Application of modern geomorphic concepts for understanding the spatio-temporal complexity of the large Ganga river dispersal system

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Significant advances have been made towards understanding the dynamics of geomorphic systems through the development of new concepts. In the last two decades, these developments were partly guided by the change in the scale of geomorphic analysis from local (landform) to regional (landscape) scale and partly due to the emergence of new scientific tools and quantitative models. The process-based understanding of some geomorphic systems of the Indian subcontinent has also advanced in a significant way and a substantial dataset is now available, especially on the Ganga river system. However, conceptual advancements in geomorphic studies have not been incorporated with the available database on large river systems, especially the Ganga river basin. This article attempts to provide a brief review of geomorphic concepts, i.e. scale, magnitude–frequency, equilibrium, threshold, hierarchy, sensitivity, connectivity, nonlinearity, complexity and multidisciplinarity, and their application for understanding the geomorphology of a large river system, i.e. the Ganga river system. This re-evaluation and synthesis of the geomorphic data of the Ganga riverscape provides useful insights into the dynamics of this multi-scale dispersal system, and thereby also helps in the identification of gaps in knowledge that need to be addressed on a priority basis. The major gaps at longer timescales (10^3–10^5 years) include lack of understanding of connectivity in river response to external forcing, the quantification of threshold of geomorphic change, and the integration of data across scales in terms of forms and processes. At modern timescale, the major challenge is to integrate the geomorphic dataset with ecological and hydrological attributes in order to develop a holistic understanding of rivers for their management.

Keywords: Equilibrium, geomorphic concepts, large rivers, nonlinearity, threshold.

IN the past two decades, the discipline of geomorphology has gone through a paradigm shift from 'geographical geomorphology' to 'geophysical geomorphology'[1]. This has resulted in a shift of emphasis towards geomorphic concepts such as scale, process–pattern relationships, hierarchy, variability, diversity, sensitivity, equilibrium, connectivity, nonlinearity and complexity to understand the evolutionary histories of landscapes/landforms. The human-induced transformation of the surface of the Earth has added a new dimension to these studies. Current geomorphological research, therefore, aims to study the anthropogenic and natural factors together to explain the spatiotemporal variability and evolutionary characteristics of landscapes and landforms. This has also led to the notion of 'critical zone', which is defined as the 'heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life sustaining resources'[2]. The 'use' of the surface of the Earth and its 'critical zone'[2] is bound to grow because of the rapidly expanding human populations. Most surface environments will consequently witness the effects of increased human-induced disturbances resulting in more complexity in coupled socio-environmental systems, such as the large rivers.

An understanding of large river systems is critical as they support large human populations. The ensemble of current geomorphic concepts is therefore applied to the Ganga basin – a large river dispersal system that supports a population of about 400 million. The insights obtained from such an analysis are important in developing an understanding of the complexities that exist in coupled human and natural systems, prime examples of which are riverscapes that have supported human civilizations for millennia.

Development of geomorphic thoughts

Scale in geomorphic studies

Spatial scale: Advances in geomorphic thoughts in multi-scale systems are considered in this study at the landscape- and landform-scale. Geomorphic concepts were

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initiated at landscape-scale with various landscape evolution models[3–5]. However, these models were too general and therefore of limited value; as such geomorphologists shifted the emphasis to smaller scale studies, i.e. landform scale. The significance of scale was further highlighted, as scales govern the causality and geomorphic processes[6].

At landform scale, Horton[7] and Strahler[8] provided a quantitative framework to characterize the fluvial landforms. Later, the system theory and feedback relationship between landforms guided a new set of research questions at the landform scale[9]. Various types of geomorphic studies were carried out which included the characterization of landforms at various scales, process-based understanding of landform development, experimental analysis, qualitative understanding of processes and geomorphic change in the system with respect to external forcings.

The understanding of landscape evolution was revived by geomorphologists as it was realized that insights obtained at a small scale are not sufficient to understand large-scale processes and their multi-scale causality[10,11]. This realization highlighted the importance of geomorphic analysis at the cross-over of scales, where high resolution, process-based studies at a small scale may be used to explain the landscape pattern. For example, the shear stress-based stream erosion and sediment transport processes were used to explain the evolution of badlands[12]. The approach was later incorporated in landscape evolution models and landscape patterns were explained on the basis of the process understanding of sediment transport and erosion processes through shear stress or stream power. These models provided a quantitative understanding of landscape evolution processes in different scenarios of climate change and tectonics[13–20] and also about basin-scale drainage network evolution[21–25].

Temporal scale: The identification of dominant process(es) or event(s) that shape(s) a particular landform has remained one of the most challenging problems in geomorphology. An important question in geomorphology is whether a high-magnitude–low-frequency event (catastrophism) will play a more effective role in the development of geomorphic characteristics or will a low-magnitude–high-frequency event (uniformitarianism) play a more significant role? An initial analysis based on the historical data of rivers from the United States has shown that events of moderate magnitude and frequency carry out the maximum geomorphic work[26]. However, palaeohydrological studies at a later stage reemphasized the occurrence of 'large' but rare events and provided support to the hypothesis of neo-catastrophism[27–29].

Concepts and approaches in geomorphic studies

Initial geomorphic studies were focused on landscape patterns to define the stages of landscape development, namely young, mature and old stages in the landscape evolution model[3]. In parallel with the evolutionary approach, the functional approach was suggested by Gilbert[30], which characterizes a landform as an equilibrium form due to the interaction between the driving and the resisting forces. Initially, these approaches were used independently in geomorphic studies to understand the genesis of landforms; later, both these approaches were integrated through the dynamic equilibrium concept[31]. Functional approaches have stressed the determination of forces in nature, to build a process-based understanding, and more importantly, to define the equilibrium form in nature[30].

In a geomorphic system, the study of equilibrium in landforms and processes remains a basic and fundamental approach for seeking geomorphic insights. An equilibrium process between input (cause) and output (effect) parameters is defined as a constant (linear) relationship between input (cause) and output (effect) or form[32]. A dynamic geomorphic system oscillates around its equilibrium form (Table 1), whereas an equilibrium landform tends to maintain relatively stable characteristics even after minor perturbations (Figure 1 *a*). This state is defined as steady-state equilibrium condition[32]. Instead, dynamic equilibrium defines a condition for landscapes which go through gradual and progressive change over medium to long timescales while preserving short-term equilibrium in the component landforms[31] (Figure 1 *a*). Steady-state equilibrium explains the process through a functional approach, whereas dynamic equilibrium has led to the merger of the evolutionary approach (gradual and progressive change in landscape) with the functional approach (maintenance of short-term landform characteristics).

However, geomorphic changes do not happen in a continuous way, but occur through steps which were termed as geomorphic threshold conditions[33,34] (Figure 1 *a*, Table 1). Threshold steps are responsible for achieving a new equilibrium stage after any major or prolonged perturbation, that results in a nonlinear relationship between forcing mechanism and landform change. Changes may occur through crossing of internal or external threshold. The determination of 'threshold condition' is currently a major challenge in geomorphology, as it defines the boundary condition for geomorphic change in response to external forcing.

The geomorphic response of a landform/landscape may be different for the same forcing mechanism, which emphasizes the significance of landscape/landform sensitivity (Table 1). Geomorphic sensitivity and threshold are related parameters. If a geomorphic system is close to the threshold value, it will be highly sensitive to change or vice versa, because, a small change in external condition may cause a significant change in geomorphic form due to the crossing of threshold condition.

The sensitivity of a landform was further analysed through a sequence of processes, which resulted in some

Table 1. Geomorphic concepts and examples from the Ganga Plains

Geomorphic concepts	Definition	Examples from the Ganga Plains
Equilibrium process	Constant (linear) relationship between input (causes) and output (effect)[32,38].	Erosion rate is in equilibrium with uplift rate in the Baghmati river basin[97].
Equilibrium state (form)	The landform state around which a landform system oscillates[32,38].	Ganga valley is an equilibrium landform in response to external controls, namely tectonics (in the upstream region), climate change (midstream region) and eustatic changes (downstream region)[74].
Magnitude and frequency	Magnitude of an event generally refers to the amount of work carried out or the degree of landform change experienced. Frequency of an event of a specific magnitude is expressed as the average length of time between events of that magnitude[155].	Sediment transport in the rivers of Eastern Ganga Plain is mostly governed by high-magnitude events[84], whereas sediment erosion in Nepal Himalaya is governed by moderate-magnitude and high-frequency event[87].
Threshold	The condition of significant landform change[33].	Different landforms in the Western Ganga Plain and Eastern Ganga Plain are separated by a zone of threshold values[75].
Sensitivity	The sensitivity of a system is defined by the system specifications that describe its propensity for change and its ability to absorb any disturbing forces[156]. Sensitivity controls the landform response to external change.	Marsyandi valley (a small-scale channel in Central Himalaya) is more sensitive to erosion in response to increase in humidity (climate change) in comparison to the Yamuna river system (larger river system in the western Himalaya). Hence monsoon intensification at 10 ka has resulted in aggradation in the Marsyandi valley, but degradation in the Yamuna valley[118,119]. In this example, scale and location (local processes) control the sensitivity of the river channel.
Hierarchy	A cross-scalar hierarchically based approach should integrate description, causal explanation, testing and prediction of riverine ecosystem (modified after Pickett *et al.*[157])	Ganga river basin → Himalayan, alluvial plains and cratonic landscapes → different river systems in the eastern and western parts (see Figure 2).
Geomorphic compartments	A landscape may be divided into different compartments, which may be a large landform or summation of smaller landforms.	First-order classification of the Ganga river basin defines different compartments[72], i.e. (1) Himalayan hinterland, (2) cratonic hinterland, (3) northern alluvial plains, (4) southern alluvial plains, (5) Lower Ganga Plains and delta.
Connectivity	The way in which different landscape compartments fit together in the catchment in a given time-frame (modified after Brierley *et al.*[47]).	Sediment residence time in the Ganga Plains varies from 2×10^6 years (ref. 111), 1×10^5 years to 2.5×10^5 years (ref. 114) and 3×10^4 years (ref. 113), which suggests different temporal scale for connectivity in the Ganga river basin.
Complexity	Nonlinear relationship between the driving and geomorphic response at different space and time[45]. In a complex system, the outputs will be inconsistent to inputs.	Temporal scale: valley aggradation followed by incision event in Marsyandi valley[118].

