Area (2006) 38.2, 165–174

Landscape connectivity: the geographic basis of geomorphic applications

Gary Brierley*, Kirstie Fryirs and Vikrant Jain****

*School of Geography and Environmental Science, University of Auckland, Private Bag 92019, Auckland, New Zealand

Email: g.brierley@auckland.ac.nz

**Department of Physical Geography, Macquarie University, North Ryde, NSW 2109, Australia

Revised manuscript received 26 October 2005

Geographic concerns for spatial relationships lie at the heart of geomorphic applications in environmental management. The way in which landscape compartments fit together in a catchment influences the operation of biophysical fluxes, and hence the ways in which disturbance responses are mediated over time. These relationships reflect the connectivity of the landscape. A nested hierarchical framework that emphasizes differing forms of (dis)connectivity in catchments is proposed. This field-based geomorphic tool can be used to ground the application of modelling techniques in analysis of catchment-scale biophysical fluxes.

Key words: *geomorphology, connectivity, disconnectivity, spatial relations, modelling, biophysical template, environmental management*

Introduction: how spatial relationships underpin geomorphic enquiry

Changes in societal needs, technological advancement and institutional arrangements have seen countless attempts to (re)define geomorphic enquiry and its relation to the discipline of Geography. Examples include the perceived threat (or opportunity) presented by the emergence of Environmental Science (and Management), Environmental or Global Change, and Earth System Science (e.g. Brown 1975; Stoddart 1987; Pitman 2005). While these concerns should not be considered lightly, the geographic label will always represent analysis of spatial relationships, human interactions with land, air and water, and concerns for adjustment or change over a range of spatial and temporal scales (from local to global, from instantaneous events to geological evolution). Increasingly, as we endeavour to predict social, economic, climatic or environmental futures, we recognize the need to appraise notions of connectivity, whether considered in terms of human–human interactions, human–landscape interactions, or interactions within the landscape itself. Such holistic concerns lie at the heart of Geography as a discipline. In this contribution, the importance of catchment connectivity as a key geomorphic consideration in environmental management is highlighted.

Landscape setting, and the configuration of any given catchment, shapes the operation of geomorphic processes over a range of spatial and temporal scales. Resulting spatial relationships determine patterns and rates of water, sediment and nutrient flux, and influence biophysical processes that affect habitat availability and viability and various biogeochemical functions. Increasingly, modelling applications are used to characterize, explain and predict these interrelationships. In this contribution, a cautionary note is flagged regarding the need to ground these insights in the field, emphasizing the need to appraise landscape (dis)connectivity within any given catchment. A conceptual framework by which notions of catchment (dis)connectivity can be appraised across an array of scales is proposed.

ISSN 0004-0894

Limitations of landscape modelling: the need to 'ground' knowledge through catchment-specific knowledge

Various technological advances have markedly improved our capacity to promote applied geomorphology through enhanced use of satellite imagery, digital elevation models and dynamical modelling techniques within Geographic Information Science (e.g. Wainright and Mulligan 2004; Coulthard *et al.* 2005). Ultimately, this knowledge must be grounded for any given catchment. This is particularly important in the design and implementation of conservation and rehabilitation measures. Limitations of available data constrain the spatial context with which 'products' of environmental models can be reasonably applied, confounding attempts at landscape-scale prediction other than in highly generalized, average terms (Montgomery 2001). Although models provide invaluable insights into the operation of processes under certain sets of conditions, it is unlikely that deterministic quantitative prediction based on mechanistic reasoning can be reliably applied at anything other than small spatial and temporal scales in artificially constrained closed systems. Many cause and effect relationships, defined through small-scale (experimental) studies, cannot simply be up-scaled in a reliable manner (e.g. Wilcock and Iverson 2003).

Overly generalized suites of catchment-scale relationships may provide a basis for comparison and extrapolation, but little is to be gained in management terms through the use of generalized morphometric descriptions and overly simplistic notions of equilibrium landscape behaviour (e.g. Phillips 1992a). While the value of general relationships and patterns detected at a regional level within any particular topographic/climatic area should not be undervalued, patterns of sediment source, transfer and accumulation zones and their connectivity may differ notably from the generalized upstream–downstream framework outlined by Schumm (1977) (see comments by Newson 1992). Black-box syntheses that convey a 'normalized' variant of reality negate the inherent diversity of individual systems.

A real-world sense of landscape forms, processes and interactions, framed in terms of qualitative probabilistic predictions, conveys an intellectually honest appraisal of the inherent complexity of landscape relationships within any given catchment. Recognition that the future state of complex systems is inherently unknowable, and surprising outcomes are inevitable, represents a stepping-stone towards best management practice (Phillips 1992b). Grounding of theoretical (or empirical) insights through field-based enquiry provides the vital linkage that is required for management applications.

