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A review of hydro-geomorphic studies in the Ganga Plains: the emergence of a new interdisciplinary area of research

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Ganga alluvial plains have attracted a diverse field of geoscientific research in the last few decades. Earlier studies were mostly focused on subsurface structure mapping using geophysical techniques followed by sedimentological and stratigraphic analyses of alluvial sediments of the Ganga Plains. Recent decades have witnessed the incorporation of hydrological data in geomorphic studies, which led to a new set of process-based studies and the application of physical models to understand the evolution and dynamics of fluvial systems in the alluvial plains. Novel methodologies, observed data of water and sediment fluxes, availability of high-resolution remote sensing datasets especially Digital Elevation Models (DEM) data for watershed modeling, and incorporation of hydrological and geomorphic models have resulted in new insights into this highly dynamic sediment dispersal system. Such quantitative understandings are essential to design scientific strategies for sustainable management of river systems, and flood hazards and to understanding river's past and future through modeling approaches. Various hydro-geomorphic approaches, concepts, and applications have been initiated in the last two decades. We provide a systematic review of these advances and highlight the emergence of a new research area for geomorphic inquiry at a modern time scale with a major emphasis on the quantitative understanding of cause-effect relationships. Finally, a new set of research questions has been suggested with the prospect to define some of the necessary required research directions in the future studies of the Ganga Plains.

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INTRODUCTION

The Indian subcontinent is characterized by three major physiographic divisions namely the Himalayas, peninsular India, and the Ganga Alluvial Plains (Valdiya, 1998; Tandon *et al.,* 2014). Until the 1960s, the geological and geomorphic studies in India were mostly focused on the Himalayan and peninsular terrains, however, the vast relatively flat alluvial Indo-Gangetic Plains (IGP) did not receive much attention from Earth Scientists at the earlier stage of geological studies of India. Pascoe (1950), Geddes (1960), and Mukerji (1963) presented the earliest geomorphic observations from the Ganga Plains and suggested a broad classification of major landforms. Sub-surface drilling and geophysical survey for hydrocarbon exploration provided the first set of geological data for the Ganga plains. The sub-surface geological maps highlighted variations in the alluvial filling and the presence of subsurface structural features (Sastri *et al.,* 1971; Karunakaran and Rao, 1979). The structure of the Ganga Basin was also discussed as part of the holistic understanding of the Himalayan evolution (Lyon-Caen and Molnar, 1985). Sedimentological and geomorphic studies on the Ganga plains were initiated from 1970 onwards with a series of publications in the 1970s and 1980s. These studies were aimed to understand sedimentological and geomorphic variability through various observations, characterizations, and measurements of alluvial sediments and geomorphic features (Singh and Rastogi, 1973; Singh and Kumar, 1974; Singh, 1977, 1987; Khan *et al.,* 1988; Singh and Bajpai, 1989; Singh *et al.,* 1990). Later works also included the neotectonic impacts on the sedimentological or geomorphic characteristics in parts of the Ganga Plains (Singh and Ghosh, 1994; Singh *et al.,* 1996; Singh *et al.,* 1993). The first review paper on the Ganga Plains was published by Singh (1996) which was focused on its Quaternary evolution. The same decade also witnessed the incorporation of hydrological data to understand the sedimentological and geomorphic variability (Sinha and Friend, 1994). By the end of the 20th century, the alluvial sediments and landforms of Ganga Plains started receiving greater attention from Earth scientists.

At the beginning of the 21st century, the application of Optically Stimulated Luminescence (OSL) dating of fluvial sediments yielded an initial set of chronological data from the Ganga Plains and provided new insights on cause-effect relationships in the geomorphic processes (Srivastava *et al.,* 2003a, b; Gibling *et al.,* 2005). Availability of OSL-based and C-14 chronological data leads to an understanding of cause-effect relationships of processes in response to external forcings at the Quaternary timescale in the Ganga Plains (Goodbred and Kuehl, 2000; Gibling *et al.,* 2008; Srivastava and Shukla, 2009; Roy *et al.,* 2012; Ghosh *et al.,* 2019). These studies -mainly focused on the Quaternary stratigraphy and fluvial sediments of the Ganga plains. The geomorphic observations mostly served as supporting data to interpret Quaternary stratigraphic sequences in the Ganga plains. This application of geomorphic investigations, which were based on the concept of 'Present is the key to the Past', was extended after the incorporation of hydrology in geomorphic analysis. Initiation of hydrological data application to interpret geomorphic and sedimentological characteristics of river systems (Sinha and Friend, 1994) opened new areas of process geomorphology. The Ganga River system was identified as the main conveyor of sediments produced by Himalayan erosion and termed as the 'sediment dispersal' system (Goodbred, 2003). The first two decades of the 21st century witnessed the inclusion of various hydrology-based approaches for geomorphic inquiry while also led to new quantitative methods including process-modeling (Jain and Tandon, 2010; Sonam and Jain, 2018; Kaushal *et al.,* 2020; Arora *et al.,* 2021a, b; Majhi *et al.,* 2021). This opens a new area of river science and wider opportunities for geomorphic applications, especially to stream management and river hazard management (Sinha and Jain, 1998; Sinha *et al.,* 2017; Tare *et al.,* 2017; Swarnkar *et al.,* 2020; Agnihotri *et al.,* 2020; Majhi *et al.,* 2021).

Contemporaneous advancements of new conceptual approaches in fluvial geomorphology at a global scale led to the source-to-sink approach for sediment budgeting with the inclusion of sediment transport mechanics as fundamental to understanding landscape dynamics and its evolution (Allen, 2017). At the forefront, were the advancement of understanding of the concept of connectivity, including hydrology (Bracken, *et al.,* 2013) and geomorphic (sediment) connectivity (Brierley *et al.,* 2006, Jain and Tandon, 2010; Wohl, 2019), nonlinearity and complexity (Phillips, 2006, 2016; Jain *et al.,* 2012), river health and river sciences (Norris and Thoms, 1999), application of stream power (SP) concept (Knighton, 1999; Jain *et al.,* 2006, 2008) and landscape evolution models (Whipple and Tucker, 1999). These approaches established 'hydrology-based studies of geomorphic processes at modern-time scale' as one of the fundamental components of geomorphic inquiry at different spatio-temporal scales. Quantification of sediment flux and its dynamics has become one of the most important research questions (Hoffmann *et al.,* 2010; Syvitski and Kettner, 2011).

The last two decades witnessed a vast number of papers on sedimentology, Quaternary geology, and geomorphology of the Ganga Plains, which were further summarized through different review papers. The review articles in the last two decades presented comprehensive summary and provided new insights of various aspects of the Ganga Plains including its Quaternary evolution (Sinha *et al.,* 2007; Tandon *et al.,* 2008; Kumar *et al.,* 2020; Sinha *et al.,* 2020), its comparison with Siwalik deposits (Jain and Sinha, 2003a), Quaternary processes in the Himalayan hinterland area (Ray and Srivastava, 2010) and source to sink sediment dispersal pattern (Goodbred, 2003; Kumar *et al.,* 2020), incised valleys (Tandon *et al.,* 2006); soil chrono-sequences and role of tectonics (Parkash *et al.,* 2000; Pati *et al.,* 2011; Srivastava *et al.,* 2015), sediment budgeting (Wasson, 2003), applications of new geomorphic concepts (Jain *et al.,* 2012), palaeohydrology of the Ganga plains (Sanyal and Sinha, 2010; Srivastava *et al.,* 2017; Dixit *et al.,* 2018), impact of anthropogenic disturbances (Jain *et al.,* 2016), flood hazards and disaster risk reduction (Jain *et al*., 2019; Wasson *et al.,* 2019) and connectivity (Jain and Tandon, 2010; Singh, *et al.,* 2021).

This manuscript reviews geomorphic analyses at modern-time scale in the Ganga Plains in the last two decades and summarizes new findings in the area of hydro-geomorphic dynamics of the Ganga Plains at modern-time scale. Various aspects of fluvial geomorphology ranging from landscape-, basin-, reach-, and sediment- scale have been considered. It includes landscape characteristics in river basins, drainage network, longitudinal profile, planform channel morphology, hydraulic units like bars, and sediment transport. The manuscript highlights new advances in geomorphic studies of the Ganga plains and its applications in various other fields. Finally, potential research areas for future studies have also been identified.

THE GANGA PLAINS

The Ganga alluvial plains are one of the world's largest areas of Quaternary alluvial deposition covering an area of about 2,50,000 km^2 (Singh, 1996). The lateral extent of the Ganga alluvial plains is about 1000 km from west to east and between 200 - 450 km from north to south (Singh, 1996). The Ganga Plains is bounded to the west by the Aravalli-Delhi ridge, to the east by the Rajmahal Hills, to its north by Main Frontal Thrust (MFT), and to its south by the Bundelkhand-Vindhyan Plateau of the Peninsular India craton (Singh, 1996). Several transverse faults and structural highs run across the basin (Karunakaran and Ranga Rao, 1979). The thickness of alluvium in the Ganga basin is variable, ranging from a few kilometers in the northern part near the Himalayan foothills to a few tens of meters towards the southern margin along with the Pre-Cambrian Bundelkhand granitic basement (Sastri *et al.,* 1971; Karunakaran and Ranga Rao, 1979; Narula *et al.,* 2000)., The basin is divided into the West Ganga plain (WGP) and the East Ganga Plain (EGP) by a major structural high known as the Faizabad ridge (Jain and Sinha, 2003a). The Ganga basin is also tectonically active. Various subsurface faults have been identified in the basin based on geophysical data, and its association with seismic data highlights the tectonically active nature of these faults (Valdiya, 1976; Dasgupta *et al.,* 1987; Banghar, 1991; Dasgupta, 1993; Narula *et al.,* 2000. These structures are also responsible for a variable rate of subsidence in different parts of the Ganga Plains (Dingle *et al.,* 2016). Further, more neotectonically active subsurface faults in the Ganga Plains were also suggested based on soil chronoassociation, fluvial stratigraphy, and river dynamics (Parkash *et al.,* 2000; Pati *et al.,* 2012, 2015; Shukla *et al.,* 2012; Sahu and Saha, 2014).