new terminologies[35,36] (Figure 1 *b*). If an external impulse of change (IOC) is initiated at time t_1, lag time (time t_1 to t_2) represents the time taken by the system to begin reacting to change; relaxation time (time t_2 to t_3) designates the time taken to achieve a characteristic form. Characteristic form time (time t_3 to t_4) indicates the time over which characteristic forms persist. Systems having less 'lag time' and 'relaxation time' will be more sensitive to change. Sensitivity of a landscape is not a static property, but it may vary in time and space and will be governed by the threshold of change[37].

The notion of landform sensitivity has redefined the equilibrium forms. A landscape may have different compartments (Table 1), which have their own sensitivity in

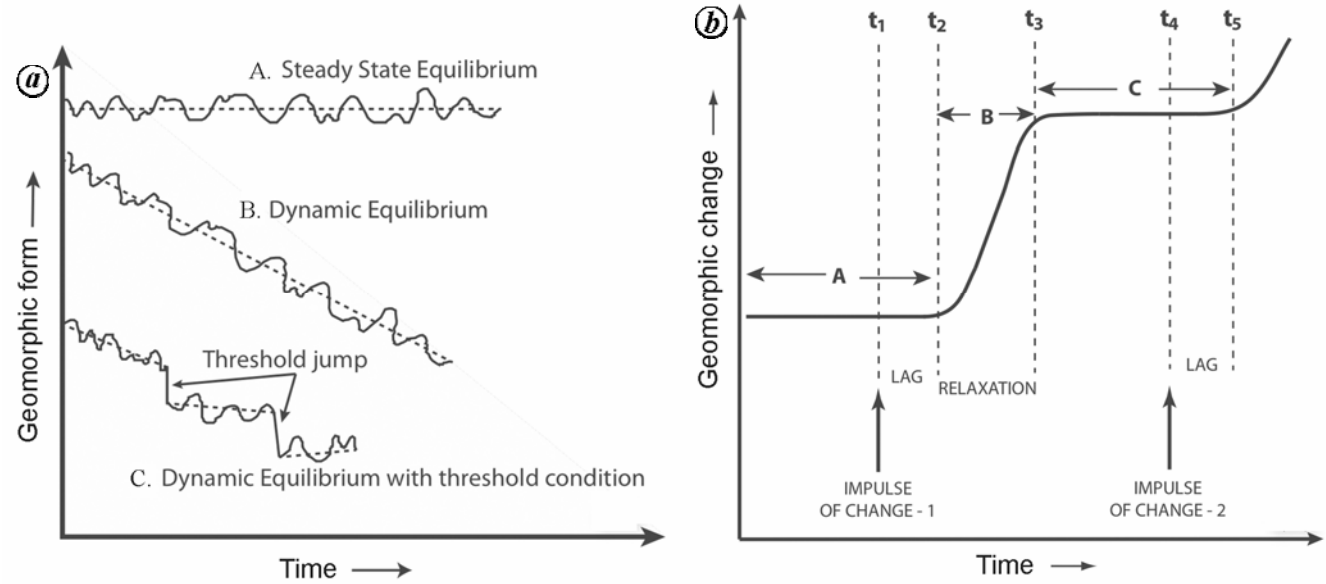

Figure 1. ***a***, A conceptual sketch of equilibrium condition, dynamic equilibrium and role of threshold. ***b***, Schematic illustration of the concepts related to landscape sensitivity and equilibrium form against forcing (impulse of change). Landform A is in nonequilibrium with impulse of change-1 (IOC-1). Landform B is in disequilibrium and landform C is in equilibrium with IOC-1. It should be noted that at time t_4–t_5, landform C is in nonequilibrium with IOC-2. A system may never reach the equilibrium stage if summation of lag time and relaxation time is too large (modified after Brunsden and Thornes[35] and Summerfield[36]).

terms of any tectonic or climate forcing. In that case, some compartments of a landscape will show characteristic forms and some other compartments may show transient forms (landform at relaxation time). Characteristic forms are in equilibrium with respect to existing external conditions, whereas transient forms are defined as landforms which are not completely in accordance with the prevailing dynamic geological and geomorphological conditions (Figure 1 *b*). Hence, the whole landscape may not be in equilibrium with respect to any tectonic or climate forcing. This illustrates the limitation of the equilibrium concept at the regional scale, as the 'whole' landscape may be characterized by all types of forms, including equilibrium, disequilibrium or nonequilibrium forms[32,38]. For example, in an experimental study, a rejuvenated fluvial system has responded at different times in the upstream and downstream reaches due to a base-level change[31]. Further, incision in the upstream reaches has increased sediment supply in the downstream reaches and hence created an aggradational condition. Therefore, the river responded with complex geomorphic changes in response to a single external change.

As geomorphic processes are broadly governed by erosion and deposition, the quantification of sediment flux has become a major focus of study. Attempts have been made to quantify erosion rate and/or sediment accumulation rate in different compartments (landforms) and flux among different compartments at different timescales[39–41]. These sediment budget analyses are now becoming a major aspect of geomorphic enquiry, because they provide quantitative representation of geomorphic processes[41].

The measurement and analysis of variability in sediment flux and the interpretation of geomorphic processes has given rise to new concepts, namely nonlinearity (nonlinear variation in sediment flux with respect to time or known variation in external control)[42–45] and connectivity (sediment and water input–output between different compartments in a basin) (Table 1)[46–48].

Nonlinearity in geomorphic response is defined as a variable geomorphic response to the same forcing. Different equilibrium stages of various landforms in a landscape also highlight the nonlinear response of a geomorphic system to external forcing at a regional scale[44]. Nonlinearity in the system may be due to various factors (see Phillips[45] for details). Nonlinearity in the system reduces the prediction capability of any geomorphic system against external controls. This renders geomorphic prediction a major challenge in geomorphic research at a regional scale[49].

A geomorphic system consisting of various compartments having different sensitivities is characterized by nonlinear response against external controls. This causes complexity in the behaviour of geomorphic systems in response to external controls[50–52] (Table 1). The complex response of a geomorphic system at a regional scale poses a challenge to geomorphologists to understand river response to multi-scale external changes at large spatial or temporal scale. Insight into complexity at landscape scale could be obtained through the determination of connectivity.

A landscape is formed of different compartments. However, in geomorphic studies, 'whole' (landscape) is larger than just the summation of individual compartments (landform), as impact in one compartment may create a

new perturbation or buffer the effect on another compartment[47]. Landscape analysis requires the study of landforms and the determination of connectivity between the landforms (Table 1). Geomorphic connectivity in a landscape will be affected by different landforms or human disturbances, which act as buffers, barriers and blankets[53]. The determination of connectivity in a landscape is important because it helps to analyse the movement of biophysical fluxes in a large geomorphic system; it shapes the operation of geomorphic processes over a range of spatial and temporal scales, and finally, it provides a basis to predict future landscape trajectories. Connectivity can be measured through flux interaction(s) (functional connectivity) and physical connectedness (structural connectivity) between landforms[48,54]. Attempts have been made to measure connectivity using mapping of buffers and barriers on the basis of slope threshold[55], run-off potential and slope characteristics at grid pattern[56], using topographical attributes, namely Network Index[57], and the role of storm on connectivity using surface roughness, slope and vegetation characteristics[58]. Connectivity in a landscape may also vary in time and space, as suggested by the sediment residence time and sediment transport datasets. Different depositional landforms in a landscape may have variable sediment residence times[59,60], as sediment movement in a landscape may vary with time[61]. Quantitative sediment flux data are important and aid the determination of connectivity in a landscape and ultimately help in understanding the nonlinear response of landscape against forcing mechanisms.

