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Review Article

River Systems in India: The Anthropocene Context

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The Anthropocene represents the time since human impacts have become one of the major external forcings on natural processes. The present review provides a synthesis of studies on the Indian rivers at modern time scale. These studies highlight the significant impact of anthropogenic forcing on modern day river processes and behaviour. Various aspects of river systems at modern time scale and their possible future trajectories have been analysed. The integration of data from modern rivers and their archives are critical for defining sustainable stream management practices. Our synthesis suggests that the multi-disciplinary river studies at modern and historical time scales need to be pursued vigorously for securing the health and futures of the Indian rivers.

Keywords: The Anthropocene; Modern River Systems; Indian Rivers; Geomorphic Concepts

Introduction

Humans have interacted with rivers from the time of ancient civilizations. The Indian sub-continent, which hosts many large and perennial rivers with significant hydrological and geomorphic diversity is also home to an ancient civilization, and is currently one of the most populated regions on the globe (Fig. 1A). The river basins in India are characterised by significant variability in human population and nature of disturbances, which poses a number of challenges in the sustainable management of these rivers (Fig. 1A). Despite this situation, the impact of anthropogenic forcing on natural geomorphic systems has not been analysed in detail. Fluvial geomorphological studies in India have mostly focused on the river response to climate and tectonic forcing at Quaternary time scale (Chamyal *et al*., 2003; Jain and Sinha, 2003; Jain and Tandon, 2003; Juyal *et al*., 2006; Tandon *et al*., 2006; Sinha *et al*., 2007). Recently, studies of the hydro-geomorphic behaviour of river systems at modern time scale have also been initiated to understand the impact of anthropogenic forcing on geomorphic processes for some of the Indian river systems. Such studies at modern time scale have not only highlighted anthropogenic impacts on river systems but have provided significant insights to river hazards, particularly flooding and river dynamics.

The current understanding of river systems at modern time scale has placed more emphasis on spatial variability and has led to new conceptual understanding that includes hierarchy, magnitude-frequency, equilibrium, threshold, sensitivity, connectivity, non-linearity, complexity and multi-disciplinarity (Jain *et al*., 2012; Gregory and Lewin, 2014). Jain *et al*. (2012) reviewed the major geomorphic studies on the Indian rivers and highlighted various research questions. One of the major research concerns is the development of hydrology-morphology-ecology relationship in the river system and the assessment of the anthropogenic disturbances on this or a part of this relationship. Anthropogenic disturbances cause flux or slope variability in the channel, which alter the morphology and ecology of the river system. However, these relationships are routed through different threshold conditions and sensitivity to external responses. Hence, sensitivity,

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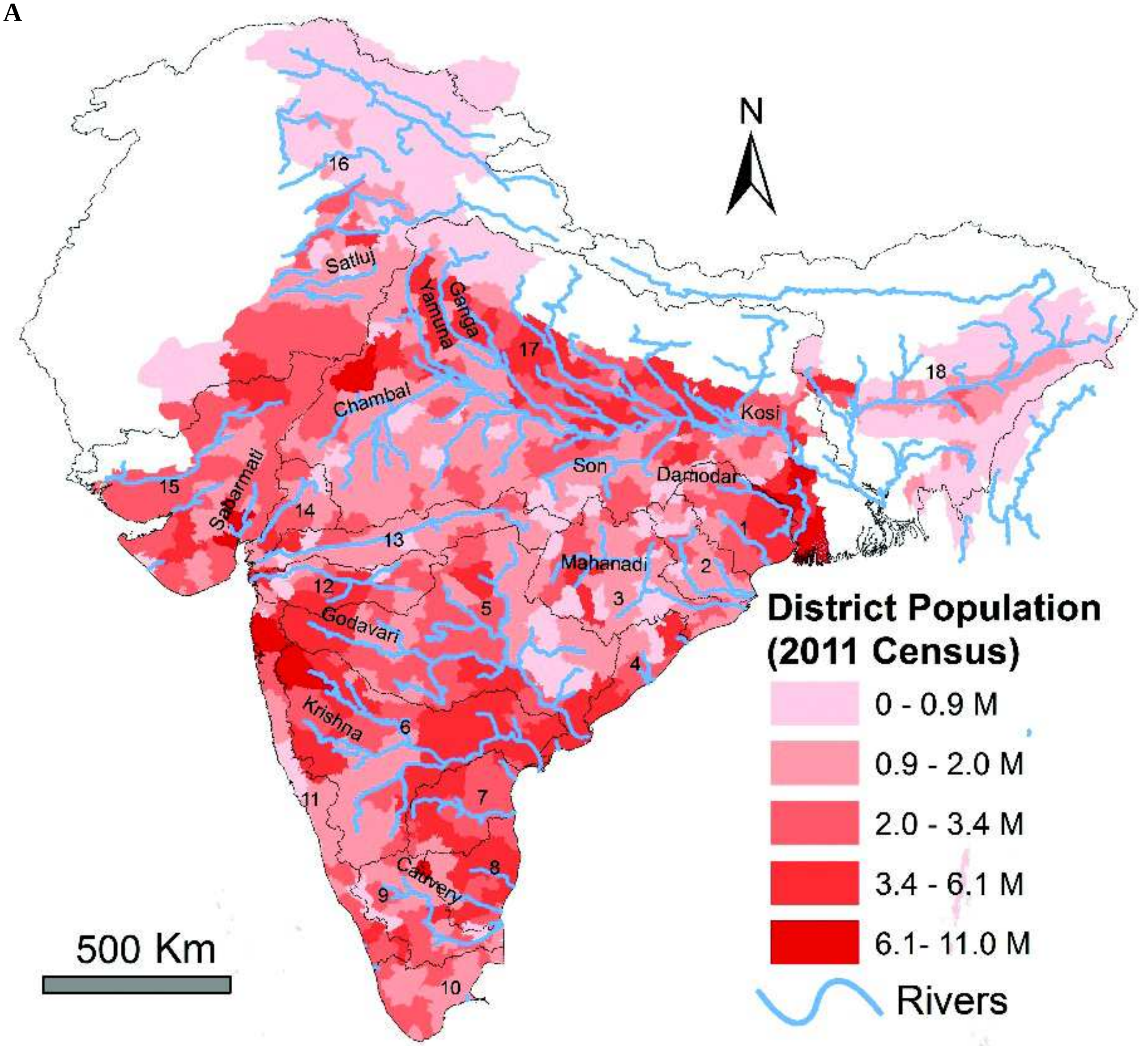