The Ganga Plains is drained by south-flowing Himalayan rivers namely the Yamuna, Ramganga, Kali, Ghaghara, Rapti, Gandak, Burhi-Gandak, Baghmati, Kamla-Balan, and Kosi, and north-flowing major cratonic rivers namely Chambal,

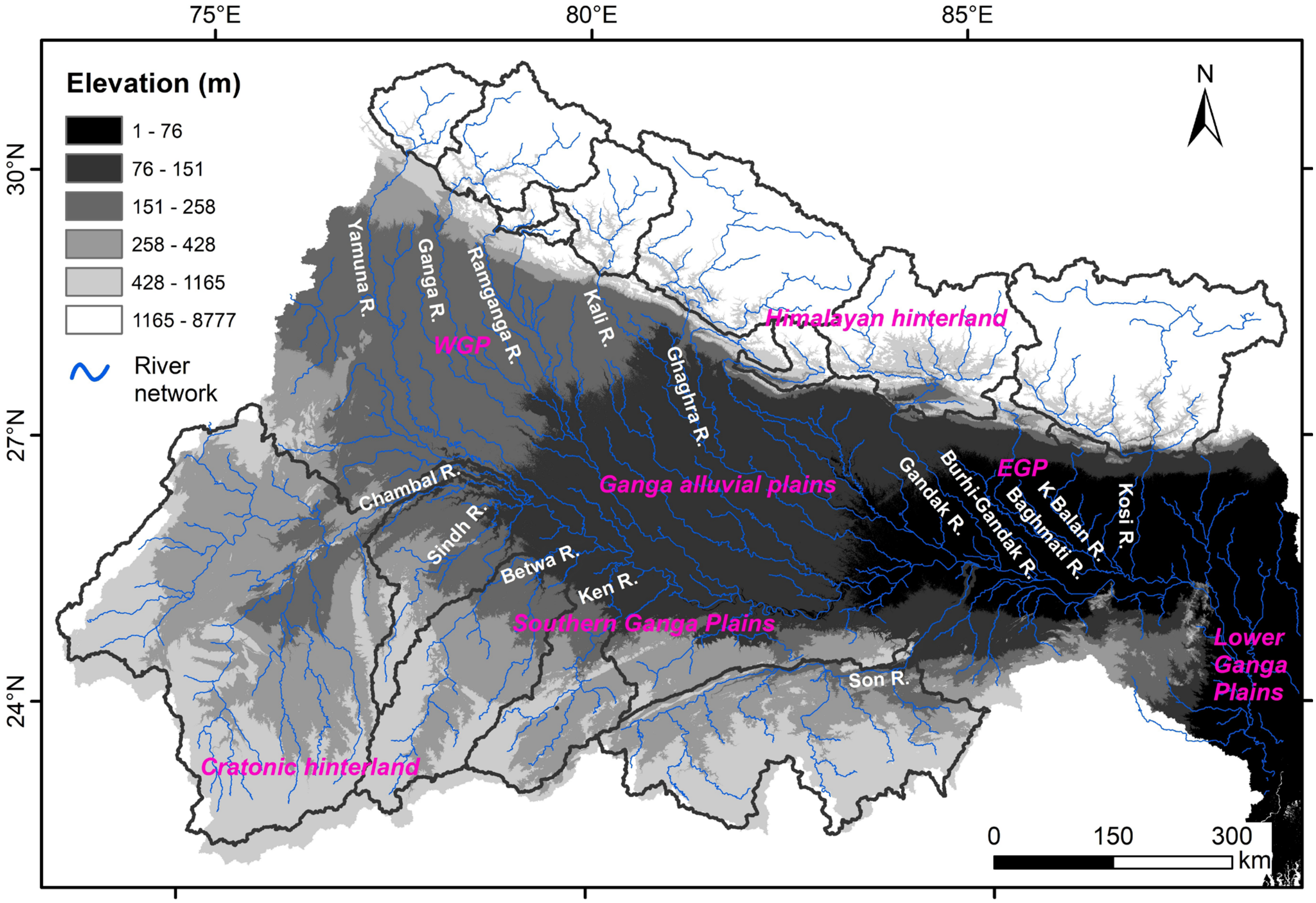


Fig. 1. The drainage network map of the Ganga River basin is superposed on the SRTM digital elevation model. The Ganga River basin is characterized by south to the southeast gradient.

Sind, Betwa, Ken and Son (Fig. 1). The main Ganga River channel flows southward at upstream reaches, while it follows the gentle eastward gradient of the Ganga Plains in the downstream reaches to join the Bay of Bengal. Yamuna river occupies a lower bed elevation in comparison to the Ganga River and has also been suggested as the trunk or axial river of the Ganga River system (Singh, 1996; Sinha, *et al.,* 2009; Verma *et al.,* 2014). Verma et al. (2014) also suggested considering the Tons River originating from the Banderpunch mountains as the trunk channel of the Ganga River system based on channel length. All these channels form a complex system of the Ganga River system. Variability of hydrological characteristics and energy conditions in addition to the basin subsidence across these channels of the Ganga River system are responsible for geomorphic variability across the Ganga Plains (Jain and Sinha, 2003; Sinha *et al.,* 2005; Dingle *et al.,* 2016). The climate in this region is tropical with average annual rainfall ranging from 600 mm/y to 1600 mm/y (Singh, 1994). Mean annual rainfall is higher in the EGP with values ranging between 800-1600 mm/y and lower in the WGP with values in the range of 400-800 mm/y (Nanditha and Mishra, 2018).

The presence of two hinterlands is a unique characteristic of the Ganga plains. The Himalayan hinterland in the north is high relief and tectonically active terrain with significant tectonic and climatic variability from west to east; while the cratonic hinterland in the south comprises the Aravalli, Vindhyan, Bundelkhand, and Singhbhum belts which are relatively low relief terrains. The deformed and tilted Quaternary sediments in the southern part and extensive gully development in ravine areas have been related to crustal up warping of cratonward margin (Agarwal *et al.,* 2002; Ghosh *et al.,* 2018). The Himalayan hinterland (a major source of sediment and water) comprises three distinct thrust-bounded litho-tectonic units south of the Indus Suture zone viz. the Higher Himalaya (HH), the Lesser Himalaya (LH), and the Sub Himalaya (SH) lying on the hanging wall of Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT) respectively (Valdiya, 1998; Hodges, 2000). Large rivers follow a deeply incised, south-flowing transverse course across the Himalayan orogen and debouch through mountain exits near the MFT into the Ganga Plains.

The Ganga plains is not a uniform geomorphic unit, but it is characterized by the regional scale geomorphic variability and different causality. Various classifications have been suggested for different parts of the Ganga Plains to characterize the sedimentological and geomorphic variability across the Ganga Plains (Pascoe, 1950; Geddes, 1960; Pathak, 1982; Sinha and Friend, 1994; Singh, 1996). A recent genetic geomorphic classification of the Ganga River basin suggests three major classes of the Ganga Plains namely northern alluvial plains; southern alluvial plains; and lower

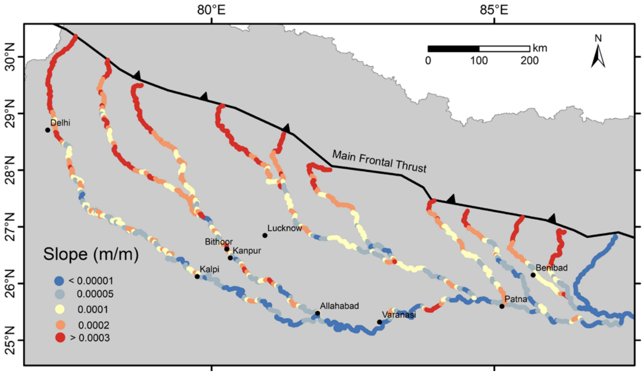


Fig. 2. Distribution of channel slope along the river longitudinal profiles within the Ganga River basin alluvial plains. The larger length of the WGP rivers is characterized by a steeper channel slope.

Ganga Plains with delta, which have been evolved through different forcing of tectonics, climate, and sea-level change (Tandon *et al.,* 2008). The northern and southern alluvial plains have evolved in response to climatic variations and tectonics, while the lower Ganga Plains and delta may have been mostly affected by sea-level change variation at the Quaternary time scale (Tandon *et al.,* 2008). The northern Ganga alluvial plains are further divided into two regions namely the Western Ganga Plains (WGP), and the Eastern Ganga Plains (EGP) (Tandon *et al.,* 2008).

GEOMORPHIC VARIABILITY ACROSS THE PLAINS AREA

Geomorphic characterization

The Ganga Plains appears as a low gradient, relatively flat, and uniform terrain. However, significant diversity in channel morphology and interfluvial landscape patterns exists among the river systems of the EGP and the WGP. The WGP rivers (e.g., Yamuna and Ganga as main channels) are characterized by relatively high channel slopes, incised valleys in the wide and thick muddy interfluves deposits (Tandon *et al.,* 2008; Roy and Sinha, 2017). In contrast, the rivers of EGP (e.g., the Gandak and Kosi rivers as main channels) are characterized by gentle channel gradient, wide and shallow aggrading river channels prone to frequent overbank flooding (e.g., Jain and Sinha, 2003a; Sinha *et al.,* 2005). The Gandak and Kosi rivers in the EGP (Geddes, 1960, Gohain and Parkash, 1990; Tandon *et al.,* 2008) and the Son river in the EGP and eastern part of the southern Ganga Plains (Shau *et al.,* 2015; Pandey *et al.,* 2021) creates large geomorphic megafan surfaces having distinct convex-shaped landforms. Such megafans are underlain by multiple sand sheets, while interfans are comprised of sand and mud ribbons (Jain and Sinha, 2003a). Further, megafan formation at the mountain exit of the Ganga River in the WGP was also suggested based on sedimentary deposits (Shukla *et al.,* 2001). Besides, the northern part of the Ganga Plains near the mountain front is also characterized by piedmont zones (Tandon and Singh, 2014; Shukla and Bora, 2003).

