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Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades

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Abstract

Catchment configuration and the nature of connectivity within and between landscape compartments affect the operation of sediment cascades and geomorphic responses to disturbance events of differing magnitude and frequency. This paper introduces the concept of landform impediments, termed buffers, barriers and blankets, that impede sediment conveyance by limiting the connectivity between landscape compartments. Buffers restrict sediment delivery to channels, barriers inhibit sediment movement along channels, and blankets drape channel or floodplain surfaces affecting the accessibility of sediment to entrainment. These features operate as a series of switches which turn on/off processes of sediment delivery, determining the effective catchment area at any given time. Using previously documented examples, the role of these features in affecting the operation of sediment cascades in a low relief, passive landscape setting such as the Australian landmass is contrasted to examples from high relief, uplifting settings in New Zealand. The Australian examples are further explored by examining how changes to landscape connectivity brought about by human disturbance since European settlement have impacted upon landscape sensitivity and prospects for river recovery. This approach to analysis of impediments to sediment conveyance is generic and can be applied in any environmental setting.

Keywords: Disconnectivity; Decoupling; Sediment cascades; Sediment budgets; Sensitivity; River recovery; Switches

1. Introduction

Catchment-scale sediment budgets quantify the efficiency of sediment conveyance as expressed by the sediment delivery ratio (Walling, 1983). Source to sink relationships that characterise sediment cascades have been effectively communicated through the use of sediment flow diagrams (e.g. Trimble, 1983; Olive et al., 1994; Fryirs and Brierley, 2001). These diagrams indicate significant basin-to-basin variability in sediment inputs and outputs and patterns of sediment storage within a catchment (Meade, 1982; Trimble, 1993). The position, effectiveness and configuration of sediment storage units in a catchment are represented by the constrictions on these sediment flow diagrams. The distribution of sediment stores and sinks reflects, and in turn influences, the routes and distances of sediment transport, providing a measure of the (dis)connectivity of any given landscape (see Brunsden and Thornes, 1979; Meade, 1982; Phillips, 1992a; Harvey, 2002; Michaelides and Wainwright, 2002; Hooke, 2003).

In an idealised river system, residence times for sediment storage increase in a downstream direction, ranging from transient ephemeral storage features such as bars to more permanent sinks such as floodplains (Meade, 1982). Amongst the many factors that influence sensitivity to reworking of alluvial sediment storage units are the type of store, the volume and calibre of materials stored, vegetation cover and distance from the channel (Brown, 1987; Brunsden, 1993a). Connectivity, defined as the transfer of energy and matter between two landscape compartments or within a system as a whole (Chorley and Kennedy, 1971), must be maintained through the system if inputs from headwater

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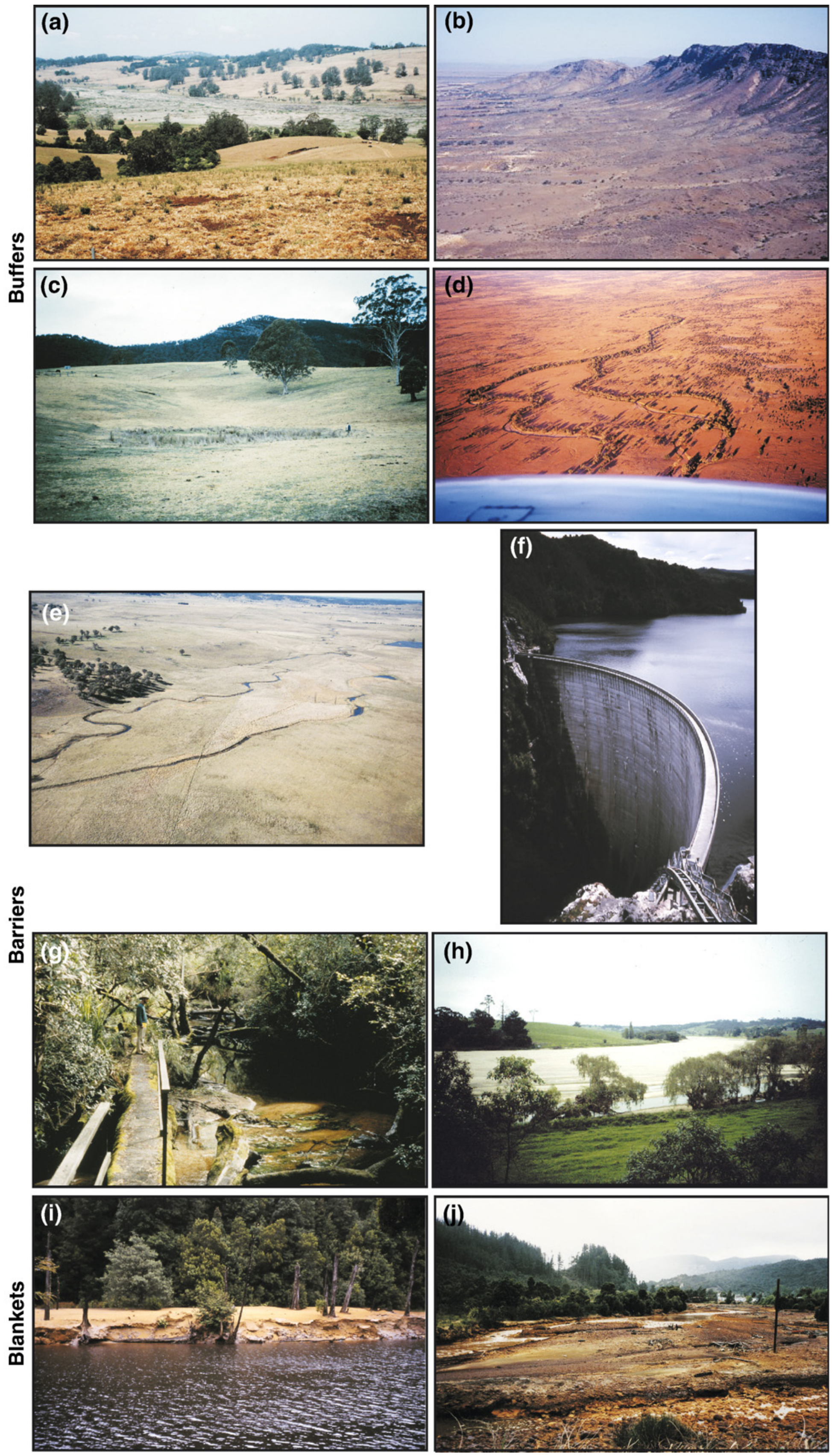
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Buffers
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Blankets

source zones are to become outputs at the basin mouth. Discontinuity in processes of sediment transfer has prompted reference to sediment cascades acting like a 'jerky conveyor belt' (Ferguson, 1981). The catchment-specific nature of these considerations highlights inherent dangers in spatial and temporal clumping in sediment budget analyses (c.f. Walling, 1983).

Many studies have highlighted decoupling between upstream sediment sources and downstream lowland basins and estuaries (e.g. Meade, 1982; Trimble, 1983; Phillips, 1992a; Brizga and Finlayson, 1994; Phillips, 1995), whether in response to inefficient sediment delivery (e.g. Walling, 1983; Olive and Rieger, 1986; Dedkov and Mozzherin, 1996), or lagged effects of downstream conveyance (e.g. Kelsey et al., 1987; Madej, 1987; Wasson et al., 1996; Benda and Dunne, 1997). In some settings, slopes and channels are decoupled, with materials mobilised on slopes re-stored on-slope or in fans at the base of slopes (Fryirs and Brierley, 1999; Harvey, 2001). Tributary systems may be disconnected from the trunk stream, with sediments trapped behind floodplain pockets at confluences or in trapped tributary fills (Timms, 1987; Brierley and Fryirs, 1999). Limited competence along a channel, or differing transport capacities of tributaries relative to the trunk stream, may lead to disconnectivity in coarse sediment movement (e.g. Rice, 1998; Hooke, 2003). Channel incision may decouple channel and floodplain processes (e.g. Schumm et al., 1984). These various forms of decoupling disconnect large parts of a catchment from the primary sediment conveyor along the trunk stream, reducing the catchment area from which sediments are delivered and transported in any given period. The spatial and temporal pattern of landscape connectivity, in turn, affects the nature and rate of lagged and off-site responses, and hence the recovery potential of a system following disturbance (Brierley and Fryirs, 2005).

In this paper, forms of landscape disconnectivity that affect the operation of sediment cascades are differentiated into buffers, barriers and blankets. Using previously documented examples, the impact of impediments to sediment conveyance that determine the efficiency of the jerky conveyor belt in high relief settings such as New Zealand is contrasted to the operation of sediment cascades in low relief settings such as the Australian landmass. The impact of human disturbance upon sediment flux is framed in terms of alterations to the operation of landforms that impede sediment transfer within catchments in these settings. Related notions of effective catchment area and effective timescales of (dis)connectivity (c.f. Harvey, 2002) are appraised as tools with which to interpret sediment budgets, landscape sensitivity and river recovery.

1.1. Forms of landscape (dis)connectivity — buffers, barriers and blankets

The nature and continuity of longitudinal, lateral and vertical linkages are controlled by different sets of processes at different positions in a catchment, such that fluxes may be connected (coupled) or disconnected (decoupled) over different timeframes (Ward, 1989; Harvey, 2002). Longitudinal linkages are defined in the context of the channel network, and include upstream–downstream and tributary–trunk stream relationships. They reflect the ability of channels to transfer sediments of variable calibre. Lateral linkages characterise the relationship between the channel network and the wider landscape, and include slope–channel and channel–floodplain relationships. Slope–channel connectivity records the frequency with which channel processes rework materials derived from hillslopes (e.g. Lane and Richards, 1997). Channel–floodplain linkages are driven by the magnitude and inundation frequency of overbank events. Vertical linkages entail surface–subsurface interactions of water and sediment. This linkage is controlled in a channel context by the texture of the bed material and the transport regime of the channel, and in a broader sense by those characteristics of the soil/regolith that control slope hydrology and relationships between surface flow, subsurface flow and groundwater.