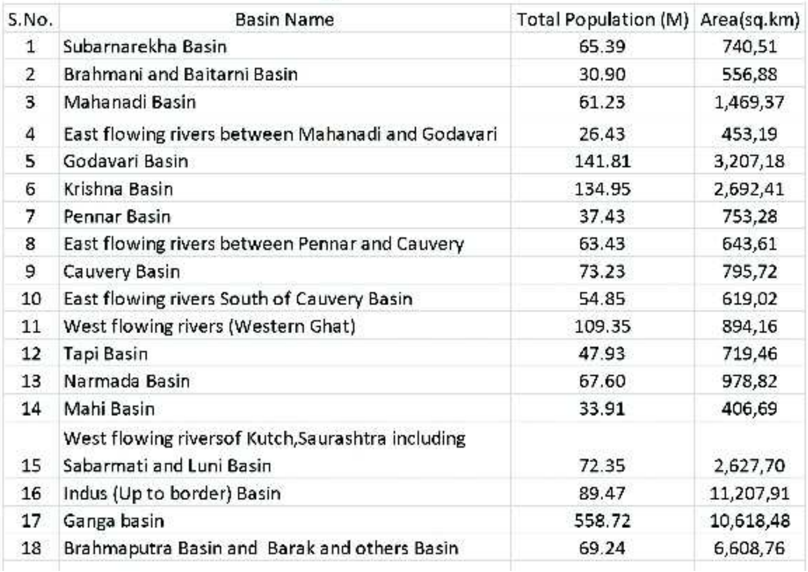

S.No.	Basin Name	Total Population (M)	Area(sq.km)
1	Subarnarekha Basin	65.39	740,51
2	Brahmani and Baitarni Basin	30.90	556,88
3	Mahanadi Basin	61.23	1,469,37
4	East flowing rivers between Mahanadi and Godavari	26.43	453,19
5	Godavari Basin	141.81	3,207,18
6	Krishna Basin	134.95	2,692,41
7	Pennar Basin	37.43	753,28
8	East flowing rivers between Pennar and Cauvery	63.43	643,61
9	Cauvery Basin	73.23	795,72
10	East flowing rivers South of Cauvery Basin	54.85	619,02
11	West flowing rivers (Western Ghat)	109.35	894,16
12	Tapi Basin	47.93	719,46
13	Narmada Basin	67.60	978,82
14	Mahi Basin	33.91	406,69
15	West flowing riversof Kutch,Saurashtra including Sabarmati and Luni Basin	72.35	2,627,70
16	Indus (Up to border) Basin	89.47	11,207,91
17	Ganga basin	558.72	10,618,48
18	Brahmaputra Basin and Barak and others Basin	69.24	6,608,76

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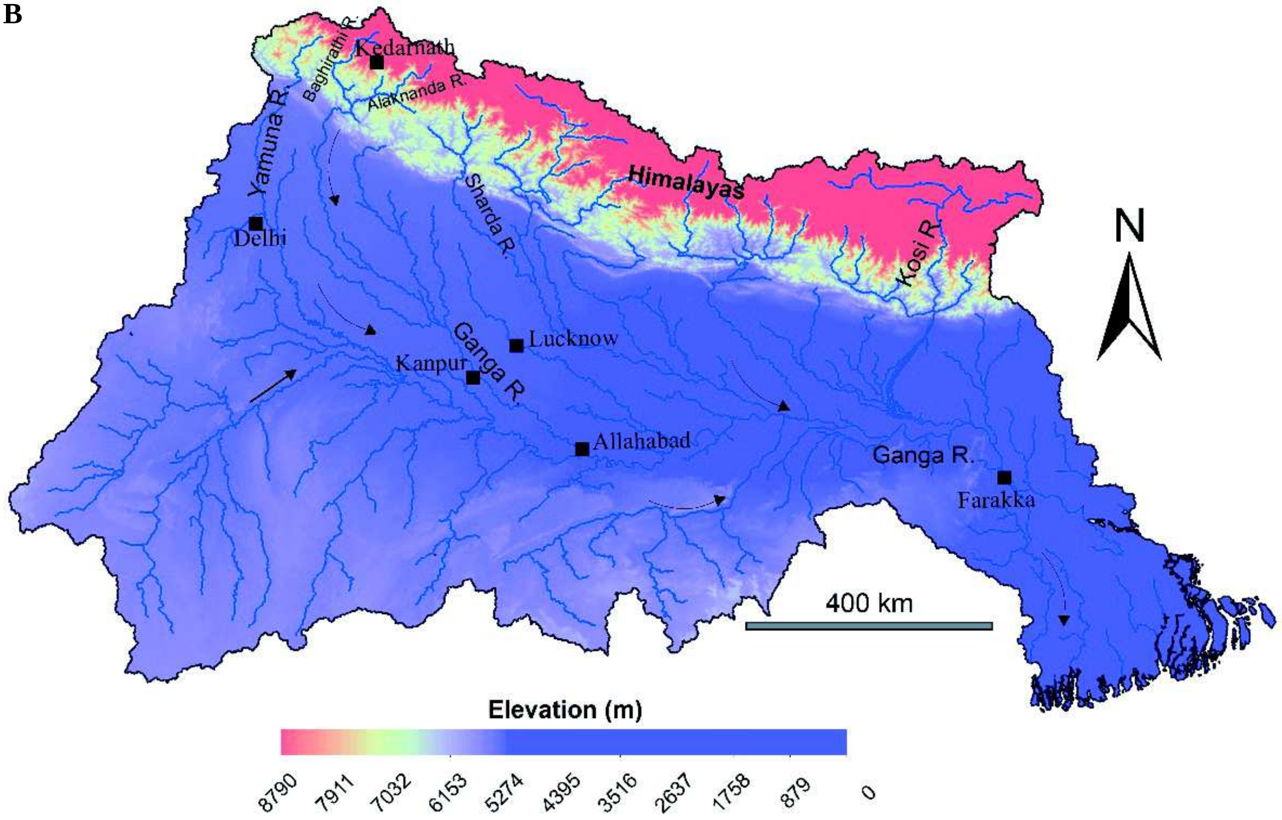


Fig. 1: (A) Major river basins of India. The Indian landscape has been classified into 18 major river basins (Source: http://www.india-wris.nrsc.gov.in/). These river basins are characterised by variable population. The shades in the figures represent district wise population distribution after 2011 census. The Table presents the basin population within the Indian part of the basin, while basin area represents the total basin area of the river system. (B) The Ganga River is the most studied river basin among all the basins. It is drained by a number of tributaries in various landscape settings. The location or reaches related with different case studies documented in this paper have also been marked

connectivity and threshold are considered to be some of the most important parameters to analyse river response at modern time scale and also to define the future trajectory of river systems.