With this conceptual understanding of geomorphic systems, 'prediction' in geomorphology is perceived as a new challenge in geomorphic research. It has been realized that deterministic prediction is not possible and focus should be on the probabilistic prediction of geomorphic systems[49,62], as the future trajectory of a landscape is not only governed by various controlling factors but also by the different levels of sensitivity to change at landform scale. It is difficult to exactly predict the future morphology of the landform, but the probability of achieving a particular state after understanding different spatio-temporal variations may be estimated[49]. Geomorphic research has moved towards (i) developing evolutionary histories from the past, (ii) understanding the relationship between present-day forcing and geomorphic change, (iii) the linearity and nonlinearity in this relationship, (iv) defining landform sensitivity and (v) predicting the future of landforms/landscapes in response to predicted change in external forcing.

Technological advancement and growth in geomorphic research

Technological advancements of the past few decades have considerably influenced geomorphic research. Initially, survey equipment and field measurements provided quantitative data for landform-scale research, while advancement in remote sensing applications in the 1990s enabled the pursuit of geomorphic research at landscape scale. A major thrust was provided by advances in chronological methods in terms of ^{14}C and OSL dating to determine the rates of depositional processes[63–66], whereas cosmogenic radionuclide dating helped in the estimation of the erosion rates of landforms[67]. The chronological database formed the basis for developments in sediment budgeting, which has helped in the quantification of the processes in different landforms and interrelationships between landforms. The estimation of sediment fluxes using sediment budgeting was further strengthened by chemical (isotope) fingerprinting of sediments to analyse provenance and spatio-temporal variability in sediment supply at landscape-scale[68–71].

The recent work on the Ganga river basin has been reviewed and reanalyzed, through application of the above geomorphic concepts.

Applications to the Ganga river system

Hierarchy and spatial and temporal dimensions

The current understanding of the Ganga dispersal system provides sufficient data to analyse hierarchy in this geomorphic system (Figure 2, Table 1). The Ganga dispersal system can be broadly divided into sediment-source regions (the Himalayan and cratonic region) and storage areas (the Ganga Plains and the delta region). These source and storage areas are further divided on the basis of the nature of driving forces, namely tectonics and climate (rainfall distribution) in the hinterland area and energy distribution in the alluvial plains[72]. This classification provides a broad understanding of the dominant processes in a given geomorphic class (compartment).

The Western Ganga Plain (WGP) has been further classified into valley and interfluve areas, which have gone through a cycle of attachment and detachment during the last 100 ka (10^5 years) time-period[73]. At the lower hierarchy levels, the Ganga valley was analysed in different spatial compartments. Valley formation at different spatial locations provides an example of multi-causality at a timescale of 10^3–10^4 years[74]. The Ganga valley at the mountain front is related to tectonic activity and in the plains it is related with high stream power and relative sediment supply[74,75].

The Eastern Ganga Plain (EGP) is characterized by fan–interfan setting[72,76–78]. Fan–interfan setting is related with the 'source area' of the rivers[77]. The fan-draining river systems are the mountain-fed systems with their large catchment areas and much higher water and sediment flux compared to the interfan-draining rivers. The interfan-draining rivers are foothills-fed and plains-fed

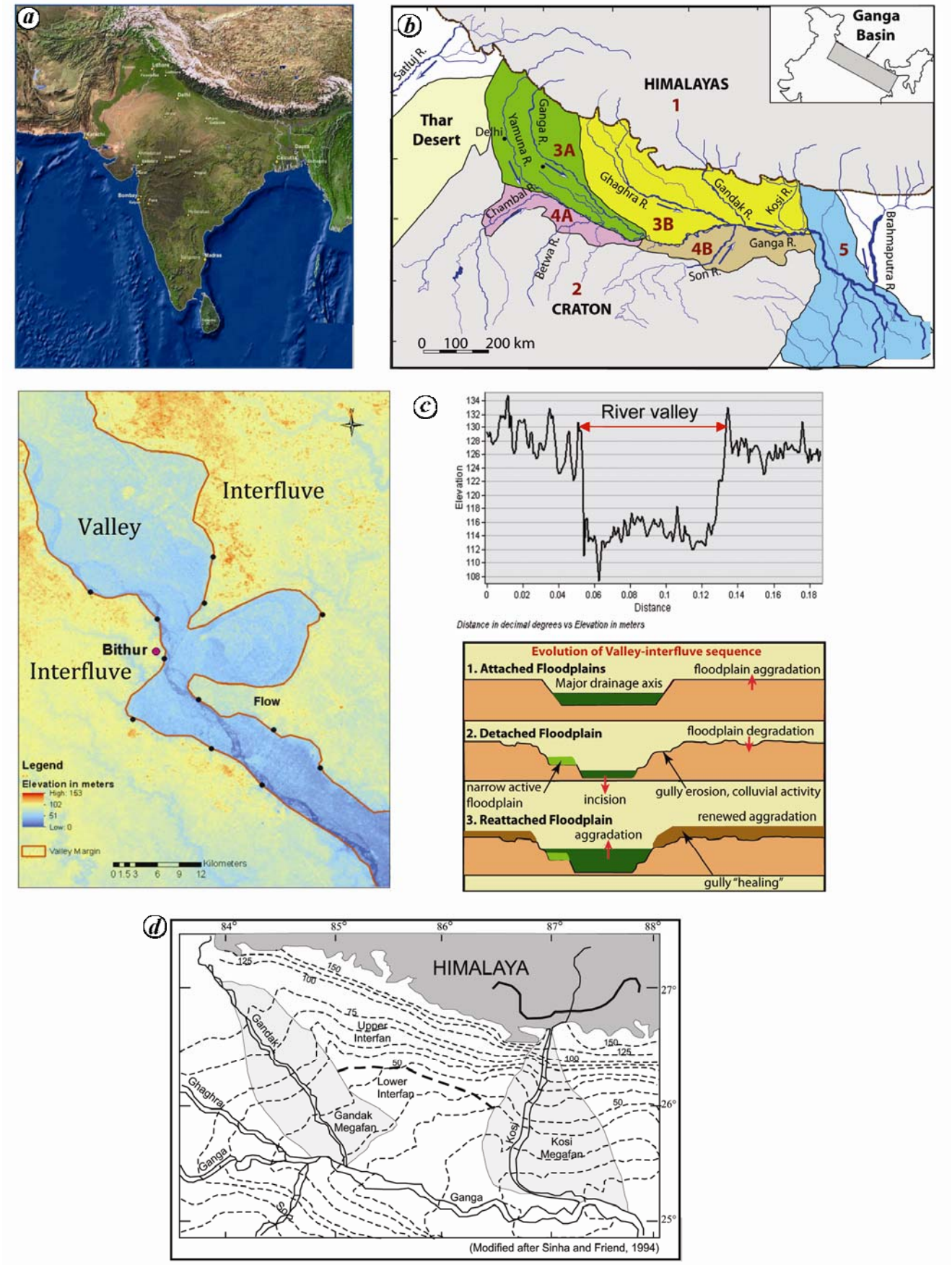

Figure 2. (*Contd*)

