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Landscape Evolution of Rivers in the Ganga Plain and Himalaya

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Rivers in Himalaya and Ganga foreland respond to the tectonics and climate operating in its geomorphic continuum. The landscape of river systems draining the two continental scale geomorphic entities evolve at various spatio-temporal scales. The studies during the last five years in India have largely focused on understanding the climate-tectonic forcing and sensitivity of landscape responses and utilized high resolution geomorphic mapping, sedimentology, and luminescence chronology. A newer dimension of river/sediment connectivity, between the source and sink, in terms of sediment erosion/ delivery and storages has been initiated. Overall, >85 research articles were published that can be classified into (i) River aggradation-incision, paleofloods and neotectonic deformation in the Himalaya, (ii) Glacial morphostratigraphy in river headwaters, (iii) Sedimentation in the Ganga foreland, and (iv) River connectivity between the Himalaya and Ganga Plain.

Keywords: Rivers; Himalaya; Ganga Foreland; Quaternary Evolution

Introduction

The Himalaya and Ganga Plain are genetically related continental scale geomorphic units that are coupled in terms of their tectonic evolution and climatic responses at different temporal and spatial scales. The rivers that originate in the Himalaya and drain through the Ganga foreland before finally meeting the ocean exhibit a variety of landforms and stratigraphy, that act as archives of the fluvial response to tectonics of region and monsoon variability. Studies have focused on the mapping of terraces, understanding their sedimentary behaviour, deciphering aggradation and incision phases and developing the chronology of events. To evaluate the linkages between the Himalaya and Ganga plain, the contributions have been made towards (i) River aggradation-incision, paleofloods and neotectonic deformation in the Himalaya, (ii) Glacial morphostratigraphy in river headwaters, (iii) Sedimentation in the Ganga foreland, and (iv) River connectivity between the Himalaya and Ganga Plain. The following text provides a brief account and review of the work done addressing the above listed themes during the past five years.

Riveraggradation-incision, Paleofloods and Neotectonic Deformation in Himalaya

The river aggradation and incision, formation of fill and bedrock terraces and their location depends upon the sediment and water supply, ability of the channel-reach to transport the sediment and tectonic conditions. The shape and geomorphic effectiveness of longitudinal river profiles in the Himalaya is strongly controlled by basin geology and climate (Jain, 2018; Sonam and Jain, 2018).The data on valley fills from Alaknanda river valley suggested that valley filling follows glacial-periglacial hypothesis implying an important role of precipitation driven dynamics in sediment generation, downstream transportation and valley filling (Ray and Srivastava, 2010; Dosseto *et al.*, 2018). The work suggested that transition between arid glacial and climatic optimum allowed valley aggradation and peak wetness leading to reduced sediment/water ratio and channel incision. Later, similar observation was made while understanding the formation of fossil valleys and epigenetic gorges and the non-glaciated rivers like the Ramganga (Chaudhary *et al.*, 2015, 2017). Further, increased hill slope erosion and reduced channel transport capacity during drier climate is envisaged as a

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*Author for Correspondence: E-mail: pradeep71s@rediffmail.com controlling factor behind river aggradation (Scherler *et al*., 2015). The analysis from Kangra and Sutlej river basin, NW Himalaya suggested aggradation in wetter climate and incision during the phases with drier climate and reduced sediment supply (Dey *et al*., 2016; Sharma *et al*., 2016a, b). Devrani and Singh (2014) argued in favour of local hillslope generated sediment and landslide damming leading to channel aggradation. The occurrences of landslides in the Himalaya are shown to follow a climate pattern and structures in the Himalaya (Chahal *et al*., 2017). The morphometric studies in Alakananda river valley helped in identification of zones of active deformation though the valley fills exhibit aseismically formed soft sediment deformation structures (Rana *et al*., 2016a, b). Towards the mountain front lie dun basins that act as transient sinks between the Himalaya and Deltaic zones. These dun basins are sediment filled and exhibit a variety of landforms like fans, fluvial terraces, piedmont fans and wide flood plains. A study in Dun basin indicated that proximal part of fan formed during ~34-21 ka and the distal part during 20-11 ka de-glacial warm phase. There are relict fan deposits that were deposited at ~43 ka. The fans were incised during intervening phases (Sinha and Sinha, 2016). The incision phases lead to the basinward progradation of depocenters and the basin contributed 1-2% of sediments to the modern Ganga and Yamuna rivers (Densmore *et al*., 2016).