Various landforms, described here as buffers, barriers and blankets, can disrupt longitudinal, lateral and vertical linkages, thereby influencing sediment cascades by attenuation of sediment conveyance. *Buffers* are landforms that prevent sediment from *entering the channel network*. Once sediment is in the channel network, *barriers* can disrupt sediment moving *along the channel*. *Blankets* are features that *smother other landforms*, protecting those forms from reworking, temporarily removing those stores from the sediment cascade. The type and distribution of these forms of disconnectivity dictate the strength of coupling between landscape compartments. In contrast, some reaches (e.g. gorges) may enhance propagation, acting as *boosters* to sediment conveyance.

Buffers disrupt lateral and longitudinal linkages within catchments. They may include alluvial pockets of floodplain, fans or piedmont zones that occur at breaks in slope along valley margins, disconnecting lateral connectivity in catchments (Phillips, 1992a; Harvey, 2001). Other buffers include features such as intact valley fills and floodouts (either terminal or intermediate) that have discontinuous or absent water courses (e.g. Brierley and Fryirs, 1998; Fryirs and Brierley, 1998, 1999) or low slope alluvial floodplains (Olive et al., 1994; Page and Nanson, 1996, Fig. 1, Table 1).

Fig. 1. Examples of buffers, barriers and blankets. Buffers are landforms that impede sediment movement into the channel network and include (a) swamps, (b) piedmonts and alluvial fans, (c) trapped tributary fills and (d) broad alluvial plains. Barriers impede sediment movement along the channel network and include (e) bedrock steps and valley constrictions (to left of photo) that induce backfilling of valleys, (f) dams, (g) woody debris and (h) sediment slugs. Blankets are features that smother other landforms and include (i) floodplain sediment sheets and (j) fines in the interstices of gravels.

Table 1
The characteristics of buffers

Form of buffer	Spatial scale (m^2)	Sedimentary character	Shape	Sediment cascade effect	Postulated effective timescale of disconnectivity	Breaching capacity
Intact valley fills/ floodouts	10^2–10^3	Fines	Elongate to lobed	Zone of dissipative flow. Sediment sink.	Thousands of years	Extreme event Infrequently reworked/ breached
Floodplain pockets	10^1–10^3	Mixed	Elongate and stepped	Localised scale geomorphic feature. Sediment sink.	Thousands of years	Overbank flow stage Infrequently reworked/ breached
Continuous floodplains	10^1–10^3	Mixed	Elongate and stepped	Landscape scale geomorphic feature. Sediment sink.	Thousands of years	Extreme event Infrequently reworked/ breached
Alluvial fans	10^2–10^3	Mixed	Conical	Landscape scale geomorphic feature. Sediment sink.	Hundreds to thousands of years	Extreme event Infrequently reworked/ breached
Piedmont zones	10^3	Mixed	Planar	Landscape scale geomorphic feature. Sediment sink.	Thousands of years	Extreme event Infrequently reworked/ breached
Terraces	10^2–10^3	Sands and gravels	Elongate and stepped	Landscape scale geomorphic feature. Sediment sink.	Thousands of years	Extreme event Infrequently reworked/ breached
Trapped tributary fills	10^2–10^3	Fines	Irregular	Sediment sink.	Hundreds to thousands of years	Overbank flow stage Infrequently reworked/ breached

Elevated floodplain or terraces along trunk streams may block tributary confluences, disconnecting material supply from lower order drainage lines to the primary channel network (Timms, 1987; Brierley and Fryirs, 1999). Notwithstanding their obstruction of fluvial transport which, by definition, could qualify them as barriers, in this contribution these latter features are referred to as buffers, as these large sediment sinks often have residence times on the order of hundreds to thousands of years and are considered to be external to the channel network (Meade, 1982; Brown, 1987).

Barriers most commonly disrupt longitudinal linkages through their effect on the base level or bed profile of a channel (Fig. 1, Table 2). For example, bedrock steps or woody debris may locally reduce slopes by introducing a local base level control. Sediments are trapped as they backfill areas immediately upstream of the step, inducing

Table 2
The characteristics of barriers

Form of barrier	Spatial scale (m^2)	Sedimentary character	Shape	Sediment cascade effect	Postulated effective timescale of disconnectivity	Breaching capacity
Bedrock steps	10^0–10^1	Bedrock	Irregular but stepped	Aid backfilling of valleys	Permanent over thousands of years	Extreme event Infrequently reworked/breached
Valley constriction	10^2–10^3	Bedrock	Irregular	Landscape scale geomorphic feature. Bottle neck to sediment transfer. Aid backfilling of valleys.	Permanent over thousands of years	Extreme event Infrequently reworked/breached
Sediment slugs	10^2–10^3	Sand or gravel	Elongate and lobed	Acts as a plug on sediment transfer along channels.	Tens to hundreds of years	Channel flows with the ability to entrain materials of varying sizes on the channel bed Frequently reworked/breached
Channel capacity (high width/ depth ratio channels)	10^1–10^2	Mixed	Symmetrical, asymmetrical, irregular or compound in cross-section	Controls flow concentration and therefore unit stream power. Sediment store.	Tens to hundreds of years	Channel flows with the ability to entrain materials of varying sizes on the channel bed Frequently reworked/breached
Woody debris	10^1–10^2	n/a	Irregular	Acts as a blockage behind which sediment accumulates	Tens to thousands of years	Channel flows with the ability to entrain materials of varying sizes on the channel bed Frequently reworked/breached
Dams	10^2	n/a	n/a	Anthropogenic, landscape scale geomorphic feature. Blocks sediment conveyance and enhances retention.	Permanent unless removed	Extreme event Infrequently reworked/breached No flow energy so no transport capacity

local discontinuity in sediment transfer. Similarly, valley constrictions can act as barriers that initiate valley backfilling and sediment storage in floodplains or instream units (e.g. Tooth et al., 2002). Sediment slugs may act as plugs to sediment movement along channels (Happ et al., 1940). Typically, these features are large fluxes of sediment that move through a system over time (Nicholas et al., 1995). However, during low-moderate flow conditions these features may remain stationary in the channel. Indeed, further sediment may be added to their tails during this time, resulting in channel backfilling (Schumm et al., 1984). Only events large enough to rework and move the slug will reinstate connectivity and sediment conveyance (Nicholas et al., 1995; Lisle et al., 2001; Kasai et al., 2004a). Similarly, over-widened channels may not have the competence to carry sediments made available to them, acting as barriers to downstream sediment conveyance.

Human modification to rivers may induce considerable barriers to sediment movement, whether advertently or otherwise. For example, dams may trap all but suspended load materials from moving through the system (e.g. Brune, 1953; Williams and Wolman, 1984; Graf, 1999). Barriers tend to be relatively localised features and are frequently reworked or breached. In some instances, sediment stores are transient, residing in the landscape for short periods of time (tens to hundreds of years) (Table 2; Meade, 1982; Brown, 1987). Elsewhere, barriers such as valley constrictions and dams are more permanent features, and require extreme events to be breached.

Blankets disrupt vertical linkages through their effect on surface–subsurface interactions and the entrainment of sediment. They can occur instream or on floodplains and may include features such as floodplain sand sheets or fine grained materials that infill the interstices of gravel bars (Fig. 1, Table 3; e.g. Petts, 1988). Bed armour acts as a blanket which inhibits the reworking of subsurface sediments (e.g. Church et al., 1988). Blankets are most commonly found along alluvial rivers where instream sediment stores and floodplain sinks are common. Depending on the position of blankets within the system, they can be extensive or localised features that are reworked over variable timeframes (Table 3).

As highlighted in Fig. 2, these various forms of (dis) connectivity can be considered within a nested hierarchy at local, zonal and system scales (following Harvey, 2002). At the local scale, (dis)connectivity is a within-compartment or within-landform phenomenon. For example, Fig. 2a shows within-hillslope connectivity in a landslide dominated terrain. In Fig. 2b, the sands of a sediment slug have infilled the interstices of a gravel and boulder-bed stream. At the zonal-scale, (dis)connectivity occurs between compartments or landforms. Slopes and channels are connected where landslide materials are contributed to the channel network and buffers are absent (Fig. 2c), or disconnected where floodplains or alluvial valley fills buffer the base of a slope (Fig. 2d). At the broader system scale, (dis)connectivity relates to the behaviour of whole catchments. The spatial configuration of all forms of (dis)connectivity is assessed to determine linkages along the sediment cascade. For example, in a highly coupled landscape, materials released from the catchment are delivered to the mouth of the Waipaoa River in New Zealand (Fig. 2e). In contrast, Fig. 2f shows the closed mouth of Australia's Murray River that disconnects sediment contributions from the catchment to the coast. These relationships are not only spatially variable in terms of their frequency and relative importance, their operation also varies markedly over different timescales.

Landscape decoupling can be expressed as the degree to which any limiting factor constrains the efficiency of sediment transfer relationships. Barriers, buffers and blankets disconnect or decouple areas of a catchment from the primary sediment conveyor belt. The spatial area that directly contributes to, or transports sediment along, the channel network, referred to here as the '*effective catchment area*', reflects the degree to which the catchment is longitudinally, laterally and vertically connected. This provides a measure of the 'variable source area concept' whereby the contributing area for sediment is identified and quantified (Graf, 1988).

