Sediment Connectivity: A Framework for Understanding Sediment Transfer at Multiple Scales

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ABSTRACT

A major challenge for geomorphologists is to scale up small-magnitude processes to produce landscape form, yet existing approaches have been found to be severely limited. New ways to scale erosion and transfer of sediment are thus needed. This paper evaluates the concept of sediment connectivity as a framework for understanding processes involved in sediment transfer across multiple scales. We propose that the concept of sediment connectivity can be used to explain the connected transfer of sediment from a source to a sink in a catchment, and movement of sediment between different zones within a catchment: over hillslopes, between hillslopes and channels, and within channels. Using fluvial systems as an example we explore four scenarios of sediment- connectivity which represent end-members of behaviour from fully linked to fully unlinked hydrological and sediment connectivity. Sediment-travel distance – when combined with an entrainment parameter reflecting the frequency-magnitude response of the system – maps onto these end-members, providing a coherent conceptual model for the upscaling of erosion predictions. This conceptual model could be readily expanded to other process domains to provide a more comprehensive underpinning of landscape-evolution models. Thus, further research on the controls and dynamics of travel distances under different modes of transport is fundamental.

KEY WORDS

Sediment connectivity; sediment-travel distance; hydrological connectivity; landscape form; frequency-magnitude.

INTRODUCTION

Sediment connectivity is the connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, controlled by how the sediment moves between all geomorphic zones in a landscape. In catchment systems, which are the primary focus of this paper, these movements are on hillslopes, between hillslopes and channels and within channels. Erosion, sediment transport and deposition occur at the grain scale, to produce landscape features at scales several orders of magnitude larger (Cooper *et al*., 2012). A major challenge in geomorphology is reconciling the disparity between erosion rates measured at small spatial scales with rates of denudation at larger spatial scales. Scaling up erosion rates to estimate landscape change is difficult because: there are problems with using linear extrapolation of erosion rates; understanding the continuum of sediment sources, processes of transfer and possibilities for deposition within catchments; and the uncertainty in the impact of changing climate and land use on sediment-transfer processes. Despite excellent progress developed from a systems-based understanding of catchment process it is timely to explore moving to use a complex-systems approach to conceptualize the continuum of sediment transfer. An approach is required that resolves both the flaws of the sediment delivery approach that monitors one point in a catchment (usually the outlet), and scale dependence of erosional processes. Any new approach must also be able to explain how small-scale measurements of erosion result in broad-scale geomorphic patterns and processes.

With a focus on hydrological and catchment systems we build on recent advances in understanding hydrological connectivity to refine and highlight novel was of thinking about sediment transfer at the catchment scale. Secondly, we make explicit links between the concepts that underpin hydrological connectivity with implications that arise from the development of transport-distance approaches to understanding sediment movement. Thirdly, we provide an integrated approach to guide future research into sediment connectivity. Integrating the concept of sediment-transport distances within a sediment connectivity framework provides a means of addressing the non-linearity of erosional processes within spatially and temporally variable environments, in order to understand the net interplay of system characteristics and erosional processes on observed sediment yield across multiple spatial and temporal scales. The sediment-connectivity framework presented provides a means by which to investigate the interplay of erosional processes (detachment, transport and deposition) that are spatially and temporally variable, and are characterized by different frequency-magnitude distributions, and how these affect system processes and landscape development at broader spatial and temporal scales. The approach presented reconciles the observed disparity between erosion rates measured at small spatial scales with rates of denudation at larger spatial scales and will enable us to understand better the sensitivity of a catchment to external forces such as climate change, tectonics and anthropic disturbances.

EXISTING CONCEPTS OF SEDIMENT CONNECTIVITY IN CATCHMENT SYSTEMS: A CRITIQUE

Background

Sediment connectivity arises through the transfer of material between two zones and occurs via transport vectors (e.g. water, wind, glaciers, gravity, animals) that move these materials over a range of spatial and temporal scales (Peters *et al*., 2008). Each zone contains two parts: the morphologic system (the landforms) and the cascading system (the energy and materials flowing through that zone) (Chorley, 1971; Schumm, 1981). A major limitation of previous discussions of ‘connectivity’ is an unclear definition of the meaning of the term within the context in which it is used (Bracken *et al.,* 2013). In a geomorphic system, connectivity may occur through the physical contact between two zones, through the transfer of material between zones, or both (Jain and Tandon, 2010). Thus, we perceive coupling (based on the morphologic system at certain locations) and sediment connectivity (founded on the continuum of the cascading system) to be different and encourage researchers to use the terms more precisely.

The concept of *sediment connectivity* can be used to explain the continuity of sediment transfer from a source to a sink in a catchment, and movement of sediment between different zones within a catchment: over hillslopes, between hillslopes and channels, and within channels. Sediment connectivity is based on the interplay of structural components (morphology) and process components (flow of energy/transport vectors and materials) that determine the long-term behaviour of the sediment flux which is manifest as a change in landform (Preston and Schmidt, 2003; Turnbull *et al*., 2008; Bracken *et al*., 2013). Thus, sediment connectivity is dependent not on individual processes, but on all aspects of the geomorphic system that control sediment flux – processes of detachment, entrainment and transport – but also the emergent characteristics of sediment deposition and sediment residence times (Preston and Schmidt, 2003; Sandercock and Hooke, 2011). Once there is a source of readily entrainable sediment, transport depends on the spatial configuration of connections between sediment source areas, the energy of key sediment-transport vectors and the relationship to morphology. Therefore, the spatial and temporal distributions of energy-transfer pathways and resulting continuity of transport vectors in combination with sediment availability are critical in determining sediment connectivity. A further, yet critical, point to make is that sediment detachment and transport processes are size selective. For example, previous research has uncovered an inverse relationship between particle size and sediment-transport distances (Wainwright and Thornes, 1991; Parsons et al., 1993; Hassan *et al.,* 1992; Ferguson *et al*., 1996; Oostwoud Wijdenes and Ergenzinger, 1998). The significant implication of this previous research is that sediment travels in more disconnected ways than the flows that transport them.

The relationship between sediment connectivity and sediment stores

Early work within a systems-based framework placed an emphasis on the distribution of sediment stores and sinks, which both reflect and influence the routes, travel distances and pathways of sediment transport within catchments (Brunsden and Thornes, 1979; Meade, 1982; Phillips, 1992; Harvey, 2002). Furthermore, it addressed the patterns of stores and sinks as advanced in Schumm's (1977;1981) model of the fluvial system, based on idealized zones of sediment production, transfer and deposition. In Schumm's model the general picture was that hillslopes form a supply of sediment, which is fed to the stream network, where it is picked up and transported downstream until it is deposited within the basin (Schumm, 1981). Yet the morphological system consists of both the geometry of the landscape (topography, internal structure) and the properties of the sediment (density, size distribution, armouring). In this way a distinction can be made between sediment sources (e.g. hillslopes or in-channel sediment stores) and transport pathways. In principle, any slope, and any place where water flows, is potentially a transport pathway (and the same holds for any location controlled by other transport vectors such as wind or glaciers). There has been a long understanding that sediment transfer is influenced by the nature, extent and location of sediment stores, but also the topography, climate, channel pattern, vegetation, land use and soil properties (e.g. Roehl, 1962). What is missing from this early research is an understanding of which stores of sediment and which routes of transport operate under different environmental conditions. These factors have only been implicitly included in past research.