The river Indus (Ladakh, NW Himalaya) experienced three phases of channel aggradation driven by strengthened monsoon, at ~52 ka, ~28 ka and ~16 ka (Kumar and Srivastava, 2017; Sharma and Phartiyal, 2018). It responded to tectonic activity in the NW syntaxis zone and the north-vergent thrusts in the suture zone, and formed the bedrock terraces. Similar inferences were drawn from the Suru and Doda rivers (Zanskar basin) where the strengthened mid-latitude Westerlies and cooler temperatures during stronger monsoon drove glaciation, whereas warm interglacial lead to build up of alluvial fans and river terraces (Sharma *et al*., 2018). The alluviation in Zanskar occurred in three monsoon strengthened phases during ~43 to ~32 ka (cool and wet MIS 3), 20-12 ka, and the youngest aggradation phase between 9 and 6 ka, corresponding with the strengthened monsoon phase of the early-mid Holocene. This study also implied that wider parts of the basin (Padam basin in Zanskar) may be acting as important sediment buffers during aggradation and incision, and even in drier Himalaya the Higher Himalayan Crystallines (HHCs) remained as an overwhelming sediment supplier (Chahal *et al*., 2019). At places the fill terraces are seen capped by thick clayey silty lacustrine deposits where a detailed study provided a model for the sedimentation in lakes that are hydrologically open and formed in high altitude, cold and arid deserts (Nag *et al*., 2016). The field mapping of these lake deposits along the Indus indicates existence of mega lake systems in Ladakh during the post-LGM times (Nag and Phartiyal 2015). Likewise, studies in the trans-Himalayan Tangtse valley provided a ~50 ka history of river responses to tectonics and climate (Phartiyal *et al*., 2015).

Valley fill terraces are often overlain by stacks of paleoflood deposits, which are found in protected places and represent past occurrences of large floods in the Himalaya. Limited studies on such paleoflood deposits in the Indus, Sutlej, the Ganga and the Brahmaputra rivers have been carried out and the role of summer monsoon and North Atlantic Oscillations behind extreme hydrological events in the Himalaya is evaluated (Srivastava *et al*., 2017; Sharma *et al*., 2017). Studies have demonstrated that modern urbanization practices and infrastructural developments that are adopted have increased the vulnerabilities in the Himalaya (Sundriyal *et al*., 2015; Zieglar *et al*., 2014, 2016; Bhambri *et al*., 2017; Mehta *et al*., 2017).

More recently, it is argued that the climate driven erosion and thrust tectonics are the main drivers of the evolution of Himalaya and that the deformation is focussed at the Himalayan front. A review of geodetic and geomorphic data suggesting crustal shortening rates in the Himalaya suggests that the rate of deformation varies both temporally and spatially (Dey *et al*., 2016). The geometry of basal decollement controls the mountain front deformation where salient and recess are formed accordingly. Between Kangra and Dehradun recesses, using geomorphic indices, various faults are identified indicating out-of-sequence tectonic activity in the Nahan salient (Kaushal *et al*., 2017). Likewise, in the western Himalaya, the Medlicott Wadia Thrust (MWT) is observed between the Precambrian limestone and Quaternary sediments at ~36 ka. Similarly, other splays of the MWT are implied being active at ~15 ka and the activity along the main boundary thrust (MBT; north of MWT) ceased at ~30 ka. The balanced cross section parallel to the MWT indicates both in-sequence and out-of-sequence tectonic activity along its various splays and that the thrust absorbs ~10 mm/yr of India-Eurasia convergence (Vassallo *et al*., 2015; Mugnier *et al*., 2017). However, the terraces close to the MWT could not be related to activity along this thrust (Vigon *et al*., 2017). In the Kumaun sub-Himalaya a ~9.5 km long splay of the MBT is mapped offsetting an alluvial fan at >20 ka that remained active until atleast 8.7 ka (Philip *et al*., 2017). Similarly, a study using geomorphic indices and Interferometric Synthetic Aperture Radar (In-SAR) mapped active deformation between the MBT and the Himalayan Frontal Thrust (HFT) in Soan Dun area and several river basins in the Kumaun and Garhwal Himalaya were evaluated to understand the neotectonic deformation in the region (Talukdar *et al*., 2019; Luirei *et al*., 2015, 2016, 2018; Kothyari and Luirei, 2016; Bhakuni *et al*., 2017; Kothyari *et al*., 2017a, b, 2019; Joshi *et al*., 2018; Asthana *et al*., 2018).