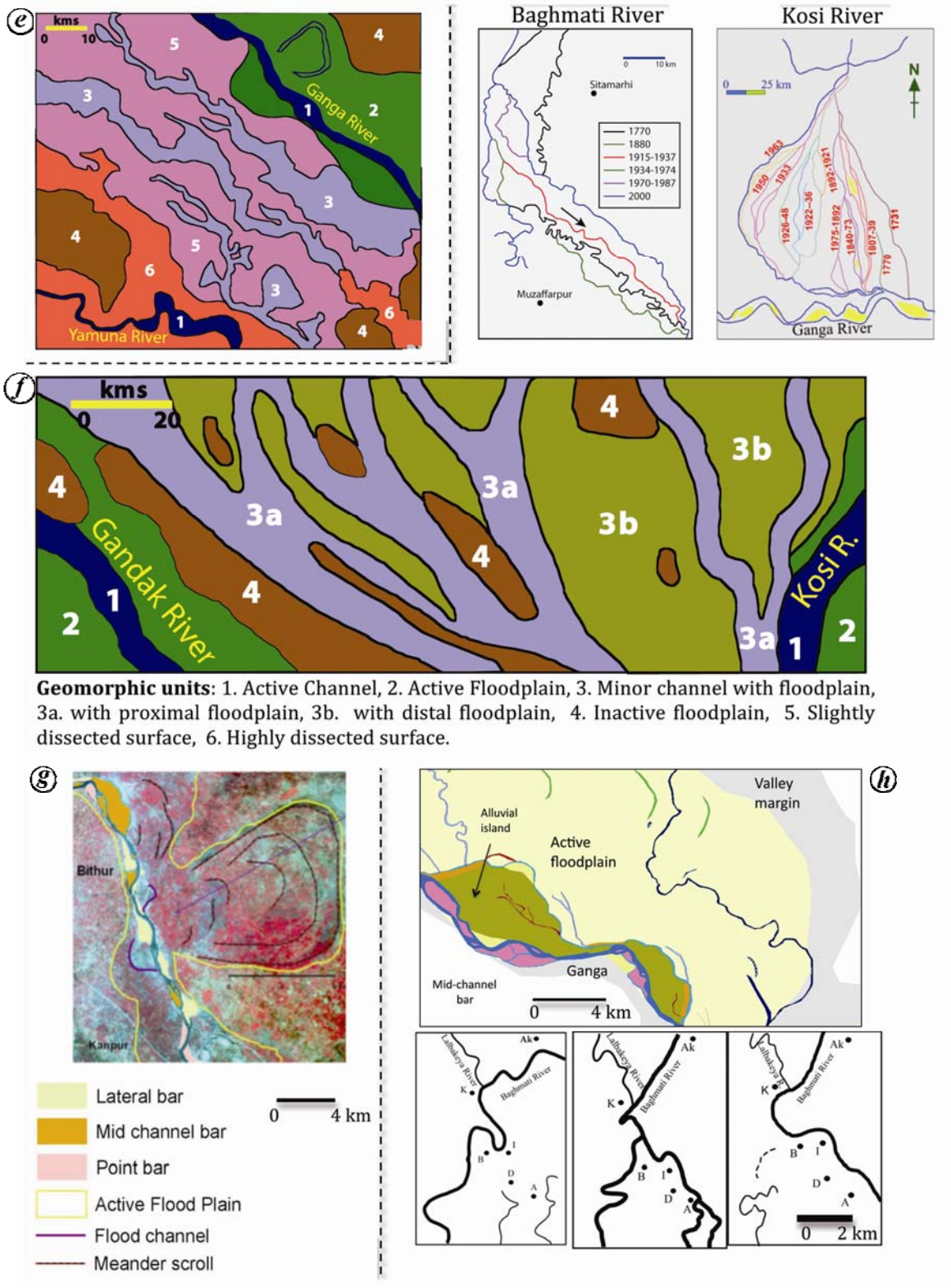

Figure 2. Hierarchical structure of the Ganga river basin. ***a***, ***b***, Different landscapes namely the Himalaya (class-1), craton (class-2) and the alluvial plains (classes 3–5) are the major geomorphic divisions in the Ganga dispersal system[72]. ***c***, the Western Ganga Plain (WGP) is characterized by valley–interfluve sequence, which has developed through floodplain attachment–detachment sequence in response to climate change[73]. ***d***, The Eastern Ganga Plain (EGP) is characterized by fan–interfan sequence related with source area of rivers[77,78] and mountain-front tectonics[127]. ***e***, Geomorphological units within the WGP[75]. ***f***, Different geomorphic units in EGP highlight significant geomorphic variability at this scale[75]. Further, EGP is also characterized by dynamic river systems with frequent channel shifting in both fan (Kosi river) as well as in interfan areas (Baghmati river). ***g***, ***h***, Geomorphic sub-units within channel area of WGP and EGP. Bar morphology is similar within the channel; however, the EGP area is characterized by wider floodplains. Further, the dynamic nature of the EGP rivers is related with avulsion process[82].

systems, which are sourced in the Lesser Himalaya and in the flat plains. In general, high sedimentation rate and the absence of incised surfaces have limited our understanding of these systems up to relatively short timescales (10^2–10^3). Studies of individual fan and interfan surfaces at the timescale of 10^2 years show the dynamic nature of rivers in this area[79–83].

Magnitude–frequency analysis

A few studies related to the sediment transport characteristics provide a preliminary magnitude–frequency analysis in the Ganga Plains (Table 1). Sediment transport at decadal scale highlights the significant role of flooding (high magnitude–low frequency) events on fluvial processes. The data from the rivers draining the north Bihar plains suggest that 90–95% of the sediment load is transported during the monsoon period, which is characterized by high discharge[77,84,85]. These findings are in accordance with the data from the neighbouring Brahmaputra river, where sediment load transportation of ≈ 85% occurs during the monsoon period[86]. However, erosion processes in the Nepal Himalaya provide a different picture. Daily discharge and sediment load data from the Nepal Himalaya suggests that the erosion process is dominantly controlled by moderate events with high frequency rather than the high magnitude and rare events[87]. Erosion is controlled by moderate events, but sediment transportation is controlled by high-frequency events, which makes hillslopes as 'transport-limited' systems, while rivers are considered as 'supply-limited' systems[87].

Besides, bedrock channel studies in peninsular India have also been used to highlight the significant role of large-magnitude events in defining channel morphology in certain reaches. For example, the different geomorphic reaches of the Tapi river are formed in response to different threshold of energy conditions, namely threshold of boulder transport and threshold of bedrock incision[88]. Specific stream power values on the basis of daily discharge data show that the threshold of boulder transport is breached on several occasions during the monsoon period[89]. It highlights that in accord with the Himalayan rivers, large-magnitude floods are also relatively more important for effective geomorphic work in the peninsular rivers.

Equilibrium and complexity

In the Ganga basin, equilibrium has been analysed through form as well as through processes (Table 1). The concept of equilibrium of a landform can be analysed at different scales. Small-scale landforms like bars, piedmont, channel slope, width, etc. can be considered as landforms in equilibrium with high-frequency and low-magnitude events. Therefore, change in these landforms (departure from equilibrium forms) is used as an indicator of high-magnitude tectonic or climate events or changes in anthropogenic activities.

A major question arises regarding the larger landforms (landscapes), which represent a complex scenario due to variable response time of different landforms within a landscape. Are these larger landforms currently in equilibrium or do they represent disequilibrium or nonequilibrium states? The complexity in terms of geomorphic form and its response to causative factors has been analysed for two major and well-studied landforms in the Ganga Plains, i.e. the Ganga Valley and the Kosi megafan.

The Ganga river valley in the Himalaya is characterized by spatial and temporal variability in its valley formation (incision) process, which has been related with tectonics[90–92] as well as climatic variability[93,94] at a timescale of 10^3–10^5 years. The incised nature of the Ganga Valley in the upstream plains area close to the mountain front is due to tectonic activity[74]. Farther from the mountain front, the valley–interfluve systems in the Ganga Plains have experienced several phases of incision and aggradation over the last 100 ka (refs 73, 95 and 96). The Ganga river has incised in response to recent tectonic or climatic events[74]. In the present scenario, the valley is dominated by aggradational processes. The Ganga valley is generally recognized as an equilibrium landform in response to Late Quaternary events, and in the present-day condition it would be considered in disequilibrium with the modern events.

The eastern part of the Ganga Plains is characterized by an aggradational regime resulting in fan–interfan settings such as the Kosi and Gandak fans[78]. Aggradational regime is evidenced by shallow channel, frequent overbank flooding, high sedimentation rate and dynamic avulsive nature of the rivers[79–83]. It is not possible to assess these landforms in terms of equilibrium as long-term stratigraphic data are lacking. These dynamic avulsive rivers are perhaps in disequilibrium condition in terms of the sediment transport at a shorter timescale (< 200 years).

Further, in terms of the geomorphic processes, the Siwalik terrain in the Baghmati river basin[97] and around Pinjaur intermontane basin[98] provides an example of equilibrium between erosion and uplift process. In the Nepal Himalaya, streams of all orders have adjusted to the rapid uplift rate of 15 mm/yr and the basin surface is in dynamic equilibrium with uplift, where relief correlates with uplift rate[97]. However, rock uplift and incision rate in the Marsyandi valley in Nepal at ~ 10^4 years timescale are in disequilibrium due to climatic pulses at shorter timescale[99]. At large spatial scale, the Himalayan orogenic wedge has not been considered to be in 'steady state' due to its low erodibility, which was analysed on the basis of the critical Coulomb wedge model[100]. Small-scale studies of relief variation on the Mohand anticline have suggested a steady state on the basis of high erosion rate of soft sedimentary rocks[101]. Further, it has been

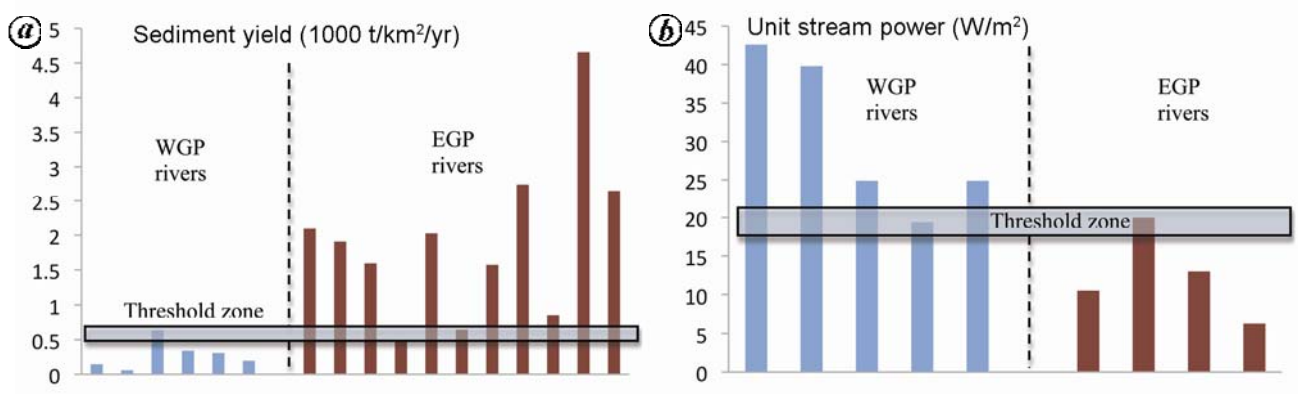

Figure 3. Threshold of sediment yield and unit stream power, which are responsible for geomorphic diversity between EGP and WGP. Threshold has been defined as a zone rather than a boundary to explain geomorphic diversity in the Ganga Plains.

shown that low relief can be maintained in a tectonically active area because local relief has been decoupled from uplift rate due to comparable erosion rate[101].