Schumm's (1977;1981) landscape model divided catchments into production, transfer and deposition zones. Schumm acknowledged that this was a simplistic representation of the landscape and noted that sediments are eroded, transported and stored in each of the zones, but proposed that a single process is usually dominant in each. The landforms and energy and material moving through that zone are interrelated over space, and through time, by the spatial structure and frequency-magnitude spectra of dominant processes. One of the fundamental aspects of Schumm's model is that it implies that landscape development occurs in neatly compartmentalized zones. However, subsequent studies of sediment-travel distance suggest that *all* parts of the landscape are potentially involved in sediment production, transfer and storage (Wainwright *et al*., 2001; Parsons *et al.,* 2006), and thus there is more of a continuum of these zones than a set of discrete entities.

Boundaries between landscape zones are critical in influencing sediment transfer (Armstrong, 1987; Brierley *et al.* 2006; Harvey 2012). Storage of sediment is often focussed at boundaries between zones within catchments, such as between hillslopes and rivers, river junctions and at larger scales between mountain belts and more lowland areas (e.g. Croke *et al*., 2013), reflecting the disconnected behaviour of sediment transfers and affecting subsequent paths of movements. Disconnections over longer timescales emphasise the effect of persistent blockages, effectively preserving sediment in areas of storage (Harvey, 2012). Understanding the rôle of sediment stores in a systems-based framework led to the notion of coupling between hillslopes and channels.

Harvey (2012) used the terms coupling and connectivity interchangeably, viewing coupling within fluvial systems as the fundamental property that affects the down-system transmission of sediment. Hooke (2003:79) referred to sediment connectivity as "the physical linkage of sediment through the channel system, which is the transfer of sediment from one zone or location to another and the potential for a specific particle to move through the system". Because these definitions are based on the mechanisms by which sediment is detached and transported, they are limited to the process of coupling between landscape units (*sensu* Harvey, 2012), and sediment transport within channels (*sensu* Hooke, 2003) and thus are limited in their broader applicability. Faulkner (2008) bases her definition on links between specific sources and sink areas and thus focuses on understanding the connected transfer of sediment within a narrow range of environmental conditions and geomorphic systems noting process-domain interactions at the relatively small scale. These approaches are typically focussed on understanding behaviour at specific points in the landscape, rather than on providing an overall framework for linking behaviour at multiple scales in the landscape. Hence the systems-based analysis of landscapes and coupling is based on analyzing the character and behaviour of landscape compartments, how they fit together (their assemblage and pattern) and the movement of sediment between them, which provides a platform to interpret the operation of geomorphic processes in any given system (e.g. Lane and Richards 1997; Harvey 2002; Michaelides and Wainwright 2002; Hooke 2003). This point is illustrated by Brierley *et al*. (2006) who proposed that understanding the connectivity between landscape compartments was pivotal to explaining spatial relationships, and hence the behaviour of biophysical fluxes and associated trajectories of adjustment (Figure 1).

We suggest that geomorphology needs to move beyond putting ‘old wine in new bottles’ and think about sediment transfer in a new and more useful way. To improve our understanding of the scaling of sediment transfers, sediment connectivity needs to be developed as a concept that is broadly applicable across different types of terrestrial systems and environmental regimes in order to understand better how small-scale erosional processes connect to large-scale observations of landform development and catchment-scale sediment export. It is critical that an alternative approach does not attempt to normalize erosion rates by area. Rather, area must be considered as a critical variable and be represented explicitly, or alternatively, the approach must be insensitive to area because the controls that would make area a variable are already included. We propose that sediment connectivity is defined as the integrated transfer of sediment across all possible sources to all potential sinks in a system over the continuum of detachment, transport and deposition, which is controlled by how the sediment moves between all geomorphic zones: on hillslopes, between hillslopes and channels and within channels. This definition of sediment connectivity is in agreement with Faulkner (2008), that sediment connectivity refers to the integrated status of a system within the catchment. Sediment connectivity can thus be considered within a nested hierarchy (Harvey, 2002), from local (within landforms), through zonal (sediment transfer between landforms such as hillslope-channel connexions), to the behaviour of the whole catchment with linkages along the sediment cascade. Temporal variability in the scale of connection at the catchment scale is related to the effectiveness of connectivity-enhancing (or reducing) features at smaller scales, their spatial configuration and frequency magnitude of processes that lead to their formation and the relative timing of their formation (Breirley *et al*., 2006; Fryirs *et al*., 2007).

Existing conceptual frameworks of sediment connectivity

There has been a shift from thinking about sediment transfer between different stores to a continuum-based approach trying to understand pathways, routes and scales of movement of sediment that has been directly influenced by the progressive development of the concept of hydrological connectivity. Hydrological connectivity has been a dynamic area of research in the last decade and has resulted in a novel framework for understanding runoff and runon (Bracken and Croke, 2007; Ali and Roy, 2009). The developments in hydrological connectivity were driven partly by calls for new ways of thinking about runoff and hydrological process conceptualization in heterogeneous landscapes (McDonnell, 2003; Ambroise, 2004; McDonnell *et al.*, 2007). Hydrological connexions via overland and subsurface flows have become conceptualized as a function of water volume (supplied by rainfall and runon, depleted by infiltration, evaporation, transpiration and transmission losses) and rate of transfer (a function of pathway, hillslope length and flow resistance) (Bracken *et al*., 2013). These processes interact with flow resistance, varying as a function of flow depth, which establishes a feedback between rainfall, infiltration and flow routing which produces the nonlinearity seen in river hydrographs and scale-dependence of runoff coefficients (Wainwright and Bracken, 2011).

An early proponent of the sediment-connectivity approach was Lexartza-Artza and Wainwright (2009; 2011). Their approach underlined that understanding the conditions for runoff generation and transmission in relation, for instance, to rainfall events, and the differences on these conditions according to temporal or spatial constrains, produces key information regarding the connectivity, and therefore, transfer of matter in the catchment, as will a careful study of pathways (Figure 1). A practical demonstration of this approach can be found in Wainwright *et al*. (2011).

Fryirs *et al*. (2007) produced a conceptual model that could be used to assess the disconnectivity of catchment sediment cascades. Catchment disconnectivity is defined as the degree to which any limiting factor constrains the efficiency of sediment-transfer relationships (Fryirs *et al*., 2007). By examining the spatial and temporal disconnectivity of linkages, multiple component cascading systems can be modelled and the internal dynamics of sediment flux of a catchment be represented (Houben *et al*., 2009; Lexartza-Artza and Wainwright, 2011). Fryirs (2013) argued that analysis of the type and strength of spatial linkages allows the sediment flux to be quantified and modelled by assessing whether it is connected or disconnected over various timeframes. Where sediment flux becomes disconnected, a sediment sink is formed which acts to remove sediment from the cascade/conveyor belt for various lengths of time. A model of (dis)connectivity could be developed analogous to the operation of a series of switches that turn on or turn off (connect and disconnect) sediment sources in a catchment under different magnitude–frequency conditions (Fryirs, 2013).

