1. Introduction

The nature and pattern of flux in a large river basin determine the basic processes of dispersal of material (water, sediment, organic matter, and nutrients) and are critically linked to catchment processes. Geomorphic processes within a landform, and landform interaction in a river basin is mostly governed by sediment flux; hence sediment flux has become an important component in geomorphic studies of a river basin. A river basin can be classified into landscape compartments or geomorphic provinces through which sediment movement takes place. The compartments of river basins may be connected or disconnected (Church, 2002; Harvey, 2002a). Connectivity is defined as the way in which different landscape compartments fit together in a catchment (Hooke, 2003; Brierley et al., 2006; Stanford, 2006).

Connectivity between different compartments is useful in determining the sensitivity of a river basin to external factors such as climate change, tectonic effects, river engineering works, or land use change (Brunsdon and Thorne, 1979; May, 2006; Gregory et al., 2008; Chiverrell et al., 2009). In addition, connectivity is also useful in explaining variation in sediment yield with little or no change in external forcing, as small-scale processes like bed armouring, sediment storage, vegetation cover, and remobilization may significantly change sediment yield at basin outlets (DeVente et al., 2006; Coulthard and VanDeWiel, 2007; Lesschen et al., 2009; López-Tarazón et al., 2009). Hence, connectivity assessment based on sediment flux is a major concern in the analysis of river response to external forcing.

The understanding of connectivity in a large river system characterized by diversity and complexity within and between its different compartments is a fundamental requirement both for understanding them as well as for river management, repair, and rehabilitation. This study applies the concepts associated with connectivity and its types to the Ganga dispersal system, with a view to appraising its significance in gaining insights into catchment processes, material and energy fluxes in a large multi-scale dispersal system.

2. Connectivity components and types of connectivity

Connectivity has been defined in different ways through its analysis in various disciplines including geomorphology (Harvey, 2002a; Hooke, 2003; Brierley et al., 2006), hydrology (Pringle, 2003; Bracken and Croke, 2007), ecology (Lindemayer and Fischer, 2006) and graph theory (Foulds, 1993). In a geomorphic system, the connectivity between two compartments has been defined either through physical contact or through transfer of material, or both these components. In general, geomorphological studies use the concept of connectivity in relation to transfer of material, i.e., sediment, water, and nutrients across well-defined compartment boundaries, as material transfer governs the connectivity between landforms or processes—specific domains. Most studies assume that transfer occurs only between physically connected compartments (see Table 1). Some case studies have considered...
material transfer (connectivity) between compartments that are not physically connected (Poole et al., 2002; Hooke, 2003). Hooke (2003) has also provided a classification of connectivity for physically disconnected bars in a channel environment on the basis of nature of coarse sediment flux. However, types of connectivity have not been assessed on the basis of both physical connectedness and sediment transfer. Further, no discussion is available of systems in which compartments are physically in contact or connected but no transfer takes place between the compartments. These different scenarios require that the concept of connectivity and its measurement be explored further with the inclusion of all possibilities of material transfer and physical contact.

Four types of connectivity are proposed on the basis of its two components: (i) physical contact between compartments (Pc) and (ii) transfer of material (Tm) (Fig. 1). Physical contact (Pc) represents the qualitative and quantitative contact relationships between two compartments. Further, these components (i.e., physical contact and material transfer) may vary from one-dimensional to three-dimensional, which will define the variable dimensions of connectivity. The first two connectivity types are suggested in physically connected (Pc) systems. Type 1 is named as active connected systems, which are characterized by physically connected compartments with material transfer between them. The material transfer may be one way (upstream to downstream) or two ways (channel–floodplain transfer). Material transfer in a physically connected system may cause significant change in the compartments. Active channel–floodplain connectivity lies in this region, where floodplain aggradation is a common phenomenon because of frequent overbank flooding (Fig. 2a). Type 2, inactive connected systems characterize systems with physically connected compartments but with no material transfer ordinarily between them in a given time frame.