Catchment-specific knowledge of landscape character and behaviour, connectivity and evolution provides a physical platform with which to engender effective engagement and maximize potential outcomes in environmental management (e.g. Brierley *et al.* 2002). Communities have every right to expect that decisionmaking is pertinent to their own system of concern, not some 'averaged' perspective based on a region other than their own. Effective *description* of landscape compartments, and their spatial organization, provides a catchment-framed basis with which to appraise system dynamics and related evolutionary tendencies. Understanding connectivity between landscape compartments is pivotal in *explaining* spatial relationships, the behaviour of biophysical fluxes and associated trajectories of adjustment. These insights must be framed in context of landscape history to appraise the sensitivity of differing parts of catchments to disturbance, any limiting factors or pressures that occur and the likely nature of cumulative off-site responses (Brierley and Fryirs 2005). Hence, catchment-specific insights are required to *predict* likely landscape futures, recognizing differing forms and scales of (dis)connectivity.

Forms of landscape connectivity

Analysis of the character and behaviour of landscape compartments, how they fit together (their assemblage and pattern) and the connectivity between them, provides a platform to interpret the operation of geomorphic processes in any given system (e.g. Caine and Swanston 1988; Lane and Richards 1997; Harvey 2001 2002; Michaelides and Wainright 2002; Hooke 2003). Lagged and off-site responses to geomorphic change vary from catchment to catchment, reflecting the pattern and degree of (dis)connectivity of landscape compartments (Fryirs *et al.* in press). Longitudinal, lateral and vertical linkages reflect the operation of different processes at different positions in a catchment (Ward 1989; Table 1). *Lateral* linkages include slope–channel and channel–floodplain relationships that drive the supply of materials to a channel network. *Longitudinal* linkages, such as upstream–downstream and tributary–trunk stream relationships, drive the transfer of flow through a system and the ability of channels to

Table 1 Forms of landscape linkage and measures of their (dis)connectivity

Type of linkage/scale	Processes	Measures used to assess strength of linkage	Controls
Within landscape compartment			
Landform-scale analyses (colluvial) (lateral linkage)	Development and reworking of hillslope processes along a catena.	Characterize sediment delivery within hillslope compartments through appraisal of the mechanisms, rates and downslope transfer of sediment along the catena. Assess any impediments to downslope sediment transfer in zero and first order systems.	Slope angle and morphology. Underlying geology and rates of sediment generation and reworking.
Landform-scale analyses (alluvial) (lateral linkage)	Formation and reworking of floodplains. Sediment transport and deposition in channels.	Characterize sediment storage and reworking on the valley floor. Appraisal of the mechanisms and rates of floodplain formation and reworking, and sediment transport capacity of channels.	Valley confinement and slope. Sediment supply and the magnitude-frequency of flows.
Surface–subsurface (vertical linkage)	Surface–subsurface exchange of water, sediment and nutrients. Infiltration and filtering. Maintenance of base flow.	Characterize sediment and water exchange between surface waters and ground water compartments. Determine the presence, distribution and role of blankets that impede exchange between surface and subsurface compartments and their potential to be reworked.	Bed material texture. Sediment transport regime of the channel. Recurrence of channel flushing flows. Ground-water mechanisms.
Between landscape compartment			
Upstream–downstream (longitudinal linkage)	The transfer of flow through a system. The efficiency of supply, transfer and storage of sediments of variable calibre.	Appraise the pattern and role of barriers and boosters (i.e. longitudinal connectivity and continuity within the system). How readily can these barriers be reworked (i.e. the threshold conditions and recurrence interval under which they are likely to be breached)? Estimation of the ratio of transport capacity for a given range of events relative to sediment availability (and the character/accessibility of stores) involves examination of the degree of channel bed aggradation or degradation, the distribution of bedrock steps along the longitudinal profile and the degree of channel and valley confinement.	Base level. Sediment transport regime of the system (i.e. sediment supply or sediment transport limited).
Tributary–trunk stream (longitudinal linkage)	The transfer of flow through a system. The supply, transfer and storage of sediments of variable calibre.	Appraise the patterns of tributary (dis)connectivity by examining how often and over what length of river course tributaries are joined or disconnected from the trunk stream. Are buffers absent/present? Examine the impact that tributary contributions have on the trunk stream at the confluence (e.g. aggradation or degradation).	Shape of the catchment (i.e. its elongation ratio). Drainage pattern and density.
Slope–valley floor (lateral linkage)	Slope denudation and erosion via mass movement, creep, wash, etc. Colluvial footslope deposition and reworking. Deposition and reworking of materials on the valley floor. Channel adjustment on the valley floor.	Appraise how readily sediments transferred downslope are made available to channels. Are buffers absent/present? What is the position of the channel on the valley floor and the nature of the hillslope–channel interface? Interpret the frequency with which impediments to sediment conveyance off hillslopes may be breached.	Confinement of the valley floor. Channel position on the valley floor. The magnitude of flow events along the valley floor will dictate whether materials will be reworked along the channel network.