Glacial Morphostratigraphy in River Headwaters

Glacial advance and retreat in the Himalaya, in terms of climatic influence, is partitioned into two zones: (i) Monsoon dominated Himalayan southern front glaciers and, (ii) Westerlies dominated Himalayan northern front glaciers. The studies during the last five years focussed on glaciers in monsoon dominated Lahaul Spiti, Garhwal and Sikkim Himalaya and westerlies controlled Zanskar, Ladakh, and Karakoram ranges. In these areas, detailed field mapping of moraines and periglacial features has been carried out to mark different stages of glacial advancement during the past. The chronology of the glacial stages is established using Optically Stimulated Luminescence (OSL), ^{14}C-AMS and Cosmogenic Radionuclide (CRN) dating techniques. A review of >1000 CRN ages derived from the glacial moraines in monsoon influenced southern Himalayan front from Pakistan to Bhutan indicates 27 regional glacial stages that are termed as Monsoonal Himalayan-Tibetan stages (MOHITS; Murari *et al*., 2014). These stages, that arguably advanced during the strengthened monsoon phases, included 5 pre-LGM stages between 483±38 ka and 122±15 ka), 13 stages in the Last Glacial cycle from 91±15 ka to 12.9±0.9 ka, and 11 stages during the Holocene between 11.4±0.7 ka and 0.4±0.1 ka (Murari *et al*., 2014). Studies from the Garhwal and Zanskar Himalaya suggest that historically and during the last decade glaciers exhibited variable retreat rates and required real time monitoring (Kumar *et al*., 2017; Chand *et al*., 2017; Garg *et al*., 2018). A review of recent studies including the identified glacial stages and their chronology focusing at 10^3-10^4 years' time scales is provided in the Table 1.

Sedimentation in Ganga Foreland

The Ganga foreland basin was formed in response to the continent-continent collision and thrust loading in the Himalaya and shows development of large alluvial tracts (Doab) separated by major rivers, river valley terraces, megafans and piedmont fans (Singh, 1996; Srivastava *et al*., 2003). The megafan stratigraphy, as understood from borehole stratigraphy of the Kosimegafan, is controlled by the geology of the mountain front and hydrology and sediment flux of rivers (Sinha *et al*., 2014a). The basin receives sediments from the rising Himalaya in the north and from the subdued peripheral bulge in the south, and river pattern, sediment supply and weathering follow foreland tectonics and climate gradient (Maharana *et al*., 2018; Jain *et al*., 2019; Ghosh *et al*., 2019). The rivers respond to extreme hydrological events, sediment flux and anthropogenic pressures, and change their planform and courses frequently, e.g., Kosi in the eastern Ganga plain is hyper-avulsive that avulsed during 2008;a recent study using high resolution topographic mapping and GIS framework evolved an avulsion threshold for this river (Sinha *et al*., 2014b; Singh *et al*., 2019). The relative contribution of sediments from within and the two sources, separately, has varied in the past and the position of axial river of the basin has moved north-south accordingly (Sinha *et al*., 2009; Shukla *et al*., 2012; Tripathi *et al*., 2013). The geomorphology and sedimentation in the Marginal Ganga Plain is controlled by the forebulge tectonics (Bawa *et al*., 2014; Ghosh *et al*., 2018). More recently, a detailed study involving sedimentology, chronology and fossil record of 17 stratigraphic sections exposed along the river Yamuna and its southern tributaries suggested craton-derived northward propagating gravelly fan in response to a tectonic uplift along the peripheral bulge at ~80-54 ka (Ghosh *et al*., 2019). The study also reported a rich