Threshold of geomorphic change

The understanding of geomorphic change due to external or internal factors has remained an important aspect of the study of Indian river systems. In a large river system, it is difficult to define a threshold value for any geomorphic change due to multi-causality and spatio-temporal variability in landform sensitivity against causality. Some of these studies were successful in suggesting a range of values to define a zone (not point) of threshold. A few of these studies in the Ganga Plains at different spatial scales are discussed below.

Geomorphic diversity in the Ganga Plains at the landscape scale is due to variability in stream power and sediment supply[75] (Figure 3, Table 1). The incised rivers in the WGP are characterized by unit stream power of greater than 25 W/m^2 (calculated for bankfull discharge) and sediment yield of less than 0.6 t/km^2/year, whereas rivers in the EGP have unit stream power less than 20 W/m^2 (calculated for bankfull discharge) and sediment supply greater than 0.6 t/km^2/year and mostly around 1.5–4 t/km^2/year (ref. 75). Thus, a range of 20–25 W/m^2 for unit stream power and 0.6–1.5 t/km^2/year for sediment yield can be used as a threshold zone to explain aggradational and degradational behaviour in different parts of the Ganga Plains. However, this represents only an initial analysis based on limited data at the given points (stations). Threshold identification and characterization of geomorphic diversity need to be further investigated with a large number of points well distributed in the dispersal system.

At reach scale, the anabranching behaviour of the Baghmati river in north Bihar has been explained by threshold range[82]. Upstream and downstream reaches are characterized by braided and meandering patterns respectively, whereas the midstream reaches are characterized by well-developed anabranching pattern. The braided/anabranching meandering threshold has been defined by a combination of hydrogeomorphic factors, namely variation in channel gradient from 0.00053 to 0.00011, width–depth ratio from 110 to 15 and Manning roughness from 0.03 to 0.06 (ref. 82).

The concept of threshold is most crucial to explain river dynamics and associated processes. The Kosi river in Nepal and north Bihar plains is known to be frequently avulsing and the most recent avulsion in August 2008 resulted in a shift of ~120 km and inundation of large areas. This large avulsion was partly attributed to the crossing of geomorphic threshold, which was caused by the aggradation of the river bed, which, in turn, was caused by embankment-related confinement of the river[83].

In catchment erosion processes, rainfall intensity is a more important variable than the total rainfall. Erosion processes are mostly governed by high-intensity rainfall above a particular threshold value. For example, in the hinterland of the Sutlej valley, the summer monsoon is characterized by lesser rainfall (≅ 40%) compared to the winter rainfall (≅ 60%)[102]. But the summer monsoon has the maximum impact on catchment erosion processes and sediment supply due to its association with high-intensity rainfall events, i.e. rainfall above a threshold value[102]. In this case, even though the identification of a threshold is not possible, conceptualization of the threshold itself provides a better understanding of the process and its causality.

Sediment budgeting and geomorphic connectivity

Significant work has been carried out on sediment dynamics and budgeting of the Indian rivers in the last two decades, which has provided a good understanding of basin- to reach-scale processes, spatial and temporal variability in sediment provenance and their implications on

Table 2. Reach-scale higher sedimentation rate from different parts of the Ganga Plains at decadal timescale

Sedimentation rate (mm/yr)	Time-period	Methodology	Remarks/location	Reference
16	1971–79	Measured suspended load data	607 km Brahmaputra River reach in Assam	86
39	1979–95	Measured suspended load data	Brahmaputra in Assam	86
> 14.7 (channel) 1.6 (FP)	Sediments from (0 to 80 cm depth)	^{137}Cs and ^{210}Pb geochronology	Brahmaputra in Bangladesh	158
39	1980–95	Measured suspended load data	Brahmaputra–Ganga in Bangladesh	159

Table 3. Power exponent of discharge–sediment load relationship for different rivers

Power exponent value (*b* value)	Location details	Reference
1.51	Ganga river in Bangladesh	103
1.56	Brahmaputra River in Bangladesh	103
1.23	Combined flow of Ganga and Brahmaputra rivers in Bangladesh	103
1.77–2.28	Brahmaputra River in Assam	86
1.15	Kosi in north Bihar	84
1.53–1.39	Gandak in north Bihar	84
1.5–2.4	Interfan rivers in north Bihar	84

geomorphic connectivity. Initial studies were focused on the sediment-yield measurements and on reach-scale sediment budgeting through measured suspended load data at different stations (Table 2). Sediment yield was computed to estimate average catchment erosion rate, while reach-scale sediment budgeting provided information about local processes[77,79,84,86]. High sediment yield for the rivers draining the EGP (e.g. Gandak and Kosi) and the Brahmaputra river in comparison to other rivers of the world has highlighted very high average rate of sediment erosion in the Himalayan catchments. However, sediment yield values may not be a true representation of erosion processes, as datasets for different time-periods may provide significantly different values. For example, the compilation of data from different sources by Islam *et al.*[103] shows that the variability in suspended sediment load of the Ganga river and Brahmaputra river in Bangladesh ranges from 316 to 1600 Mt/yr and from 402 to 1157 Mt/yr respectively. Such 200–300% variability suggests that it is difficult to consider a single value of sediment yield for a small (decadal) time-period. High sediment yield from the hinterland was also responsible for significant deposition in the downstream reaches, although the midstream to downstream reaches may also be characterized by reach-scale variability. Sediment-load data indicate that the variability in sedimentation rate in the downstream reaches may be related to hinterland processes or may entirely depend on aggradation/degradational behaviour of midstream alluvial reaches. For example, in most of the rivers draining the north Bihar plains, the sediment is eroded and transported from the upstream hinterland area[77,84]. However, decadal-scale analysis of sediment load of the Brahmaputra river suggests that up to 70% variation in sediment supply in the downstream reaches may be attributed to aggradation/degradation processes in the midstream alluvial reaches[86].

Causality of erosion characteristics was initially analysed through rating curves that explain the role of rainfall on erosion processes. A rating curve is represented as

$$Q_s = aQ^b,$$

where Q_s is the suspended sediment load, Q is the water discharge, and a and b are coefficients. The coefficient b, which is a power exponent, defines the rate of change in sediment load with change in discharge values. Hence, it indicates the sensitivity of erosion processes to rainfall variability on discharge. The b values for different rivers are compiled in Table 3. In general, sediment load increases 1–5 times in response to unit increase in discharge, which suggests higher sensitivity of the hinterland area for erosion processes against increase in discharge (rainfall). Higher b values in sediment rating curves of the Brahmaputra river suggest that the erosion processes of this river are most sensitive to rainfall[86].

Besides rainfall, sediment erosion is also governed by other causative factors like tectonics, anthropogenic disturbance, etc. The analysis of sediment provenance at different spatial and temporal scales has provided valuable information in this regard. Besides, suspended load data, geochemical and chronological data have been used to compute long-term (10^3–10^4) average erosion rate[68–71]. In

general, the erosion rate is higher in the Brahmaputra river basin (458 mm/10^3 years (ref. 103); 795 Mt/yr (ref. 104) in comparison to the Ganga river Basin (303 mm/10^3 year (ref. 103); 590 Mt/yr (ref. 104). Further, the preliminary sediment budgeting using suspended load data from the Ganga river basin shows that the Higher Himalaya is a major source of sediments (80 ± 10%), in comparison to the Lesser Himalaya, Sub-Himalaya and peninsular India[104]. Isotopic analysis of the suspended load of the Ganga river system also shows a major sediment contribution from the Higher Himalaya[69,70]. Further, a systematic study in a smaller sub-basin, i.e. the Alaknanda river basin, based on downstream sampling across lithological boundaries and corresponding ε_{Nd} and Sr analysis, suggest that the Higher and Lesser Himalaya contribute 54% and 46% respectively, of the total sediments at Rishikesh (upstream of the Siwaliks), while the Tethys Himalaya has a negligible contribution[71] (Figure 4). This highlights the insignificant role of glacial melting and a dominant role of tectonic and deforestation processes on sediment erosion. However, the isotopic data-based provenance analysis in large river basins becomes ambiguous in the reaches downstream of the Siwaliks, as the ε_{Nd} and Sr isotope signatures of the Siwalik rocks are similar to those of the Higher Himalaya[105,106]. Therefore, the contribution from the Siwaliks in the sediment load of large river systems could not be assessed, although extensive erosion has been reported from the Siwalik terrain[107]. Isotopic signatures from the sediments of smaller rivers, which originate in the Lesser Himalaya, indicate a higher contribution from the Sub-Himalaya. The Baghmati river in Nepal is characterized by a major contribution from the Siwaliks[108], while sediments in the Ghaggar river in western Himalaya show dominant signals from the Subathu Formation[109]. These findings support an important role of lithology and tectonics but lesser importance of relief on erosion processes, as the Sub-Himalayan rocks are characterized by soft and younger lithologies and form the hanging wall of the active Himalayan Frontal Thrust (HFT). Though a significant Sub-Himalayan contribution has been recognized in smaller basins, the relative sediment contribution from the Tethys, Higher and Lesser Himalaya and the Sub-Himalaya remains ambiguous in the large river systems.