Such investigations will lead to a new understanding about the present status of the river systems and will help to "project the future behaviour and form of rivers in the scenario of uncertainties associated with climate change and the ever growing impacts of anthropogenic activities" (Jain *et al*., 2012). Some of these issues have been recently studied on different kinds of river systems in India. This review provides a summary of these studies carried out during the past few years (2012-16) on the Indian rivers at the 'Anthropocene' time scale; it is an exemplar and does not intend to be comprehensive. The work includes an understanding of the morphological processes and their controls, nature of hydrological and geomorphological connectivity in anthropogenically altered systems and its implications, role of inherent geological and climatological controls on modern day river systems, and the impact of social diversity on the river studies.

River Processes and Channel Morphology in the Anthropocene

Channel morphology is a manifestation of the river characteristics and river behaviour. Its spatial variability not only represents the variability in hydrology and channel processes but also governs the ecological diversity in the channel. In order to understand the spatial variability, a geomorphic diversity framework has been developed for the Ganga River and its tributaries (GRBMP, 2010; Sinha *et al*.,

2016) (Fig. 1B). The geomorphic features at different spatial scales were used in a hierarchical framework to divide the Ganga River system into different reach types. This protocol aims to understand the morphological controls on biodiversity and to suggest the long-term sustainable river management strategies.

Anthropogenic disturbances on channel morphology due to changes in water and sediment fluxes have been highlighted in the Yamuna River from the mountain front to Allahabad (Fig. 1B) through systematic stream power based channel morphological study (Bawa *et al*., 2014). The alluvial reaches of the Yamuna River were divided into seven distinct geomorphic classes that represent the broader variability in channel behavior through three main process zones of the Yamuna River. The stream power based process zones are a direct reflection of human interference on the river system, and these zones are named as (a) high energy 'natural' upstream reaches, (b) 'anthropogenically altered', low energy middle stream reaches, and (c) 'rejuvenated' downstream reaches again with higher stream power (Fig. 2). Stream power and sediment flux variability explains the geomorphic variability in the 'natural' high-energy reaches; however it fails to explain the spatial variability of river characteristics in the anthropogenically disturbed reaches, which is characterised by different barriers (barrages). This work highlights the major challenges in understanding the geomorphic processes in 'anthropogenically' affected river systems, where traditional cause-effect relationship may not be sufficient to understand the variability. It is suggested that the incorporation of human controlled flux variability and the role of barriers in the understanding of morphological processes is important. Further, the concept of Maximum Flow Efficiency (after Huang and Nanson, 2000) was used to define the threshold condition related with major morphological change, and to assess the impact of human disturbances on channel processes.

The low energy 'Anthropogenically disturbed' stretches in any river requires significant increase in discharge for proper geomorphic and ecological functioning of the channel. Such estimates of e-flows are crucial for the sustenance of rivers and their habitats. The consortium of IITs recommended the integration of geomorphological and ecological parameters with hydraulic modeling to estimate flow depth and flow volumes necessary for channel maintenance (GRBMP, 2010). Computation for the Ganga River suggested that monthly E-flows for the wet period (mid-May to mid-October), at various sites vary from ~23% to ~34% of the virgin flows; however, the recommended E-flows for the dry period (mid-October to mid-May) vary significantly from one site to another (GRBMP, 2010). A preliminary estimation of flow requirement for the full sediment mobilization in the low energy 'Anthropogenically disturbed' stretch of the Yamuna River around Delhi (Fig. 1A,B) suggests 50% of virgin monsoon flood and 60% of virgin flow in non-monsoon period (Soni *et al*., 2014). Such sediment transport driven approach for e-flow estimation is required for most of the anthropogenically impacted river systems, where the decrease in flow volume is responsible for insignificant morphological processes in the channel.

The Damodar river basin (Fig. 1A) in peninsular India represents one of the oldest Indian examples where basin scale anthropogenic disturbances occurred through construction of series of dams, barrages and embankments. A hydrogeomorphic study after 50 years of dam construction suggests significant variability in channel behaviour and processes (Ghosh and Guchhait, 2014). The flow regime of the Damodar river has changed with temporal shift in flood peak and decrease in discharge in downstream reaches, which has caused significant aggradation in the downstream reaches and a decrease in bankfull capacity. Further, sediment starvation condition has also caused bank erosion at selected reaches, which has further changed the channel sinuosity and eroded a significant part of the floodplain along the river channel. Ghosh and Guchhait (2014) have suggested that sustainable solutions will require better use of flood water and sediment, while considering the basin resources as ecological resources rather than as economic resources.

Sediment transport is considered as a fundamental geomorphic process in a river channel. Recent studies have analysed the sediment load data to get new insight on sediment transport process. The analysis of thirty years time series of hydrological data was carried out for a stretch of the Ganga River to understand the suspended sediment transport process and major controls on channel processes (Roy and Sinha, 2014; in press). This mid-stream stretch of the