Even though the upstream reaches of the larger rivers in both WGP (i.e., Ganga and Yamuna rivers) and the EGP (i.e., the Gandak and Kosi rivers) are braided, the braid/channel ratio (up to 5.4) of the Gandak and Kosi rivers in the EGP is much higher than the Ganga and Yamuna rivers in the WGP (Roy and Sinha, 2017). In the EGP, the braided Gandak River is consistent in its channel patterns while the Kosi River changes systematically between braided, straight, and meandering patterns along ~160 km alluvial reach (Jain and Sinha, 2003a). The smaller interfluve rivers in the WGP e.g., Pandu and Rind rivers are incised but mostly sinuous with varying degrees of sinuosity (Jain and Sinha, 2003a). The smaller interfluve rivers in the EGP e.g., Baghmati River are braided in the upstream alluvial reaches and meandering in the downstream alluvial reaches, while its midstream reaches have a well-developed anabranching pattern (Jain and Sinha, 2004). Channel geomorphic diversity in the EGP is determined by channel avulsion owing to the high width-depth ratio and overbank spilling even at low flow stages (Roy and Sinha, 2017).

Further, geomorphic variability also exists within the WGP and EGP (Table 1). In terms of drainage density and drainage frequency, WGP rivers have low drainage densities and frequencies. However, the Yamuna River system is characterized by relatively higher values of drainage density and frequency in comparison to the Ganga River (Sinha *et al.,* 2005). This difference in drainage network characteristics is because of the development of badland topography and gully erosion along the mid-stream channel reach of the Yamuna River.

The subsurface structural features in the Ganga Plains, associated with the neotectonic movements and seismic events (Sastri *et al.,* 1971; Karunakaran and Rao, 1979; Valdiya, 1976; Agrawal, 1977; Dasgupta *et al.,* 1987), are also responsible for geomorphic diversity across the Ganga Plains. Additional neotectonic structures have also been interpreted based on soil chrono-sequences and geomorphic markers (Parkash, *et al.,* 2000; Pati *et al.,* 2011), though independent geophysical and seismic evidence is lacking for these features. Neotectonic activity along known subsurface faults governs longitudinal profile shape, and hence indirectly controls planform morphology, fluvial dynamics, and flood hazard variability, though such geomorphic impacts of these subsurface features are more prominent in EGP (Jain and Sinha, 2005; Verma *et al.,* 2017).

River longitudinal profile shape characteristics such as concavity are different across the Ganga Plains, which finally exert an important control on channel process variability. The WGP is characterized by rivers with higher concavity (with highest concavity values equal to 0.36) and graded profiles compared to the rivers of the EGP (with highest concavity values equal to 0.23) which display some convexities (Roy and Sinha, 2017). Further, the channel slope values normalized for its upstream basin area also indicate that the river channel along its longitudinal profiles is steeper in the WGP relative to the EGP (Dingle *et al.,* 2016). Shuttle Radar Topography Mission (SRTM) DEM derived slope profile of rivers also indicates overall steeper river channels in the WGP compared to the EGP (Fig. 2)

Table 1. Summary of the geomorphic and tectonic characteristics of the Western Ganga Plains (WGP) and the Eastern Ganga Plains (EGP)

Description	WGP	EGP	References
Channel slope	Steep gradient	Gentle gradient	Tandon *et al.,* 2008; Dingle *et al.,* 2016
Channel slope normalised for upstream basin area	High	Low	Dingle *et al.,* 2016
Stream Power (SP) in the hinterland area	Low	High	Sonam and Jain, 2018
SP/Unit SP in the alluvial plains	High	Low	Jain and Sinha, 2003a, Sinha *et al.,* 2005; Singh *et al.,* 2007
Sediment supply from hinterland	Low	High	Jain and Sinha, 2003a, Sinha *et al.,* 2005
Downstream fining trend of sediment grain size	Low	High	Dingle *et al.,* 2016
Valley geometry	Incised, low width-depth ratio	Wide and shallow, high width-depth ratio	Tandon *et al.,* 2008; Roy and Sinha, 2017
Channel pattern	Upstream: braided with low braid/channel ratio Downstream: meandering	Upstream: braided with high braid/channel ratio Downstream: Braided to straight to meandering	Roy and Sinha, 2017
Drainage density and its frequency	High for the Yamuna River basin Low for the Ganga River basin	Low drainage density	Sinha *et al.,* 2005
Overbank flooding frequency	low	high	Kale, 1997; Sinha *et al.,* 2005; Dingle *et al.,* 2016; Roy and Sinha, 2017
Long profile concavity	Well developed, well-correlated with discharge	Not well developed, with convex zones above subsurface faults, not well-correlated with discharge	Roy and Sinha, 2017
Subsidence Rate	Low	High	Dingle *et al.,* 2016
Convergence velocities of Indian plate & uplift along fluvial terraces at mountain front	Low	High	Wesnousky *et al.,* 1999; Peltzer and Saucier, 1996; Lave´ and Avouac, 2000; Stevens and Avouac, 2015; (In: Jain and Sinha, 2003a, Sinha et al, 2005, Dingle *et al.,* 2016)

The channels in the southern Ganga Plains are incised and mostly characterized by ravines and the absence or poorly developed floodplains (Sinha *et al.,* 2005; Bawa *et al.,* 2014). The lower Ganga Plains are characterized by the shifting of meandering channels including the meander neck cut-off process at a decadal scale (Rudra, 2014; Bandyopadhyay *et al.,* 2015). Widespread coastal erosion owing to changing fluvial and coastal processes is also observed in the downstream reaches. Reduced sediment supply owing to anthropogenic impacts such as sediment trapping in reservoirs is a major reason for the enhanced coastal erosion process in the delta region (Bandyopadhyay *et al.,* 2015). Sediment trapping in the upstream reservoirs, and sediment compaction in the delta because of oil, gas, and water extraction from subsurface delta sediments are also responsible for the higher sinking rate of the Ganga-Brahmaputra delta (Syvtski *et al.,* 2009).

Variability in hydrological fluxes

The Ganga Plains is characterized by a westward gradient in rainfall, which is also reflected in discharge characteristics. The area–discharge analyses highlight that the average annual discharges for any given catchment area of EGP rivers are higher than those of WGP rivers (Sinha *et al.,* 2005). Further EGP rivers are also characterized by higher values of unit discharge which represents their flashy nature, unlike WGP rivers.

A correlation of sediment yield with catchment area suggests that WGP rivers have significantly lower sediment yield in comparison to EGP rivers despite similar areas (Jain and Sinha, 2003a; Sinha *et al.,* 2005). Lower sediment supply manifested through the lower sediment yield in WGP rivers is because of lower rainfall and low terrain steepness compared to the EGP hinterland. The incised nature of the river channels in the WGP is related to higher SP and low sediment availability in the channels (Sinha *et al.,* 2005). On the other hand, the interfan rivers of the EGP show even higher sediment yields indicating vigorous sediment remobilization through overbank flooding and bank erosion processes in these rivers (Jain *et al.,* 2003a; Sinha *et al.,* 2005).

Bedload and suspended load grain size data along the Ganga River and its tributaries highlight a pattern of downstream variability along with the long profile from the WGP to the EGP (Singh *et al.,* 2017). An expected downstream fining trend of grain size is perturbed by coarser grain size in the midstream reaches, which indicates important input from the cratonic rivers (Singh *et al.,* 2017). Grain size variability along with long profile also provided insights into sediment dynamics and the role of stream power variability (Singh *et al.,* 2007). The rapid rate of downstream fining near the mountain front and occurrence of gravel-sand transition around 40 km distance was initially related to the selective transport phenomena rather than abrasion. However recently, Dingle et al. (2017) observed a nearly uniform distance of gravel-sand transition from mountain front (10-40 km) in smaller or larger river systems having different transportation capacities. Hence, Dingle et al. (2017) suggested the dominant role of abrasion in defining the gravel-sand transition across the Ganga Plains. Further, the downstream fining rate in major rivers is different from the WGP to the EGP. The higher downstream fining rate in EGP rivers in comparison to WGP rivers was related to the higher rate of subsidence in the EGP (Dingle *et al.,* 2016).

Various methodologies were used to quantify the eroded flux from different parts of the hinterland. Rivers in the EGP are characterized by higher sediment yield (0.9-4.6 $t/km^2/y$) in comparison to the WGP (average sediment yield around 0.1-0.6 $t/km^2/y$) (Jain and Sinha, 2003a; Sinha *et al.,* 2005). Another decadal-scale suspended sediment load-based study from the Nepal Himalaya further highlights higher erosion rates in the hinterland of the EGP with the highest value for the Gandak River ($2.8^{+5.4}_{-1.4}$ mm/y) (Andermann *et al.,* 2012). The eastern Himalayan hinterland area, specifically the Gandak River basin has also been identified as the dominant sediment supply region based on Sr-Nd based isotopic study of sediments (Singh *et al.,* 2008). Within the WGP hinterland, the erosion rate estimates based on cosmogenic nuclides in Alaknanda and Bhagirathi rivers suggest that Higher Himalayas is experiencing the highest erosion rates (2.7±0.3 mm/y) followed by the southern Tibetan plateau (1.2±0.3 mm/y) and finally (0.8±0.3 mm/y) the Lesser Himalaya (Vance *et al.,* 2003). Erosion rates from cosmogenic data suggest larger variability in erosion rates from 0.5 to 2.4 mm/y from the western as well as eastern parts of the hinterland area (Lupker *et al.,* 2012). Sediment flux estimation at the mountain front indicates higher erosion rates (1.9 to 2.75 mm/y) in the eastern rivers (except the Kosi River) in comparison to the western rivers (1.6-1.8 mm/y) (Dingle *et al.,* 2017 and references therein). Further, there also exists variability within the EGP and WGP. For example, the Kosi and Gandak rivers are characterized by significant contrast in sediment supply as derived by recent studies using Sr and Nd isotopes (Singh *et al.,* 2008). Within the Kosi River basin, the Tamur-Kosi River subbasin is characterized by a higher erosion rate of 1.39±0.11 mm/yr (Olen *et al.,* 2016). Similarly, the average sediment flux from the Ganga River basin at the mountain front in the WGP is 93 Mt/y (Dingle *et al.,* 2017 and references therein). This is twice as much as the sediment flux from the Yamuna River (39 Mt/y) at its mountain front (Dingle *et al.,* 2017 and references therein), and the average erosion rate is also higher as derived using cosmogenic nuclide data (Rahaman *et al.,* 2017). The Bhagirathi River subbasin is characterized by a higher erosion rate (3.42 mm/y) in comparison to the neighbouring Alaknanda River sub-basin (3.25 mm/y) within the Ganga River basin (Chakrapani and Saini, 2009).