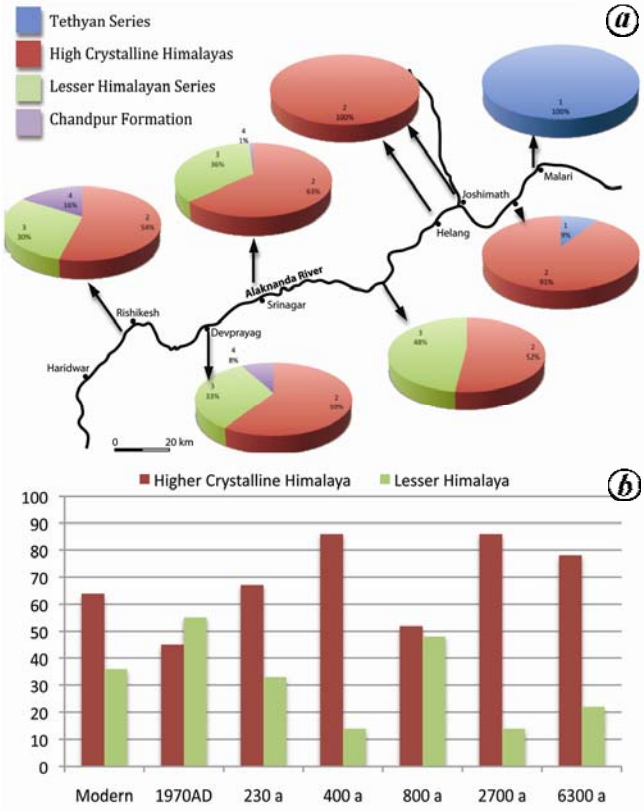

Figure 4. Spatial and temporal variability in sediment provenance suggests dynamic characteristics of landscape and erosion forcing. ***a***, Downstream variability in sediment contribution from different source areas along the Alaknanda river in the Himalaya[71]. Insignificant contribution from Tethyan Zone indicates its disconnectivity from the downstream reaches. ***b***, Temporal variability in sediment contribution in Alaknanda river at Srinagar[71]. At any station, sediment contribution from any individual terrain may have significant variability, which highlights the dynamic nature of erosion forcing.

Further, the dominant source area may also temporally shift in response to tectonic/climatic or anthropogenic controls. Isotopic data from stratigraphic sequences have provided preliminary data on the temporal variability. For example, the relative proportion of the sediment flux from different compartments in the Himalaya is known to be variable at longer timescales (10^3–10^5 years) in response to glacial–interglacial cycles and monsoonal precipitation[110]. Sediment contribution from the Higher Himalaya in the Ganga Plains decreased during ~ 20 ka and ~ 70 ka periods due to decrease in monsoonal precipitation and an increase in glacial cover[110]. Further, a reconstruction of ~ 7 ka erosional history in the Alaknanda basin has shown significant variation in the source area[71]. A higher contribution from the Lesser Himalaya was estimated in the deposits of the 1970 flood event and 800 ± 100 year event, whereas the time-periods of 400 ± 40 years and 2700 ± 700 years witnessed a major contribution from the Higher Himalaya[71]. The higher contribution from the Lesser Himalaya in the 1970 flood event was attributed to deforestation activity in the catchment area, but a similar contribution in older deposits highlights that natural (tectonic/climate) factors are also important in such erosion processes[71].

Sediment budgeting through the application of different tools at different spatial and temporal scales has provided a quantitative appraisal of geomorphic connectivity and a new set of questions has emerged on river response on the basis of source–sink (the Himalayan hinterland–delta) links[48] (Figure 5). Initially, Metivier and Gaudemer[111] highlighted the buffering effect of large floodplains in the Ganga Plains and suggested that the Himalayan

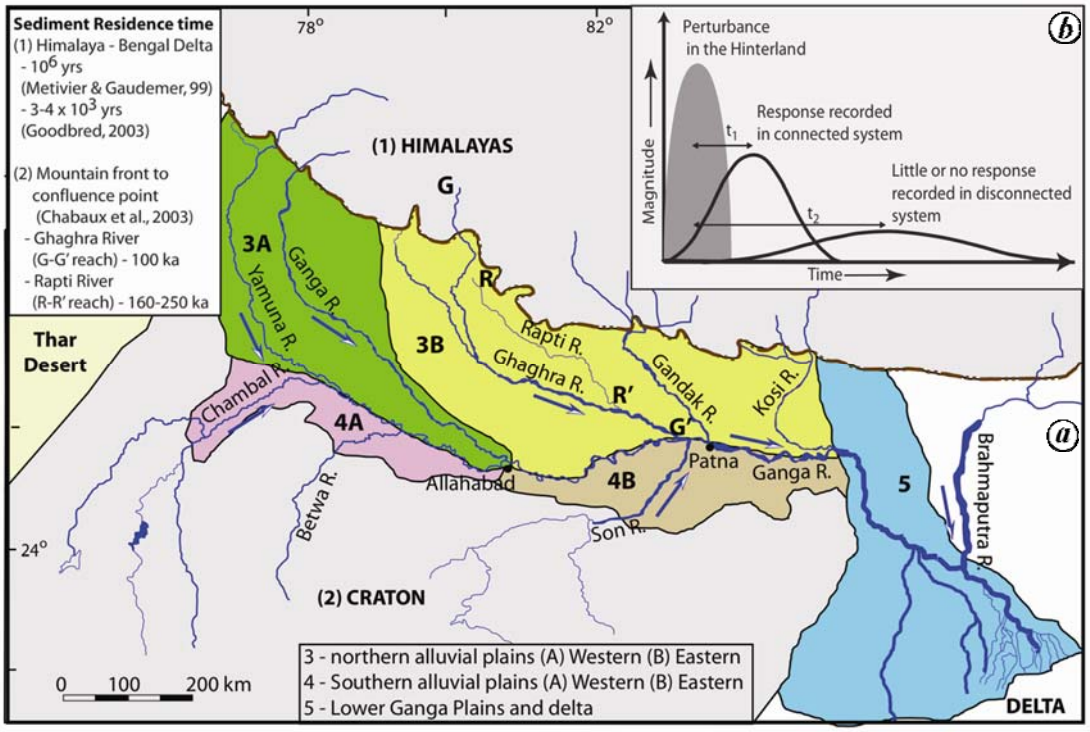

Figure 5. ***a***, Major channels and sediment source areas in the Ganga river basin (modified after Tandon *et al.*[72]). ***b***, Sketch showing the different possibilities of connectivity structures on the basis of sediment residence time in the Ganga Plains by different workers. Any perturbation in the upstream hinterland will be recorded in the downstream reaches for less lag time t_1, example after Goodbred[85]. However reaches characterized by higher lag time (examples after Metivier and Gaudemer[111] and Chabaux *et al.*[114]) will be disconnected with upstream control.

response (i.e. sediment erosion) cannot be transferred to the delta region within 1 Ma time-period, due to the buffering effect of a large floodplain[111].

An estimation of aggradation in the Brahmaputra river (> 14.7 mm/year) and floodplain (1.6 mm/year) in Bangladesh alone on the basis of ^{137}Cs and ^{210}Pb geochronology of sediments down to 80 cm depth suggested that around 30–40% of the estimated sediment flux of the Ganga–Brahmaputra system is deposited in the Bangladesh deltaic region and not being transferred to the ocean[112]. Further, estimates on the basis of suspended load data show much higher (49%) buffering effect in the Bangladesh Plains, including channel (21%) and floodplains (28%)[103]. Another estimate from the modern suspended-load data[104] suggested that the buffering effect of the entire Ganga and Brahmaputra Plains was around 60%, i.e. only 40% of the eroded sediment was able to reach in the subaqueous delta and fan area. Diffusion model-based analysis[111] and modern suspended load data suggest disconnected or partially connected structure in the Himalayan foreland, as eroded sediment from the Himalaya could not reach the downstream sink area in a given time-frame. However, in strong contrast, sedimentation rates in the Bay of Bengal, computed from drill cores and chronometric data, have changed significantly (by around 100%) in the mid-Holocene[113] in response to enhanced erosion in the Himalaya on a millennial timescale from 4 to 7 ka (ref. 85). Further, sediment residence time in a channel on the basis of U–Th disequilibria series lies in the range 100–250 ka for different Himalayan rivers, which supports disconnectivity for bed-load data within this time-period[114,115]. High residence time of sediments in the Ganga Plains is probably due to large-scale sediment recycling, which has been suggested on the basis of geochemical evidences[116].

These datasets on sediment load have raised several issues regarding geomorphic connectivity in the Ganga Plains[48] (Figure 5, Table 1). Suspended-load, isotopic and chronometric data of sediments from the Himalaya, the Ganga Plains and from the Bay of Bengal are not consistent and provide different estimates of geomorphic lag time. This suggests different scenarios of connectedness between major compartments (Table 1) in the Ganga River system[48]. There is a need to estimate connectivity for different fluxes between source and sink; this will require more densely distributed chronometric data to define sediment residence time for different landforms. Further, the role of larger geomorphic landforms like intermontane basins is yet to be established for understanding the sediment dispersion patterns of large river systems and their buffering effect over different timescales[117].