In a physically disconnected system, sediment transfer may occur through aeolian or fluvial geomorphic agents, and these systems are

<table>
<thead>
<tr>
<th>No.</th>
<th>Physical contact (Pc)</th>
<th>Transfer of material (Tm)</th>
<th>Graphic Representation</th>
<th>Type of Connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Active Connected System</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td></td>
<td>Inactive connected system</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Yes &gt; Episodic (rare event/wind)</td>
<td></td>
<td>Partially active connected system</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>No</td>
<td></td>
<td>Disconnected system</td>
</tr>
</tbody>
</table>

Fig. 1. Types of connectivity on the basis of two components, i.e., physical contact (Pc) and transfer of material (Tm).
Spatial connectivity is a three-dimensional property that requires to be analysed in longitudinal, lateral and vertical directions (Ward, 1989; Stanford and Ward, 1993; Brierley et al., 2006). The interaction between these different connectivity dimensions is responsible for different response of a whole catchment. Interaction between connectivity dimensions can be visualized in different planes. Longitudinal and lateral connectivity interacts in a horizontal plane, while vertical–longitudinal and vertical–lateral connectivity interacts in vertical planes. This interaction provides the basis for 3-D understanding of processes.

The effect of lateral and longitudinal connectivity on vertical connectivity can be analysed in a hyporheic zone. Hyporheic zone is characterized by mixture of surface water and groundwater and is an important aspect in geomorphological and ecological studies (Dahm et al., 2006). The dynamics of the hyporheic zone is characterized by spatial and temporal variability of vertical connectivity. However, the distribution and boundaries of the hyporheic zone are governed by features related to connectivity in the horizontal plane, which include occurrences of unconfinned floodplains (Stanford and Ward, 1993), river discharge, and channel shape (Boulton et al., 2004; Mika et al., 2008), whereas the processes (mixing pattern of surface and groundwater) in the hyporheic zone are governed by geomorphic complexity in the channel. The hyporheic process increases with an increase in streambed undulations or an increase in bed porosity (gravel-bed rivers) (Packman and Bengala, 2000; Boulton et al., 2004; Mika et al., 2008). On a horizontal plane, anthropogenic disturbance of a river system may smooth the bed profile or change the nature of sediment supply (governed by lateral and longitudinal connectivity), which may change the mixing processes in the hyporheic zone (vertical plane). The pattern of vertical connectivity also varies with channel morphology as vertical connectivity decreases with the decrease in grain size, a result of lateral and longitudinal connectivity (Kasahara and Hill, 2008). Hence, variation in connectivity in the horizontal plane may impact the connectivity in the vertical plane.

3.2. Temporal dimension of connectivity

The magnitude or type of spatial connectivity and their interactions may change with time, which provides it the fourth dimension. Most of the connectivity studies are based on short time scale(s) related to modern process studies (see references in Table 1). The concept of connectivity at large spatial scale and at longer timescales is highlighted by Harvey (2002a) in his detailed analysis of connectivity at different spatial scales. The temporal nature of variability may be driven by tectonic, climate, or land use changes.

Tectonics in the hinterland may increase or decrease longitudinal connectivity. Uplift in the hinterland area will enhance connectivity through increase in channel gradient. However an uplift-induced structural barrier transverse to river flow reduces connectivity between landforms upstream and downstream of the barrier (Fig. 3).

Extreme events may erode channel bars or significantly cause erosion of the terrace or floodplains. In this case, the disconnected landforms may be connected suddenly for a short time, and sediment supply will increase manifold. Hence, climate change may increase sediment yield at the basin outlet not only by increase in hinterland erosion processes (Blum and Torquqvist, 2000) but also by enhancing the intracompartment and intercompartment connectivity. This increase in sediment yield may not necessarily be related directly with the hinterland erosion, but may be the result of increase in coupling at different scales. On the other hand, rainfall increase may also cause large landslides from the increase in pore pressure on hillslopes (Hoek and Bray, 1977; Schmidt and Montgomery, 1995), which in turn, form barrier(s) across the channel and reduce sediment transfer (Pratt et al., 2002). Hence, climate change could influence
sediment supply in either way through enhancing or reducing connectivity in the channel.