Recent studies have applied modeling approaches, calibrated and validated with observed data to infer longer terms variation trends in river hydrology parameters. Analysis of the Variable Infiltration Capacity (VIC) model simulated evapotranspiration and surface water availability for periods 1901-2012 highlight the role of climate change through anthropogenic activities, and land use land cover (LULC) changes on the availability of surface water in the Ganga River basin (Shah and Mishra, 2016). Though the available river water increased between 1901 to 1947, a decline in surface water availability by 8% has been observed from the years 1947 to 2012 and has been attributed to atmospheric warming in the post-1975 period (Shah and Mishra, 2016). Hydrological forcing is also responsible for strong seasonal variation in the monsoonal river system. This has governed sediment as well as nutrient fluxes and thus water quality and river ecology. Modeling results based on the integrated catchment (INCA) model, using daily flow (for the time 1994-2011) suggest an increase in sediment load for WGP rivers during the monsoon and a decrease in the sediment load for upstream reaches in the Himalaya by the end of 21st Century (Khan *et al.,* 2018).

Energy condition, the complexity of sediment dispersion pattern, and morphological variability

Fluvial morphological characteristics are a function of fluxes, energy distribution, and channel conditions (Brierley and Fryirs, 2005; Montgomery and Buffington, 1993). These are represented as a balance between driving and resisting forces and are quantified by (a) SP and (b) sediment supply and caliber respectively. SP (Ω) is defined as the rate of conversion of the potential energy of water flowing downslope into kinetic energy to perform geomorphic work (Bagnold, 1966). It is expressed as:

$$\Omega = \gamma * Q * S \ldots \ldots (1)$$

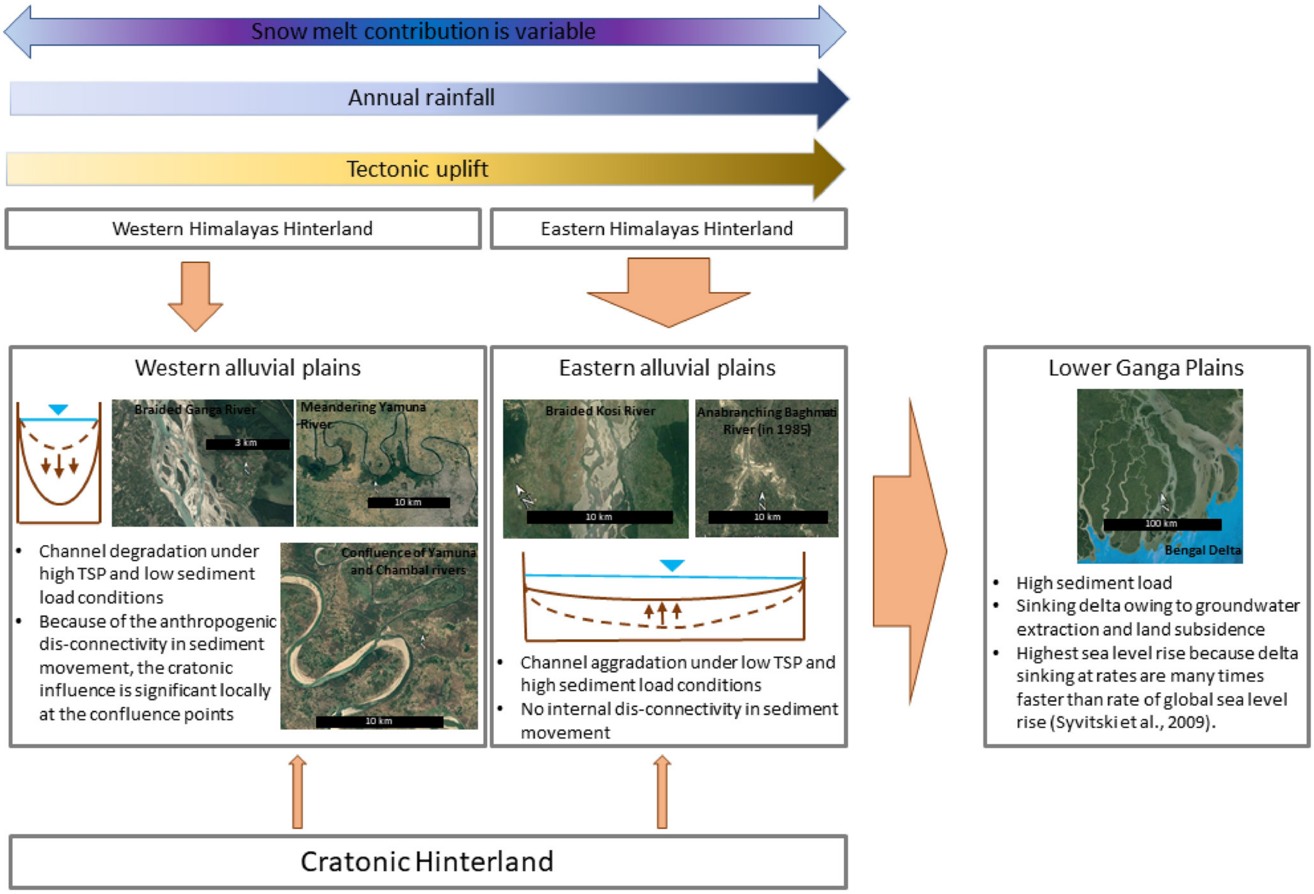
where – γ is a constant value for the product of the density of water and gravitational acceleration, Q and S denote discharge and slope respectively. Hence, these two variables represent hydrological forcing, required against channel roughness to transport available sediment load. Data on slope, discharge, and sediment flux variability is useful in explaining the spatial variability of channel processes and channel morphology.

WGP rivers are manifested by higher SP owing to relatively higher channel slope along with its longitudinal profiles (Jain and Sinha, 2003a; Sinha *et al*., 2005). High SP combined with lower sediment yield in these channels results in degradation of channels (Jain and Sinha, 2003a; Sinha *et al.,* 2005). This is characterized by the more incised nature of rivers with steep alluvial cliffs (e.g., Roy and Sinha, 2017). Contrastingly, EGP rivers have lower SP which in combination with higher sediment yield characterize its aggradation-dominated river system (Jain and Sinha, 2003a; Sinha *et al.,* 2005). Further higher rate of grain size fining in the EGP is correlated with a higher basin subsidence rate in this part (Dingle *et al.,* 2016).

These studies highlighted important information on the geomorphic variability across the Ganga Plains. Further, sediment flux dynamics have become a key research question for understanding the geomorphic dynamics of the Ganga Plains.

Controls on sediment flux and geomorphic variability

An understanding of regional- and local-scale controls on channel geomorphic variability is critical for assessing



- Channel degradation under high TSP and low sediment load conditions
- Because of the anthropogenic dis-connectivity in sediment movement, the cratonic influence is significant locally at the confluence points

- Channel aggradation under low TSP and high sediment load conditions
- No internal dis-connectivity in sediment movement

- High sediment load
- Sinking delta owing to groundwater extraction and land subsidence
- Highest sea level rise because delta sinking at rates are many times faster than rate of global sea level rise (Syvitski et al., 2009).

Fig. 3. Spatial variability in regional-scale controls namely tectonics and climate, and resultant river morphology in the Ganga alluvial plains. Spatial geomorphic variability across the northern Ganga Plains is strongly governed by hinterland climatic and tectonic characteristics, while geomorphology of the lower Ganga Plains is mostly governed by Quaternary sea-level change. The width of the arrows depicts sediment flux magnitude.

the spatial variability in river processes, for effective river management and rehabilitation planning, and for predicting how a reach may respond to future disturbance(s). We are defining the regional-scale controls as hinterland controls, (Fig. 3) while local-scale controls include the parameters within the alluvial Ganga Plains.

Hinterland controls

The geomorphic diversity among the EGP and WGP has been ascribed to spatial variability in precipitation, topography, drainage network, stream power distribution, lithology, and tectonics of the Himalayan hinterland (Jain and Sinha, 2003a; Sinha *et al.*, 2005; Dingle *et al.*, 2016; Sonam and Jain, 2018; Swarnkar *et al.*, 2020). A higher tectonic uplift rate has been recognized in the hinterland of the EGP (11.9 ± 3.1 mm/y in the Nepal Himalayas) compared to that of the WGP (6.9 ± 1.8 mm/y in Uttarakhand Himalayas) (Peltzer and Saucier, 1996; Bilham *et al.*, 1997; Wesnousky *et al.*, 1999). The Nepal Himalaya (hinterland of the EGP) also receives higher average annual precipitation (900 to > 1600 mm) in comparison to the NW Himalaya (hinterland of the WGP, 600 to 1400 mm) (Swarnkar *et al.*, 2020). In general, there is an east-to-west rainfall gradient with the eastern region receiving nearly six times higher rainfall owing to its proximity to the Bay of Bengal (precipitation source) than the western part (Bookhagen and Burbank, 2006). Further, rainfall events played a major role as most of the sediment generation (>90%) from the Nepal Himalayas occurs during the monsoon season (Sinha and Jain, 1998). Another case study from the Lesser Himalaya of the NW Himalaya highlighted the generation of 62–78% of annual sediments in only five peak events from 2008–to 2011 (Qazi and Rai, 2018). Overall, the higher sediment flux in the EGP hinterland is a consequence of high rainfall events superimposed over steeper hillslopes and the exceptionally high topographic relief developed in response to a higher tectonic uplift rate.