Houben (2008) focused on one aspect of buffers as used by Fryirs *et al*., (2007) and researched hillslope processes as the primary filter for resulting floodplain response in regard to land-use and climate change. Thus Houben's framework of sediment connectivity centred on the role of the hillslope in controlling the net delivery of sediment to streams and valley floors through the production of hillslope sediment, hillslope sedimentation, and on-hillslope connectivity. By applying the sediment-budget approach at the field scale, Houben (2008) deduced that the degree of on-hillslope connectivity is the key control of the long-term net delivery of slope-derived sediments to valley floors rather than simply the extent of arable ground, erosivity or rates of sediment production when accounting for fragmented hillslopes in gently sloping landscapes. The sediment-budget approach was used as a way to sample the sediment transfer continuum, but does not consider the integrated transfer of sediment within a catchment. Houben's approach is constrained by being routed in the systems framework and conceptualizing sediment transfer as individual movements between certain stores and hence does not consider the continuum of sources and stores and how sediment is transferred between them.

More recently, Cavalli *et al*. (2013) implemented Fryirs' framework using an index of hydrological connectivity (developed by Borselli et al., 2008) to assess spatial sediment connectivity in two small catchments in the Italian Alps. Heckmann and Schwanghart (2013) present a second application of the framework. They applied mathematical graph theory to explore the network structure of coarse sediment pathways in a central alpine catchment. Analysis of the spatial distribution, composition and frequency of sediment cascades was shown to yield information on the relative importance of geomorphic processes and their interaction. However, recognition of processes is arbitrary and subjective and depends on circumstance, such as: location, observer's goal, perception, conceptualisation and methods used (Schumm, 1991). These approaches tend to measure catchment characteristics and attributes which are then extrapolated, interpolated and accumulated to infer process. It is this inferring of processes which remains a major limitation.

Summary

Geomorphologists have fully embraced the systems-based understanding of catchment processes and developed an excellent understanding of sediment sources, transfer processes and sediment sinks in catchments. Research has been fruitful at determining relationships between sediment characteristics and sediment transport distances. Yet we continue to infer processes and do not consider the continuum of sources and stores and how sediment is transferred between them. If we remain bounded by established practices and existing ways of approaching sediment transfer we may not be able to exploit the full potential of the concept of sediment connectivity. Hence a novel framework is required that can integrate: i) the frequency-magnitude distributions of sediment detachment, transport and deposition processes with ii) spatial and temporal feedbacks between sediment detachment and transport processes; and iii) mechanisms of sediment detachment and transport.

A NEW SEDIMENT-CONNECTIVITY FRAMEWORK FOR UNDERSTANDING SEDIMENT TRANSFER ACROSS MULTIPLE SCALES

Here, we present a new sediment-connectivity framework to show the relationships among sediment detachment and transport, and key emergent behaviour of the geomorphic system: frequency-magnitude distributions of sediment detachment and transport processes and the temporal and spatial sequencing of sediment detachment and transport processes (i.e. explicit consideration of spatiotemporal heterogeneity of process and form in geomorphic systems) (Figure 2). Three key elements of this framework are:

1. Frequency-magnitude distributions of sediment detachment, transport and deposition processes.
2. Spatial and temporal feedbacks between sediment detachment and transport processes.
3. Mechanisms of sediment detachment and transport.

Of particular importance in this sediment-connectivity framework is the characteristics of the relationships between these three key elements. This framework emphasizes the co-dependency (relationships and feedbacks) of each of the three elements. For example, the frequency-magnitude distributions of sediment-detachment processes and transport processes will be partially controlled by the extent to which they are driven. Although systems may be hydrologically dominated, other processes are also involved in sediment transfer, such as mass movement, glacial or aeolian processes. Such processes have characteristically different recurrence intervals. The extent to which the effects of sediment detachment and transport will propagate through a system yielding sediment connectivity at broader spatial scales will depend largely on the temporal and spatial sequencing of sediment-detachment and transport processes. The effect of spatial scale in this sediment-connectivity framework is inherent through its effect on mechanisms of sediment detachment and transport, controls on frequency-magnitude distributions and in particular, through spatial and temporal sequencing of detachment and transport processes which becomes increasingly heterogeneous with increases in spatial scale.

Frequency-magnitude distributions of sediment detachment and transport processes

Wolman and Miller (1960) introduced the frequency-magnitude concept of geomorphic events. They proposed that the magnitude of force applied by a geomorphic process can be measured in terms of the relative amount of work done on a landscape, and that it is not only the magnitude of the force applied by the geomorphic process that is important, but also the frequency with which that force is applied. Thus, the frequency-magnitude distributions of geomorphic events will change with spatial scale, which therefore represents a means of estimating the temporal scale over which sediment connectivity should be gauged at a specific spatial scale. However, the frequency-magnitude distribution of a specific process at a certain spatial scale is not independent of other processes. For example, mechanisms of sediment transport, such as high-magnitude débris flows that entrain sediment stored within the channel network and thus continue to grow in size, will have a given return interval that is dependent in part on the return intervals of detachment processes that provide a supply of sediment available for transport (Carson and Kirkby, 1972; Bovis and Jakob, 1999). The redistribution, accumulation and storage of sediment at short timescales, and often over relatively short transport distances, facilitates sediment connectivity at much broader spatial and temporal scales. Therefore, sediment connectivity at broader spatial scales may be a function of sediment accumulation during higher frequency and lower magnitude events. When the dominant processes of sediment entrainment and transport operating at a given frequency-magnitude distribution is a consequence of a supply of sediment available for transport from processes with a different frequency-magnitude distribution, sediment connectivity at a given temporal scale will depend upon the time elapsed since previous events (see Figure 3; Wolman and Miller, 1960). Thus, the sequencing of events operating over different frequency-magnitude spectra can be important (Beven, 1982; Richards, 1999). Furthermore, position within a catchment is important as sediment-transport events on slopes and in rivers have markedly different frequency and magnitude distributions (Ergenzinger, 1992). Sediment connectivity at larger spatial and temporal scales results from the spatial interaction of sediment pathways and the corresponding process domains (Becht *et al*., 2005; Wichmann *et al*., 2009), each of which has its own frequency-magnitude spectrum, but are not always independent of each other. Thus, the critical challenge is to identify the intersecting process regimes, that are all interrelated, but all work to their own frequency and magnitude distributions (see Crozier, 1999), in order to determine the spatial and temporal scales over which sediment connectivity should be gauged.