Sensitivity

The sensitivity of a landform defines the pattern of geomorphic response to external forcing. In the Nepal Himalaya, for example, two river valleys with similar terrain characteristics show different process response to the same event. The Marsyandi valley in the Nepal Himalaya aggraded in response to monsoon intensification around ~ 10 ka due to high sediment supply in the valley as the basin was sensitive to erosion processes[118], whereas the relatively larger Yamuna river in the Sub-Himalaya shows the opposite trend for the same climatic event[119] (Figure 6 *a*). Also, no major aggradation in the upstream reaches of the Gori Ganga in the Higher Himalaya during 10 ka has been observed[120]. Hence, a single event of monsoon intensification at 10 ka caused different processes in similar landforms (valleys) situated at different locations. Variable response was due to different sensitivity of hillslope erosion to monsoon intensification, which causes variability in sediment supply and hence in river processes. Sensitivity is responsible for geomorphic divergence[34] and is characterized by spatial variability (Table 1).

The significance of sensitivity on geomorphic response of river systems has also been highlighted from other regions of India. The Luni river, Mahi river, Sabarmati river are endogenic (rivers sourced entirely within a dryland region) and allogenic (rivers sourced within more humid regions and flowing through a dryland region) rivers in Upland Maharashtra were characterized by different phases of channel incision, bed-material characteristics and planform morphological variation in response to similar late Quaternary climate change due to different vegetation cover in the catchment area[121] (Figure 6 *b*). The authors[121] have also observed that desert streams are more sensitive to climate change in comparison to the desert-margin rivers, and are characterized by very small response time and geomorphic threshold[121].

Multi-disciplinary approach in geomorphic analysis

In the past few decades, geomorphic studies have been integrated with many other disciplines. At longer timescale (~ 100 ka), geomorphic observations have been integrated with stratigraphy and sedimentology, whereas remote sensing, isotope geochemistry, magnetic characteristics and chronometric methods, namely OSL and ^{14}C have served as tools to provide the temporal framework (Figure 7 *a*). A significant understanding of landforms in parts of the Ganga Plains at the timescale of 10^3–10^5 years has been achieved through the integration of these disciplines to interpret the role of climate and tectonics on the evolution of landforms at this timescale.

Stratigraphic information available for the upper 50 m of the alluvial cover in the southern part of the Ganga river basin studied through river-bank sections[73,74,122–124] and drill cores[95–96,122] covering the time-period of the last ~ 100 ka reveals a complex history of dynamics of large and small river systems, and a strong climatic control. Several cliff sections exposed along the river banks in the WGP record discontinuity-bounded sequences with alternate aggradational and degradational units in the interfluve area[73]. The aggradational units are characterized by overbank mud and sand, whereas the degradational units show gullied surfaces, palaeosols, lacustrine mud and eolian silts. A section along the Belan river, for example,

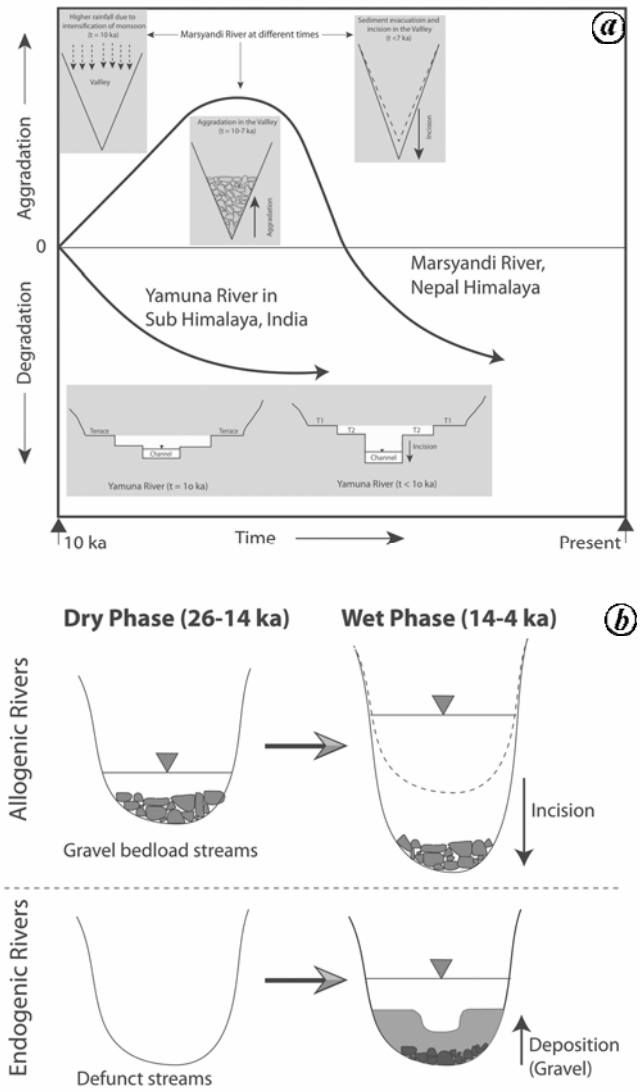

Figure 6. ***a***, Variable response of different rivers to the monsoon intensification event at 10 ka due to differential sensitivity. Marsyandi responded in terms of aggradation followed by valley incision (after Pratt *et al.*[118]), whereas the Yamuna river was characterized by valley incision (after Dutta *et al.*[119]). ***b***, Allogenic and endogenic rivers in upland Maharashtra are characterized by different responses to the same climatic event (after Jain and Tandon[121]). The figure also highlights the significance of place resulting in different sensitivity to geomorphic change. The mixed responses due to different sensitivity also generate complex geomorphic response of a landscape.

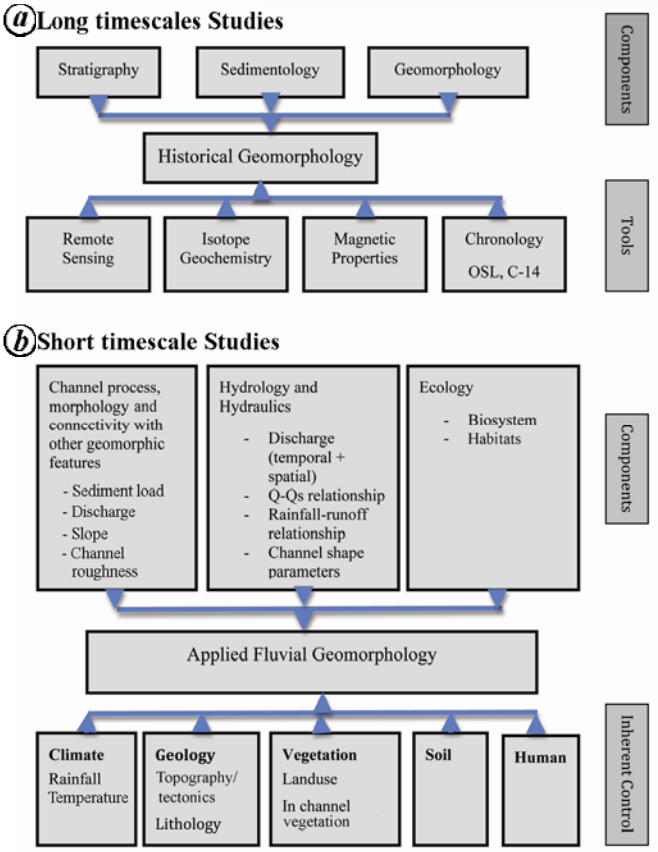

Figure 7. Examples of the importance of multidisciplinarity in geomorphic studies.

has cut into the bedrock (Proterozoic quartzites) and the cliff section starts with channel-base calcretes above the Vindhyan Unconformity overlain by fluvial sediments (~85 to 16 ka). The record for the ~70 ka period of fluvial activity consisting predominantly of muddy floodplain deposits with some meandering-river channel bodies is in accord with generally high precipitation levels during Marine Isotopic Stage 3 to 5 (ref. 123). Another section at Kalpi along the Yamuna river records aggradational sequences during ~120–65 ka and 90–40 ka bound by major discontinuities represented by carbonate cemented sand and carbonate gravels[73]. Deep gully fills within the floodplain sequence from 30 to 40 ka suggest incision during this period. It was suggested that such 'aggradation–degradation rhythms' are in accord with modelled monsoonal fluctuations during this period.

In the Ganga valley, valley margin sequences and valley fill cores in Kanpur region record two major channel sands corresponding to the pre-LGM (Last Glacial Maxima) and Holocene separated by intra-valley floodplain deposits[122]. A multi-proxy approach using sedimentary facies, mineralogy and magnetic data for the reconstruction of the depositional environments during the Late Quaternary suggested that valley aggradation occurred between 30 and 15 ka during the climatic transition from a humid to a cold-arid phase. The adjoining cliff section at the valley margin (Bithur) showed the accumulation of lacustrine and eolian sequences around this time, indicating floodplain detachment around the LGM[73]. The authors[73] suggested that the Ganga river became 'underfit' during this period with a much reduced channel capacity. Holocene monsoonal intensification rejuvenated the main flow of the Ganga river and a renewed phase of valley filling occurred during the transition from early Holocene warm–humid conditions with higher precipitation and high sediment supply, to a relatively less humid period after 6 ka.