Further, LULC and high magnitude catastrophic events such as large earthquakes also superimpose their control on the sediment generation process in the hinterland. Large sediment volumes have been generated by major earthquake events (Goswami, 1985; Schwanghart *et al.*, 2016; Roback *et al.*, 2018). Additionally, the sensitivity of denudation rate to topographic gradient is modulated by vegetation density as observed in the hinterland of the EGP where denudation rate and topographic steepness are positively correlated with remote sensing derived metrics of vegetation density and rainfall (Olen *et al.*, 2016). Further, the suspended sediment contribution from degraded forested catchment was noted to be ~2-6 times higher than that from the densely forested

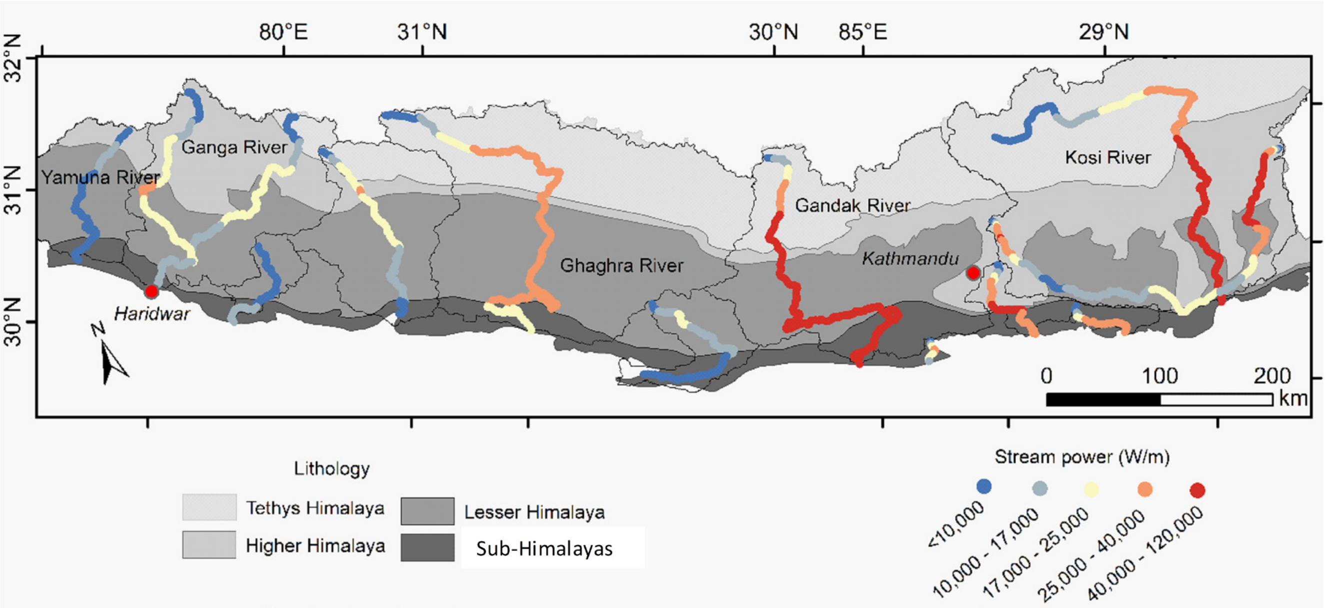


Fig. 4. Stream power distribution pattern in the Himalayan hinterland (modified after Sonam and Jain, 2018). EGP rivers in the hinterland area are characterized by significantly higher stream power values, which leads to a higher sediment supply in the EGP.

catchment (Qazi *et al.,* 2017). Since the annual runoff was considerably greater for the degraded catchment, Qazi *et al.* (2017) inferred that storm flow follows subsurface pathways in densely forested catchments whereas infiltration-excess overland flow contributed to stormflow in the degraded catchment.

Large variability of sediment erosion pattern gets associated with variability in sediment transport characteristics, which finally impact rivers and the landscape of the Ganga Plains. Sediment transport in a channel is governed by SP distribution pattern and hillslope-channel connectivity structure in the Hinterland area. Recent studies also provided quantitative estimates about these two important parameters. A connectivity assessment in the Kosi River catchment in association with the SP distribution pattern derived through a semi-distributed hydrological model suggests that high sediment flux in the Upper Kosi Basin is ascribed to the higher rainfall superposed over its steep hill slopes and longitudinal profiles (Mishra *et al.,* 2018; Swarnkar *et al.,* 2020). Quantification of connectivity is an emerging dimension of research to understand sediment dynamics and their control (Brierley *et al.,* 2006; Wohl *et al.,* 2019). However, more such work in the Himalayas is needed, which will provide new insight into sediment dispersal processes from the Hinterland region to the Ganga Plains.

SP distribution pattern in the major Himalayan tributaries of the Ganga River basin further explains the variability in the sediment transportation capacity of the western (Ganga and Yamuna rivers) and eastern (mainly Kosi River) rivers (Sonam and Jain, 2018) (Fig. 4). SP of main rivers in the EGP hinterland area is significantly higher (40, 000 to 1, 20, 000 W/ m^2) than SP values of rivers in the WGP hinterland area (10, 000 to 40, 000W/m^2) (Sonam and Jain, 2018). These SP variabilities indicate a higher sediment transport capacity of EGP rivers. Therefore, a higher erosion rate associated with higher transport capacity is responsible for high sediment supply at the EGP, which in turn governs the river processes and morphology in the plains region.

SP values are a function of discharge and slope characteristics in the hinterland area. While, the channel slope values are a function of tectonics and lithological characteristics (Sonam and Jain, 2018), the discharge of major Himalayan rivers is governed by rainfall as well as glacial and snowmelt. New data have also provided quantitative glacial-fluvial relationships across the Himalayas. In general, the hydrology of the major rivers in the hinterland area is significantly governed by rainfall events in the monsoon season and snow melt in the pre-monsoon summer seasons (Bookhagen and Burbank, 2010). Snow melt contributions to discharge vary extensively along with the Himalayan range. As a fraction of the total annual discharge, snowmelt constitutes ~50% of the Indus River catchments in the west, ~25% of the Tsangpo River catchments in the east, and <20% in other places (Bookhagen and Burbank, 2010; Pritchard, 2019). Regardless of these along-strike variations, snowmelt contribution to river discharge is significant in the pre-monsoon season (April to June). Quantitative partitioning of discharge values highlights more complexity in river morphology and processes in near future because of enhanced glacial and snow melting in response to climate change. SP-based study of Sutlej and Yamuna River highlights that river sensitivity will be different to climate change scenarios, as different reaches will be affected by variable ranges of enhanced discharge (Varay *et al.,* 2017).

New studies on sediment budgeting and sediment dynamics have highlighted relative sediment contribution from the different litho-tectonic units of the Himalayas. Most of the sediments (80-90%) in the Ganga plains is originated from the Higher Himalaya (Galy and France-Lanord, 2001; Wasson, 2003; Singh *et al.,* 2008), which is characterized by steeper slopes, higher rainfall, and SP values (Wasson *et al.,* 2008; Sonam and Jain, 2018). Glacial lake outburst flows (GLOFs) and landslide lake outburst flows (LLOFs) are major processes in the Higher Himalayas responsible for sediment generation (Wasson, 2003). Further, erodibility of rocks defines the distribution of source rocks in the gravel or sand fraction of river sediments. For example, less erodible quartzite from the Higher Himalaya dominates the gravel bedload at the mountain front, while highly erodible meta-sedimentary rocks contribute to the sand fraction of bedload material in the Ganga Plains (Dingle *et al.,* 2017). However, sediment supply in the smaller river systems, which drains interfluve or interfan area of the Ganga plains, is mostly governed by the Sub Himalayan terrain (Tripathi *et al.,* 2004; Jain *et al.,* 2022). The Sub Himalayan terrain comprises mostly low relief Tertiary sedimentary rocks (of Siwalik Group) in the tectonically active thrust sheet experiencing major erosion and sediment supplies from landslides together with channel erosion processes. Further, erosion of geomorphic surfaces in the Intermontane valleys is providing additional fluxes to river systems. The sediment entrapment process in the intermontane valley at the Quaternary time scale is well known (Densmore *et al.,* 2016). The Quaternary sediments in these intermontane valleys also serve as sediment source areas through processes of sediment reworking (Parida *et al.,* 2019). A small proportion of sediment is also contributed by the hinterland area in cratonic terrain which has relatively lower relief and highly resistant rocks compared to the Himalayan hinterland. Cratonic rivers contribute around 10% of sediments to the Ganga plains, where sheet erosion, rill erosion, and wind erosion together with channel erosion are dominant sediment generation processes (Wasson, 2003). Cosmogenic derived erosion rates also highlight significantly less erosion in the Craton area (Lupker *et al.,* 2012; Rahaman *et al.,* 2017).

Hence, (a) this process-based understanding from the hinterland and (b) sediment-provenance identification of different terrains having variable geomorphic and geological characteristics summarise that a range of controlling parameters govern the sediment erosion and transportation processes. Climate, lithology, tectonics, topography, SP, and vegetation are dominant controls on sediment supply from the hinterland of the Ganga plains, though, the dominance of specific parameters varies across different river basins.

Local controls

Sediment dynamics and morphological characteristics in the Ganga Plains are also governed by parameters or processes within the Ganga Plains. Recent studies have highlighted various such controls. This section provides an overview of such local controls.

Discharge, which represents the most important hydrological forcing is not only governed by rainfall gradient, but groundwater-surface water interaction is also important in defining the spatio-temporal variability of discharge across the Ganga Plains (Soni, 2007; Shekhar and Prasad, 2009). The perennial nature of flow in the lower reaches of most of the river channels is attributed to groundwater base flow contributions. River floodplains and the water holding capacity of underlying sandy aquifers in the Ganga Plains play a crucial role in surface water-groundwater connectivity relationships and its hydrological and ecological dynamics within the river space (Soni, 2007; Shekhar and Prasad, 2009). Similarly, the presence of a large palaeochannel in the Ganga plains and its connection with the main channel may have an important impact on the hydrological variability of main channels (Chandra *et al.,* 2021). However, the last five decades (the 1970s to 2019) have witnessed ~59% depletion in base flow contribution to river flow in lower reaches owing to ongoing observed groundwater storage depletion in the adjoining Ganga basin aquifers (Mukherjee *et al.,* 2018). Unsustainable rates of ground water pumping could jeopardize irrigation water requirements and food production, river transport, and in-stream ecology (Mukherjee *et al.,* 2018). Similarly, an oxygen isotope-based study along the Ganga River channel highlights higher groundwater-surface water mixing in the midstream reaches (Kumar *et al.,* 2019). These studies, though few in numbers, highlight the importance of ground water in supporting river processes.