Sediment connectivity requires a unifying conceptual framework that deals explicitly with the confounding effects of spatial and temporal variability in system structure and process, over wide-ranging environmental régimes. A major challenge to the concept of sediment connectivity is gauging the temporal scale over which sediment connectivity should be assessed, i.e. what constitutes a relevant event? If, for example, the temporal scale of analysis is considerably greater than the frequency of key processes (i.e. a timescale that is sufficiently long to encompass sediment cascades in which all components of a catchment will be connected) then sediment connectivity will be perceived to be exceptionally high. Alternatively, if the temporal scale over which sediment connectivity is evaluated is less than the frequency at which key sediment-transport related processes within the study domain operate, then sediment connectivity will be perceived to be lower. Defining the temporal scale of an ‘event’ is clearly dependent on the process in question. One straightforward definition is that “events should be characterized by a process intensity higher than the mean, and preceded and followed by a steady phase” (Starkel, 1999: 22). Although such a definition might not always work, for instance for a period of drought that then has a flow event that is smaller than some long-term mean, but is still important for sediment transfer. Hence using the term ‘running mean’ in Starkel’s definition may be more precise.

Changes in sediment connectivity take place over different timescales depending on the nature of exchange and timescales of sediment storage (Brierley *et al*., 2006). Vegetation has the potential to decrease channel erosion and sediment transport by increasing channel roughness and bed resistance (Graf, 1979, 1983; Sandercock and Hooke, 2011). In-stream disconnectivity of sediment transfer has been likened to a “jerky conveyor belt” (Ferguson, 1981: 91). In the intervening periods between infrequent and high-magnitude events, higher frequency and smaller magnitude events will continue to liberate sediments from hillslopes or channel banks, but, the rate at which sediment will be generated will be in part biotically controlled, since the stabilising effect of vegetation will continue to reduce the magnitude of sediment generation, until a particularly high structural threshold is breached (Figure 4).

An alternative approach to address issues relating to spatial and temporal scales is to define the appropriate timescale according to the frequency-magnitude distribution of dominant processes operating at a given spatial scale, which, because of the aforementioned cross-scale dependencies in geomorphic processes will account implicitly for other relevant processes operating at higher frequencies.

For extremes of the frequency-magnitude spectrum, infrequent, high magnitude events affect sediment connectivity in three ways (Figure 5):

1. Energy input to the system causes sediment detachment and sediment transport, with the system becoming fully connected during the episodic event (Jain and Tandon, 2010), following which sediment connectivity returns to baseline levels.
2. Energy input to the system causes sediment detachment, but inadequate energy for sediment transport causes a long-term reduction in sediment connectivity as detached sediment impedes transport pathways.
3. The event removes landscape features such as floodplains, thereby allowing a much stronger subsequent connectivity between hilllslopes and channels.

Spatial and temporal feedbacks between sediment-detachment and transport processes

A fundamental limitation of the frequency-magnitude concept in geomorphology is that it focusses on processes as causes of forms, thus neglecting the role of landforms as controls of processes (Richards, 1999). However, the importance of two-way feedbacks between morphology and processes are well recognized in geomorphology (Richards, 1999; Turnbull *et al*., 2008, 2012; Mueller *et al*., 2013). These feedbacks – which affect erosional processes, the energy of transport vectors, sediment transport and morphology – have implications for sediment connectivity and thus catchment sediment yields. These feedbacks may be both positive and negative.

Débris flows are one example of sediment connectivity where positive feedbacks over a relatively short (event) timescale occur. Large-scale experiments have shown that entrainment of material is accompanied by increased flow momentum and speed if large positive pore pressures develop in wet bed sediments, since this facilitates progressive scour of the bed and reduces basal friction, thus initiating a positive feedback that results in an increase in the speed, mass and momentum of the debris flow (Iverson *et al*., 2010). Thus, under these conditions, sediment connectivity has a two-phase positive feedback: 1. a positive feedback associated with slope failure, and 2. a positive feedback associated with débris-flow propagation (Figure 6).

Negative feedbacks between sediment detachment and sediment transport may also occur, potentially impeding sediment connectivity over both short and long timescales. Here, we draw upon two examples; landslide dams and alluvial fans. In the mountainous regions, rockslide-dammed lakes may persist for over 10,000 years before infill or dam failure (Korup, 2002; Korup *et al*., 2006), at which point the potential for hydrological and sediment connectivity will resume. Similarly, the Ama Dablam Rock Avalanche created a landslide dam in Nepal Himalaya in 1979, which, when breached initiated a debris flow that aggraded the valley floor by 3 m (Korup, 2003). Other examples include that of a lake created by the Costantino landslide in the middle reaches of the Buonamico basin in Italy, in 1973 (Ergenzinger, 1992) and the Bairaman landslide dam in Papua New Guinea (King *et al*., 1989). Thus, mass movements of sediment can break hydrological and sediment connectivity, for both long and short (several decades to millennia) durations, followed by a sudden spike in connectivity when a catastrophic threshold is reached. In some instances dams caused by landslides can relocate river channels through diversion or seepage, potentially forming high-energy breach channels (Korup et al, 2006), thus altering dramatically the characteristics of flow pathways which will in turn affect hydrologically driven sediment connectivity. In the case of débris flows, small débris flows occur commonly when the hillsopes that are close to the angle of response (thus, a structural threshold) become saturated with water and fail (Iverson, 1997). Larger debris flows may result from multiple small slope failures that subsequently coalesce (Iverson, 1997). In the case of alluvial fans, aggrading alluvial fans may act as a buffer within the system, by trapping and storing coarse sediment, thus disconnecting the lowland drainage from major sources of sediment supply upslope of the alluvial fan (Harvey, 1996) and reducing sediment connectivity within the upland-lowland system. Increases in sediment storage and aggradation will continue to increase the capacity of the alluvial fan to reduce sediment connectivity in a negative feedback. If, on the other hand, alluvial fans become entrenched (for example due to base level change or climate), sediment connectivity may be re-established throughout the system, thus disrupting the negative feedback. Hence hydrological connectivity and sediment connectivity are different. What is important is how we deal with this difference: an approach is needed that harmonizes sediment and hydrological connectivity.

Mechanisms of sediment detachment and transport: implications for sediment flux

Sediment flux is defined as the solid volume of sediment particles crossing a surface per unit time, per unit width. From a transport-distance perspective, sediment flux at a point is the integral of the detached material from upslope that moves at least the distance between the point of detachment and the point of measurement (Einstein, 1950; Wainwright *et al*., 2001; Parsons *et al*., 2004; Furbish *et al*., 2012). Sediment-detachment and sediment-transport mechanisms can be ordered along a spectrum depending on the degree of hydrological control. As sediment detachment changes from not being hydrologically to being hydrologically controlled, sediment detachment by water-driven processes increases, and similarly, as transport varies from being not hydrologically to hydrologically controlled, the travel distance will increase. For example, detachment by raindrop impact is a relatively inefficient process. Long *et al*. (2014) have estimated that only 2-4 % of raindrop-impact momentum is transferred to movement as splash. As shallow, surface flows start to occur, the effects of rainfall and flow energy initially combine (Parsons *et al*., 1993), but then as the flow depth increases the energy reaching the bed from raindrop impact exponentially decreases (Torri *et al*., 1987) so by then, flow detachment dominates (Parsons *et al*,. 2004). Because flow transport in turbulent flows is a far more efficient detachment and transport mechanism than detachment and transport by splash or by interrill flows (which fall typically in the laminar or transitional régimes), both detachment and transport distance (and thus flux) increase by one or more orders of magnitude once such flows are established (Hassan *et al.,* 1992; Parsons *et al*, 2004;2008; Wainwright *et al*., 2001, 2008a). The end-members of the degree of hydrological control on sediment detachment and transport processes thus control a phase space in terms of detachment (D) and transport distance (λ) which define the overall sediment flux (q_s) as a series of isolines (Figure **7**).