Table 1: Review of glacial chronologies and forcing factors

S.No.	Glacier	Glacial stage, extent and chronology basin, region	Forcing factor	Reference
Monsoon dominated Himalayan southern front glaciers				
1	Din gad, Dokriani, Garhwal Himalaya	5 Dokriani glacial stages (DGS) DGS-I: 2883 m, ~25-22 ka DGS-II:3211 m, ~14-11 ka DGS-III: 3445m, ~8 ka DGS-IV:3648 m, ~4 ka DGS-V: 3733 m, ~3-1 ka Snout:3965 m	Global temperature lowering, variable monsoon and North Atlantic Climate	Shukla *et al*., 2018
2	Dunagiri, Garhwal Himalaya	3 Bagni glacial stages (BGS) BGS-I, 3200 m, 12-9 ka BGS-II, 4000 m, 7.5-4.5 ka BGS-III, 41000 m, ~1 ka Snout: 4400 m	Lowered temperature and decreased monsoon	Sati *et al*., 2014
3	Kosa Valley Glacier, Garhwal Himalaya	4 Raj bank stages (RBS) RBS-I, 3145 m, 2017LGMRBS-II, 3684 m, ~6 kaRBS-III, 3713 m, ~5-4 ka RBS-IV, 3820 m, ~2.2-1.6 ka Snout: 3910 m	Lowered temperature and decreased monsoon	Bisht *et al*.,
4	Miyar basin, Lahaul Himalaya	3 Glacial stages Miyar Stage, 3063 m, >MIS-4 Khanjar stage, ~10-7 ka Menthosa stage, 18th CE Snout: 4060 m	Variable climate	Deswal *et al*., 2017
5	Purvi Kamet Glacier, Dhauliganga basin, Garhwal Himalaya	4 Purvi Kamet Stages (PKS) PKS-I, 3369 m, MIS-3 PKS-II, 3940 m, LGM, PKS-III, 4086 m, ~8 ka, PKS-IV, 4352 m, >3 ka Snout: 4589 m	Lowered temperature and decreased monsoon	Bisht *et al*., 2015
6	Chopta Valley, Sikkim Himalaya	Characterized LGM glaciation, ~4000 m	Lowered temperature and increased moisture	Ali *et al*., 2019
Westerlies dominated Himalayan northern front glaciers				
7	Gopal Kangri, Stok Valley, Ladakh	4 Glacial stages MG_1, 5200m, ~1.5 ka MG_2, 5130 m, 37-21 ka MG_3, 4720 m, 33-29 ka MG_4, 4350 m, 124-100 ka Snout: 5260 m	Largely correlated with periods of strengthened monsoon but chronology is insufficient for robust correlations	Orr *et al*., 2017
8	Stok Kangri, Ladakh	4 Glacial stages MS_1, 5300 m, ~1.5 ka MS_2, 5290 m, 1-0.5 ka MS_3, 4970 m, 22-16 ka MS_4, 4575 m, 56-39 ka	Largely correlated with periods of strengthened monsoon but chronology is insufficient for robust correlations	Orr *et al*., 2017
9	Western Zanskar, Ladakh	4 Glacial stages SZS-4, >300 ka SZS-3, ~19-23 ka SZS-2, ~16-14 ka SZS-1, ~6-5 ka	Cooling during the periods of strong westerlies indicating coupling with the Northern Atlantic	Sharma *et al*., 2018
10	Eastern Zanskar, Ladakh	3 Sarchu Glacial Stages (SGS) SGS-III, MIS-4SGS-II, ~20 kaSGS-III, ~9 ka	Cooling during the periods of strong westerlies	Sharma *et al*., 2016
11	Lato massif, Central Zanskar	Lato Stage-I, 244–49 ka, Shiyul Stage-II, 25-15 ka, Kyambu Stage-III, 3.4–0.2 ka	No conclusion drawn	Orr *et al*., 2018
12	Hamtah valley Lahul; Karzok, Lato and upper Stok valleys in Zanskar Himalaya	5 Local glacial stages are dated to ~10.4, ~6.1-3.3, ~2.1-0.9, ~0.7-0.4 and ~0.3-0.2 ka	Early Holocene glacier advances correspond to orbitally-forced northerly migration of the Intertropical Convergence Zone and enhanced summer monsoon. Whereas mid- and late Holocene are controlled by North Atlantic cooling teleconnected via mid-latitude westerlies	Saha *et al*., 2018
13	Shyok valley, Karakoram, Ladakh	3 Glacial stages Tirith-II, ~60 ka Titith-II, ~30-20 ka Siachin Glacial advance, ~7 ka	Decreased temperature and increased moisture during strong mid-latitude westerlies	Ganju *et al*., 2018