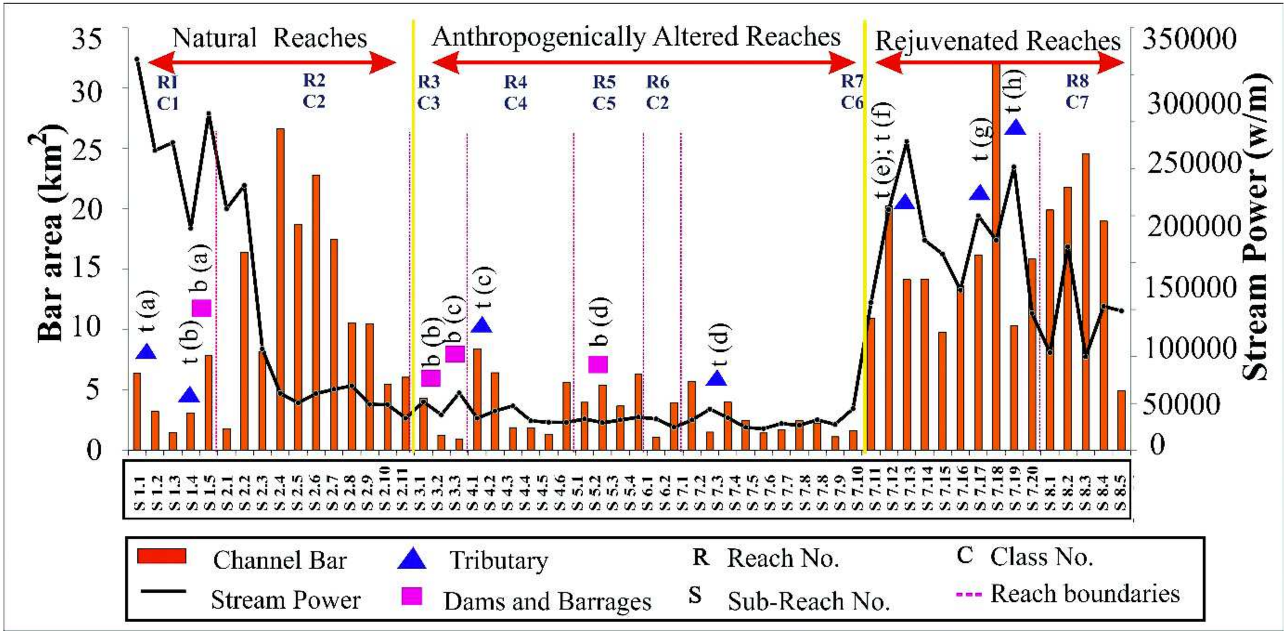


Fig. 2: Three major process domains of the alluvial reach of the Yamuna River with their characteristic stream power distribution patterns. The 'Anthropogenically altered'midstream reach is characterised by very low value of stream power, which makes it amorphologically inactive reach (modified after Bawa *et al*., 2012)

Ganga River around Kanpur (Fig. 1A) is efficient in terms of sediment transport at around 40% of discharge. The 'effective discharge' is generally less than the bankfull discharge, but it is sufficient to cause maximum transportation of the suspended sediment load. The channel needs flooding event(s) to transport its sediment load, as its mean annual discharge (RI = 2.33 years) cannot transport more than 10% of sediment load. Downstream variability in 'effective discharge' values was also used to explain the dominant aggradational or degradational processes at channel reach scale. It has been suggested that an understanding of spatial variability in 'effective discharge' and sediment dynamics are important parameters to understand the spatial variability in fluvial landscape variability (Roy and Sinha, in press) and also to analyse the impact of external factors on river systems.

A new approach on the basis of high-resolution field data has also been initiated on Indian rivers to understand the morphological dynamics at reach and site scales. High-resolution field measurements of hydro-morphological parameters using Acoustic Doppler current profiler (ADCP) integrated with Differential GPS provided new insights on the threshold condition of braided and meandering rivers (Gaurav *et al*., 2014). The understanding of threshold condition to distinguish meandering and braided rivers is a significant question in fluvial geomorphology. The Kosi megafan provides an ideal locale for such a study, where the main Kosi River channel is braided and a large number of palaeochannels on the fan surface are meandering (Fig. 3A). This work has shown that the hydraulic geometry relationship for a meandering river behaves in a similar fashion as that of a single channel of a braided river although the dimensionless slope values were 3 times higher for the braided river in comparison to the meandering rivers. The morphologically comparable forms of braided and meandering suggest similar sensitivity of channel form to discharge variability. Hence, anthropogenic disturbances on different channels will have similar impact. Further, the understanding of channel form sensitivity can also be used to estimate channel discharge from satellite data, which may provide multi-point data to analyse the human impact on channel processes.

Large scale morphological features of large river systems such as the Majuli Island of the Brahmaputra River support human populations in villages and are therefore of significant interest to different workers (Sarma and Phukan, 2004; Lahiri and Sinha, 2014).

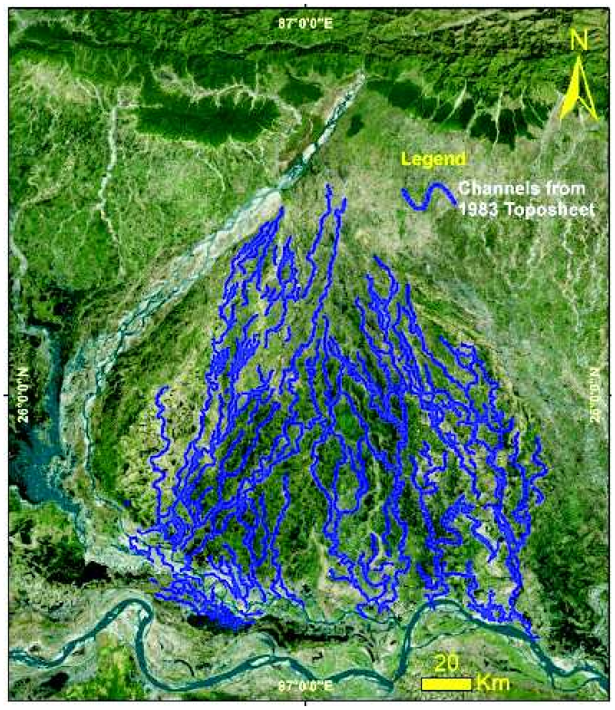
The Majuli Island has been shrinking with an average erosion rate of 3.2 km^2/yr. A recent study shows that the erosion trend closely correlates with the various geomorphic parameters of the Brahmaputra River, which includes channel belt area (CHB), channel belt width (W), braid bar area (BB), channel area (CH), thalweg changes and bank line migration, which highlights the role of channel processes on the evolution and erosion of the island (Lahiri and Sinha, 2014). It was also suggested that subsurface tectonic processes also governed its evolutionary trajectory. This new understanding of the evolutionary trajectory of the Majuli Island highlights the complexity in the management of this mega- geomorphic feature.

Humans and the Nature of Connectivity in River Systems

The connectivity structure of a landform is one of the fundamental characteristics used to define the process dynamics and to assess the risk associated with any river hazard. Connectivity is defined as a three dimensional entity (Ward, 1989; Brierley *et al*., 2006; Jain and Tandon, 2010), which includes longitudinal, lateral and vertical connectivity. A recent study on the stream network connectivity structure in longitudinal and lateral dimensions has shown its utility for the prediction of inundation areas in the scenario of avulsion driven flooding (Sinha *et al*., 2013). The connectivity structure was quantified by a connectivity index (Ic) defined as a function of the length and slope properties of the channel network. This topography-driven connectivity model was successfully used to simulate the avulsion pathway of the Kosi River during the August 2008 breach (Sinha, 2009). In general, avulsion prone reach of the Kosi River is characterised by different palaeo channels, which makes it difficult to predict the inundation zone due to avulsion event (Fig. 3C,D). However, such an approach provides a priori information about possible inundation zones and could be used to predict flood risk in populated and vulnerable regions. This study demonstrated that the mapping of connectivity structure for a stream network on a part of a fan surface can be used as an important tool in the management of flood hazards.