Table 1 ***Continued.***

Type of linkage/scale	Processes	Measures used to assess strength of linkage	Controls
Channel–floodplain (lateral linkage)	Channel adjustment on the valley floor. Floodplain formation and reworking.	Appraise the character and volume of materials stored on valley floors, and the contemporary flux (i.e. floodplain accretion or reworking). Determine whether the reach operates as a sediment source, transfer or accumulation zone. What is the channel size and shape? What is the degree of channel aggradation or degradation relative to floodplain height? What is the floodplain inundation frequency? Is there any evidence of channel migration, avulsion, expansion, contraction?	Bed and bank material texture. Sediment transport regime of the channel relative to the floodplain. The magnitude and inundation frequency of overbank events that drive mechanisms of channel adjustment, and floodplain formation and reworking.
Subcatchment scale			
Valley segment–valley segment	The pattern and sequence of sediment source, transfer and accumulation zones along the valley floor.	Examine the pattern of upstream–downstream connectivity through the subcatchment as a whole. What is the sequence of valley settings (i.e. confined, partly confined or laterally unconfined valleys)? Are these sediment source, transfer or accumulation zones? Appraise the pattern and role of barriers and boosters (i.e. longitudinal connectivity and continuity within the system). Interpret the capacity for downstream propagation of sediment release from primary sediment stores, and their likely off-site impacts. Assess whether this is a transport-limited or a supply-limited system.	Valley confinement, valley slope, valley morphology which are controlled by underlying geology and landscape evolution.
Land system assemblage	Areas of relatively uniform topography measured in terms of relief, landform morphology, valley confinement and geology. Summarize slope–valley floor configuration.	Appraise tributary–trunk, slope–valley floor and channel–floodplain in the subcatchment as a whole. The role of buffers to sediment conveyance is examined.	Hillslope morphology, valley floor confinement, valley slope, valley morphology which are controlled by underlying geology and landscape evolution.
Catchment scale			
Catchment configuration	How valley segments and land systems fit together and are connected across a catchment to explain across-catchment variability in patterns of (dis)connectivity and flux.	Measure the effective catchment area. Appraise how subcatchments fit together at the catchment scale through integration of subcatchment-scale relationships. Frame this in terms of analysis of how catchment shape, elongation ratio, etc. impact upon sediment conveyance, storage, etc. Determine the position of the most downstream blockage that impedes sediment output from the system. Predict the sensitivity of the landscape to change, where change will occur and be propagated from, and likely geomorphic responses.	Subcatchment variability in patterns of valley segments and land systems which are controlled by underlying geology and landscape evolution.

transfer or accumulate sediments of variable calibre on the valley floor. *Vertical* linkages refer to surface–subsurface interactions of water, sediment and nutrients.

At any position in the landscape, these linkages may be connected (coupled) or disconnected (decoupled) over differing timescales (Harvey 2002; Fryirs *et al.* submitted). Various buffers, barriers, blankets and boosters can disrupt (or enhance the strength of) longitudinal, lateral and vertical linkages (Fryirs *et al.* submitted). *Buffers* are landforms such as swamps, alluvial fans and floodplains that impede sediment transfer to the channel network. Once sediment is in the channel network, *barriers* such as bedrock steps and sediment slugs can temporarily disrupt sediment moving along the channel network. *Blankets* are features such as floodplain sediment sheets that smother other landforms, protecting them from reworking and temporarily removing those stores from the sediment cascade. In contrast, reaches such as gorges may enhance propagation, acting as *boosters* for sediment conveyance.

Effective description and explanation of the (dis)connectivity of sediment movement throughout a catchment provides a basis to identify sensitive parts of the landscape, thereby enabling prediction of the future trajectory of geomorphic change. 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 (Fryirs and Brierley 2001; Brierley and Fryirs 2005). These various concerns for spatial relationships in catchments highlight how geographic insights that underpin geomorphic practice are of critical concern for a host of management applications.