Anthropogenic and land use change may result in the decrease of channel roughness (Brooks and Brierley, 1997), increase of sediment supply (Langedal, 1997), construction of civil-engineering barriers (Brandt, 2000), and increase/decrease of channel slope through channelization work (Emerson, 1971; Brooks, 1987; Brooks and Gregory, 1988; Surian and Rinaldi, 2003). All these activities change connectivity in a fluvial system. This temporal variation in connectivity results in different sets of processes and resultant morphology/landforms. The nature of longitudinal connectivity in a channel may increase because embankment construction restricts flow and causes concentration of flow energy followed by erosion of depositional features in the channel. Embankments also disconnect floodplains from channels (lateral connectivity), resulting in significant effects on floodplain accretion rates, river basin ecosystems and agricultural productivity in the floodplain region. Lateral channel–floodplain disconnection is short lived, and breaching of embankments and channel avulsion results in sudden channel–floodplain connectivity causing significant hazards on the plains. In an avulsive system, the nature of connectivity between active and abandoned channels in a landscape highlights the instability of avulsive system(s). In the case of connected systems, the active channel may (re)occupy the abandoned channel, and the probability of avulsion will always be higher (Jain and Sinha, 2003, 2004). Connectivity in such an avulsive system may be measured through a function including distance between channels, and channel slope values and would be helpful to define an unstable avulsive system. For example, the active channel and abandoned channel on the Kosi megafan are connected, which causes channel reoccupation and, hence, results in a highly unstable avulsive system (Sinha, 1998, 2009). Therefore, an understanding of the temporal dimension of lateral connectivity is an important aspect in fluvial hazard studies.

3.3. Connectivity: time–space considerations

On the basis of time and spatial scales the nature of connectivity may be divided into four classes: namely (A) small space–short timescale, (B) large space–long timescale, (C) large space–short timescale, and (D) small space–long time scale combinations (Fig. 4). The closely spaced, small spatial units generally remain well connected; and hence, short timescale–small space combinations (class A) are a common occurrence, e.g., hillslope–channel connectivity, reach-scale longitudinal connectivity or floodplain–channel connectivity. In a hierarchical scheme, involving progressive integration of successively higher spatial scales, class A may shift toward either class B (large space–long timescale) through trajectory 1 or toward Class C (large space–short time scale) through trajectory 2 (Fig. 4). The assignment to a particular trajectory will depend upon sediment residence time. A low energy fluvial system with development of large floodplains will be characterized by high sediment residence time; the river system will follow trajectory 1 and basin scale river system will be classified under class B. A high energy fluvial system with low floodplain sediment accumulation and distribution will be characterized with less sediment residence time and the basin will follow trajectory 2 and be classified under class C. Class B type connectivity in a large river system will result in relatively less influence of climate change or hinterland tectonics because of buffering effects. Further, these types of fluvial systems are characterized by low recovery potential in river rehabilitation programs (Fryirs and Brierley, 2001). Thus, characterization of connectivity classes is an important aspect to analyse the future states of fluvial systems.

Class D connectivity represents a greater time lag between small spatial units. It may either occur in a lower energy environment (topography) characterized by low relief and gentler slope or between the closely spaced spatial units separated by barriers like dams (longitudinal connectivity between channel reaches) and embankments (lateral connectivity between floodplain and channel) (Fryirs et al., 2007a).

4. Measurement of connectivity

Connectivity estimation in the past has been made on the basis of physical contact only. It was either based on physical contact of subbasin area (Fryirs et al., 2007b) or saturated zones along hillslopes (Reid et al., 2007). As noted earlier, connectivity is defined on the basis of two aspects: namely physical contact and amount of sediment transfer. The integration of these two aspects will better define connectivity between two compartments. A conceptual representation of the connectivity index for physically connected compartments ($C_{pc}$) (type 1 and type 2 connectivity of Fig. 1) may be written as

$$C_{pc} = AV_{in}$$

where $A$ is area of physically connected dimensions, and $i_{in}$ is the rate of material transfer. In an inactive connected system (type 2 connectivity), the value of connectivity index will be null because $i_{in}$ will be zero; whereas in an active connected system, the value of connectivity index between any two compartments having similar connected area ($A$) will be different on the basis of variability in sediment transfer rate ($i_{in}$). Further, rate of material transfer for a given area will be higher in high energy compartments. Hence, relatively high energy compartments will have strong connectivity for the same amount of physical connectedness ($A$), which highlights the role of geomorphic aspects on connectivity measurement.