Linkages between landscape compartments operate in differing manners, or with differing degrees of efficiency, in

Table 3
The characteristics of blankets

Form of blanket	Spatial scale (m^2)	Sedimentary character	Shape	Sediment cascade effect	Postulated effective timescale of disconnectivity	Breaching capacity
Floodplain sediment sheets	10^1–10^3	Mixed	Planar sheet — can be relatively thick	Changes soil profile and hydrological properties. Sediment sink.	Tens to hundreds of years	Overbank flow events with ability to rework floodplain surfaces Recurrently reworked/breached
Fine-grained material in interstices of gravels	10^{-1}–10^1	Fines	Planar draped — relatively thin	Changes hydrological properties at a 1 mm to 1 m scale. Sediment store.	Individual event to years	Channel flows up to bankfull with the ability to flush fines Recurrently reworked/breached
Channel bed armouring	10^1–10^2	Mixed, but tends to be gravels or cobbles	Various — elongate, diagonal, arcuate, etc.	Changes hydrological properties at a 1 mm to 1 m scale. Sediment store	Years to tens of years	Channel flows with ability to entrain and rework surface armour and release subsurface materials. Recurrently reworked/breached

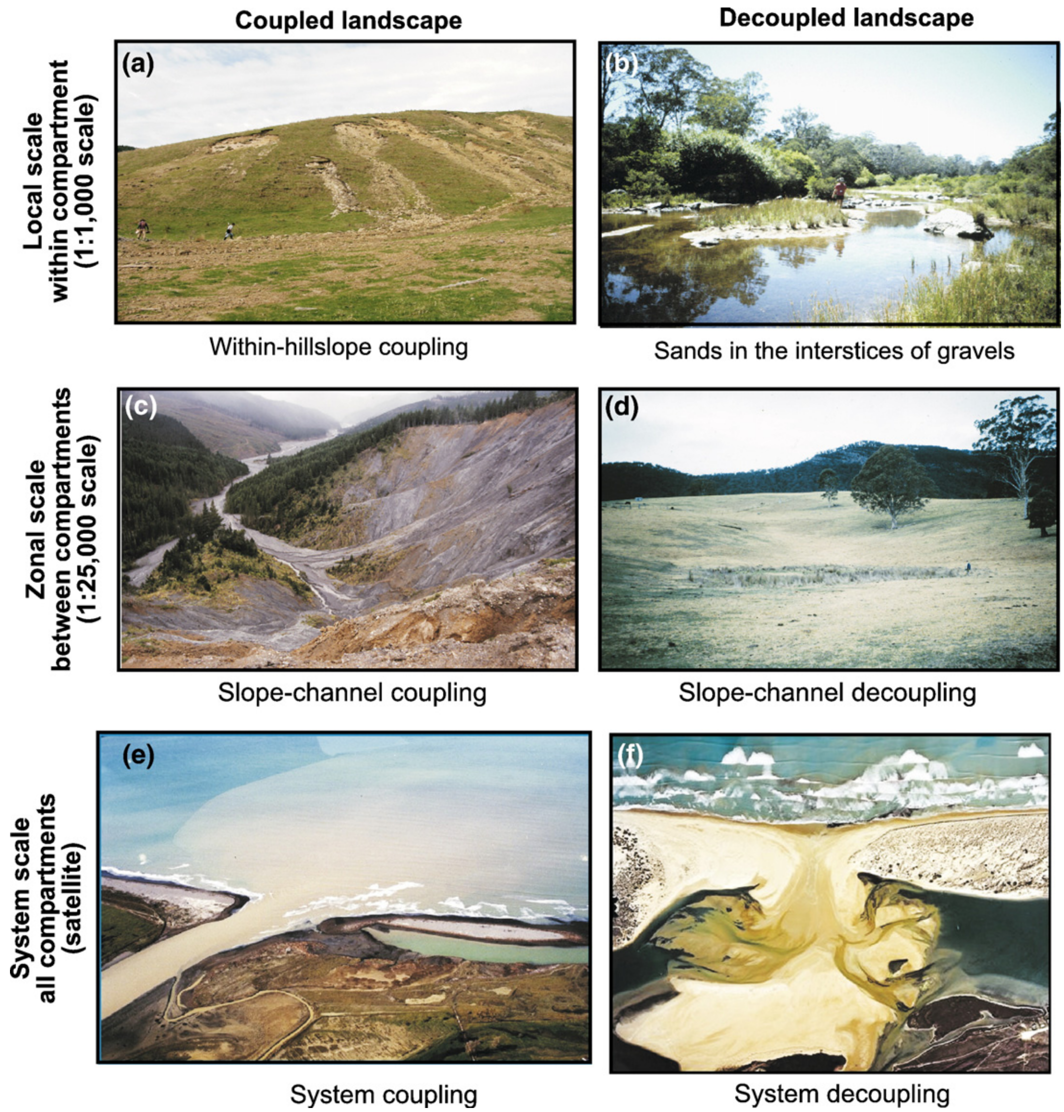


Fig. 2. The nature of (dis)connectivity at a range of scales within a nested hierarchy (c.f. Harvey, 2002). Within compartment or local-scale (dis)connectivity describes the degree to which materials are moved within an individual landform. This can be (a) connected where sediment is sliding off the slope or (b) disconnected where sediment clogs the interstices between gravels. Zonal-scale connectivity examines the linkage between landscape compartments such as slopes and channels. These linkages can be (c) connected where landslides contribute sediment directly to a channel, or (d) disconnected where a levee traps a tributary forming a trapped tributary fill (note photograph taken from crest of levee). At the system scale the linkages between all landscape compartments are examined to determine whether the system acts an efficient conveyor of sediment and the effective catchment area from which sediments are derived. (e) Shows direct sediment contributions to the Waipaoa River mouth, North Island, NZ, courtesy of Dave Peacock (f) shows the closed mouth of the Murray River, South Australia, courtesy of Mapland, Environmental and Geographical Information, Department of Environment and Heritage, South Australia.

response to events of differing magnitude and frequency. This impacts markedly on landscape sensitivity and the nature, extent and consequences of propagatory, off-site responses (Brunsden, 2001; Thomas, 2001). The spatial configuration of buffers, barriers and blankets in any given catchment conditions the geomorphic effectiveness of landscape-forming events and the periodicity or duration of entraining flows over differing timescales (Wolman and Miller, 1960; Wolman and Gerson, 1978; Costa and O'Connor, 1995). In geomorphic terms, '*effective timescales*' relate to the magnitude–frequency characteristics of perturbations required to breach a buffer, barrier or blanket, and the propagation time for change to be manifest in the system (c.f., Harvey, 2002). This is dictated by the spatial scale of the buffer, barrier or blanket, and the position of that feature in the catchment (Meade, 1982).

At the local and zonal scales, temporal variability in (dis) connectivity is related to the size and sedimentary composition of the buffer, barrier or blanket, and to the magnitude–frequency of geomorphically effective events that rework these impediments to sediment conveyance. This is termed the *breaching capacity* (c.f., Brunsden, 1993a, 2001). It can be considered as the recurrence interval of the event required to breach the buffer, barrier or blanket, or as the residence time of these landforms (Tables 1, 2, and 3). Landforms that sit close to a threshold of change will respond to events of lower breaching capacity (Schumm, 1973, 1979). Effective timescales can range from the individual event, with sub-annual return periods for local-scale connectivity, through decadal to century timescales for zonal-scale connectivity (Harvey, 2002).

At the system scale, changes to the (dis)connectivity of a catchment are related to the position of buffers, barriers and blankets within the system, the nature of their interaction (i.e. whether the formation or reworking of one leads to the formation or alteration of others), and the lag time for change to be manifest in the system. The distribution of buffers, barriers and blankets dictates how the effects of geomorphic changes are propagated through a catchment (Allen, 1974; Brunsden and Thornes, 1979; Harvey, 2002). In highly connected landscapes, the cumulative effects of alterations to forms of (dis)connectivity in upper parts of a catchment are manifest relatively quickly. In contrast, in highly disconnected landscapes, changes to the nature of (dis)connectivity in one part of a catchment are absorbed or suppressed in the system and geomorphic changes are not propagated through the catchment (Thomas, 2001). At the system scale, effective timescales of connectivity may be hundreds or thousands of years (Harvey, 2002). For example, if significant geomorphic change and sediment release occur in a tributary system, the degree of connectivity between the tributary and the trunk stream will dictate whether downstream impacts eventuate (c.f. Petts, 1979). If a buffer or barrier occurs in the tributary system, such that sediment conveyance is disconnected, propagation of geomorphic change will not occur until the buffer or barrier is breached. This may only occur after a significant lag period. All forms of (dis)connectivity and their interactions must be combined to assess system scale (dis)connectivity and sedimentary cascades.

Increasing landscape connectivity and effective catchment area through breaching of certain types of buffers, barriers and blankets can be considered analogous to the operation of a series of switches which determine which parts of the landscape contribute to the sedimentary cascade over different time intervals. This may be considered at the scale of an individual event (i.e. the rising or waning stages of floods), sequences of events of varying magnitude (i.e. a low magnitude flow event one year followed by a high magnitude event the following year), or in response to changes in system boundary conditions (e.g. land-use or climate change). Fig. 3 conveys a conceptual framework by which these interactions may be assessed. In this conceptualisation, slopes and channels are buffered by alluvial fans in the upper tributary systems and floodplains and terraces occur along the lower trunk stream. At various positions along the tributary networks, fine-grained materials blanket gravel bars. A valley constriction along the trunk stream acts as a barrier that disrupts the transfer of sediment from the upper catchment to the lower catchment. Sediment supplied to the lower catchment forms a sediment slug along lowland reaches.

The spatial pattern of buffers, barriers and blankets characterised in Fig. 3 influence the timeframe over which sediments are reworked in different landscape compartments. At low flow stages associated with frequent, low magnitude

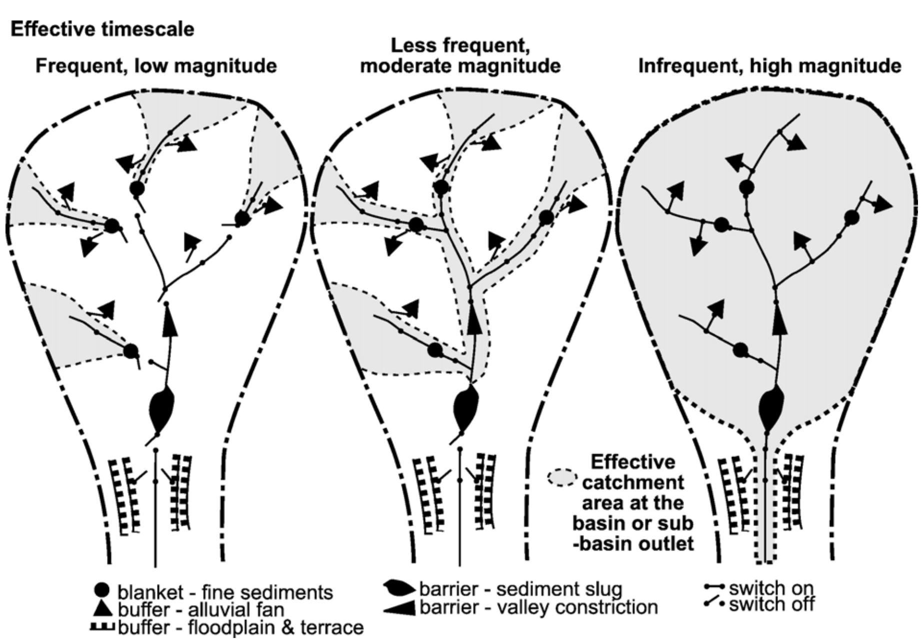


Fig. 3. Switches in catchments. The effective catchment area is defined as the spatial area which directly contributes to, or transports sediment along, the fluvial network. The effective timescale is expressed as the magnitude of event required to breach buffers, barriers or blankets or the residence time of sediment stores and sinks. It reflects the timeframe over which (dis)connectivity occurs. The effective catchment area increases as the magnitude of the event required to breach buffers, barriers and blankets increases. This is analogous to switching on and off certain parts of catchments over certain timeframes.