A generic, scalar approach to assessment of landscape connectivity is presented in Figure 1. In this conceptual framework, process understanding of individual landforms is related to the connectivity between landscape compartments, emphasizing how different parts of the landscape fit together. These interactions are then integrated at the subcatchment and catchment scales (Fryirs *et al.* in press submitted). Within-compartment analysis of biophysical fluxes is appraised on hillslopes (i.e. the catena compartment) and on valley floors (the alluvial compartment). Between compartment connectivity examines hillslope–valley floor, channel–floodplain, upstream–downstream and tributary–trunk stream linkages in different valley segments and land systems that make up a subcatchment. Impediments to the conveyance of water, sediment and nutrients at any level in the hierarchy are characterized and mapped. Determination of the conditions under which these impediments are likely to be breached is a major consideration in modelling of biophysical fluxes and related management applications.

Geomorphologists have developed sophisticated process-based understanding for certain components of landscapes in particular settings. However, other than in small-scale applications (e.g. Harvey 2001 2002), we have been far less effective at putting these insights together to provide guidance into the cumulative operation of arrays of processes and system responses to disturbance events at the catchment scale. In a sense, the framework presented in Figure 1 endeavours to balance knowledge of the boxes on a systems diagram with insight into the arrows between boxes. For example, as processes that generate and transfer materials on hillslopes operate with markedly different frequency/magnitude spectra from channel processes, phased (dis)connectivity operates over differing temporal scales. Hence, propagation of disturbance responses through catchments depends on the (dis)connectivity between adjacent compartments, and how these compartments fit together in a catchment. These relationships change over time.

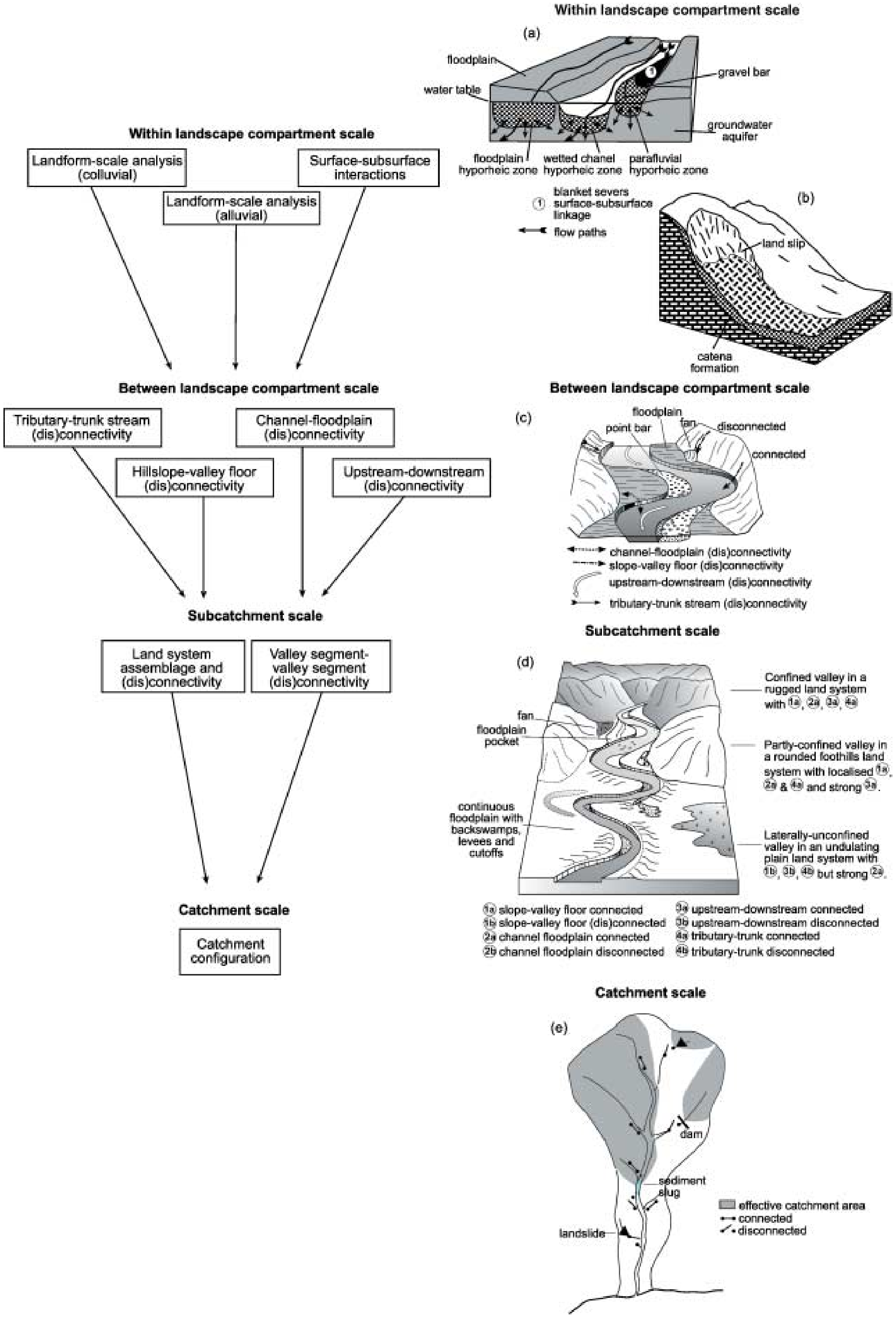
Practical applications of the scalar approach to analysis of landscape connectivity