Also, the connectivity structure of networks at a landscape scale is impacted by human disturbances. The megafan of the Kosi River provides one such example, which is known for its dynamic river behaviour due to frequent avulsion events (Gole and Chitale, 1966; Wells and Dorr, 1987; Chakraborty *et al*., 2010). Channel shifting process on the megafan surface has also resulted in a number of palaeo channels. At present, the main river is flowing along the western margin of the megafan, while the rest of the megafan surface is drained by a number of palaeo channels (Fig. 3A). These palaeo channels are responsible for the redistribution of water and sediment flux across the megafan surface. However, the same megafan surface is also characterised by a dense network of rail-road transport, which is at a few meters higher elevation on the surface, so that these transport structures could remain unaffected in flooding condition (Fig. 3B). The higher elevation of these structures is responsible for creating a ‘barrier’ for palaeo channels and hence controls the distribution of water and sediment fluxes on the megafan surface. A connectivity analysis on the megafan surface has shown that both water and sediment distribution on the surface has been severely impacted by these rail-road transport barriers (Kumar *et al*., 2014). The density of transport network has increased with time, which has enhanced the disconnectivity on the megafan surface (Fig. 3B). The study shows that anthropogenic ‘barriers’ have caused» 45% disconnectivity on the megafan surface during the period of study (1955-2010). It was also demonstrated that the increase in disconnectivity represented by the density of the intersection points between the rail-road network and river channels corresponds directly to the increase in waterlogging on the fan surface caused by drainage congestion (Kumar *et al*., 2014).

Formation of various barriers across the rivers like dams and barrages has also caused significant disconnectivity in the system. A number of major dams constructed on the Himalayan and Peninsular rivers in India have disturbed the water and sediment fluxes. In the Mahanadi River basin (Fig. 1A), the time series data of the rainfall at different monthly and seasonal scales show that the rainfall trend is spatially variable (Panda *et al*., 2013). Increasing or decreasing trend characterizes the annual rainfall at different locations, whereas the annual water flow at the basin outlet is consistently characterized by a decreasing trend. This disconnectivity between rainfall and stream flow trend in the Mahanadi river basin is governed by the storage of water in the Hirakund dam.



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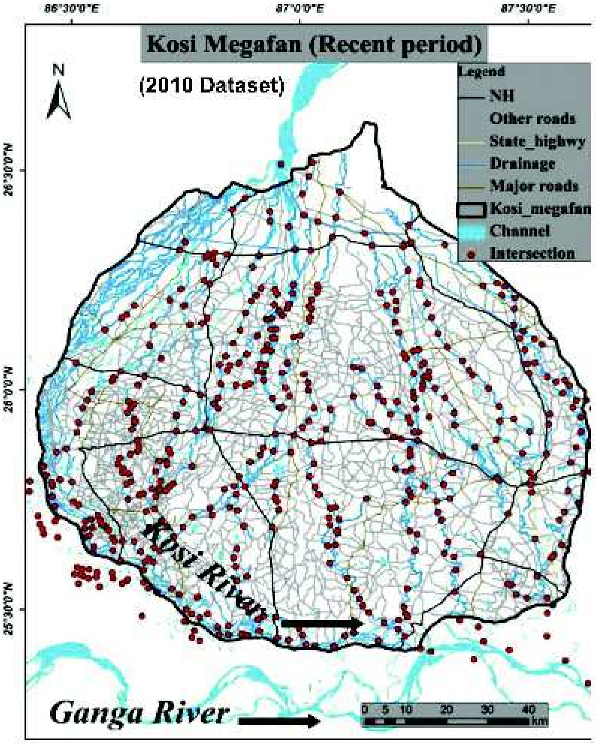

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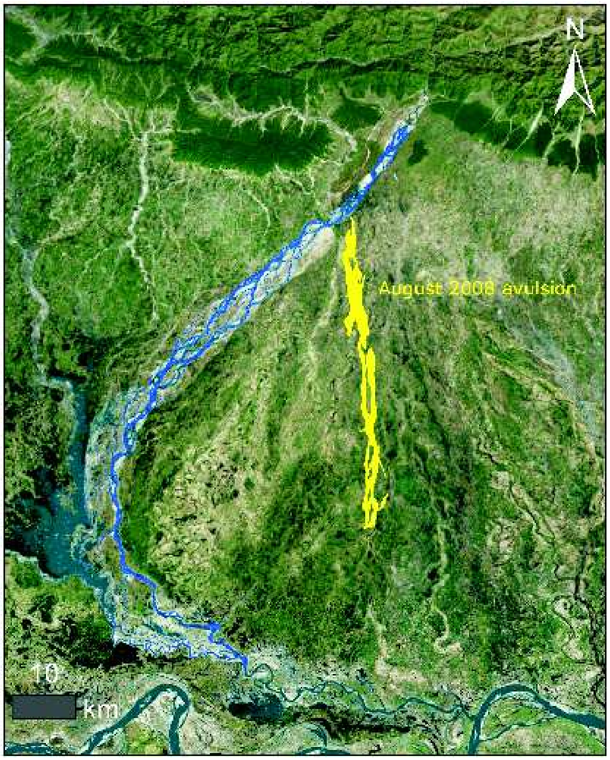

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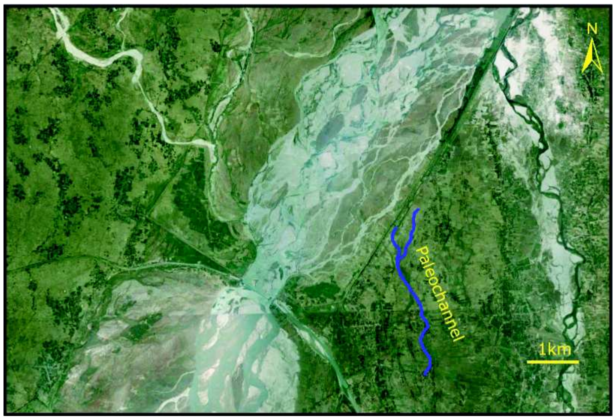

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Fig. 3: (A) The Kosi megafan with braided channel of the main Kosi River on its western part and number of meandering channels on the main megafan surface. The meandering channels, which represent different palaeochannels of the main Kosi River are drawn from 1983 Survey of India toposheet, (B) Intersection points between river channels and transport structures, which are responsible for creating disconnectivity on the Kosi megafan surface. Transport structures on the Kosi megafan surface have enhanced the disconnectivity by 45% (modified after Kumar *et al*., 2012), (C) A major avulsion event in 2008 caused flooding in the central part of the Kosi megafan affecting ~40 lakhs of population. This event caused major destruction as this area was not flooded from the last 100 years and people were not from prepared and (D) Palaeochannels near avulsion prone reach suggest that future avulsion events may cause inundation in several parts of the basin as demonstrated by Sinha *et al*. (2014) using connectivity index as a tool to predict the future inundation area after an avulsion event