Hydrological and geomorphic dynamics at the confluence zones are another important control of the geomorphic characteristics at local reaches. For example, even though flux contribution from cratonic rivers to the Ganga River is insignificant, the Chambal River at the Yamuna-Chambal confluence contributes three times more discharge and eleven times more sediment load in comparison to the Yamuna River (Bawa *et al.,* 2014). The high sediment supply from the Chambal River system may be because of extensive ravine development in the Chambal River basin. A detailed study based on a Real-Time Kinematic (RTK) survey and CARTOSAT images of ravined zones indicate a very high value of specific sediment yields (SSY) (600 ± 100 t/km^2/y and 1600 ± 200 t/km^2/y) in the ravines (Ghosh *et al.,* 2018). Hence, reaches downstream of the confluence point are characterized by a six times higher average SP of the Yamuna River and a seven times increase in sediment load. This has resulted in different morphological appearances with a significant increase in the bar area, even though the SP has also increased (Bawa *et al.,* 2014). A higher density of sand bar deposition with the mid-stream reaches of the Yamuna, which is also a high SP reach in the alluvial plains settings, exemplifies the complexity and inter-connected nature of river process dynamics.

Geomorphic studies also highlighted the dynamic behaviour of river confluences and their causes at the local scale. The confluence point between Ganga-Ramganga has shifted downstream by up to 20 km and a combination of processes including channel movements through local cut-offs and river capture, and channel aggradation have been suggested as the main causes (Roy and Sinha, 2007). An analysis of discharge connectivity at confluence points for identification of polluted reaches in the Ramganga River basin indicates that even the relatively small river tributary basin (basin area ~22, 000 km^2) contributes nearly comparable flow to the Ganga River compared to its flow before the confluence with Ramganga River (Gurjar and Tare, 2019). The tributary contributions become particularly significant in the pre- and post- monsoon seasons, despite substantial diversions and abstractions of water (Gurjar and Tare, 2019). Such results provide insights into the prospects and significance of managing smaller sub-basins of the larger river for river reach health and water quality maintenance.

Neotectonically active subsurface structures in the Ganga Plains are another controlling parameter on reach-scale river processes, morphological variability, flood hazard variability, and river dynamics by controlling the slope at the reach scale. Such subsurface geological control on river channels is more significant in the EGP (Agarwal and Bhoj, 1992; Jain and Sinha, 2005; Sahu *et al.,* 2010, Sahu and Saha, 2014). A river longitudinal profile analysis highlights the variable role of subsurface features on channel slope across the Ganga Plains. A good correlation between the channel forming effective discharge values and longitudinal profile concavity of WGP rivers indicates that discharge variations control channel longitudinal profile concavity in the WGP (such as Ganga trunk stream, Ramganga, Garra rivers) and its longitudinal profiles have a graded shape (Roy and Sinha, 2017). However, rivers in the EGP (Gandak, Burhi-Gandak, Baghmati, Kosi rivers) that flow across the tectonically active subsurface faults do not correlate with river longitudinal profile concavity and channel-forming discharge (Roy and Sinha, 2017). Its river longitudinal profiles show convexities along the location of faults, and channel longitudinal profiles are not concave. The movement along these subsurface faults is one of the important governing factors for river dynamics, channel planform morphological variation, and flood hazards (Jain and Sinha, 2005). Further, tectonic tilting along parallel or sub-parallel faults has been suggested as one of the causative factors for channel shifting through avulsion and channel migration in the Ganga River in the WGP (Shukla *et al.,* 2012), Son and Ganga rivers in the EGP (Sahu *et al.,* 2010, Sahu and Saha, 2014), the Kosi river (Agarwal and Bhoj, 1992) and Baghmati River (Jain and Sinha, 2005) in the EGP.

Dis-connectivity in sediment and discharge has been caused by anthropogenic structures in the river corridor such as dams, weirs, and barrages (Jain and Tandon, 2010; Bawa *et al.,* 2014; Cohen *et al.,* 2014; Khan *et al.,* 2018). Anthropogenic forcings such as deforestation and inadequate soil conservation measures intensify the soil loss processes in the watershed area, which further increases sediment supply to the river systems. Further, anthropogenic impacts through diversion and damming cause attenuation of peak discharge and decreases the sediment load dramatically at different sites (Swarnkar *et al.,* 2021). For the Ganga River catchment outlet at Farakka, INCA model-based computations of total annual suspended sediment load and sediment yield for unregulated flow conditions were 356×10^6 t/y and 369 t/km^2/y respectively (Khan *et al.,* 2018). This estimate was found to be nearly 180% higher than the observed CWC daily flow data-based estimates for the time 1995-2007. Agricultural and barren lands (covering 57.2 % and 20% respectively of land total area) were found to be the focal areas of the high sediment yield (Khan *et al.,* 2018). The canals, barrages, and dams have altered the natural sediment flow of the Ganga River system (Khan *et al.,* 2018).

IMPLICATIONS

Stream Management

In recent years, ecology-based management approaches have gained importance in river management practices and understanding of the hydrology-morphology-ecology relationship has become a key research area in river studies (Jain *et al.,* 2012; Sinha *et al.,* 2013). Consequently, fresh insights about geomorphic processes and riverine flux distribution from the Ganga Plains provided new tools to plan sustainable management strategies. Geomorphic studies have now become one of the fundamental parts of stream management practices for the Ganga River basin (Tare *et al.,* 2015). A detailed understanding of hydro-geomorphic processes is needed to help in ecosystem-based stream management, as hydrology-geomorphology linkages define the sustainable habitat for various riverine biodiversity. For example, a comprehensive geomorphic classification of the main Ganga River channel using water and sediment flux, and SP distribution pattern has defined habitat suitability and environmental flows for different river reaches that have direct applications in ecosystem-based river management (Sinha *et al.,* 2017). Degrading river health owing to poor maintenance of river discharge and habitat (morphology) degradation have led to tremendous loss of riverine biodiversity and the introduction of invasive species in rivers e.g., the near extinction of Ganga River dolphins and several native fish species (Sinha, 1997; Kelkar *et al.,* 2010; Sonkar *et al.,* 2020). Data base generation and regular mapping of river dynamics including mapping of instream and floodplain geomorphic features, cross-section mapping and assessment of river sensitivity, including mapping of connectivity relationships at changing flow stages are needed for the success of stream management approaches and flood risk assessment in the long term (Jain and Tandon, 2010; Bawa *et al.,* 2014; Kumar *et al.,* 2014; Sinha *et al.,* 2017; Mishra and Sinha, 2020).

Maintenance of river morphology and ecology needs an optimum range of water discharge in the river system, which is defined as environmental flow or e-flow. The concept of e–flow focuses to determine the range of water discharge required to maintain hydro-geomorphic conditions for the sustenance of the ecological species in a river at a reach scale (Poff and Matthews, 2013; Tare *et al.,* 2017). Estimation of such flow depths and discharge needed for river ecology and maintenance of channel processes requires an integrated approach that incorporates ecological and geomorphological parameters with the hydrological and hydraulic investigation of different reaches of a river. E-flow requirement for the upper Ganga River channel in the WGP varies downstream (29-35% and 43-53% of average natural flow for monsoon and pre-monsoon season respectively) (Tare *et al.,* 2017). These e-flow values are site-specific depending on its geomorphic characteristics, longitudinal and lateral connectivity, and river cross-sections. For the Yamuna River in the WGP, about 50% of natural flow during monsoon season and 60% of the natural non-monsoon flow have been prescribed as the essential flow needed by the river to perform its natural functioning such as sediment transport, maintain a desired Biological Oxygen Demand, floodplain aquifer recharge, and dilution of sewage inputs (Soni *et al.,* 2014). However, similar assessments are required for the flood-prone EGP rivers and future studies may focus on the development and assessment of e-flow strategies for EGP rivers.

Nutrient transfer in river channels is another important aspect of river health. Pathak et al. (2018) highlighted significant seasonal variability in nutrient concentrations in the Ramganga River. The high river flows during the monsoon season transport ~50% of the nutrient load indicating a strong hydrological control on the ecological dynamics of the Himalayan river systems (Pathak *et al.,* 2018).

The limited availability of hydrological data for the Ganga River system is a major hindrance in river studies. A well-defined and consistent relationship between geomorphic, hydraulic, and discharge parameters can help in setting proxies to represent the hydrological condition of a river channel. A novel approach to studying the process relationship between hydraulic geometry and discharge (Gaurav *et al.,* 2017) has opened a new scope to use channel width as a proxy of bankfull discharge. The study is based on cross-sections and hydrological data from all major river channels of the Ganga River system, which highlights the applicability of this proxy across the Ganga River basin.

River Hazards

Floods are the most frequent type of natural disaster causing serious damage to human life and property (Merz *et al.,* 2021). Flood hazards occur when river discharge exceeds the channel capacity, leading to the submergence of adjacent land which is usually the floodplain. Based on the causality, floods have been categorized as overbank flooding, channel shifting through the avulsion process, and outburst floods (Jain *et al.,* 2019). Geomorphic processes namely aggradation/degradation directly affect overbank flooding and channel avulsion (leading to channel shifting). The aggradation process at a given site reduces the bank full capacity of the channel which may cause overbank flooding. Similarly, aggradation-dominated reaches are characterized by a 'superelevation' condition, which may reduce channel slope and make the condition favorable for channel avulsion (Sinha *et al.,* 2014). The dominance of the aggradation and degradation process is governed by a geomorphic threshold (Bull, 1979), and quantitative analysis of such a geomorphic threshold is important for the sustainable management of flood hazards. Such analysis needs a quantitative assessment of water and sediment fluxes with SP distribution patterns during flooding (Jain *et al.,* 2019).