In a physically disconnected system (partially active connected system, type 3 connectivity), the connectivity (transfer) between two compartments will depend on the energy condition and distance between compartments. Hence, connectivity index between physically disconnected compartments ($C_{pd}$) can be conceptually represented as

$$C_{pd} = E / d$$

![Diagram](image-url)
where $E$ is energy in the system, which represent the driving force in the compartment; and $d$ is distance between the compartments.

5. Assessment of connectivity in a large river system: issues and complexity

Large river systems have been defined on the basis of physical parameters, namely channel length, basin area, or sediment load (Potter, 1978; Tandon and Sinha, 2008). Generally, river systems having more than an 800,000 km$^2$ basin area and/or a 2500 km channel length are classified as large river systems (Hovius, 1998; Tandon and Sinha, 2008). The study of large river systems includes the issues of multiple scales, patterns, processes, hierarchy, diversity, multicausality and variability in its different compartments. Multicausality and complexity causes nonlinear response of a large river system to any disturbance, hence, understanding of large river system(s) requires a detailed study of (dis)connectivity between different compartments to understand the complex nature of a large river system.

5.1. The Ganga River system

The concept of connectivity is applied to a large river system—the Ganga River system. The Ganga River is one of the world’s largest dispersal systems with 2510 km channel length, 980,000 km$^2$ basin area, and a particularly very high suspended sediment load of 524 Mt/y. It is characterized by a vast diversity of geomorphic forms and operating processes that are related to the available energy in different compartments and energy transfer between compartments. The genetic classification of the Ganga River system on the basis of energy distribution (stream power) allows the recognition of five major compartments, namely, (1) Himalayan hinterland extending from source to mountain exit divisible into western (1A) and eastern (1B) parts; (2) cratonic hinterland comprising the Aravalli, Bundelkhand, and Singhbhum belts; (3) northern alluvial plains divisible into western (3A) and eastern (3B) parts; (4) southern alluvial plains divisible into western (4A) and eastern (4B) parts; and (5) Lower Ganga Plains and delta (Fig. 5) (Tandon et al., 2008). Understanding of catchment-scale surface processes in the Ganga dispersal system needs to be based on the analysis of connectivity between these compartments (intercompartment connectivity) and of connectivity between the landforms and processes within the individual compartment (intracompartment connectivity).

5.1.1. Intercompartment connectivity in the Ganga dispersal system

The neighbouring compartments in the Ganga plains are actively connected as both components, including physical connectedness and sediment transfer, are important in this case and Eq. (1) can be used for connectivity assessment between compartments; whereas, connectivity between distant compartments could be assessed through Eq. (2). The nature of longitudinal connectivity between different compartments is shown in Fig. 6a.

The hinterland area (source area) provides sediments to the Ganga dispersal system; the Ganga plains act as temporary storage for sediments as well as a zone of transportation. The Himalayan hinterland is a younger Cenozoic orogenic belt that is characterized by higher relief and steeper slopes in comparison to the cratonic hinterland of Precambrian age. The high relief is also responsible for orographic precipitation from the monsoon system and causes high rainfall (1400–2000 mm) over the Himalaya, whereas the cratonic...
hinterland is a drier region (600–1200 mm rainfall) (Singh, 1994). Steeper slopes and higher rainfall are responsible for higher values of the driving force (stream power = f(discharge Q, channel slope s)), and hence the Himalayan hinterland is better suited to flush the sediment to the Ganga plains in comparison to the cratonic hinterland area. High rate of material transfer (i_m) is responsible for better connectivity between the Ganga plains and the Himalayan hinterland area relative to the cratonic hinterland (see Eq. (1)). Higher sediment generation in the Himalaya and better connectivity with the Ganga plains is responsible for dominance of the Himalayan-derived sediments in the Ganga plains (Goodbred, 2003; Sinha et al., 2009). For example, in the Yamuna River basin, even though the Himalayan hinterland area is less than the cratonic hinterland area, the Himalayan-derived sediments are far more than the craton-derived sediments (Goodbred, 2003; Sinha et al., 2009). The role of cratonic hinterland further decreases in downstream compartments i.e., WGP and LGP, which are at a distance and weakly connected (Eq. (2)) with the craton (Goodbred, 2003).