energy inputs, the capacity for slope erosion and fluvial sediment reworking is limited. Landscape disconnectivity is significant and the effective catchment area is low. At this stage, none of the buffers, barriers or blankets are breached and sediment cascading in the channel network is limited. As flow stage increases within the channel network, more readily reworked instream barriers and blankets are breached. There is sufficient energy to initiate reworking of interstitial fines that form instream blankets, and sediments are conveyed through the valley constriction, connecting the upstream channel network to the lowland plain. As connectivity increases, the effective catchment area increases. In a high magnitude–low frequency event, other buffers and barriers are breached. Reworking of alluvial fans connects the hillslopes to the channel network. The sediment slug along the lowland plain is reworked, contributing sediment to the river mouth. However, unless an extreme event occurs, the floodplains and terraces along the lowland plain are not reworked and maintain their buffering capacity. Indeed, sediments derived from upstream may be deposited on the floodplain surface forming a blanket. During high magnitude events connectivity within the system is at its highest and the effective catchment area the largest.

Processes of sediment transfer may alter the distribution and types of buffers, barriers and blankets in a catchment. For example, blankets may be fully reworked, reconnecting vertical linkages. Alternatively, sediment slugs may form in tributaries forming a barrier to subsequent sediment movement. Changes to the location and spatial arrangement of sediment sources and sinks alter the operation of sediment cascades through their impacts upon the effective catchment area and effective timescales of (dis)connectivity. Catchment-specific configuration and landscape history determine the distribution and geomorphic role of buffers, barriers and blankets, and resulting sediment flux.

The spatial and temporal context of (dis)connectivity outlined in this conceptual framework, and the associated notion of 'switches' in catchments, can be applied to any given catchment (e.g. Fryirs et al., in press). Although an exhaustive list of buffers, barriers and blankets has not been presented, the definition and description of examples provides sufficient guidance on the types of impediments that might occur in any fluvial landscape. Catchment-specific variants can be readily added without changing the way in which the approach is applied. By comparing catchments, variability in landscape response to disturbance (either natural or human-induced), or the operation of cascades in different landscape settings can then be appraised. For example, there is significant variability in sediment cascading processes and system response times in arid and humid settings, reflecting the nature and strength of (dis)connectivity in these different settings.

Humid systems have more seasonal and consistent discharge regimes than arid counterparts. The movement of bed sediment is recurrent and consistent (Trimble, 1995). The concept of 'slowing sediment removal' (Gilbert, 1917) in a downstream direction describes the re-storage of sediments (e.g. on floodplains) and hence removal from the sediment cascade (e.g. Trimble, 1983; Knox, 1987; Phillips, 1992a, 1995). As such, a relatively high proportion of sediment remains stored within the system and sediment yields/delivery ratios tend to be lower than for arid and semi-arid systems. Phillips (1992a) described these systems as decoupled over long timeframes (i.e. hundreds or thousands of years). In contrast, arid and semi-arid systems are characterised by movement of large quantities of bed sediments during infrequent, episodic scour periods (Graf, 1988). The pattern of sediment source, transfer and accumulation zones, and the degree of (dis)connectivity is more likely to reflect the last high magnitude–low frequency event that was capable of inducing 'flushing' or 'pulsing' of sediment through the system (Schumm, 1977; Graf, 1988; Trimble, 1995). Less sediment is stored internally within arid/semi-arid basins and they are characterised by higher relative sediment yields (Graf, 1988). Event-driven (dis)connectivity is a more common characteristic of these catchments.

In the following sections, the role of buffers, barriers and blankets as agents of landscape disconnectivity that disrupt the operation of sediment cascades are contrasted in high relief, uplifting terrains and low relief passive margin settings, using documented examples from New Zealand and Australia respectively.

1.2. The operation of sediment cascades in high relief, uplifting terrains

New Zealand is located in a tectonically active, convergent plate setting that is characterised by both uplift and volcanism. Axial mountain ranges aligned perpendicular to the prevailing atmospheric flow are subject to frequent, high magnitude orographic precipitation. Steep, high relief landscapes, generally comprising relatively weak rocks, generate vast volumes of materials via a range of mass movement mechanisms (e.g. Page et al., 1999; Trustrum et al., 1999; Hicks et al., 2000; Reid and Page, 2002). Sediment generation is also promoted by the high drainage density, rapid weathering processes, allochthonous input (i.e. loess, tephra) and abundant trigger events (e.g. storms, earthquakes). Faulting and folding induced by tectonic forces deform surface rocks and parent materials from which soils and regolith form are typically non-massive or shattered. Because of their relative youth, soils typically exhibit only residual shear strength (Preston and Crozier, 1999) and are susceptible to water erosion and shallow mass movement processes. High rates of process activity and sediment reworking promote short residence times. As a consequence, sediment supply to New Zealand rivers is high, resulting in sediment yields that are amongst the highest in the world (Griffiths and Glasby, 1985; Hicks et al., 1996; Walling and Webb, 1996).

Taking the example of the Weraamaia–Waiapu catchment in New Zealand (Fig. 4), effective coupling of slope and

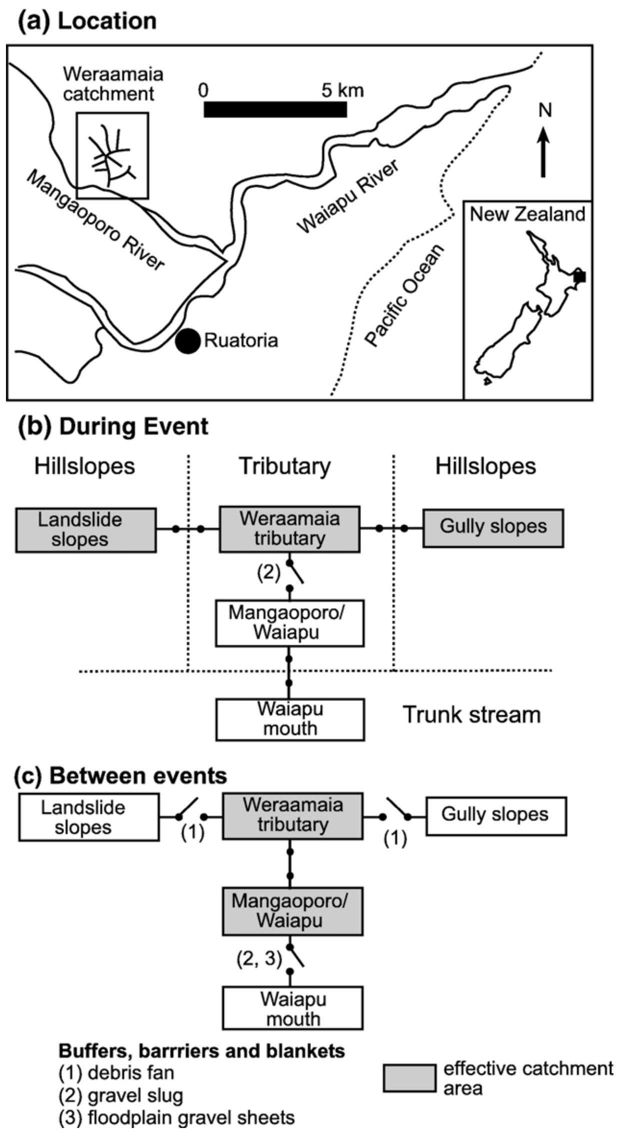
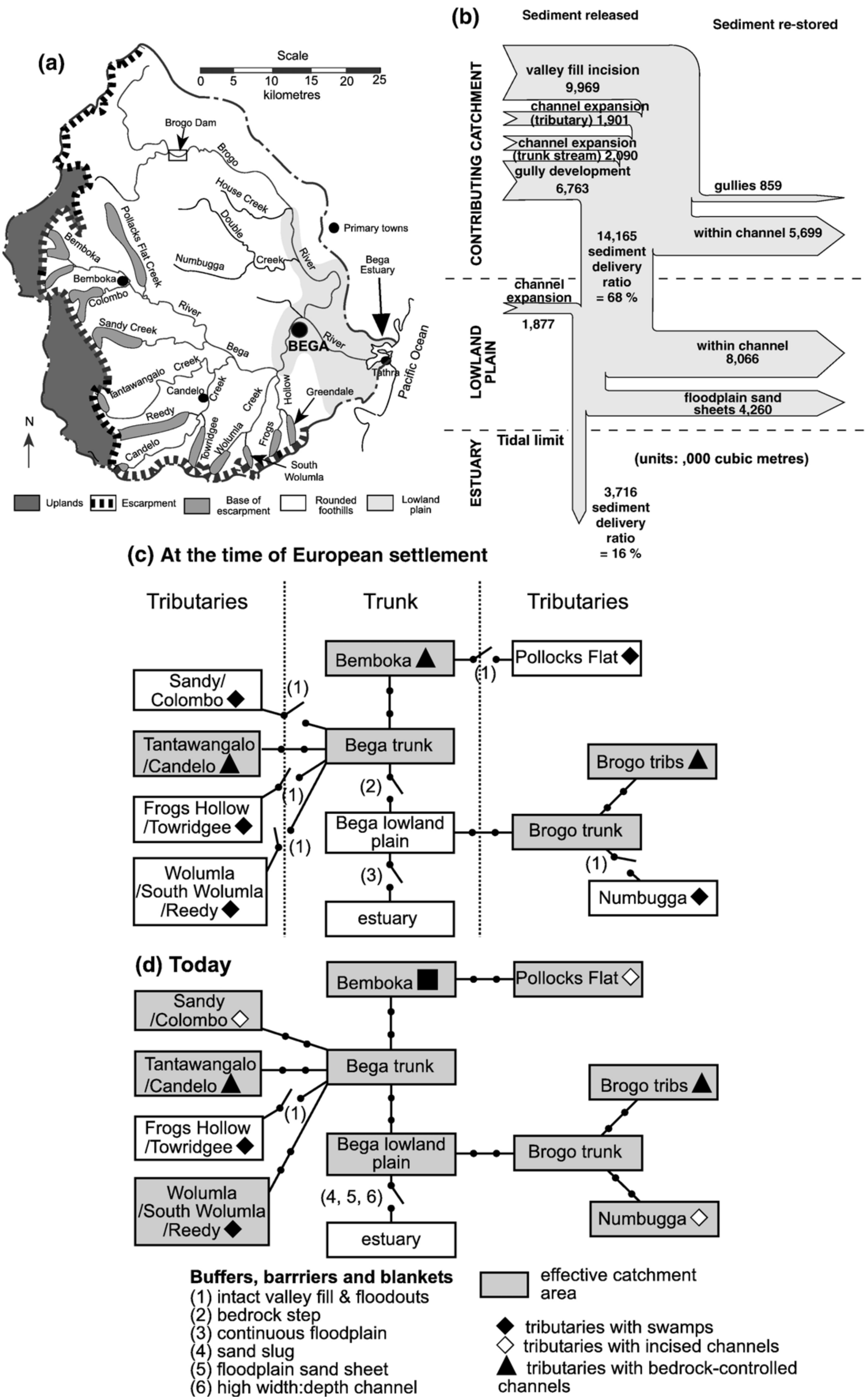