Geomorphic variability across the Ganga Plains is also responsible for spatial variability in flood hazards across the Ganga Plains. Incised and stable channels in a degradational setting of the WGP do not experience severe flooding (Jain and Sinha, 2003a; Sinha *et al.,* 2005). On the other hand, an aggradational setting in the alluvial rivers of the EGP is prone to frequent overbank flooding owing to reduced channel capacity during monsoon high flow events due to high sediment supply (Jain and Sinha, 2003a; Sinha *et al.,* 2005). Further, the rivers in north Bihar plains experience frequent channel avulsion (Jain and Sinha, 2004). In the last 250 years, the Kosi River has drifted ~150 km westwards (Wells and Dorr, 1987) in response to high sediment supply and the presence of structural features below the Kosi fan (Agarwal and Bhoj, 1992; Densmore *et al.,* 2016). Basin-scale detailed geomorphology-based flood studies of Baghmati River basin further highlighted the role of active tectonics, topography, drainage network, and longitudinal profile shape on the spatial distribution of flood hazards within the Baghmati River basin (Jain and Sinha, 2003b; Jain and Sinha, 2005).

Geomorphic data have also become useful in the analysis or assessment of flood event(s). Assessment of flood hydrographs in the absence of gauging stations in a river basin is a major challenge. In such a scenario, drainage network analysis using Horton's ratios can provide a solution for flood management through the generation of the Geomorphological Instantaneous Unit Hydrograph (GIUH) (Rodrigues and Valdes, 1979). Morphometric data has been successfully used to derive flood hydrographs of the Himalayan River (Jain and Sinha, 2006). This GIUH-based geomorphic approach to quantify the hydrological response of a river basin or design flood estimation or understand the causality of flood hazard has been extensively used for ungauged river sub-basins including part of the Ganga River system (Jain, 1998; Jain *et al.,* 2000; Jain and Sinha, 2006; Sarangi *et al.,* 2008). Additionally, the recent availability of satellite altimeter datasets of relatively high temporal and spatial resolutions along with channel cross-section data have enabled modeling discharge of the Ganga River using a stage-discharge rating curve (Rai *et al.,* 2021). Recent studies have also utilized machine learning tools combined with different ensembles of models for flood susceptible area zonation (Arora *et al.,* 2021a, b; Pandey *et al.,* 2021b). SP derivation using Soil Water Assessment Tool (SWAT) model has helped to assess the seasonal variability in SP and to calculate the flood power distribution in the Kosi River basin (Kaushal *et al.,* 2020). In the SWAT model the seasonality is river discharge was simulated at a basin-scale using a continuous-time of observed discharge data and by identifying several unique combinations of LULC, soil characteristics, and terrain steepness known as hydrological response units (HRUs). The hydrological processes are modeled at the HRU scale using the water balance equation (Arnold *et al.,* 1998) and used for SP estimation along the river longitudinal profiles. As sediment dispersion pattern has a strong role to play in the flood hazard, parameters responsible for sediment dynamics further indirectly govern the flood hazard. Quantitative assessment of geomorphic connectivity using connectivity indices and application of SP distribution pattern derived through SWAT hydrological model helped to identify the hotspots of sediment contribution area in the large Kosi River basin (Mishra *et al.,* 2018; Kaushal *et al.,* 2020). Such zones can be focused on sediment management, which will eventually help to manage avulsion events in the downstream reaches. Similarly, LULC changes impacted by anthropogenic factors have been identified as significant drivers of river hazards. The impacts of legacy sediments owing to LULC changes such as mega-dam constructions and deforestation are also debated as a significant environmental crisis in the Himalayas adding to the ever-existing uncertainties in sediment delivery estimations from the dynamic hinterlands of the Ganga plains (Wasson *et al.,* 2008; James, 2013). In the lower Ganga Plains and delta region, the sinking of the delta has already enhanced flood hazards in this region and is going to cause severe flooding and inundation of large areas in near future (Syvtski *et al.,* 2009).

Outburst floods which are governed by different geomorphic processes are the most hazardous events. The effectiveness of severe rainfall is amplified by landslide dam bursts and GLOFs which are common in the steep hinterlands of the Ganga plains (Wasson *et al.,* 2013). The effects are likely to worsen over the next century as per the projected rainfall scenarios (Shah and Mishra, 2016).

Geomorphic data and analysis not only serve as an important dataset for the understanding of flood causality, but it also helps to analyze the impact and identification of vulnerable areas. After the initiation of a flood wave, its impact along the river path is governed by longitudinal profile characteristics. Longitudinal profile indexes such as normalized channel steepness and chi-gradient profiles have been used to provide a first-order prediction of flood damage or aggradation-dominated sites along river channels during high magnitude flood events (Devrani *et al.,* 2015). In western Himalayas (Bhagirathi and Alaknanda river basins), a combined assessment of the frequency of high magnitude flow events during 1980–2003 and chi-gradient of river longitudinal profile has suggested that flooding in downstream reaches has doubled owing to the significant increase in trend of maximum river discharge (Chug *et al.,* 2020). The steep slopes of the landscape have rapidly responded to extreme precipitation translating into severe floods (Chug *et al.,* 2020). Further, in the plains area, modeling of geomorphic connectivity in the Kosi River basin provided the high-probable paths for an avulsive channel (responsible for flood hazard) after any avulsion events in the future (Sinha *et al.,* 2005).

Water logging is another important river hazard and is termed a slow-spreading hazard (Broad *et al.,* 2010). Kumar *et al.* (2014) highlighted the significance of geomorphic (dis) connectivity on the water logging problem over the Kosi megafan area. The waterlogging area correlates well with the disconnected channels affected by dense rail-road networks over the megafan.

River future and challenges from anthropogenic and climate change disturbances

The present-day understanding of hydrological–geomorphological linkages will also help to assess the future trajectory of river systems in response to anthropogenic disturbances or climate change scenarios. A process-based understanding of controls of geological, climatic, and anthropogenic forcings on river fluxes and their morphology exists (Fig. 5). Integration of hydrological and climate models has provided hydrological projections of different river systems, which are essential for informed river basin development and planning in response to both climate and human disturbance (Shah and Mishra, 2016). Such results have facilitated design-specific mitigation needs such as afforestation in the barren lands or managing soil erosion in agricultural lands (Jain *et al.,* 2016; Sinha *et al.,* 2017; Jain *et al.,* 2019; Wasson *et al.,* 2019).

Results from an analysis of the hydro-geomorphic implications of anthropogenic structures and climate change in the Upper Ganga basin suggest that low and moderate river discharge have been significantly disrupted by the operation of hydraulic structures in the Alaknanda and Bhagirathi rivers (Swarnkar *et al.,* 2021). During pre-and post-monsoon, the downstream reaches experience reservoir-induced moderate flow alterations and an increase in high magnitude flow during the monsoon period (Swarnkar *et al.,* 2021). Further, increasing anthropogenic interventions in response to changing climatic conditions have significantly modified the flow and sediment fluxes in the hinterland basins (Swarnkar *et al.,* 2021). The various hydraulic structures, in the hinterland of the western tributary, have led to modifications in the flow regime.

Besides, the reach to channel scale understanding of modern hydro-geomorphic processes, the study of past environmental conditions from sedimentary (floodplain and lake sediments and paleontological records) and archeological records will be a useful tool for understanding basin-scale fluvial response to climatic changes in the geologically recent past (Giosan *et al.,* 2012; Saxena and Singh, 2017; Dixit *et al.,* 2018; Khan *et al.,* 2018; Trivedi *et al.,* 2019; Singh *et al.,* 2021). Furthermore, all palaeohydrological data and future hydrological projects need to be integrated with a hydro-geomorphic physical model, which will help to define the river morphology and ecology in future scenarios. The development of such a geomorphic model needs quantitative data about geomorphic connectivity and threshold (Jain *et al.,* 2012; Jain *et al.,* 2018). More such hydro-geomorphic work on various sub-basins of the Ganga Plains will help to develop one such model.

Landscape evolution pattern: landscape response to external forcings in Quaternary

In the last decades, the data on measurements of the topography of riverbeds and hillslope has advanced vastly. Additionally, the high-resolution semi-automated data collection tools like LIDAR and laser scanners, terrain analyses tools such as Topotoolbox, CASCADE (Braun and Sambridge, 1997; Tangi *et al.,* 2019), and modeling tools such as LANDLAB have enabled a detailed and consistent model of the Earth's topography and surface process dynamics, (Tucker and Hancock, 2010; Gasparini and Brandon, 2011; Shobe *et al.,* 2017). The landscape evolution models (LEMs) have also become more sophisticated by accounting for improved and accurate descriptions of the physical processes involved in landscape change. Physical models have been developed based on an improved assessment of terrain morphometric characteristics and better constrains of scaling relationships among the governing variables (Tucker *et al.,* 2010; Gasparini and Brandon, 2011; Scherler *et al.,* 2015; Gaurav *et al.,* 2017; Shobe *et al.,* 2017). The growing complexity introduced in landscape evolution models and advancements in computation technology have empowered geomorphologists and river engineers to model the rate of landform change. These state-of-art numerical tools which are based on the physics of geomorphic processes also aid to examine and replicate landscape forms and dynamics such as river meandering and braiding (Coulthard 2001; Chen *et al.,* 2014; Valters, 2016; Willgoose, 2018). The general governing equation for the spatio-temporal evolution of Earth's landscape in a fluvial domain is described as the following continuity equation:

$$\frac{\partial z}{\partial t} = U - E\ldots \quad \ldots.\ (2)$$

where z is the channel bed elevation, t represents time and U represents rock uplift rate relative to a fixed base level and E denotes the channel bed erosion in bedrock settings (Whipple and Tucker, 1999). One of the widely used physical laws to model river channel evolution in sediment supply