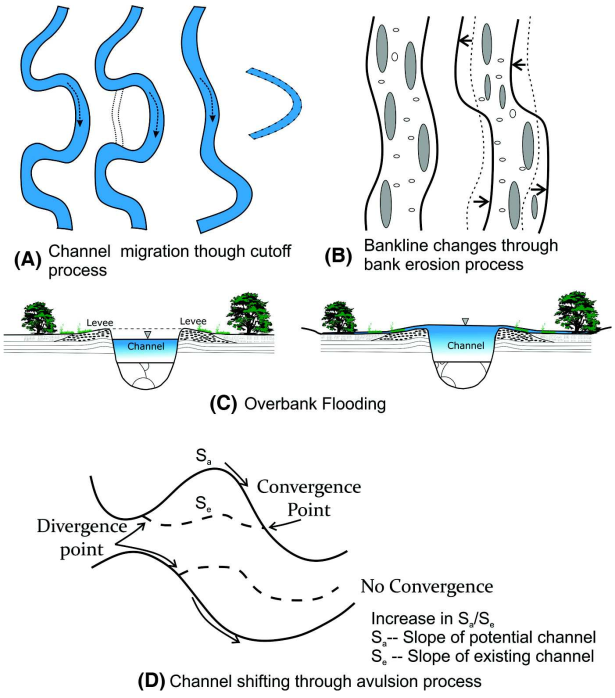
Large dams have caused more pronounced disconnectivity on the sediment fluxes. The Peninsular rivers are characterized by significant decrease in sediment supply during the last few decades. Using hydrological data from 1986 to 2006, Panda and Mohanty (2011) have shown that all the Peninsular rivers are characterized by decrease in sediment supply to ocean in response to decrease in rainfall and anthropogenic impact. The source-sink disconnectivity is more explicit in the highly regulated Narmada and Krishna rivers, where climate (rainfall variability) has no significant control on sediment flux variability. The sediment supply in the ocean has decreased by 65-70% in these regulated river basins.

This is so despite the fact that the anthropogenic disturbances have caused significant decrease in forest cover from 89 million ha to 63 million ha and an increase in agricultural area from 92 million ha to 140 million ha (Tian *et al*., 2014). This should instead have favored an enhanced sediment supply in the river-ocean systems. However, the source to sink disconnectivity due to large dams is so strong that sediment supply from rivers to oceans has decreased around 70-80% in most of the Indian river basins (Gupta *et al*., 2012). Decrease in sediment supply in coastal area due to source-sink disconnectivity is further responsible for a significant increase in the coastal erosion processes (Panda *et al*., 2011).

Flood Hazard and River Dynamics

Flood is one of the most severe natural hazards, which causes misery to a large section of human population. Jain *et al*. (2016) reviewed types, processes and causative factors of floods in the Indian rivers and suggested the need for the integration of hydrological and geomorphic data for better management of flood hazard. Floods could be broadly categorised into overbank flooding, channel shifting and outburst flooding. The Himalayan rivers are some of the worst affected rivers in the world in terms of flood hazard (Agarwal and Narain, 1996) and this has been attributed to high monsoonal discharges and very high silt load of these rivers (Sinha, 1998; Sinha and Jain, 1998; Sinha *et al*., 2005, 2014a). Extensive siltation is responsible for reduction in the channel capacity, which creates potential conditions for channel avulsion and flooding (Sinha *et al*., 2014a). Even in the peninsular India, where dams have created low flow regime in downstream reaches, enhanced siltation has increased the flood hazard in the downstream reaches (Ghosh and Guchhait, 2014). Additionally, the damming of rivers by landslides and glacier deposits in the Himalayan terrain creates potential conditions for outburst flooding (Wasson *et al*., 2013a). Recently, significant progress has been made towards understanding of processes and impacts of these flood hazards, which have been discussed in the following sections.

The dynamic nature of the Himalayan rivers also creates another river hazard. River dynamics occurs because of meander migration through cutoff processes, or shifting of channel through avulsion process (Fig. 4). In places, bank erosion driven bank line migration also forms a major hazard in high-energy braided rivers (Fig. 4B).The understanding of river dynamics not only provides an important insight for


(A) Channel migration though cutoff process

(B) Bankline changes through bank erosion process

(C) Overbank Flooding

(D) Channel shifting through avulsion process

Fig. 4: Different processes responsible for fluvial hazards in a basin area (a) Meander cut-off driven river migration (b) Bankline migration due to bank erosion, which is a common process along high energy braided rivers (c) Overbank flooding is governed by hydrological condition and changes in bankfull capacity of the channel (d) Sudden change in flow direction due to avulsion processes causes channel shifting, which is governed by gradient change in river channel

river processes and associated hazards, but it also provides an understanding of the habitat dynamics in the river system. The availability of multi-temporal satellite data and maps has provided an important tool to analyse the river dynamics. A remote sensing based study on the Sharda River downstream of the mountain front (Fig. 1B) highlights major planform and bankline changes in the alluvial reaches (Midha and Mathur, 2013). Such baseline information provides an important dataset to assess ecological disturbances due to hydromorphological variability in the channel. Similar remote sensing based study in the Lower Ganga plains around Farakka (Fig. 1B) highlighted anthropogenic disturbances in the channel through detailed study of river dynamics. Variability in channel sinuosity, braid-channel ratio, and bank-line position has changed significantly in the wide Ganga River valley. These changes have occurred due to sedimentological readjustments, which are indirectly governed by the anthropogenic impacts (Sinha and Ghosh, 2012).

The downstream area of the Ganga Plains and its deltaic region are also characterised by the shifting of meandering channels (Rudra, 2014; Bandyopadhyay *et al*., 2015) (Fig. 1B). Neck cut-off process at decadal scale has caused significant changes in the location of the Ganga River channel. Downstream reaches are characterised by extensive coastal erosion in response to changes in the fluvial and coastal processes. The abandonment of western distributary and interception of westward movement of shelf sediments have reduced the sediment supply and hence enhanced coastal erosion process (Bandyopadhyay *et al*., 2015). These observations indicate that stream management strategies should be based on an understanding of river processes in the area.

Further, significant progress has been made in recent years to develop process-based understanding of channel shifting and avulsion. This will help to build new scientific tools for the management of river hazards associated with dynamic rivers. Avulsions are known to be promoted by super-elevation condition, or by high ratio of cross-valley to down valley slope (Mackey and Bridge, 1995; Bryant *et al*., 1995). Sinha *et al*. (2014a) presented a detailed topographic analysis to highlight the causes of avulsion in the Kosi River. A reach-scale analysis of cross-sectional profiles and planform parameters coupled with field surveys using kinematic GPS highlighted a condition of super-elevation at downstream of mountain front (Fig. 1B, 3A), where the floodplain surface was observed to be around 2 m higher than the channel bar surface in several reaches. These criteria were used to identify the future potential sites for avulsion along the Kosi river. The authors suggested anthropogenic controls such as increased channel siltation due to embankments in creating the super-elevation condition and thereby triggering avulsion.