Further, tectonic-related connectivity along the Himalayan Mountain Front (MF) is characterized by temporal variability at the million year timescale (Gupta, 1997; Singh and Tandon, 2008). Transverse growth of fold structures along MF has deflected several river channels forcing them to debouch onto the plains in different locations. Hence, the structural evolution of landforms has changed the nature of connectivity. This temporal variation in connectivity was also suggested as a major cause for generating new landforms, such as megafans (Gupta, 1997).

In the Ganga plains, the West Ganga plains (WGP) are longitudinally connected with the East Ganga Plains (EGP) through the trunk Ganga River, which is further connected with the Lower Ganga Plains (LGP). Connectivity between these compartments of the Ganga plains will depend on its storage characteristics and sediment residence time. These aspects are discussed in detail in a later section.

The LGP and the Bay of Bengal are a connected system. The LGP provides sediment to the Bengal delta with rapid sedimentation over the Holocene; sea level fluctuations on longer timescales affect sedimentation processes in the LGP. In this case, longitudinal connectivity will also be defined by downstream to upstream connectivity, as variations in sea level at different temporal scales will affect geomorphic processes in the LGP through headward propagation of incision following a base-level fall. The downstream to upstream connectivity in the LGP will depend on sediment supply from upstream, channel slope and sea floor slope, and rate of sea level fall (Schumm, 1993; Van Heijst and Postma, 2001). The high sediment supply, high channel slope in comparison to the sea floor slope, and the slow rate of sea level change decrease the downstream–upstream connectivity (Schumm, 1993; Van Heijst and Postma, 2001). Further, as the effect of sea level rise moves upstream (against the energy gradient), the rate of downstream effect will be very slow and its effect will be limited in the upstream reaches (Schumm, 1993; Blum and Tornqvist, 2000; Harvey, 2002a; Blum, 2008). In this case, the upstream compartments (WGP and EGP) cannot be considered to be directly connected with the Bay of Bengal.

Fig. 6. The compartments and connectivity in the Ganga dispersal system at different scales: (a) intercompartment connectivity and (b) intracompartment connectivity.

5.1.1. Sediment residence time. Connectivity between different compartments is governed in part by sediment residence time in the particular compartment, as it indicates relative material transfer in a given time interval (see Eq. (1)). Sediment residence time is defined as the average storage time in a given geomorphic unit. In a river system, sediment residence time depends on different landforms that can be defined as buffers, barriers, and blankets in the catchment (Fryirs et al., 2007a). Residence time is linked to a time lag in river response to external controls as eroded sediment (signature of tectonic, climate, or land use change) will be delayed in reaching its downstream reaches and will also increase reaction time of the whole basin in response to

Table 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Observation</th>
<th>Basis of analysis</th>
<th>Sediment</th>
<th>Time for downstream transfer of signal (high sediment pulse)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No sediment variation in the delta of major Asian rivers throughout Quaternary</td>
<td>Modeling of sediment load on the basis of diffusion process; significant buffering of signal from large floodplains</td>
<td>Total sediment</td>
<td>Himalaya to Bengal delta—1 million years (decoupled at submillion scale)</td>
<td>Metivier and Gaudemer (1999)</td>
</tr>
<tr>
<td>2</td>
<td>Doubling of sediment volume in the Ganga delta from 7–11 ka</td>
<td>Sediment budgeting on the basis of Quaternary stratigraphy</td>
<td>Total sediment</td>
<td>Himalaya to Bengal delta—1–2 ka (tight coupling between source and sink)</td>
<td>Goodbred and Koebl, 1999; Goodbred, 2003</td>
</tr>
<tr>
<td>3</td>
<td>Sediment load and radioactive measurement</td>
<td>230Th–234U–238U disequilibria analysis</td>
<td>Suspended and dissolved load</td>
<td>Ghaghra R (from MF to confluence with Ganga R) ×100 ka</td>
<td>Chabaux et al. (2003, 2006)</td>
</tr>
<tr>
<td>4</td>
<td>Sediment in the plains area to interpret sediment provenance</td>
<td>87Sr/86Sr and εNd values of sediments</td>
<td>Floodplain sediment (suspended load)</td>
<td>Tight coupling between Himalaya and Ganga plain</td>
<td>Rahman et al. (2009)</td>
</tr>
</tbody>
</table>
any external change (Brunsden and Thornes, 1979). Estimates of residence time using different methods have resulted in vast differences in time lag computations for the Ganga plains, thus highlighting the importance of studying and understanding connectivity and the interconnections between compartments. These different sets of data for residence time are summarized in Table 2. On the basis of a sediment diffusion model, a duration of $10^6$ years is suggested for sediment movement from the Himalayan hinterland to the Bay of Bengal (Metivier and Gaudemer, 1999). The value of residence time in the diffusion model was based on the elevation difference between upstream and downstream ends of the plain, channel length, floodplain width and sediment yield (Metivier and Gaudemer, 1999). Further, a recent study based on $^{238}\text{U}-^{234}\text{U}-^{230}\text{Th}$ disequilibria series computed the sediment residence time in transverse drainage systems from the mountain front to the confluence with the Ganga River as 150 ka for the mountain-fed Ghaghra River and 250 ka for the plains-fed Rapti River (Chabaux et al., 2006). This suggests that the average residence time in the EGP is in the range of 150–250 ka, with the implication that the Himalaya and the Bengal delta region cannot be considered as connected parts of the dispersal system within the time frame of 150 ka, i.e. Bengal delta will not record signatures of Late Quaternary climate change and Himalayan tectonic pulses.