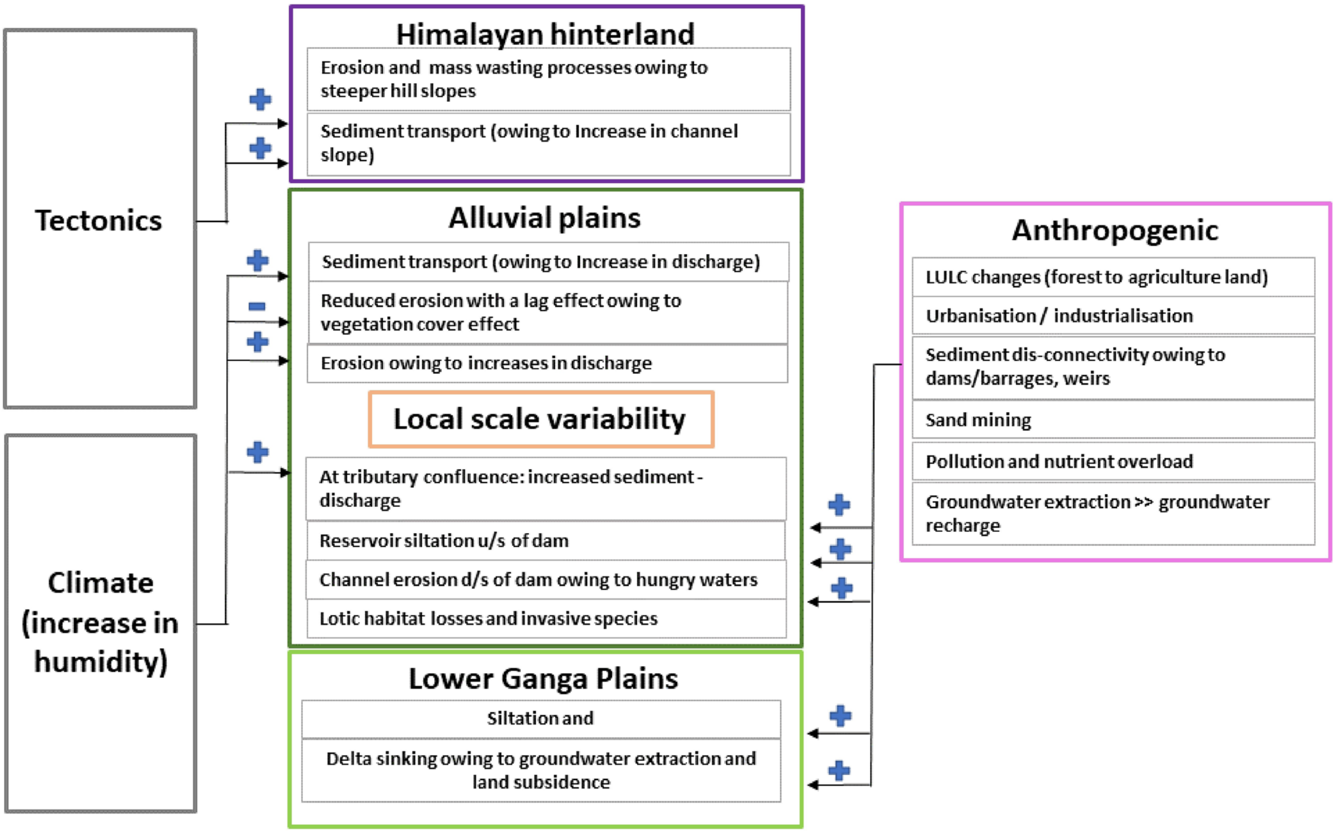


Fig. 5. Feedback relationships between the Ganga alluvial plains and the external controls namely tectonics, climate and anthropogenic factors highlight the role of regional and local controls. Modern-day geomorphic processes across the Ganga Plains are controlled by hinterland topography (in response to tectonics), climate change and anthropogenic disturbances at the local scale.

limited systems (i.e., bedrock rivers) is the SP Law (SPL) which relates the rate of erosion (E) to upstream catchment area (A) and local topographic gradient (S) (Whipple and Tucker, 1999) –

$$E = K * A^m * S^n \text{ ... ... (3)}$$

Here, m and n, the basin area (A) and channel slope (S) exponents govern the channel concavity along with its longitudinal profile. The value of these parameters is variable for different landscape settings depending on the geomorphological, climatic, and tectonic context (Whipple and Tucker, 1999; Perron, 2017). The K factor in particular is a sensitive parameter and fixes the response time of the fluvial systems. It needs an understanding of sediment dynamics, grain size, discharge-basin area relationship, ground water-surface water connectivity relations, and hydraulic geometry relationship (Howard *et al.,* 1994; Cassel *et al.,* 2021).

For the Himalayan region and specifically the Ganga River system as well, now a good amount of hydro-geomorphic data is available to better constrain the terrain morphometric characteristics. Uplift rates at the mountain front have been constrained through studies of incision rates along river terraces (Wesnousky *et al.,* 1999; Lave and Avouc, 2000, Dey *et al.,* 2019 and references therein). These pools of datasets further enable users to constrain the SPL parameters and coefficients of the SPL equations including abrasion rates, rate of decay in elevation along with river longitudinal profiles, seasonal variability in SP values (Dingle *et al.,* 2017; Sonam and Jain, 2018; Kaushal *et al.,* 2020; Sahoo *et al.,* 2020; Swarnkar *et al.,* 2020). A set of mathematical equations for river longitudinal profiles and channel slope are known which have been used to estimate the location and magnitude of SP peak values (Sonam and Jain, 2018). The new set of data from hydro-geomorphic studies at a modern-time scale will be helpful to develop a process-based evolutionary trajectory through the application of landscape evolution models.

CONCLUSIONS

After the initiation of sedimentological and geomorphic studies of the Ganga plains in the 1970s, the following decades witnessed significant work on the Ganga Plains. This manuscript summarises major advancements in hydro-geomorphic studies in the last two decades. Hydro-geomorphology is process-based geomorphic understanding at a modern-time scale mainly to focus on the basin-to reach scale water and sediment fluxes, and energy conditions through various physical models and indices. It is an extension of earlier studies on Quaternary geomorphology, which was mainly based on stratigraphy, geochronology, and sedimentological analysis.

The Ganga River basin is characterized by significant geomorphic variability, which is governed by hydrological variability across the Ganga plains. Hinterland controls are the most significant in governing the discharge and sediment delivery to the alluvial Ganga Plains. Further, local controls such as the role of tributaries i.e., tributary-trunk stream connectivity, ravines, channel slope variability in response to local-scale tectonic movements, the role of groundwater, anthropogenic control on water-sediment (dis)connectivity are important for reach-scale variability at annual to decadal time scale. The process-based geomorphic understanding has various implications and applications, which will play a fundamental role in future river basin management strategies. Hydro-geomorphic investigations in the Ganga Plains are establishing a new interdisciplinary research area as river science.

Advancements in hydro-geomorphic studies in the Ganga Plains are also opening up a new area of research, which will lead to a deeper process-based understanding of geomorphic systems and their applications for sustainable management of river systems and river hazards. Some of the important trends, which are going to be the key research areas in the next decades are as follows –

1. There is a need for improved and upscaling the quantification of fluxes directly or through various proxies and the application of physical models to understand geomorphic processes and their controls. Further, the use of new field equipment like Acoustic Doppler current profiler (ADCP), Echosounder, and Kinematic GPS will generate high resolution topographic and hydrological data. Further, high-resolution remote sensing data will help to develop proxies for the indirect assessment of fluxes. Process-based understanding will lead to various measurable geomorphic proxies to quantitatively assess the fluxes in the river system.
2. Climate change and anthropogenic disturbances are going to be a major challenge to geomorphic systems. A quantitative assessment of hydrological and geomorphic connectivity and its incorporation in geomorphic models will provide a deeper insight into the cause-effect relationship in a quantitative manner. Hydrological connectivity addresses the interaction of water in various components and will include the rainfall-discharge relationship in regulated rivers of the Ganga Plains. Further, it will include new studies to assess ground water-surface water connectivity, and glacial and snowmelt contribution to discharge. Similarly, sediment (dis)connectivity between different landscape compartments of fluvial systems will be vital for geomorphic models. Such, an enhanced understanding of geomorphic processes and landscape will be vital to understanding river futures in response to climate change and anthropogenic impacts. The major goal would be to build up a fundamental understanding of the climate-change-driven river process dynamics by taking numerical simulations and field measurements as new tools.
3. The geomorphic studies have gained significantly through the incorporation of hydrology. In the future, the geomorphic studies will be benefitted further from the incorporation of hydraulic studies, which will help to integrate site-scale hydraulic processes with reach and basin-scale geomorphic processes. For example, the linkage of physics-based understanding of sediment transport processes is now supporting the models to study reach-scale channel morphological variability or landscape evolution in response to external forcings.
4. Process-based understanding of the hydrology-geomorphology-ecology relationship is going to be an important research area. This requires developing a strong archive of field-based mapping of data sets, statistical modeling, and remote sensing methods to generate information about channel morphology-discharge-biodiversity relationships. It is extensively recognized that river ecosystems are dependent upon the natural flow regime that is typical of each hydro-climatic region. This natural flow regime defines the geomorphic diversity of a river system, which finally governs the range of habitats within each channel type. As the complexity of physical (hydrological and morphological) models has advanced, the future extension will be towards the integration of physical and ecological models.
5. The lower Ganga Plains and southern Ganga Plains are relatively less studied parts of the Ganga Plains. These studies will help to understand the relative role of sea-level change and the role of the cratonic hinterland on river processes and morphology respectively.
6. An important dimension of geomorphic studies is moving toward stream management applications, and a new discipline of River Science is emerging. Process-based geomorphic understanding and its integration with hydrology, hydraulics, and ecology at a cross-over of scales are going to be the center stage in the assessment of river health and e-flow computation for various reaches and sub-basins areas. Further, geomorphic diversity defines the habitat for the ecosystem. Geomorphic process-based understanding will be needed to develop any restoration plan for various keystone species and aquatic animals in the Ganga River system to ensure the delivery of ecosystem functioning and services in the future. Future growth in River Science will also require further interaction of process geomorphology with social science. The growth of geomorphic science in this direction will lead to new geomorphic approaches and frameworks to assist sustainable stream management and hazard management.

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