High energy braided rivers are also characterised by the dominance of bank erosion processes during the monsoon period. Erosion driven bank line migration is a common process responsible for the channel migration of wider braided river systems. The Brahmaputra River in Assam (Fig. 1A) is a classic example of the same, where extensive bank erosion problem is a major threat to nearby towns and villages in the area (Sarma and Phukan, 2006). The trend of bankline migration has been used by various workers to get new insights about bank erosion processes (Lawler, 1993 and references therein; Nanson and Hickin, 2012). Recently, Lahiri and Sinha (2012) documented the bankline migration of both banks of the Brahmaputra River from 1912 to 2005. The frequency content of the bankline was also analysed though application of fast Fourier transform (Lahiri and Sinha, 2015) that highlighted different levels of surface and subsurface controls on erosion processes.

Some major flood events in recent years have also become an important part of hydro-geomorphic studies. Flooding in the Alaknanda river basin (Fig. 1B) in June 2013 was a major catastrophic outburst event, which caused severe loss of property and life. A number of studies have been carried out on different aspects of this event. The flood was caused by the outburst of a moraine-dammed lake and very high intensity rainfall in the area (Dobhal *et al*., 2013). The river carried significant amount of sediments including boulders that destroyed the upper part of the Kedarnath town and buried most of the downstream area with few meters thick sediments in the valley. A geochemical and field based analysis suggested two different sediment sources in the downstream reaches i.e. moraines and old landslides

(Sundriyal *et al*., 2015). This study also highlighted the role of anthropogenic disturbances in terms of legacy sediment (James, 2013) generated by hydroelectric power-projects that further enhanced the flood damage at local scales. The authors suggested that even though the flooding event was climate driven, its impact on destruction and human life was due to the random growth of towns in this Himalayan area. The study argues for a better integration of geomorphic studies with human disturbances in the ecologically sensitive Himalayan terrain.

Devrani *et al*. (2015) have observed a remarkable spatial variability in the impact of June 2013 flooding event in the Alaknanda River basin. The flood wave caused intense erosion at some sites, but sediment deposition and flooding at different sites. It was suggested that this variability was strongly controlled by the shape of the long profile. Channel steepness measured by integrating areas over upstream distances (chi analysis) of the long profile explains the spatial variability in the impact of flood wave. This approach can be used as a predictive tool to assess the geomorphic impact of flood wave in steeply sloping channel reaches.

The role of climate in the recurrence of such massive floods has also been analysed through palaeoflood studies in the Himalaya. Extensive sediment deposition in such catastrophic flood events serves as an archive to study the palaeoflood history in the area. The occurrence of various flood deposits in the Higher Himalaya suggests that it was not an isolated event, but such major floods have also occurred in the past. Wasson *et al*. (2013a) analysed 1000 years history of large floods in the Alaknanda and Bhagirathi river valley (Fig. 1B) using the sedimentary archive, and suggested that high magnitude impacts in the last 1000 years are characterized by temporally variable frequency, which follows the monsoonal variability. Monsoon strengthening resulted in more landslides in the High Himalayan terrain and caused damming of rivers by landslide debris, the bursting of which triggered major floods. Hence, the occurrence of major floods in the steeply sloping Himalaya is a natural process, though human impacts have made it more catastrophic in nature.

Role of climate change on the flood events has also been analysed using the historical data. Kale (2012) compiled the temporal distribution of extreme flood events for the large South Asian rivers, and highlighted a major clustering of flooding events in three decades namely 1940s, 1950s and 1980s, which were also the periods of above normal rainfall. A comparison of historical floods and palaeoflood records further suggests that modern floods (post-1950) are characterized by higher magnitude in comparison to the late Holocene floods (Kale, 2014). The floods are not only increasing due to enhanced frequency of flood-generating extreme rainfall, but they have also become more destructive due to various human interventions (Kale, 2014). In a recent study, Cho *et al*. (2016) have also suggested the increasingly large summer rainfall in northern India since late 1980s. Interestingly, this variation in climatic parameters is also characterised by anthropogenic footprint, as enhanced rainfall since late 1980s is related to the increase in the concentration of greenhouse gases and aerosols (Cho *et al*., 2016).

Modern Rivers and the Role of Inherent Controls

The form and behaviour of modern rivers are governed by water and sediment fluxes and downstream channel slope. All these parameters are governed by inherent geological, climatic and landuse-landcover characteristics of the river basins. A landform at modern time scale should not be considered as an isolated entity but it is hierarchically related to the inherent characteristics of the area. This impact of landscape memory on landform processes is one of the new focus areas in fluvial geomorphology (Brierley, 2009), which if integrated with existing datasets would achieve scientifically sound management strategies for any particular geomorphic system.

Most of the Indian rivers fall under the tropical climatic setting (Sinha *et al*., 2014b). The tropical rivers in India are strongly monsoon-driven with strong seasonality, significant flooding, high sediment load and with distinct biogeochemical signatures (Syvitski, 2014). The flux characteristics of the tropical rivers are significantly different with respect to the low-runoff rivers. These climate driven tropical rivers are the main transporting agent for an extensive suspended and dissolved load to the world’s oceans, while bedload availability may act as a limiting factor in the total sediment transport. Such flux characteristics in tropical rivers further govern the channel morphology, dynamics and flood hazard conditions. Hence, the climatic setting of these tropical rivers sets them apart as typical river systems distinct from the better studied temperate rivers. Some of the major research queries for tropical rivers include the impact of biogeochemical factors and temperature on sediment transport, feedbacks of tropical rainforests on rainfall, and the impact of excessive rainfall on deltas and their morpho dynamics (Syvitski, 2014).

Sediment flux in a river system is governed by the topography and lithology of the area. Besides this, the older landforms such as river terraces and fan surfaces may act as secondary sources of sediments in the river system. Intermontane valleys are prominent landforms in the Himalayan frontal zone. These valleys have aggraded during different episodes in the Late Quaternary. However, most of the depositional landforms like alluvial fans, and fill terraces in the intermontane valleyare presently going through the degradation phase (Sinha and Sinha, 2016), and contribute to sediment flux downstream river basin. A first order sediment budgeting of these deposits in the Dun valley, NW Himalaya shows that these secondary sediment sources are contributing only 1-2% of the modern suspended-sediment discharges of the Ganga and Yamuna rivers (Densmore *et al*., 2015). Another study of valley fill terraces in the Lesser Himalaya of Alaknanda River basin suggests that they could be a significant source of sediment supply in a river basin (Singh *et al*., 2012). These fill terraces in the Himalayan region are extensively used for human settlement and agricultural activities. A preliminary estimation of the erosion rate through Total Station based field mapping was of ~3350 t/km^2 (Singh *et al*., 2012). Such data sets are important in estimating the sediment budget of a river valley and for the assessment of the anthropogenic impact on sediment supply.