The four end-members of this phase space correspond to the following detachment and transport conditions:

i. Sediment detachment and sediment transport are hydrologically controlled;
ii. Sediment detachment is hydrologically controlled; sediment transport is not hydrologically controlled;
iii. Sediment detachment is not hydrologically controlled; sediment transport is hydrologically controlled;
iv. Neither sediment detachment nor sediment transport is hydrologically controlled.

Further detail and examples of these four end-members of the sediment detachment-transport phase space are as follows:

i. Sediment detachment and sediment transport are hydrologically controlled

Sediment detachment often occurs as a result of hydrological processes, for example detachment by rainsplash, or by hydrologically connected flow (Bryan 2000). Once there is a source of readily entrainable sediment, sediment connectivity depends on the spatial nature of connections between sediment source areas and the ability of runoff to transport the sediment. Once sediment is entrained it is transported by flow (overland or in-stream), with sediment-transport distances inversely related to particle size (Parsons *et al.*, 1993; Wainwright and Thornes, 1991; Hassan *et al*. 1992; Hubbell and Sayre, 1964). Following the detachment of sediment, hydrologically connected flow provides a transport vector to connect areas of entrainable sediment (e.g. Hooke 2003; 2007). Thus, in this region of the phase space, hydrological connectivity provides a strong basis upon which to understand sediment-transport connectivity, in particular the transport of fine sediment which has longer sediment-transport distances (Parsons *et al*., 1998;2004;2008). This linkage is true at multiple scales and points in a catchment. For example Govers (1992) proposed that the sediment transport in rill flow could be predicted in terms of slope, discharge and material characteristics alone, without any further knowledge of rill geometry. For interrill areas, Malam Issa *et al*. (2006) found that at the field scale the soil particles detached by splash were notably coarser than those transported by wash, suggesting a transport-limited erosion process at the field scale. Experimental data have also shown that the soil-detachment rate decreases as the runoff depth increases, indicating that the detachment power of the raindrops is partially dispersed by the water layer (Torri *et al*., 1987). Therefore in situations where the process of sediment detachment and sediment transport is driven by hydrological connectivity, sediment connectivity (including sources, pathway, sink and connections) is likely to be able to be identifiable from observations of runoff source areas and hydrologically connected flows. Modelling studies have demonstrated that the majority of sediment inputs occur from hydrologically connected areas close to the channel network during moderate sized rainstorms that occur relatively frequently (Reid *et al*., 2007). Thus, the spatial and temporal patterns of sediment connectivity change as a function of landscape and rainfall-runoff event characteristics (Medeiros *et al*., 2012).

ii: Sediment detachment is hydrologically controlled; sediment transport is not hydrologically controlled

Under certain conditions sediment detachment may be hydrologically controlled, while sediment transport may be driven by other processes, such as mass movement or aeolian processes. For example, surface runoff or snowmelt may increase pore-water pressure/slope weight to initiate Coulomb slope failure. Intensive monitoring at a site in Oregon has revealed that hydrologically connected subsurface stormflow through a shallow bedrock zone can increase pore pressure, triggering landslides, in some instances, even in non-convergent topography (Montgomery *et al*., 2009). In this example, hydrological processes, via vertical and horizontal hydrological connectivity, are an important driver of sediment detachment (Duvert *et al*., 2011). The sediment detached during slope failure may then trigger débris flows (Iverson, 1997) which, in mountainous catchments, strongly control sediment-transfer patterns. Alternatively, detached sediment may be (selectively) transported by wind which is similarly not driven by hydrological connectivity. Thus, in this region of the phase space, hydrological processes can only help us to understand sediment detachment processes, not sediment transport, and thus, knowledge of both hydrological controls on sediment detachment and knowledge of non-hydrological controls on sediment transport is required to understand sediment connectivity.

iii: Sediment detachment is not hydrologically controlled; sediment transport is hydrologically controlled

In rapidly incising environments, mass movements are major agents of sediment transport. While mass movements may be driven by hydrologically connected flow (outlined previously) mass movements are not exclusively driven by hydrologically connected flow. Mass movements may be initiated as bedrock landslides (e.g. Berger *et al*., 2011) or by tectonic activity (Dramis and Sorriso-Valvo, 1994). Material deposited in channels may subsequently be transported by fluvial processes. Different linkages control sediment transfer in a catchment: lateral linkages which drive the supply of sediment to the river channel (slope-channel, channel-floodplain); longitudinal linkages which drive the transfer of sediment through a system which denotes the ability of a river to transfer or accumulate sediment; and vertical linkages that link surface-subsurface interactions of water, sediment and nutrients (Brierley *et al.* 2006). Linkages can be connected or disconnected over different timescales (Harvey, 2002; Fryirs *et al*., 2007). Thus, in this third region of the phase space, the concept of hydrological connectivity does not help us to understand the source of sediment available to transport, but it can help determine the sources, pathway, sink and connections for sediment connectivity.

iv: Neither sediment detachment nor sediment transport is hydrologically controlled

There are some terrestrial systems (particularly those with low precipitation) when hydrology has little or no influence on sediment detachment and transport processes, and thus, has minimal influence on sediment connectivity. An example of this situation is when an anthropic disturbance of the soil surface may create a source of readily entrainable sediment, or sediment detachment caused by landslides resulting from an increase in shear stress created by loading, earthquakes or undercutting of slopes. This detached material may then form a débris flow or may be transported by wind. Sediment entrainment and transfer may occur simultaneously by landscape instability in mountainous regions. Other examples of processes that fall within this scenario are sediment transport occurring on resistance substrates such as limestone (Lesschen *et al*., 2009), on biological soil crusts (Belnap, 2006) and on other stable surfaces (stone pavement: Wainwright *et al*., 1995). Thus, in this region of the phase space, the important non-hydrological mechanisms of sediment detachment and transport need to be identified and process rates need to be quantified in order to understand sediment connectivity.

