for geomorphological, biological, cultural and livelihood parameters. The key geomorphic considerations were to maintain the longitudinal connectivity and occasional lateral connectivity through flooding in different reaches. Similarly, the biodiversity considerations emphasized the maintenance of the habitat for different species and the socio-cultural criteria emphasized on sustaining the livelihoods and cultural practices. All data was integrated to define the required discharge using hydraulic modeling to provide estimates of flow depth and flow volumes necessary for channel maintenance from ecological perspective. The analysis was carried out for different seasons to document temporal variability in the dataset and for different scenarios such as normal rainfall, drought year, and high rainfall (Fig. 9). Results indicated that while the present flow conditions are largely acceptable in the upper reaches, there are major problems of inadequate flow and poor water quality downstream of Narora (WWF, 2011). Sinha *et al*. (2010c) carried out a pilot study in parts of the Ganga river in India using satellite based remote sensing data which involved the analysis of (a) longitudinal form, (b) cross sectional form and (c) planform of the channel at these sites and derivation of various morphometric parameters. Twelve geomorphic parameters were been identified which influence the aquatic life along with the Land Use/ Land cover in the floodplain, planform dynamics, and channel-floodplain connectivity. For each parameter, four classes are defined as Excellent (A), Good (B), Degraded (C) and Poor (D). Various geomorphic parameters for different reaches were integrated in a GIS environment to assess the present geomorphic condition of the river for habitat suitability (Sinha et al., 2010c).

In the Indian context, the failure of single discipline approach for river control and new challenges in stream management specially the need to define river health in terms of its hydrological, morphological, ecological and chemical parameters and estimation of water (e-flow) and space requirement for river functioning have resulted in the adoption of multi-disciplinary approaches to the study of river systems. A large programme on Ganga River Basin Environmental Management Plan (GRBEMP) has been

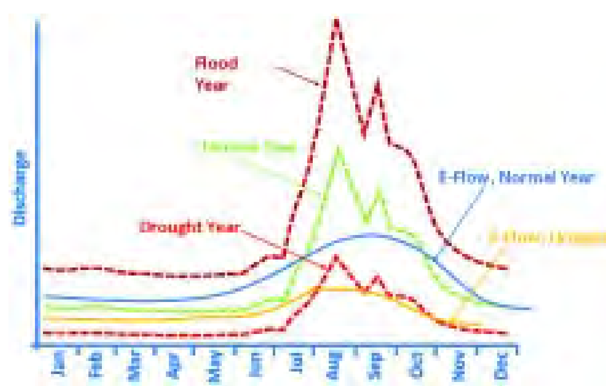

Fig. 9: Concept of e-flows required for the maintenance of the ecological integrity of rivers; hydrographs for normal, flood and drought years are shown as dashed lines and the e-flows for normal and drought years are shown as solid lines (WWF, 2012)

initiated by the Ministry of Environment and Forests which aims to provide a basic framework for developing a river management plan based on five fundamental premises: (i) river must continuously flow, (ii) river must have longitudinal and lateral connectivity, (iii) river must have adequate space for its various functions, (iv) river must function as an ecological entity, and (v) river must be kept free from any kind of wastes. This initiative emphasizes on the ecosystem-based approach for river management and is the first of its kind to be implemented on a large river system such as the Ganga. While variability of the physical environment generally defines the habitat template to which organisms adapt, the temporal and spatial variability of geomorphic processes have particularly important controls on both local community composition and adaptive strategies for aquatic and riparian ecosystems. The fluvial geomorphic component of this project includes the definition of 'river space' in terms of active floodplain and valley margin (Fig. 10) using satellite remote sensing data and SRTM based digital elevation models (GRBEMP, 2010). Geomorphic mapping of the Ganga and its major tributaries has been carried out to understand the morphological complexity of the river system in space and time. Stream power distribution along the Ganga River has been computed to understand the river energy and sediment dynamics. All data is being integrated on a GIS platform to assess the 'geomorphic condition', defined as the present state of the river system and its ability to perform various geomorphic and ecological functions.

7. Future Perspectives

Large river systems of India need sustained attention in terms of research as well as policy level interventions. Our understanding of the processes controlling the form and dynamics of such large systems is still fragmentary. The causal factors for the geomorphic diversity and their manifestations need to be taken into account for a sustainable management of these large rivers.

In addition, the impacts of climate change on the river systems in terms of the availability of water and modifications in hydrological regime are yet to be determined. Apart from the water shortage and more importantly round-the-year water supply, glacier melting will also cause other severe impacts and environmental problems. It has been debated that the glacier melt would increase the runoff in the rivers initially but it would cause significant seasonal shifts in water supply, and would increase the flood risks. Continued and rapid melting of glaciers can lead to flooding of rivers and to the formation of glacial melt water lakes, which may pose an even more serious threat. These negative impacts on water resource systems will eventually offset the benefits gained by short-term increases in runoff from glacier melt.