Fig. 7. (a) Sketches showing the effect of geomorphological features on the intracompartment (dis)connectivity. (b) Field photograph showing disconnected hillslope–channel system due to presence of a terrace surface, which acts as a barrier. (c) Field photograph of a connected hillslope–channel system where all eroded sediments from the hillslope will contribute to the channel.
In a different set of sediment budgeting studies, a twofold increase in sediment delivery to the Bengal delta at ∼ 10 ka was directly related with erosional processes in the Himalaya (Goodbred and Kuehl, 1999, 2000). This study assumes insignificant residence time in the large-scale dispersal of sediment caused by millennial-scale climate change(s).

Such divergent data (Table 2) highlight the contrasting picture and raises the question of how strongly or weakly are the sediment data from the Bengal delta or Ganga plains regions connected directly to the Himalaya, as well as the timescale(s) of these connections? A better appreciation of connectivity is required to have an in-depth understanding of this cause–effect relationship.

Land use changes in the Himalaya have been implicated for sedimentation of downstream reaches and flooding from the alluvial channels on the Ganga Plains (Blaikie and Muldavin, 2004; Wasson et al., 2008). Also, tectonic processes and climate change have been advanced as major reasons for sediment erosion. It is therefore appropriate to question whether the increased sedimentation in the plains is the result of (i) land use change in recent times or (ii) time lag in response to monsoon intensification or tectonic pulses during Holocene or earlier times? Such questions need more data sets and better estimation of sediment residence time in these compartments to assess connectivity between upstream–downstream processes.

5.2.1. Intracompartement connectivity in the Ganga dispersal system

Each compartment of a large river system is characterized by an assemblage of various landforms. The landforms and landform-scale processes may be connected or disconnected (Fig. 6b). Hillslope–channel connectivity is an example of lateral connectivity in a geomorphic compartment. The sediment produced from hillslope erosion processes may be directly contributed to the channels or may remain stored in geomorphic units like pediments, terraces, or floodplain surfaces between hillslopes and channels (Fig. 7). The mapping and distribution of such geomorphic units is helpful in assessing the lateral connectivity. Disconnectivity causes storage of available sediment, which increases sediment residence time. The Himalayan–Ganga plain (near Mountain Front) connectivity will depend on hillslope–channel lateral connectivity and longitudinal connectivity between channel reaches. For example, during the early Holocene monsoon strengthening, the enhanced hillslope erosion in the Marsyandi catchment, Nepal Himalaya, filled the bedrock valleys in the Himalaya (Pratt et al., 2002). At that stage, hillslope–channel was laterally connected; however, all sediment could not move downstream, hence longitudinal connectivity was relatively weak. After slope stabilization from enhanced vegetation on hillslopes around 7 ± 1 ka, the valley sediments were transported downstream (Pratt et al., 2002). This temporal variation in hillslope–mountain channel–plains channel connectivity has caused a time lag of around 4–5 ka and was responsible for nonlinear variation in the sediment supply in downstream reaches in response to climate change.