Fig. 4. The event-driven nature of (dis)connectivity in the Weraamaia catchment, New Zealand. This figure depicts the changing nature of (dis) connectivity in the bedload sediment flux of Weraamaia catchment in New Zealand during a disturbance (flow) event and in the intervening periods. This diagram is represented as a switch diagram whereby hillslopes feed into tributaries and the tributaries to the trunk stream. The nature and degree of (dis)connectivity (i.e. whether switches are on or off) changes as the magnitude of event changes. The numbers at each switch reflect the type of buffer, barrier or blanket responsible for the switch being turned off. The effective catchment area is also noted. Information sourced from Kasai et al. (2005).

channel networks in steep headwater settings ensures significant sediment release during large storms. Large volumes of sediment liberated via complex mass movement processes are contributed directly to the channel network (Fig. 4b). If the channel has a high transport capacity, fine materials contributed from shallow landslides are flushed directly downstream. However, low transport capacity relative to sediment input volume and calibre can induce the formation of debris fans or talus cones at the slope–channel interface (Betts et al., 2003). These features subsequently act as buffers to sediment conveyance during intervening periods (Fig. 4c). In the periods between large events, smaller magnitude events continue to liberate sediments from hillslopes, but vegetation growth tends to decrease the rate of sediment supply (Kasai et al., 2005). Under these conditions, slope-derived sediments tend to be buffered from the channel network by the debris fan or talus slope deposits, disconnecting slopes and channels until the buffers are reworked by fluvial action. Hence, it is typically large rainfall events that drive slope–channel connectivity in these systems. This impacts on the nature of upstream–downstream and tributary–trunk stream interactions elsewhere in the catchment.

During periods of slope–channel coupling, high rates of sediment input lead to channel aggradation and the formation of sediment slugs (Fig. 4b). These features form a temporary barrier to sediment movement along the trunk stream and tributary channels. When slopes and channels are disconnected and sediment supply is reduced, reworking of the slug material is accelerated (Fig. 4c; Kasai et al., 2005). At any point in time, tributary and trunk stream systems may aggrade or degrade, reflecting different phases of the sediment flux cycle and phased longitudinal (dis)connectivity. Depending on the size of supplied material relative to the original bed materials, and hydraulic conditions, sediment slugs may translate and/or disperse (c.f. Lisle et al., 2001). Over time, and with distance downstream, the degree and nature of this response tends to dissipate and the role of the slug as a barrier to sediment movement decreases. The timeframe over which cycles of slope–channel and upstream–downstream (dis) connectivity occur reflects the period required to generate sufficient sediment stores and reactivate phases of channel bed aggradation. Working in a similar steepland setting in Kyushu, Japan, Kasai et al. (2004b) indicate that hillslope rejuvenation together with high magnitude typhoons about every 20 years trigger catchment-wide landslide failure, promoting cyclic aggradation along the channel network. In the Weraamaia catchment, New Zealand (Fig. 4), a relaxation period of more than 70 years is required to attain a quasi-equilibrium bed configuration and rate of sediment flux (Kasai et al., 2005). The relaxation pathway is shaped by the magnitude and frequency of subsequent rainfall events, the capacity of these events to transport available sediments, and the efficiency of longitudinal linkage between reaches. Adjacent reaches may demonstrate differing relaxation pathways, reflecting spatial and temporal variability in sediment transport threshold conditions.

Larger river systems fed by these small headwater catchments accumulate vast volumes of sediment in wide, shallow, braided channels. In circumstances where erosion occurs via gully mass-movement complexes, slopes and channels are coupled and channel network connectivity is high (see Fig. 2c; Betts et al., 2003). This accumulation of sediment may take the form of slugs or waves in receiving channels (Fig. 4c). Sustained aggradation may create a large barrier, inducing base-level adjustments along both the trunk and tributary systems. Aggradation and alluvial fan formation


(a)
Scale
0 5 10 15 20 25
kilometres
Brogo Dam
Brogo
House Creek
Double
Creek
River
Primary towns
Bega Estuary
Pollacks Flat Creek
Bemboka
Bemboka
Colombo
Numbugga
River
Sandy Creek
Bega
BEGA
River
Pacific Ocean
Tathra
Tantawangalo
Creek
Candelo
Creek
Reedy
Candelo
Towridgee
Wolumla
Creek
Frogs
Hollow
Greendale
South Wolumla
N
Uplands
Escarpment
Base of escarpment
Rounded foothills
Lowland plain
(b)
Sediment released
Sediment re-stored
CONTRIBUTING CATCHMENT
valley fill incision 9,969
channel expansion (tributary) 1,901
channel expansion (trunk stream) 2,090
gully development 6,763
gullies 859
within channel 5,699
14,165 sediment delivery ratio = 68 %
LOWLAND PLAIN
channel expansion 1,877
within channel 8,066
floodplain sand sheets 4,260
Tidal limit
ESTUARY
(units: ,000 cubic metres)
3,716 sediment delivery ratio = 16 %
(c) At the time of European settlement
Tributaries
Trunk
Tributaries
Bemboka
Pollocks Flat
Sandy/ Colombo
Tantawangalo /Candelo
Bega trunk
Brogo tribs
Frogs Hollow /Towridgee
Bega lowland plain
Brogo trunk
Wolumla /South Wolumla /Reedy
estuary
Numbugga
(1)
(2)
(3)
(d) Today
Bemboka
Pollocks Flat
Sandy /Colombo
Tantawangalo /Candelo
Bega trunk
Brogo tribs
Frogs Hollow /Towridgee
Bega lowland plain
Brogo trunk
Wolumla /South Wolumla /Reedy
(4, 5, 6)
estuary
Numbugga
Buffers, barrriers and blankets
(1) intact valley fill & floodouts
(2) bedrock step
(3) continuous floodplain
(4) sand slug
(5) floodplain sand sheet
(6) high width:depth channel
effective catchment area
tributaries with swamps
tributaries with incised channels
tributaries with bedrock-controlled channels

may thus effectively disconnect tributaries from the trunk stream during intervals between major disturbance events (Betts et al., 2003). However, although sediment connectivity between tributary and trunk streams is thus broken, the high energy nature of these settings, along with the vast volumes of stored sediment, ensure that reworking results in significant sediment yields at the river mouth being maintained more-or-less constantly. Connectivity between headwaters and the lowlands may be accompanied by high rates of vertical accretion of floodplains along the lowland plain (Gomez et al., 1998, 1999). Further, the frequency of high magnitude events is such that lateral disconnectivity in headwater zones is likely to be maintained for relatively short periods.

1.3. The operation of sediment fluxes in low relief, passive margin settings

The Australian landmass is a low relief, low slope landmass. Roughly 70% of the continent lies at elevations lower than 500 m above sea level. This tectonically stable, passive margin setting has exceedingly low rates of uplift. Direct impacts of Quaternary glaciation are negligible and highly localised. Climatic oscillations during the Quaternary have induced relatively short formative phases of declining river activity separated by significant periods of time when the sedimentary record indicates very little geomorphic change (Nanson et al., 2003). Rates of sedimentation are highly irregular, with large, low relief alluvial plains in some areas subjected to gradual but episodic accretion of materials that have been stored and reworked over timeframes extending back over tens of thousands of years (e.g. Page and Nanson, 1996). These antecedent conditions exert a significant control on the contemporary capacity for river adjustment, and induce significant longitudinal and lateral disconnectivity along many Australian rivers.