Sediment budgeting of a local area in the alluvial plain region is mostly governed by climate and landuse pattern. Wasson *et al*. (2013b) used $\approx$6 ka sedimentary records in a pond area (Misa Tal) in the Ganga Plains near Lucknow (Fig. 1B) to assess the role of climate and landuse-landcover change on erosion processes. Temporal sediment yield variability in the pond area directly correlates with the climatic fluctuations and with major anthropogenic activities. Anthropogenic disturbances caused landuse and landcover changes that was assessed through pollen records. Agricultural intensification in the area around 100-200 AD is reflected as an increase in soil loss process in this part of the Ganga plains. Further, variability in soil loss since 1770 AD was related to major landuse changes driven by social unrest and partially due to dry climatic condition.

River Futures

River futures in the scenario of climate change and enhanced anthropogenic disturbances will always be uncertain due to its nonlinear response to external forcing (Jain *et al*., 2012). A few attempts have been made in recent years to assess the river futures in response to climate change and anthropogenic disturbances with the use of different climatological, and hydrological models, and through its integration with social diversity.

Whitehead *et al*. (2015a) used a dynamic, process-based INCA model to simulate hydrology and water quality for the Ganga basin for 2050s and 2090s and predicted an increase in monsoon flows and increased availability of groundwater recharge, but also more frequent flooding. Model results for the 2050’s and the 2090’s are similar to the climate driven prediction, which suggest a significant increase in the monsoon flows and more likelihood of flooding during monsoon period. Low non-monsoon flows are predicted to fall with extended drought periods. These low flows events will have significant impacts on water and sediment supply, irrigated agriculture and saline intrusion. In contrast, the socio-economic changes had relatively little impact on flows due to high volume flow in these river systems. However, in the low flow regimes, increased irrigation could further reduce water availability and may cause significant impact on river health.

Mishra and Lilhare (2016) have used Soil Water Assessment Tool (SWAT) hydrological model on the downscaled and bias corrected future climate projections to get future scenarios of all the major Indian rivers (Fig. 1A) in the Near- (2010-2039), Mid- (2040-2069) and End- (2070-2099) term climate change scenarios. Climate projections suggest warm and wetter climate that may result in more runoff.

Model results have shown that the surface runoff displayed more sensitivity to changes in precipitation and temperature than evapotranspiration (Mishra and Lilhare, 2016). Hence, most of the basins will be characterised by more than 40% increase in streamflow by the end of the 21st century, which may create major flooding condition along the river reaches. In the Near- and Mid-term climate change scenarios, most of the basins are likely to witness increase in runoff except a few rivers in western India, which may be characterised by a decrease in the streamflow. However, these scenarios do not include the glacial melt contribution due to climate warming, which is yet another factor of uncertainty in the future projections.

Khan *et al*. (2016) have highlighted the uncertainty in glacial melt estimation and application of multi-proxy approach for its better estimation as part of their work on the Bhagirathi River (Fig. 1b). The hydrological budget in the upstream Himalayan reaches is governed by glacial melt, groundwater contribution and rainfall contributions. These hydrological sources are characterised by significant seasonal variability and one method is not sufficient to get good estimation of glacial melt runoff. An integrated approach including remote sensing, field estimation, isotope analysis and hydrological data is used to reduce uncertainties in the glacial melt estimation (Khan *et al*., 2016). Such an approach needs to be integrated with the hydrological model to achieve future projections of the glacial-fed rivers. Senzeba *et al*. (2016) analysed the response of smaller rivers with seasonal snow cover to climate change scenario. They have integrated the Snowmelt runoff model (SRM) output with projected temperature and precipitation for different emission scenarios. The study suggested that future variations in streamflow would be mostly governed by precipitation variations rather than by the change in snowmelt depth.

Recently, some studies have also tried to superimpose the complexity of human interference on river systems on the output of climatic models. The future of Ganges-Brahmaputra-Meghna in terms of flow and water quality in the near future were defined through Integrated Catchment Model (INCA-N) for the following three scenarios of socio-economic pathways- (1) a business as usual future, (2) a more sustainable future, and (3) a less sustainable future (Whitehead *et al*., 2015a). The INCA-N was integrated with higher resolution 25 km Regional Climate Model (RCM). The anthropogenic impacts were analysed through various parameters namely 1) Population change 2) Sewage treatment works capacity and design for water quality control 3) Water demand for irrigation and public supply 4) Atmospheric nitrogen deposition 5) Land use change 6) Water transfer plans. However, the impact of dams was not considered in this analysis. Further, water quality may be significantly impacted by different socio-economic scenarios. Model outputs suggest major alteration of nutrient flux transfer into the delta region (Whitehead *et al*., 2015a; 2015b). However, the increase in flow amount will also cause decrease in nitrogen and ammonium concentration. Water quality will be influenced by anthropogenic impact, as the model output suggests that 'less sustainable' way of life will have a significant impact on water quality.

Conclusions

Modern rivers in India have been studied in different geographical and geological settings. Human imprints are being manifested significantly in the processes and morphology of all the modern rivers. Such studies require multiple datasets, such as hydrological and morphological data, remote sensing based spatial datasets, geochemical data, climate models and their projections, glacial runoff models and their outputs, field observations and measurements, and the application of different river models. Studies on modern rivers in the background of the Anthropocene context are still in the initial stage in India, and there is a need to develop new inter-disciplinary approaches to understand feedback mechanisms in these large and complex river systems. Such approaches are of considerable interest for designing sustainable scientific strategies for stream management in the scenario of climate change and human disturbances, and will also help to gain insights on the future trajectories of river systems.

It is also important to consider that a river is not a closed geomorphic system. River processes are governed by flux and energy transfers and it maintains equilibrium with the inherent climatic, geological and landscape settings. Unless human impact on modern rivers is documented in such complex framework, threshold dynamics and sensitivity of the various components of large river basins cannot be understood. Given the importance of rivers as a fundamental resource for the large human population of our country, it is imperative that suitable initiatives are taken and implemented by the various Earth Science organisations in India for strengthening the different facets of River Science, some of which have been elucidated in this review.

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