In addition, increasing flash floods and rockslides degrade roads and trails. Most Himalayan watersheds have experienced a substantial deforestation and overgrazing, making the hillsides much more vulnerable to landslides,

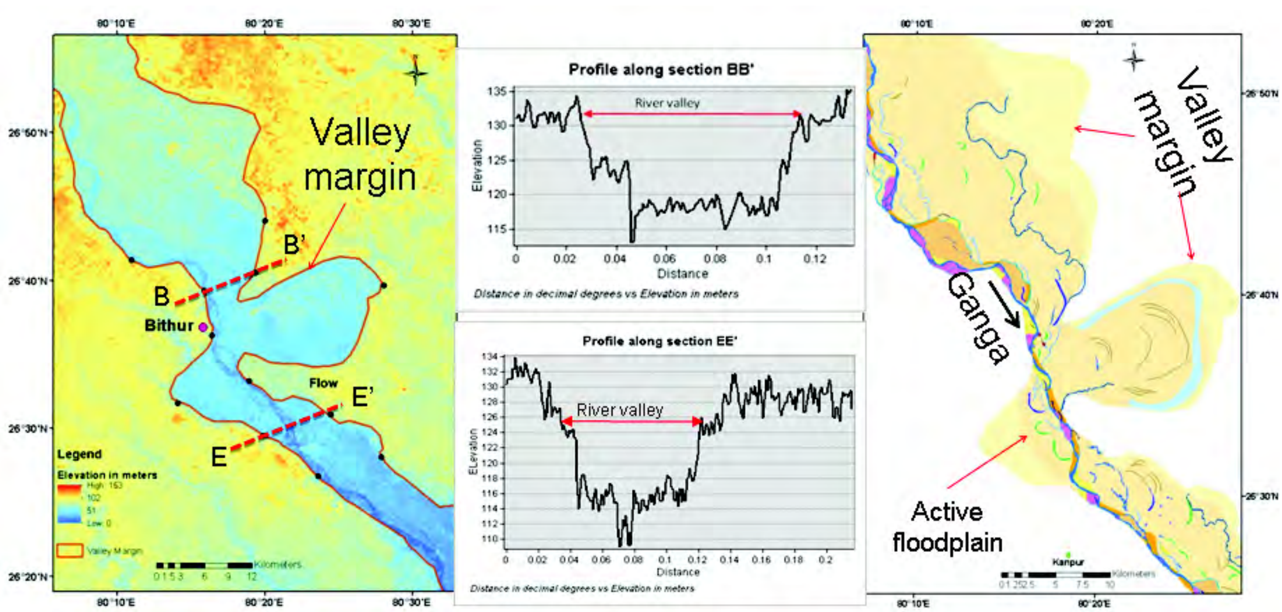

Fig. 10: Defining 'River space' as active floodplains and valley margin for a stretch of the Ganga river around Bithur (Kanpur); valley margin was mapped from SRTM-DEM and active floodplain was delineated from the satellite image (GRBEMP, 2010)

either during peak snowmelt or in relation to tectonic activity. For an energy constrained economy like India, and the planned hydropower projects along the Ganga River, flow reduction and modification are likely which may have serious consequences and the country must gear up to meet these challenges. Environmental Flows (E-flows) are one of the fundamental parameters in river management and planning. The assessment of E-Flows in the large river systems continues to be a major challenge, as it requires multidisciplinary approach and high-resolution dataset. The GRBEMP project is a major effort in this direction and the results from this project will improve our understanding significantly.

Also the dynamics, morphology and stratigraphic modeling of the Large River systems are yet poorly understood (Bridge, 2003) and river management plans have so far targeted only the smaller ones. Whereas a lot of new data is being generated on the interaction between surface processes, tectonics and geomorphic forms (Burbank and Anderson, 2011), and many aspects of geomorphic responses to other controls are being debated (Molnar, 2003), little has so far been done on the translation of this aspect to the stratigraphic record and basin analysis (Miall, 2006). Availability of high resolution dataset, modern precision technology and large computation power provides a new scientific challenge of developing a more inclusive understanding of the large river systems through projects like the GRBEMP.

The use of high-resolution remote sensing and DEM data in river studies has increased significantly in recent years, which has helped towards quantification and modeling of surface processes. Integration of such data with high resolution ground survey data namely kinematic GPS, Total Station, DGPS Eco Sounder based measurement will provide a better understanding of the causative factors through integration of various scales. Integration of DEM with hydrological data will provide an important understanding of the energy distribution in a river system, which will provide quantitative measures of spatial distribution of the driving forces. These distribution patterns will serve as an important tool to analyze river processes and to assess the thresholds of geomorphic changes at various scales.

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