Another integrative approach of geomorphic studies with stratigraphy, sedimentology and structural geology/tectonics has resulted in the emergence of the subdiscipline of tectonic geomorphology[125,126]. It aims mainly to understand the tectonic–landform interaction at different timescales. In the Ganga river basin, drainage development and morphological changes in response to tectonic deformation has been studied over the past two decades. Gupta[127] and Friend *et al.*[128] have demonstrated that the development of the Himalayan foothills led to the merging of streams and the enhancement of stream power, which enabled them to cut through the tectonically formed barrier. Detailed studies by different workers in the NW Himalaya also relate the growth of Chandigarh and Janauri anticlines with drainage readjustments in the area[129–131]. These drainage readjustments have caused changes in the river pattern and style due to variations in the sediment supply. In the alluvial plains area, the role of subsurface structures and channel pattern and its dynamics have also been suggested[132]. These aspects were further analysed by detailed mapping and process-based analysis in the Baghmati river, where subsurface faults, namely the Sitamarhi Fault, East Patna Fault and West Patna Fault were shown to have significant control on river processes[133]. These are reflected by anomalous meander, local convexity in long profile and spatial variability in channel sinuosity, overbank flooding, channel shape related to channel incision and abandonment of active channels.

Studies at shorter timescales were focused to analyse the spatial variability in the surface processes and its applications in stream management. In short timescale studies, fluvial geomorphology has been integrated with hydrology, hydraulics and ecology to understand the dynamics of riverscape. These integrated studies rely on multiple tools such as remote sensing, isotope fingerprinting and mathematical modelling. Understanding of the riverscape is important to define river health and for the development of sustainable stream management programmes[134]. An example of river science, its components and inherent independent controls are explained in Figure 7 *b*. River science is defined as 'the study of how hydrological, geological, chemical and ecological processes

interact to influence the form and dynamics of riverine systems and how riverine ecosystems in turn influence these processes across multiple spatial and temporal scales'[135].

However, in India, the discipline of river science is still in its infancy. Even though significant work has been carried out on the individual components of river science, integration of these datasets, i.e. hydrology–geomorphology–ecology is still a major challenge. Some attempts have been made to map and predict the temporal variability in hydrological characteristics. Future changes in the hydrological budget due to climate change have been suggested based on the time-series data[136], downscaling of General Circulation Models (GCMs)[137,138] and through modelling of soil and meteorological parameters[139]. However, the outcomes of different approaches show non-coherence, which emphasizes the need for a critical analysis of the various assumptions in different approaches. For example, the assumption of stationarity and ergodicity in the time-series dataset needs critical evaluation as it can change the output in a significant way[140,141].

Further, little information is available on how the future changes in hydrology will be reflected in river processes and morphology and in riverine ecology. It will require better understanding of processes and feedbacks between hydrology–geomorphology and geomorphology–ecology. However, case studies involving integration of hydrology in geomorphic studies are generally lacking. Hydrological input in geomorphic queries also provides a process-based framework to analyse landform/landscape dynamics. A hydrology-based geomorphic classification, i.e. the source area classification[77], provides one such example of understanding geomorphology–hydrology relationship at basin scale. Hydrological data and discharge–sediment relationship have also been used to develop a process-based understanding of landscape evolution and diversity in the Ganga Plains[75]. More such studies are required on the modern-day geomorphic setting and processes to provide a greater spatial coverage. Geomorphic controls on the hydrological behaviour of a river system have been investigated through the application of geomorphological instantaneous unit hydrograph (GIUH) concept[142], which provides a quantitative relationship between drainage basin morphometry and basin hydrology. GIUH application has been successfully used on the Indian rivers to understand the geomorphic control on hydrological characteristics. It includes geomorphic control on unit hydrograph behaviour of a river[143], spatial variability in hydrological behaviour of a river[144], in-design flood estimation and run-off modelling[145], and the prediction of surface run-off[146]. More such case studies are needed to develop different basin-specific hydrology–geomorphology relationships. Currently, geomorphology–ecology integration is almost non-existent for the Indian river basins. A better understanding between geomorphic processes, and habitat suitability for riverine biota will help in the establishment of hydrology–geomorphology–ecology framework for securing river futures.

Discussion

Geomorphic studies on large river systems in India could be broadly divided on the basis of temporal scale. Landscape/landform studies in India are mostly carried out on millennial timescales (10^3–10^4 years), which have helped to understand the evolutionary pattern of landforms and the role of climate and tectonics on landform changes. However short-term (10^0–10^2 years), process-based, landform-specific geomorphic studies are limited. Especially in the 'Anthropocene' period, the understanding of modern-day processes in geomorphic systems of one of the most populated parts of the planet will be crucial to develop appropriate sustainability strategies and models. Sensitivity, connectivity and threshold will be the most important parameters to define the future trajectory of a landform, as they help analyse nonlinearity in the geomorphic system. Currently, little or no understanding exists about the projected future behaviour and form of rivers and other natural systems in India in the scenario of uncertainties associated with climate change and the ever-growing impacts of anthropogenic effects. It is this conceptual understanding that will determine the 'course' of human interactions with the earth, its environment and its over-exploited 'critical zone[2].

Further, the available geomorphic understanding needs to be integrated with other disciplines to enable a better understanding for the sustainable management of the large river systems. Especially, geomorphology–ecology relationship has become an important issue for the assessment of the ecological health of a river, as well as for determining the role of anthropogenic influences[134,147–150]. Geomorphology plays an important role in this research area as landscape/landform and its changes determine the type of ecosystem. On the other hand, ecological parameters (vegetation growth) also control the nature and rate of biofeedbacks on geomorphic processes. Such approaches emphasize the reciprocal coupling between a river system, its landforms, and ecological and evolutionary processes[151]. Further, the concept of hierarchy, equilibrium, complexity, threshold and sensitivity is common in both geomorphology and ecology. There is a need to analyse geomorphic and ecological data together in the above-mentioned conceptual framework. In this regard, some of the important research questions are as follows:

1. How are landforms and their ecosystems nested at different scales?
2. What is the measure of landform (river reach) sensitivity in a given area and how will it define variable river response to external forcing?
3. What is the threshold of a geomorphic change for a given landform? Is the particular given geomorphic

system close to threshold, and what factors will determine its sensitivity for geomorphic change?
4. How will spatial variability of geomorphic sensitivity govern the controlling parameters for ecosystem dynamics?
5. How will the practice of stream-management planning be different in different reaches of variable sensitivity? How will the integration of multi-scale data be helpful in stream management?

Studies on the long-term (10^3–10^5 years) aspects of the Ganga Plains have emphasized the evolutionary trajectory of landforms in response to changes in tectonics and climate[73,74,95]. However, the analysis of landform dynamics needs more multidisciplinary datasets because landform dynamics and its present attributes are an outcome of interaction between physical, chemical, biological and human processes at different scales[152]. The new set of challenges in geomorphic research at longer timescale will need an integration of several disciplines, namely hydrology, geomorphology, Quaternary geology, geophysics, ecology, remote sensing, GIS, geochronology and mathematical modelling[1,152,153], and would also require further integration of new disciplines in the future. The geomorphic studies of large river systems in India will constitute an important element in the study of earth surface processes as projected by Murray *et al.*[152], and it will be in consonance with the major challenges and high-priority research areas suggested by the National Research Council, USA[154], which include: (i) landscape and climate interaction, (ii) quantitative reconstruction of landscape dynamics across timescales, (iii) ecosystem–landscape interaction, and (iv) the future of landscape in 'Anthropocene'[154]. Some of the major research questions at long-term scale are:

1. What is the nature of connectivity between different compartments in a large river basin? What is the sediment residence time in different compartments?
2. How does a river basin respond to external forcing? What is its time lag? Can we define different landforms within a larger river basin in terms of equilibrium, nonequilibrium and disequilibrium forms in response to any single external forcing?
3. What is the threshold of geomorphic change for different landforms in a large river basin? Why do different landforms show variable response to the same external forcing?
4. What is the cause of nonlinear response of a landform/landscape at different spatial and temporal scales? Can this nonlinear behaviour be explained through the estimation of geomorphic threshold and (dis) connectivity?
5. Does integration of landform-scale understanding explain complex response at landscape scale?

Conclusions

Rivers, particularly large river systems are a fundamental resource for the survival of human societies. In this particular study of a large river system, the importance of scale, process–pattern relationships, hierarchy, variability, diversity, sensitivity, equilibrium, connectivity, nonlinearity, complexity and multi-causality has been emphasized for the dynamically coupled natural and human systems of the earth. The applicability of geomorphic concepts to the existing geomorphic, sedimentological, stratigraphic, hydrological and geochemical data of the Ganga river system has resulted in a geomorphic synthesis of the system[160] that highlights various issues. These include the difficulties in applying the equilibrium concept to large river systems, the importance of threshold in explaining landform diversity, the importance of connectivity in understanding the parts and the whole of a large river systems, and the importance of multidisciplinarity in building a science-based knowledge system for practising river management and engineering.

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