Sediment flux in the channel is a function of the properties of longitudinal connectivity. Structural evolution of these areas is changing the longitudinal connectivity among landforms in the debouchment zone of the Ganga dispersal system. Over relatively long time scales, the Himalayan thrusts are propagating southward, resulting in active anticlinal and fault related uplifts. The intermontane Dehradun valley provides one such example, where the uplift of the Mohand ridge has affected the connectivity between the Mussoorie Range and the Ganga plains (Fig. 8). Before uplift of the Mohand ridge (έ 500,000 ka extrapolated from the Pabbi hills (Keller et al., 1977), the Mussoorie range was a source area for the Ganga plain sediment, and it was directly connected with it. However, after uplift of the Mohand ridge, the Ganga plains have been less directly connected with the Mussoorie range. The sediments from the Mussoorie range directly fill the intermontane valley north of the Mohand ridge. Further, activation of faults (namely the Santaurgarh thrust, and the Bhauwala thrust) (Raiverman et al., 1983; Singh et al., 2001) in the dun area has caused channel incision, which converted some of the depositional areas into hanging wall uplift-related sediment source areas. The incision has resulted in the availability of terrace sediments for transport to tributaries of the Yamuna and Ganga River systems. Part of the sediment from the Mussoorie Range is delivered to the axial river in the intermontane valley and is reworked into the Ganga plains. Similar examples have earlier been reported from elsewhere, for example Marchante Ridge, Spain (Harvey, 2002b) and Wheeler Ridge, California (Keller et al., 1998). It suggests that sediment supply from an upstream area in response to major events will mostly be a nonlinear function over relatively longer time scale of 104–105 years and will be governed by upstream–downstream connectivity.
5.3. Ganga plains connectivity: time–space considerations

The imprints of geological, climatic and anthropogenic controls are located in the evolutionary trajectory of a landscape. The sensitivity of different compartments to these external controls is mediated by connectivity in different dimensions. The assessment of compartment connectivity should be based upon field based understanding of compartment connectivity. Time–space relationships provide a way to analyse cross-scale relations and the relative roles of individual compartments in landscape evolution (Fig. 4).

The limited data from the Ganga plains have been analysed from different compartments in time–space domain to obtain a preliminary insight into the evolutionary nature of such a large river system. As noted earlier, the data on sediment flux (Galy et al., 1999; Metivier and Gaudemer, 1999; Goodbred, 2003; Chabaux et al., 2006) show that these are not coherent. If higher sediment residence time of 250 ka to 2 million years is considered after Metivier and Gaudemer (1999) and Chabaux et al. (2006), the B-type connectivity class for the Ganga River basin is indicated through trajectory 1. However, if the millennial-scale transfer of signals of processes between the Himalaya and delta sedimentation are considered as suggested by Galy et al. (1999) and Goodbred (2003), class C connectivity through trajectory 2 would be favored.

In order to obtain a detailed understanding of landscape evolution, and also to resolve the noncoherence in the existing data, more data using quantitative approaches on sediment flux at different scales are required. This will then allow a dependable assessment of connectivity at the scale of the entire Ganga River system.

6. Conclusions

The conceptual assessment of (dis)connectivity and its application to a large river dispersal system has resulted in the following conclusions:

1. Four types of connectivity—active connected, inactive connected, partially active connected and disconnected are suggested on the basis of both physical connectedness/contact and material transfer.

2. Multi-scale large river systems involve both space and time hierarchy, and connectivity is a tool that can help understand landscape trajectories using time–space diagrams. Time–space domains (past, present, and future projection) of connectivity should be analyzed for obtaining insights on the evolutionary trajectories of river systems.

3. (Dis)connectivity between landscape compartments is an important factor to analyse the catchment response to external controls, such as tectonic, climate change, or anthropogenic activity. Most of the studies are carried out through sediment load/sediment transport in the downstream reaches, without obtaining any understanding of connectivity between different landscape compartments in a river basin. The qualitative and quantitative understanding of connectivity becomes even more important in large river systems like the Ganga because of complexity and diversity in processes and patterns in compartments in a multi-scale context.

4. The source to sink approach of the Ganga dispersal system needs connectivity understanding between all compartments. The neighbouring compartments in the Ganga plains are connected. However, the connectivity understanding between all compartments of the Ganga plains requires more data of residence time at different scales, as limited available data show conflicting values of residence time.

References