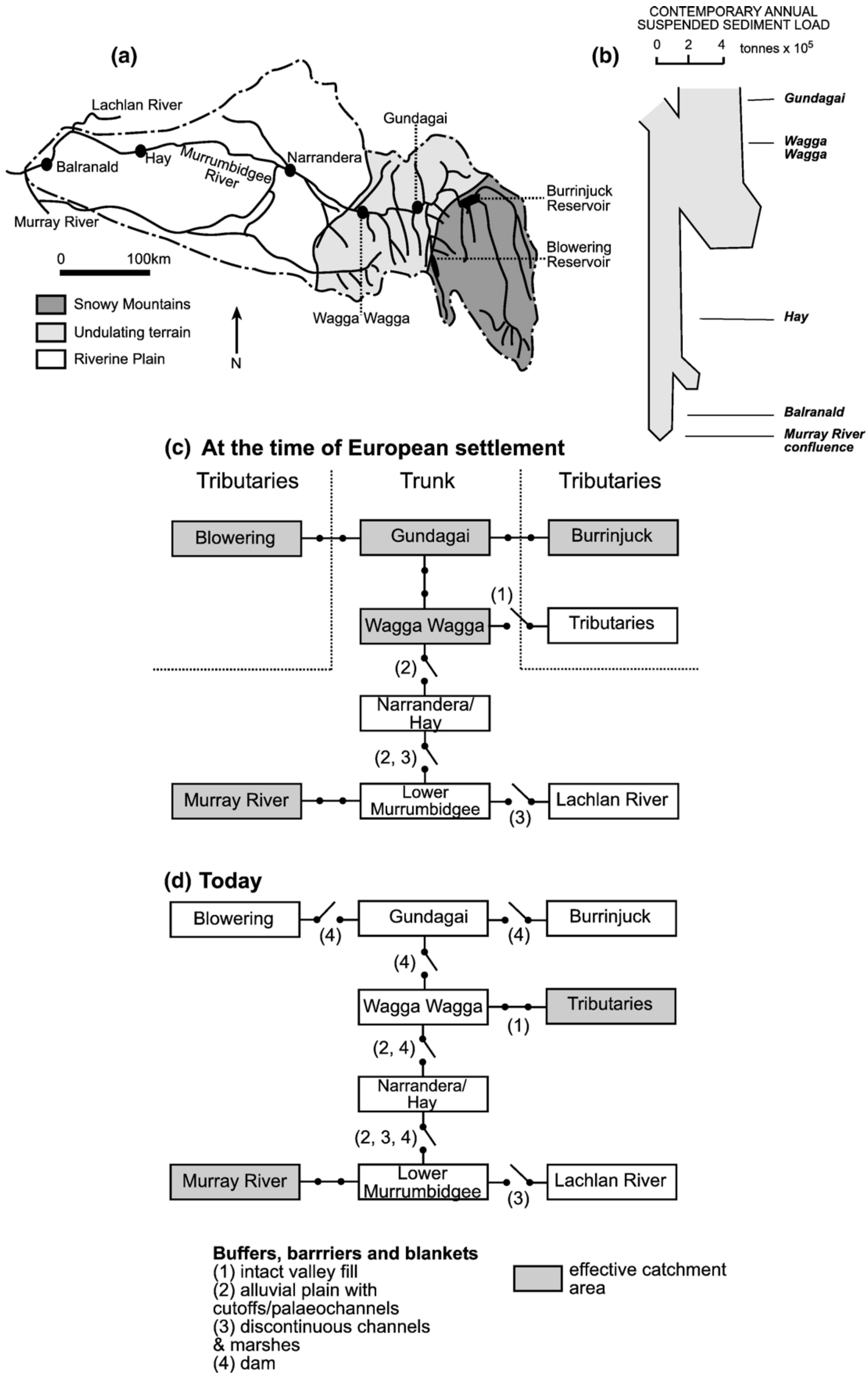
Australian rivers are also noted for their high flow variability and extreme flood behaviour (McMahon et al., 1991). Sediment movement is episodic, with long periods of relative inactivity punctuated by short phases of localised, event-driven activity. This results in inefficient and pulsed sediment conveyance through systems. Much of the landscape is characterised by relatively stable sediment sinks and stores with residence times extending back for many thousands of years. However, depending on the spatial configuration of the catchment, different forms of (dis)connectivity induce considerable variability in the propagation of reworked sediments through catchments.

Given the highly denuded nature of much of the landscape and low rates of rejuvenation, sediment supply to rivers is low (Olive and Rieger, 1986; Wasson, 1994). At the continental scale, sheetwash and rill erosion processes on hillslopes dominate sediment supply processes. However, it has been estimated that less than 8% of soil moving on hillslopes actually reaches river networks (NLWRA, 2001). Much of the material released from hillslopes is re-deposited a short distance downslope, at the base of slopes or in filter strips on top of floodplains (Lu et al., 2003). Although there are strong regional patterns in the type of sediment sources generated in different landscape settings, with significant variability in catchment to catchment sediment delivery and (dis)connectivity, sediments that are transported by contemporary channel networks are primarily derived from alluvial sediment stores via gullying and bank erosion processes (Wallbrink et al., 1994; Wasson et al., 1996; Fryirs and Brierley, 1999; Rutherfurd, 2000). The low slope, low energy conditions ensure that sediments that are made available to rivers tend to be re-stored for extended periods of time. As a consequence, Australian rivers have very low sediment delivery ratios and Australia's off-shore sediment contributions are trivial at the global scale (Wasson, 1994).

Working in the Bega catchment, Fryirs and Brierley (2001) and Fryirs (2001) outlined the impact of European settlement on the bedload sediment flux. Prior to European settlement, many tributary valleys comprised discontinuous water courses or intact valley fills with no channels (Fryirs and Brierley, 1998). These buffers effectively disconnected large proportions of the upper Bega catchment from the sediment cascade (Fig. 5). Since European settlement, increased connectivity of tributaries (induced by incision) and enhanced connectivity along the trunk stream have promoted significant downstream transfer of sediment (Fryirs and Brierley, 1999, 2001). Where valley fills remain, lower order drainage lines remain 'protected' from gullying processes by the buffer provided by fills or floodplain pockets. Slopes and channels along many lower order drainage lines remain decoupled with low rates of sediment generation from hillslopes (Fryirs and Brierley, 1999). In these tributary systems, materials generated are restored on-slope or are retained on the intact valley floors. Hence, a large proportion of hillslopes and lower order drainage lines in Bega catchment are disconnected from the sedimentary cascade. Elsewhere, bedload conveyance is much more efficient along bedrock-controlled rivers (Fig. 5d). Even in these systems, however, discontinuous pockets of floodplain along valley margins act as buffers that produce irregularities in slope–channel and tributary–trunk stream connectivity (Brierley and Fryirs, 1999).

Prior to European settlement, channel dimensions decreased downstream along the lower Bega River (Brooks and Brierley, 1997). Floodplain sedimentation along the lowland plain removed sediment from the cascade, acting as a buffer

Fig. 5. The nature of (dis)connectivity in Bega catchment pre- and post-European settlement. This figure depicts the changing nature of (dis)connectivity in the bedload sediment flux of Bega catchment in Australia in the periods pre- and post-European settlement. This diagram is represented as a switch diagram whereby tributaries with swamps, incised channels or bedrock-controlled channels contribute materials to the trunk stream and the estuary. The nature and degree of (dis) connectivity (i.e. whether switches are on or off) has changed as a result of geomorphic changes that occurred as a result of human disturbance post-European settlement. The numbers at each switch reflect the type of buffer, barrier or blanket responsible for the switch being turned off. The effective catchment area is also noted. The sediment flow diagram is modified from Fryirs and Brierley (2001) and represents the post-European settlement sediment budget.


(a)
Lachlan River
Gundagai
Balranald
Hay
Murrumbidgee River
Narrandera
Burrinjuck Reservoir
Murray River
Blowering Reservoir
0 100km
Snowy Mountains
Undulating terrain
Riverine Plain
N
Wagga Wagga
(b)
CONTEMPORARY ANNUAL SUSPENDED SEDIMENT LOAD
0 2 4 tonnes x 10^5
Gundagai
Wagga Wagga
Hay
Balranald
Murray River confluence
(c) At the time of European settlement
Tributaries
Trunk
Tributaries
Blowering
Gundagai
Burrinjuck
(1)
Wagga Wagga
Tributaries
(2)
Narrandera/ Hay
(2, 3)
Murray River
Lower Murrumbidgee
Lachlan River
(3)
(d) Today
Blowering
(4)
Gundagai
(4)
Burrinjuck
(4)
Wagga Wagga
Tributaries
(1)
(2, 4)
Narrandera/ Hay
(2, 3, 4)
Murray River
Lower Murrumbidgee
Lachlan River
(3)
Buffers, barrriers and blankets
(1) intact valley fill
(2) alluvial plain with cutoffs/palaeochannels
(3) discontinuous channels & marshes
(4) dam
effective catchment area