By identifying where on the sediment detachment-transport phase space a terrestrial system resides (which is likely to be spatially and temporally heterogeneous), important information can be harnessed on mechanisms that regulate sediment connectivity. This information can guide investigators on whether or not information on other processes can be used as a proxy for sediment connectivity (for example, when information on hydrological connectivity can be readily used to characterize sediment connectivity, or when information landslides that result in debris flows alone can be used to characterize sediment connectivity). This framework highlights that without intimate understanding of the terrestrial system in question, and the dominance of different detachment and transport mechanisms and their magnitudes and sequencing through space and time, it is challenging to ascertain on what basis sediment connectivity should be addressed.

Clearly, there are conditions (both sediment detachment and transport are hydrologically controlled) when hydrological connectivity can be used as a proxy for sediment connectivity, but there remains the questionable assumption that flow of a certain discharge has a specific capacity to transport sediment (Wainwright *et al*., 2008a). Notably, increasing sediment concentrations will alter the nature of flow, producing hyperconcentrated flow and ultimately débris flows (Iverson, 1997; Wainwright *et al*., 2008a; see also Beverage and Culbertson, 1964). Therefore, variations in hydrological connectivity within a catchment will give rise to different sediment sources, sediment transport characteristics and size selectivity of transport processes, thereby confounding the utility of hydrological connectivity as a conceptual basis for sediment connectivity. A further confounding factor is that sediment detachment driven by hydrological connectivity is very different conceptually from sediment detachment driven by other mechanisms, such as earthquake-induced landslides. Sediment detachment arising from hydrological connectivity will have a higher frequency and lower magnitude than mass movement events which have a lower frequency but higher magnitude. For a generally applicable conceptual framework of sediment connectivity, the inclusion of geomorphic processes such as rockfalls, landslides and debris flows that deviate from existing conceptualizations of sediment connectivity that are based on non-mountainous catchments is essential, especially if approaches used to gauge sediment connectivity are to be broadly applicable to varied environmental regimes, and those encompassing upland geomorphic systems (Heckman and Schwanhard, 2013). The varying spatial and temporal scales over which the drivers of geomorphic processes operate (i.e. climatic or tectonic), and their resulting effects, have a correspondingly wide range of frequency-magnitude spectra (Preston and Schmidt, 2003). For example, processes that generate and transfer sediment in uplands and on hillslopes operate with markedly different frequency/magnitudes than in-channel processes (Brierley *et al*., 2006).

As the hydrological control of processes increases, the net flux also increases, recognizing the different aspects of hydrological control of the sediment-transfer processes. From a Langrangian perspective, individual sediment particles may sit in a relatively small area of this phase space until either a cumulative series of small transfers or a single major transfer allows forces that promote transport to overcome thresholds controlled either by the process domain or by the location of boundaries in the landscape. In relation to different landscape components, the grouping of different particles within the phase space defines the overall effectiveness of sediment connectivity between different landscape elements. The boundaries between different groupings will also be fluid, as a function of the frequency and magnitude of transporting events. In this way, the concepts of hydrological connectivity, sediment connectivity, landscape position and event frequency and magnitude can all be interlinked in a way that provides a sound conceptual basis for the estimation of sediment-transport rates across different spatial and temporal scales.

Summary of sediment-connectivity framework

This framework helps to identify relevant processes and variables for studying spatial and temporal dynamics of sediment detachment and transfer through geomorphic systems which together which together characterize sediment connectivity. It emphasizes the need to characterize the frequency-magnitude distributions of sediment detachment and transport processes and evaluate the extent to which they are temporally and spatially synchronized, identify critical feedbacks between detachment and transport within the system in question and investigate how these feedbacks evolve through space and time, and evaluate the where a system resides in the sediment detachment-transport phase space (Figure 7). Explicit consideration of these three elements of the sediment-connectivity framework is essential in any system in order to obtain a holistic understanding of sediment connectivity and mechanisms regulating the scaling of erosion rates. Without a framework such as this one, to organize relevant processes and effects of spatial and temporal heterogeneity in geomorphic systems identified in theories and empirical research, isolated knowledge acquired from isolated studies of diverse geomorphic processes operating in connected geomorphic systems is not likely to cumulate in a holistic understanding of how sediment detachment and transport processes yield spatially and temporally variable sediment connectivity.

CONCLUSIONS

In this paper we define sediment connectivity as the connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, which is controlled by how the sediment moves between all geomorphic zones: on hillslopes, between hillslopes and channels and within channels. Thus we perceive coupling and sediment connectivity to be different and encourage researchers to use the terms more accurately and precisely in their research. We argue that existing frameworks and experiments to determine sediment connectivity are not complete because they focus on disconnectivity and are dominated by the movement of sediment by water. A significant gap in the existing approaches is that they have all been developed without consideration of the mechanisms of sediment detachment, transport mechanisms or transport capacity of processes.

We propose a new framework for sediment connectivity which includes three key elements as follows: i) the frequency-magnitude distributions of sediment detachment and transport processes; ii) the spatial and temporal feedbacks between sediment-detachment and transport processes; and iii) mechanisms of sediment detachment and transport. Of particular importance in this sediment connectivity framework are the characteristics of the relationships between these three key elements. Notably, these three elements have formed the basis of prior research in geomorphology, but this framework emphasizes the co-dependency (relationships and feedbacks) of each of the three elements.

The end-members of the degree of hydrological control on sediment detachment and transport processes thus control a phase space in terms of detachment and transport distance, which defines the overall sediment flux. We presented four end-members of phase space of sediment connectivity which correspond to the following detachment and transport conditions: i) sediment detachment and sediment transport are hydrologically controlled; ii) sediment detachment is hydrologically controlled; sediment transport is not hydrologically controlled; iii) sediment detachment is not hydrologically controlled; sediment transport is hydrologically controlled; and iv) neither sediment detachment nor sediment transport is hydrologically controlled.

Sediment entrainment and travel distance are demonstrated to map onto these end-members. Thus, the understanding of the changing dynamics of travel distance under a range of process domains, environmental conditions and over various timescales is likely to be the most fruitful route to produce robust approaches for upscaling estimates of erosion rates, and coupling our process understanding with the understanding of landform evolution. It would therefore seem imperative that novel field and modelling investigations are carried out to develop these ideas further, and provide the empirical basis for models that are robust across spatial and temporal scales appropriate to representing landscape evolution.

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Figure 1: The conceptualization of connectivity applicable within catchment systems, adapted from Artza and Wainwright (2009).

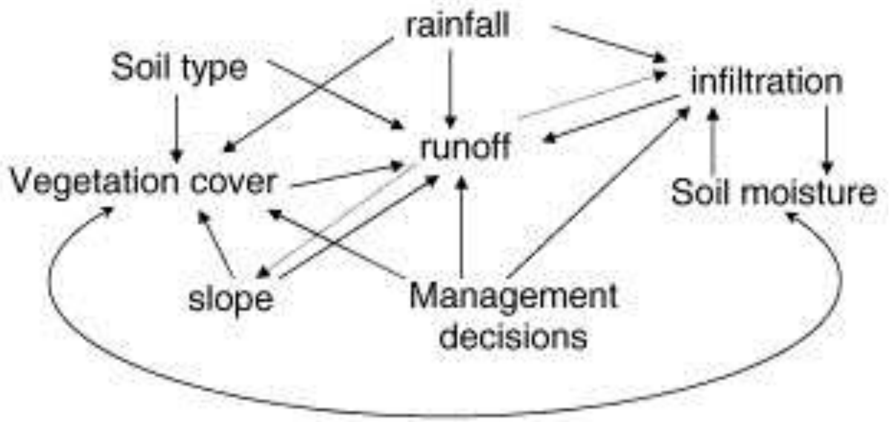

Figure 1: The conceptualization of connectivity applicable within catchment systems, adapted from Artza and Wainwright (2009).