vertebrate fauna and some archaeological finds (Ghosh *et al*., 2016). Such a stratigraphy, using borehole data, is also reported from further east in the Son river basin (Sahu *et al*., 2015). A study of drill core sediments in the Ganga-Yamuna interfluve indicated three phases of humid climate-driven paleosol development during 90-80 ka, 50-30 ka, and 10 ka with drier conditions in between (Srivastava *et al*., 2018). A similar study involving pedo-geomorphology following a climatic gradient of the Ganga plain (from Yamuna plains to Delta) suggested development of five geomorphic surfaces during the last 13.5 ka. These surfaces exhibit a climate control over development of soil types, e.g., the soils in Yamuna uplands show development of pedogenic carbonates during the arid climate of <5 ka (Srivastava *et al*., 2016). Further, a review of all published literature and a new dataset provided state-of-art information on a pedogenic response to past climatic variations, neotectonic deformation of the surface and human activities in the Ganga plain (Srivastava *et al*., 2015). The stratigraphy of the Ganga plain, using stable isotopes in calcrete and outcrop scale observations, is explored for climate, vegetation and faunal variability during the past ~100 ka (Agrawal *et al*., 2014 a, b; Ghosh *et al*., 2017; 2019) and seismic tectonic/ activities (Pati *et al*., 2015, 2019; Verma *et al*., 2017).

River Connectivity and Sediment Routing Between the Himalaya and the Ganga Plain

The Himalaya-Ganga foreland-delta is a geomorphic continuum that in terms of sediment water delivery and source to sink relationship bears a complex response in time and space. The large river systems like the Indus, Ganga, and Brahmaputra play an overarching role in defining sediment generation, transfer and storage between the source (the Himalaya) and the ultimate sink (the delta). During the last five years a new research exploring aspects of sediment and river connectivity in various river systems of the Himalaya and the Ganga foreland is initiated. A study in the Kosi river basin suggests that sediment connectivity in such large basin is a function of its land use, land cover and slope and basin shape, where distribution of rainfall in the basin also plays an important role (Mishra *et al*., 2019). This river, at Chatara, where most tributaries meet, receives ~56% of its discharge from western part of its basin that makes ~34% of the area. Likewise, the central and eastern segments of the Kosi basin supply 38% and 16% of discharge that make only 57% and 8% of the basin area, respectively (Sinha *et al*., 2019). The sediment routing also follows a similar pattern (Sinha *et al*., 2019). The connectivity structure of the Kosimegafan was studied to understand its sediment, water fluxes and avulsive behaviour that highlighted that rail/road network provided a negative feedback to the connectivity structure of the megafan resulting into drainage malfunctions in the region (Kumar *et al*., 2014).

Conclusions

Following conclusions are drawn from the contributions made during past five years:

1. Studies focused on (i) landscape evolution of river systems in the Ganga plain, southern Himalayan front and drier Ladakh Himalaya, (ii) understanding river connectivity between source and sink, (iii) reconstruction of past glacial advances. More than 85 research articles were published on these topics and are reviewed here. Few may have inadvertently remained unattended.

2. Utilizing, field geomorphology, mapping, sedimentology and largely luminescence dating a model of river aggradation, incision and sediment storage in the Himalayan rivers is proposed where role of climate and tectonics is emphasized.

3. Past glacial advances are reconstructed using moraine morphostratigraphy and luminescence dating in drier and monsoon dominated Himalaya. In most cases, climate forcing is evaluated, and varied conclusions are drawn.

4. The Ganga plain stratigraphy exhibited a 100 ka history of basin filling. The stratigraphy suggests a climate control of aggradation where variation in sediment sources (Himalaya *vs.* forebulge) is controlled by the foreland dynamics. The pedo-stratigraphic studies indicate development of regional sedimentary hiatus at ~80 ka and 2-3 soil forming phases during Late Pleistocene-Holocene.

5. Studies related to river connectivity and sediment delivery systems evaluating rainfall distribution

and landscape in this context comprised a newer theme that attracted attention during the last five years focussing largely on the Kosi river and the megafan system.

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