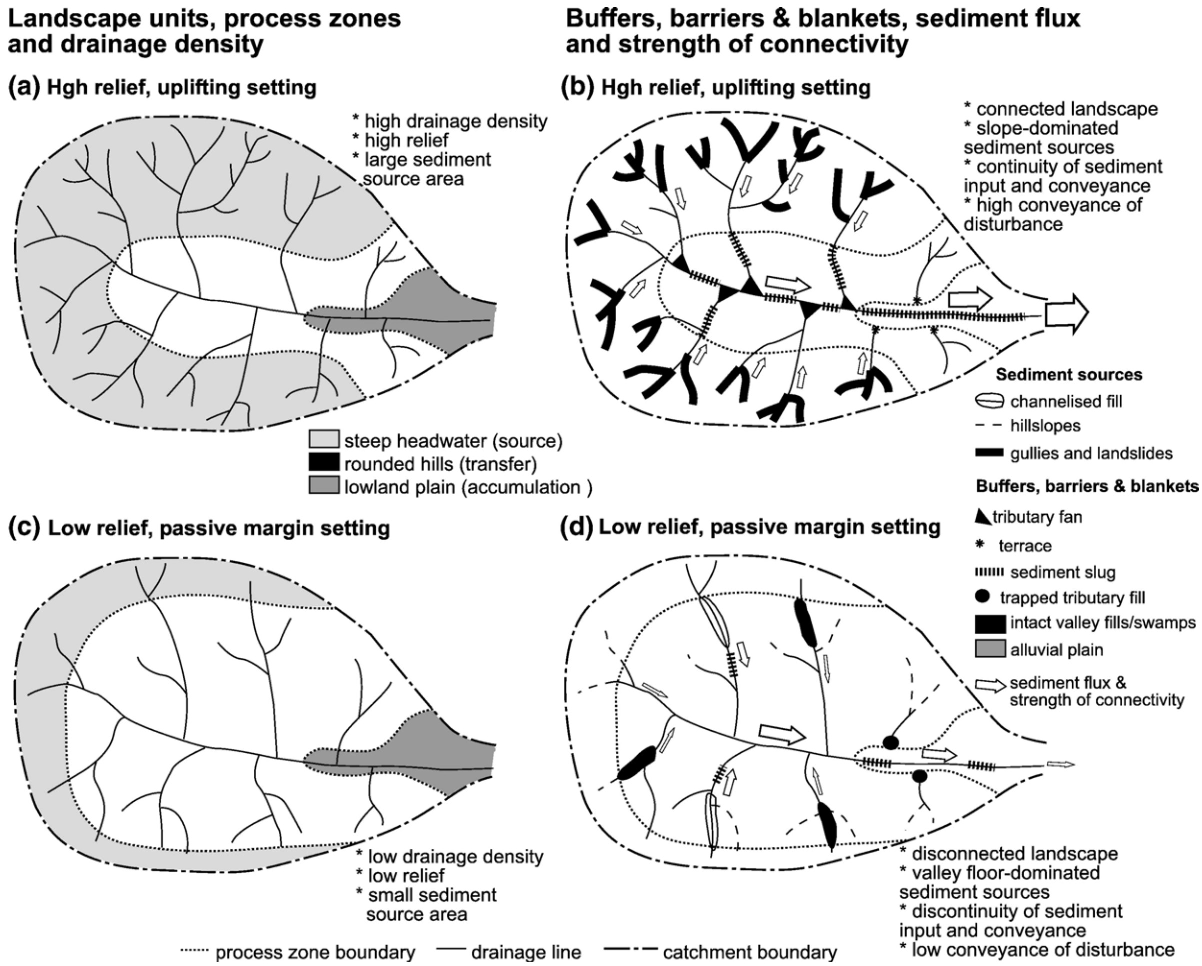


Fig. 7. Generalised patterns of (dis)connectivity in sediment fluxes in high relief, uplifting terrains versus low relief, passive margin settings. (a) Catchments in high relief, uplifting terrains tend to have high drainage densities. The catchment configuration is dominated by steep headwater (sediment source) zones which are transitional to very efficient transfer zones and expansive lowland plains (c.f. Schumm, 1977). (b) Within the source zones, significant volumes of material are supplied from hillslope gully complexes and landslides. These materials are effectively transferred along the tributary and trunk stream network in the form of translating and dispersing sediment slugs. Occasional blockages in the form of alluvial fans impede the downstream conveyance of sediment. Along the lowland plains, sediments are effectively evacuated from the catchment. Overall, the degree of catchment connectivity is high and sediment delivery to the river mouth is high. (c) In contrast, catchments in low relief, passive margin settings tend to have low drainage densities and a catchment configuration dominated by subdued topography. Steep headwater zones tend to be relatively small and lowland alluvial plains expansive. (d) Significant sediment stores occur in these landscapes which act to buffer and disconnect sediment conveyance through the system. The majority of sediments delivered to the channel network are derived from valley floor stores which are irregularly reworked. Sediment slugs tend to form blockages within the system and significant blanketing of floodplains/alluvial plains leads to downstream decreasing sediment conveyance. Overall, there is significant disconnectivity and sediment delivery ratios at the basin mouth are low.

to sediment supply to the ocean (Fig. 5c). Today, the lowland river contains a sediment slug comprised of materials derived from incision into intact valley fills and bank erosion (Fig. 5d). This sediment slug, generated within a few decades of European settlement, acts as a plug on sediment movement to the estuary (Fryirs and Brierley, 2001). In addition, a sand sheet covers parts of the lowland floodplain of the lower Bega River, presenting a blanket that further removes sediment from the cascade.

Sediment conveyance is equally disrupted across much of inland Australia, where low relief limits the potential for efficient sediment movement. Vast volumes of sediment are locked up in sediment sinks, as exemplified by the suspended load sediment budget for the Murrumbidgee catchment derived by Olive et al. (1994) (Fig. 6). In this catchment, the disconnectivity in sediment flux is a function of limited sediment source area and the pattern of deposition along the Riverine Plain. Moving downstream, sediment load increases

Fig. 6. The nature of (dis)connectivity in the Murrumbidgee catchment pre- and post-European settlement. This figure depicts the changing nature of (dis) connectivity in the suspended load sediment flux of the Murrumbidgee catchment in Australia in the periods pre- and post-European settlement. This diagram is represented as a switch diagram whereby tributaries contribute materials to the trunk stream and eventually the Murray and Lachlan Rivers. The nature and degree of (dis)connectivity (i.e. whether switches are on or off) has changed as a result of geomorphic changes that occurred as a result of human disturbance post-European settlement. The numbers at each switch reflect the type of buffer, barrier or blanket responsible for the switch being turned off. The effective catchment area is also noted. The sediment flow diagram is modified from Olive et al. (1994).

progressively only as far as Wagga Wagga (Olive et al., 1994). Gully and bank erosion in small, relatively steep tributary basins contributes over 90% of the sediment load that reaches this locality (Wallbrink et al., 1994; Wasson, 1994; Page and Carden, 1998). In the period prior to European settlement, when most valley fills were intact, these tributaries acted as buffers between sediment delivered from the range and the broad alluvial plains further downstream (Fig. 6c). Hillslopes remain a minor source of sediment, with buffers disconnecting slopes from channels (Wallbrink et al., 1994). Following impacts of European disturbance, sediment conveyance has been enhanced by increased longitudinal connectivity in the upper parts of the catchment as formerly intact valley fills have been evacuated.

Further inland, sediments derived from the headwaters have infilled a large alluvial basin, forming large anastomosing distributary networks with floodouts, terminal lakes and extensive, low lying floodplains. This landscape condition, combined with a lack of tributary inputs to the lower Murrumbidgee, ensures that the very low slope, low energy, semi-arid system below Wagga Wagga is an area of sediment storage. The majority of floodplain deposition occurs between Wagga Wagga and Narrandera where approximately 60% of the load is removed from the sediment cascade and stored in large sediment sinks (Olive et al., 1994). This floodplain system acts as a buffer to downstream sediment conveyance. Less than 20% of the sediment transported through Wagga Wagga is delivered to the Murray River (Fig. 6; Olive et al., 1994).

1.4. Comparison of landscape connectivity in high relief, uplifting terrains relative to low relief, passive margin settings

Although end-member situations have been used, the contrast between Australian and New Zealand landscapes provides a picture of how (dis)connectivity and (de)coupling notions can be used to explain spatial and temporal variability in fluvial dynamics, evolution and sediment cascading processes. In general, the connectivity of uplifting terrains, such as New Zealand, is dynamic and variable. The high drainage density of the dissected landscapes that are characteristic of this setting presents a ‘connected’ landscape configuration that promotes efficient sediment conveyance (Fig. 7a,b). In these settings, high relief promotes both the generation of large volumes of sediment and efficiency of conveyance of hillslope-derived sediment. High energy conditions on valley-floors also enhance rates of sediment reworking along the channel network. While disconnectivity does occur in this landscape setting, it is typically short lived. Hence, effective catchment areas are high and a large proportion of the catchment area is connected to the sediment cascade. Given the relatively high proportion of the landscape comprised of steep terrain and the efficiency of lateral connectivity, the dominant sediment sources are colluvially derived (e.g. headwater landslide sources). Exceptionally high sediment yields, ongoing sediment generation and sustained sediment reworking maintain catchment connectivity and geomorphic change over relatively short timeframes.

This scenario contrasts starkly with the low relief, low drainage density landscapes of passive margin terrains such as eastern Australia, where source areas are relatively small and extensive sediment stores form impediments to sediment conveyance in ‘disconnected’ landscapes (Fig. 7c,d). In these low energy settings, sediment conveyance is restricted to episodic, infrequent, large magnitude events. Residence times of sediment stores may extend over tens or hundreds of thousands of years. Indeed, these sediment stores, in themselves, act as impediments to the contemporary sediment flux. At the continental scale, only 20% of the total load to Australian rivers is exported from these systems (NLWRA, 2001). Around 90% of the river sediment load is generated from only 20% of the contributing catchment area i.e. effective catchment areas are small (NLWRA, 2001). Reworking of alluvial sediment stores via incision of valley fills and bank erosion is the dominant contemporary sediment source in this supply-limited or sediment-starved landscape. Significant disconnectivity ensures that long lag times may be experienced between phases of geomorphic change and off-site response.

2. Discussion

2.1. Landscape (dis)connectivity and propagatory effects in catchments

Continuity of sediment movement in different landscape settings reflects the availability of energy to drive geomorphic processes that mobilise sediments. The nature of system response to perturbation is contingent on the inherent sensitivity of the system to change, the volume of sediment stored within the system, the ease with which it can be conveyed and the strength of connectivity within and between landscape compartments (Brunsden and Thornes, 1979; Brunsden, 2001; Thomas, 2001). Given the range of contingencies acting in different landscape settings, responses to geomorphic adjustments will be non-linear and catchment-specific (Chorley and Kennedy, 1971; Phillips, 1992b).

The distribution of landforms or features that suppress or impede the transmission of propagatory effects influences potential responses of systems to geomorphic change (c.f. Brunsden, 1993b, 2001). Whether associated with external triggers such as climatic or tectonic events (e.g. Schumm and Rea, 1995) or internal changes in system state such as land use changes (e.g. DeRose et al., 1998; Fryirs and Brierley, 2001), the position and geomorphic role of buffers, barriers and blankets will affect the degree to which disturbance impacts are propagated and will have an off-site impact. As a result, responses to disturbance may be manifest throughout the system or absorbed within certain parts of the system. It is only within the effective catchment area that linkages maintain and propagate geomorphic responses to disturbance.

The geomorphic role of buffers, barriers and blankets, and their impacts upon sediment fluxes, are scale dependent. As noted by Walling (1983), Milliman and Syvitski (1992), Wasson (1994) and others, smaller catchment areas are able to deliver a greater proportion of available sediment to their outlets relative to larger catchments. This reflects the buffering effects of larger systems, the greater capacity for sediment storage, and relative reduction in the effective catchment area that contributes to the sediment flux. Similarly, the geomorphic effectiveness and off-site consequences of disturbance events will be influenced by the scale and location of impediments to sediment conveyance, and the recurrence with which they are reworked/breached. For example, the location of any given floodplain pocket determines whether its primary role is to disconnect lateral or longitudinal linkages. In headwater zones, floodplains or alluvial fans disconnect lateral linkages by buffering slopes and valley floors at the zonal scale (e.g. Harvey, 2001). However in lowland zones, floodplain accretion removes sediment from the cascade, thus also disrupting longitudinal sediment conveyance at the system scale (e.g. Trimble, 1983; Knox, 1987; Phillips, 1992a, 1995).