Figure 2. Sediment connectivity framework highlighting important linkages between three key elements: mechanisms of sediment detachment and transport, their frequency-magnitude distributions and their spatiotemporal variability and resulting spatial and temporal sequencing.

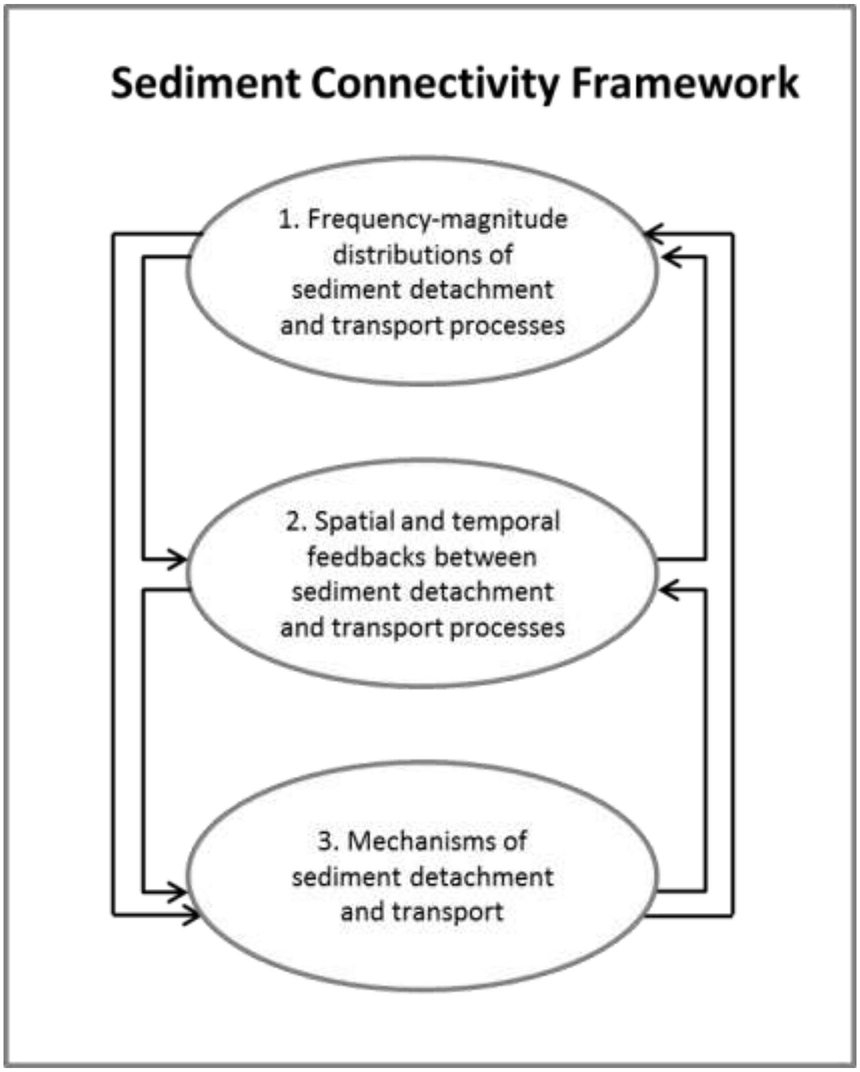

Figure 3. Conceptual figure showing the linkage between sediment accumulation and sediment connectivity, and the dependence of the latter on the sequence of previous events. Event (A) produces a significant amount of sediment connectivity because of the extensive sediment accumulation before its occurrence, but event (B), shortly afterwards is limited by the sediment supply. Sediment connectivity is subsequently stronger when accumulation has again reached a suitable level, as in event (C).

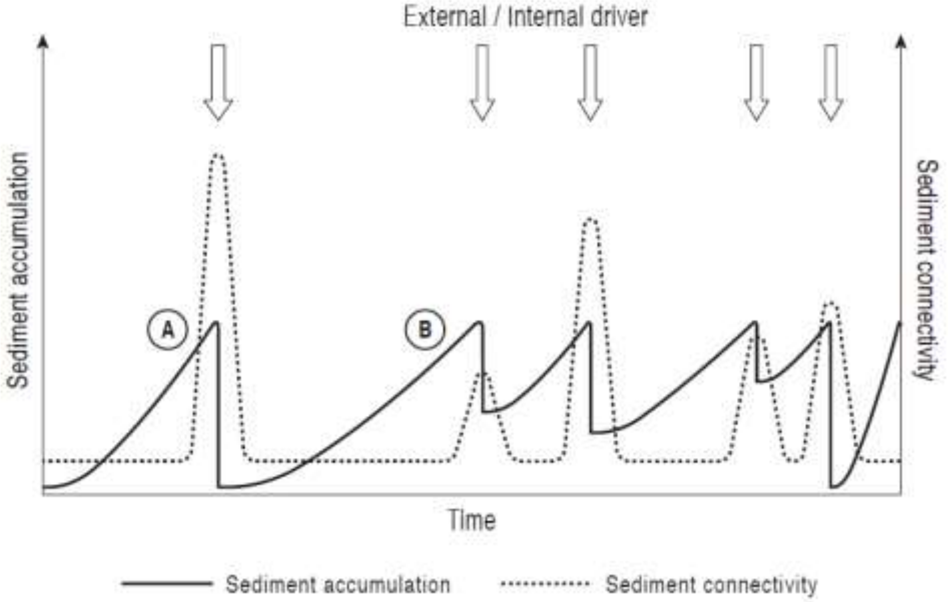

Figure 4. Diagram showing the effect of a major, infrequent event followed by low magnitude, high frequency events, which tend to decrease in magnitude over time as vegetation stabilizes hillslopes and river banks, as well as removing water from sediment transport via transpiration. This pattern continues until another high magnitude event occurs, leading to some form of resetting of the system.

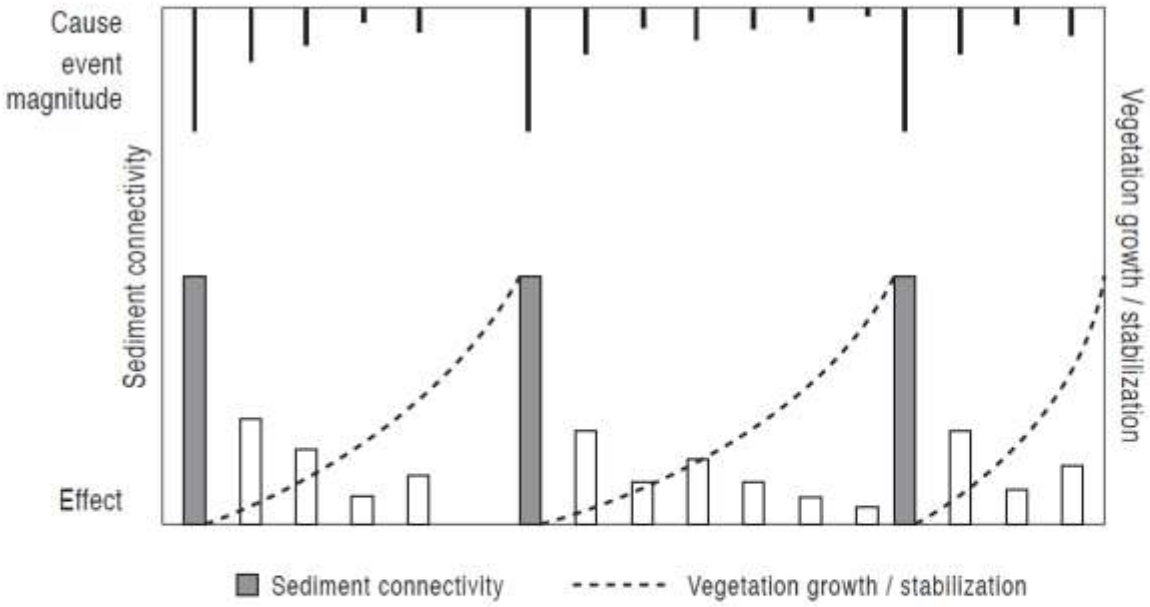

Figure 5. Conceptual examples of how infrequent, high-magnitude events affect sediment connectivity: (1) the system may experience a dramatic decrease in sediment connectivity when parts of the system become disconnected. For example, the formation of a landslide dam may disconnect uplands from lowlands, or channels may become dammed by coarse debris from tributaries thus disconnecting downstream from upstream reaches [e.g. Woolley, 1946]); (2) the system may experience a pulse in sediment connectivity as sediment is mobilized and transported during high-energy events, after which sediment connectivity will return more or less to baseline conditions (depending on any structural modifications to the system); and (3) the system experiences much stronger subsequent connectivity for example as a result of the removal of a floodplain that previously disrupted hillslope-channel coupling.

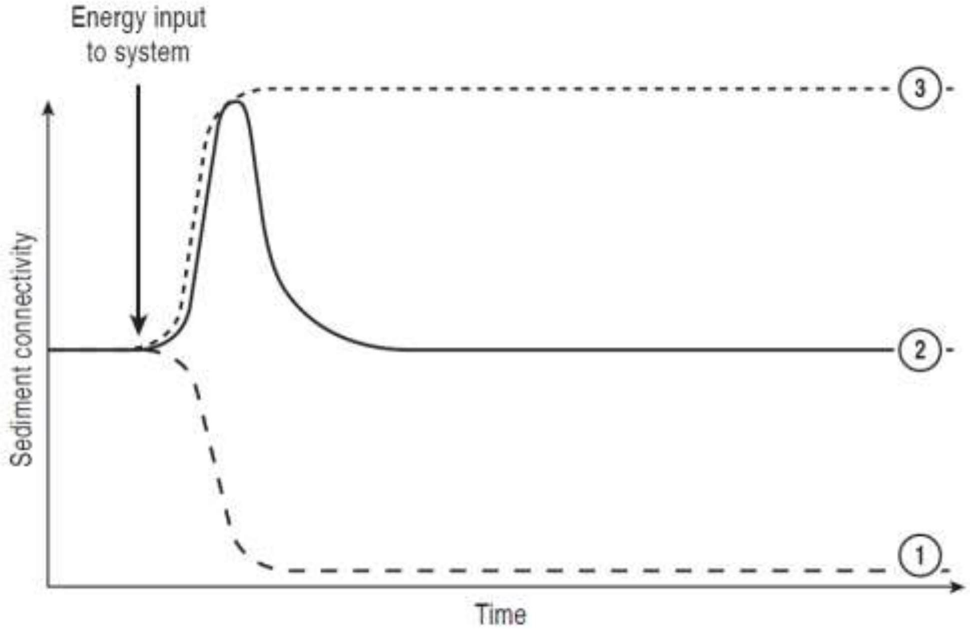

Figure 6. Positive feedbacks producing sediment connectivity in débris flows over a relatively short (event) timescales.

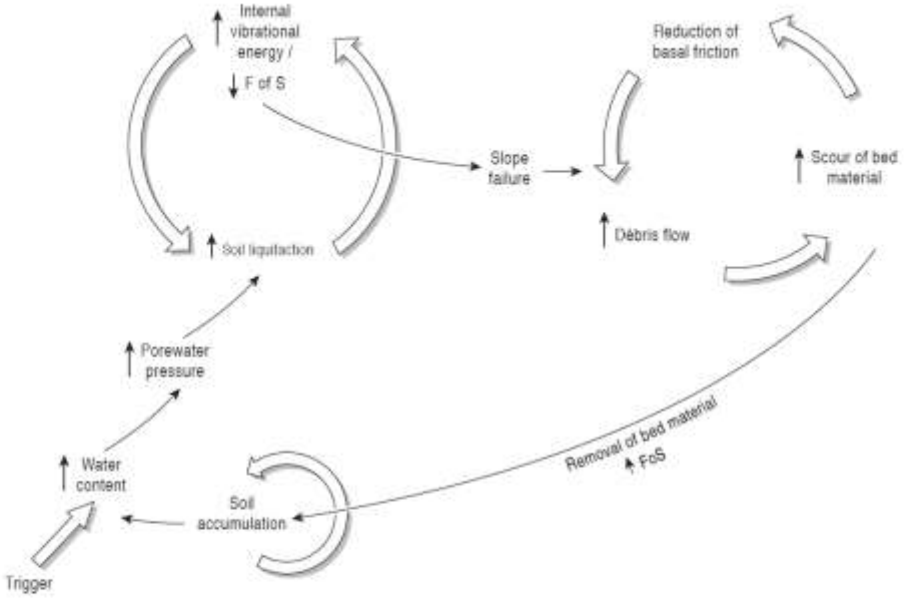

Figure 7: Diagram showing how the degree of hydrological control on sediment detachment and transport processes can be combined into an integrated model for the scaling of sediment transport. The numbers in the grey circles refer to the four end-members discussed in the text, and the grey dotted lines are isolines of sediment flux, defined as a function of detachment (*D*) and transport distance (λ). This phase space in *D* and λ describes the behaviour of individual particles, and by extension the behaviour of different landscape elements. Trajectories through this phase space will be controlled by the frequency and magnitude of different events as well as the form of the landscape and the presence of boundaries within it.