Catchment configuration and scale are critical determinants of system responses to disturbance events. The distribution of buffers, barriers and blankets determines the capacity of any given part of a landscape to be involved in the sediment flux over any given time interval. Changes to the distribution of impediments to sediment conveyance alter system performance over time (Brunsden, 2001). Understanding the spatial and temporal distribution of landscape (dis)connectivity enhances our capacity to isolate the source and impacts of perturbations and predict whether a system will manifest that change or dilute/absorb that change (Thomas, 2001). Consequently, potential off-site impacts may be identified and lag times forecast.

2.2. The role of human disturbance in changing landscape (dis)connectivity

The type, extent and consequences of human disturbance to landscape connectivity vary markedly in different landscape settings. Changes to the types and pattern of buffers, barriers and blankets determine the timescales over which human disturbance responses are transmitted through landscapes. In some settings, riverscapes have become increasingly disconnected as a result of human disturbance. For example, the construction of dams and reservoirs along the Murrumbidgee River has further disrupted the longitudinal movement of sediment in an already highly disconnected landscape (Olive et al., 1994; see Fig. 6a,d). Elsewhere, human disturbance has increased landscape connectivity and hence effective catchment area. For example, the channelisation of previously discontinuous watercourses in the upper Bega catchment and enhanced sediment conveyance along the trunk stream has increased longitudinal connectivity, thereby enhancing the efficiency of the sediment cascade (Brierley et al., 1999; Fryirs and Brierley, 2001; see Fig. 5d).

In other settings, human disturbance has altered the effective timescales over which connectivity occurs. For example, in the Weraamaia catchment in New Zealand, deforestation in the late 19th and early 20th centuries exerted a lasting influence on erosional activity prior to reafforestation in the 1980s (Kasai et al., 2005). Initially, gully complexes were the dominant sediment source, with effective slope–channel coupling for almost 100 years (DeRose et al., 1998). Recent reafforestation has lead to a shift in the dominant sediment source from gully complexes to shallow landslides that recover within a few years (Harmsworth et al., 2002; Reid and Page, 2002). As a result, effective timescales of disconnectivity have increased.

2.3. Implications for assessment of geomorphic river recovery

Appraisals of geomorphic river recovery potential entail determination of trajectories of change, placing reaches within their catchment context (Fryirs and Brierley, 2000, 2001). Effective description and explanation of the history and connectivity of sediment movement throughout a catchment provide a basis to predict the likely future trajectory of geomorphic change by examining where future sediment source, transfer and accumulation zones will be located. The character, behaviour and evolutionary traits of each catchment, with its specific configuration and landscape history, determine the capacity, type and rate of recovery (Phillips, 1992b). Factors that influence these relationships include the nature and extent of disturbance, the inherent

Layer 1: **Within-compartment sensitivity** = capacity for adjustment and breaching of intrinsic thresholds (i.e. ability of sediments to be supplied and reworked on a hillslope or on the valley floor).

Layer 2: **Between-compartment sensitivity** = connectivity between slopes-channels, channels-floodplains, tributaries-trunk streams, upstream-downstream and surface-subsurface as expressed through the distribution and breaching of buffers, barriers and blankets.

Layer 3: **Landscape/ catchment sensitivity** = The degree of propagation through a catchment as expressed by the effective catchment area.

Fig. 8. The layers of information required to assess landscape sensitivity.

sensitivity of the river type, and the operation of biophysical fluxes (both now and into the future) as determined by landscape connectivity. When these notions are combined with interpretations of limiting factors to recovery and appraisal of ongoing and likely future pressures that will shape river forms and processes, a basis is provided to assess the degree/rate of propagating impacts throughout a catchment, and hence predict likely future river condition (Brierley and Fryirs, 2005).

In an Australian context, limited sediment availability and inefficient sediment delivery severely constrain the prospects for river recovery (Fryirs and Brierley, 2000; Fryirs, 2001; Fryirs and Brierley, 2001; Brooks and Brierley, 2004). The timeframe of geomorphic river recovery is relatively long as large parts of catchments are disconnected from the sediment cascade. In contrast, in landscape settings where connectivity is high, and sediment reworking along river courses is rapid, the potential for geomorphic river recovery is relatively enhanced. For example, in landscape settings such as New Zealand, sediment availability is high and sediment delivery efficient. The timeframe of geomorphic recovery is relatively short as large parts of catchments are recurrently connected.

2.4. Implications for analysis of landscape sensitivity

Landscape sensitivity cannot be explained independently from appraisals of landscape connectivity (Brunsden, 2001; Thomas, 2001; see Fig. 8). Appraisal of *within-compartment* sensitivity to change entails assessment of the ease with which differing sediment stores respond to disturbance events of a given form or magnitude. Areas of within-compartment sensitivity generally occur where significant sediment sinks or stores are coincident with energy conditions that are sufficiently high to induce sediment entrainment and evacuation. This requires assessment of event sensitivity/resistance (Crozier, 1999; Fryirs, 2001) and event stratigraphy/sequencing (Brunsden, 2001; Thomas, 2001). Key guidance may be provided by determining the ratio between sediment availability and transport capacity within the landscape compartment, determining whether the compartment is sediment transport-limited or sediment supply-limited (Fryirs and Brierley, 2001). Event sensitive compartments have large sediment stores that are primed for change (i.e. exceedance of either intrinsic or extrinsic thresholds could induce change given a large enough event). These landscape compartments may be considered sediment transport-limited (sediment supply $\gg$ transport capacity) (Bull, 1979). Event resilient compartments have limited sediment stores which experience no significant geomorphic change notwithstanding receipt of energy impulses that elsewhere would be sufficient to elicit geomorphic response. These landscape compartments may be considered sediment supply-limited (sediment supply $\ll$ transport capacity) (Bull, 1979). The degree to which a landscape compartment is event-sensitive or event-resilient may change over time. Of particular importance is the determination of those parts of catchments that are ‘primed for change’, whereby exceedance of threshold conditions promotes the reworking of sediment stores (Schumm, 1973, 1979). *Between-compartment sensitivity* is assessed by examining the strength of longitudinal, lateral and vertical linkages within catchments. Analysis of the breaching capacity of buffers, barriers and blankets, expressed as the magnitude, frequency and sequencing of events required to rework sediments, and the effective timeframe over which this will occur, determines the degree to which landscape compartments are (dis)connected (Harvey, 2001, 2002). In this context, buffers, barriers and blankets act like a filter through which change may or may not progress (Phillips, 1992a; Crozier, 1999).

Analysis of patterns of compartments within a catchment, and related changes to effective catchment area and effective timescales of (dis)connectivity, dictates the degree of *landscape/catchment sensitivity*. The sensitivity of landscapes to change, in terms of the rate and extent of adjustment following disturbance events, is influenced markedly by the ease with which propagatory effects may be expressed through a system (Brunsden and Thornes, 1979; Brunsden, 1993a,b; Thomas and Allison, 1993; Brunsden, 2001; Thomas, 2001). Event-sensitive landscapes are highly connected (have large effective catchment areas), and are able to readily transmit geomorphic changes. In contrast, event-resilient landscapes are disconnected (have small effective catchment areas), and the propagatory effects of geomorphic change may not be manifest in the system or may only be expressed after a significant time lag.

2.5. Landscape (dis)connectivity, modelling and interpreting sedimentary archives

Because barriers, buffers and blankets affect landscape connectivity at various scales, their presence directly and explicitly precludes extrapolation of small-scale studies to larger areas (Meade, 1982; Thomas, 2001). This is the classic sediment delivery dilemma identified by Walling (1983). A clear implication of this dilemma is that researchers and managers working in areas of limited data availability must beware the dangers of averages or extrapolation. Knowledge of sediment redistribution dynamics for part of a catchment does not equate to a full understanding of the system in its entirety (Thomas, 2001). Because the most basic effect of buffers, barriers and blankets is to attenuate or impede sediment movement, storing it in various places and for various times, simple spatially and temporally undifferentiated information cannot adequately describe sediment fluxes at larger spatio-temporal scales. Hence, modelling procedures used to derive catchment sediment budgets require catchment-specific information on the location and residence time of storage units that act as buffers, barriers and blankets (c.f. Preston and Schmidt, 2003; Schmidt and Preston, 2003). Obviously, the operation of the sedimentary cascade differs depending on the nature of the landscape setting, as has been demonstrated here through contrasting examples from

Australia and New Zealand. Although generalised relationships of connectivity across/between landscapes settings can be derived, significant variability in local conditions dictates the degree and type of connectivity observed in any catchment.

One of the more important implications of (dis)connectivity for geomorphology is its effect on the formation of sedimentary archives. The episodic, irregular and interrupted nature of sediment fluxes that result from changing spatio-temporal patterns of connectivity must inevitably be reflected in complex modes of formation of sedimentary sequences (Maklin and Lewin, 1989; Maklin et al., 1992). Accumulated sediments, especially those in higher order depositional sites, will potentially be derived from a variety of different sources that vary in relative importance through time (Meade, 1982; Thomas, 2001). This impacts directly on the inferences that are made about the past behaviour of sediment redistribution processes, and thus reconstruction of past climates and the nature and mechanisms of landscape change. As Lang and Hönscheidt (1999) have demonstrated, the sedimentary archives of even small systems can reveal a complex pattern of formation reflecting both the frequency, magnitude and duration of erosional, transport and depositional processes and the spatial context in which they operate. The importance of these phenomena has long been recognised (e.g. Walling, 1983). Unravelling these complexities represents a significant challenge to geomorphologists. A common element linking these phenomena, and at least part of the reason for their complexity, is the role of landscape (dis)connectivity.

3. Conclusion

This paper presents a conceptual framework that builds on existing concepts of landscape (dis)connectivity and (de) coupling in longitudinal, lateral and vertical linkages within catchments. Analysis of buffers, barriers and blankets has significant implications in validating catchment-scale sediment cascades/budgets, sediment transport modelling and the interpretation of environmental histories through examination of stratigraphic sequences. In addition, assessment of landscape (dis)connectivity over various spatial and temporal scales provides a platform with which to examine river recovery potential, landscape sensitivity and the functioning of various biophysical fluxes (such as water flow, organic matter processing, nutrient cycling, etc.). These insights into catchment-scale fluxes provide critical tools with which to design and implement river rehabilitation strategies.

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