Differing scales of landscape connectivity affect the way in which disturbance responses are transmitted through catchments, presenting important considerations in the way that we interpret system responses to disturbance events and associated management actions. Various applications of these notions are highlighted below.

The importance of landscape connectivity in interpreting landscape responses to disturbance events

The long-term record of external disturbances to river systems, whether brought about by tectonic, climatic or anthropogenic controls, is primarily assessed through analyses of depositional sequences that accumulate in downstream reaches. For example,

ISSN 0004-0894 © The Authors.


Within landscape compartment scale
Landform-scale analysis (colluvial)
Landform-scale analysis (alluvial)
Surface-subsurface interactions
Between landscape compartment scale
Tributary-trunk stream (dis)connectivity
Channel-floodplain (dis)connectivity
Hillslope-valley floor (dis)connectivity
Upstream-downstream (dis)connectivity
Subcatchment scale
Land system assemblage and (dis)connectivity
Valley segment-valley segment (dis)connectivity
Catchment scale
Catchment configuration
Within landscape compartment scale
(a)
floodplain
water table
gravel bar
groundwater aquifer
floodplain hyporheic zone
wetted chanel hyporheic zone
parafluvial hyporheic zone
① blanket severs surface-subsurface linkage
flow paths
(b)
land slip
catena formation
Between landscape compartment scale
(c)
floodplain
point bar
fan
disconnected
connected
channel-floodplain (dis)connectivity
slope-valley floor (dis)connectivity
upstream-downstream (dis)connectivity
tributary-trunk stream (dis)connectivity
Subcatchment scale
(d)
fan
floodplain pocket
continuous floodplain with backswamps, levees and cutoffs
Confined valley in a rugged land system with 1a, 2a, 3a, 4a
Partly-confined valley in a rounded foothills land system with localised 1a, 2a & 4a and strong 3a.
Laterally-unconfined valley in an undulating plain land system with 1b, 3b, 4b but strong 2a.
1a slope-valley floor connected
1b slope-valley floor (dis)connected
2a channel floodplain connected
2b channel floodplain disconnected
3a upstream-downstream connected
3b upstream-downstream disconnected
4a tributary-trunk connected
4b tributary-trunk disconnected
Catchment scale
(e)
dam
sediment slug
landslide
effective catchment area
connected
disconnected

Schumm and Rea (1995) suggested that changes to sediment yield over time provide an analytical tool with which to interpret past tectonic/climate events in upstream regions. However, while gross erosion may be directly related to the nature/extent of external disturbances, the consequences and manifestations of these events are poorly predicted by sediment yield from the basin. Ultimately, the sediment delivery ratio (SDR), which is defined as percentage of total catchment erosion transported from the basin (Roehl 1962; Walling 1983; Milliman and Syvitski 1992), provides a measure of catchment scale (dis)connectivity. Indeed, variability in SDR can be explained through appraisal of differing forms of (dis)connectivity in a river basin. Hence, in order to interpret the sedimentary record of any particular geological or geomorphological event in depositional sequences, sediment yield must be related to assessment of (dis)connectivity in the system.

Appreciation of landscape (dis)connectivity is particularly important in analyses of sediment conveyance, and resulting depositional sequences, in large river systems. This can be considered as a form of downsystem functional (dis)connectivity. While 'coupled' basins are sensitive to upstream disturbance, lowland basins in 'decoupled' systems may be minimally affected by upstream perturbations. Hence, in some instances, depositional records in lowland basins may provide an insensitive guide to the history of disturbance events in upstream areas. For example, quantitative analysis of sediment discharge in large river basins (drainage area of the order of 10^5–10^6 km^2) in south and east Asia, namely the Ganges–Brahmaputra, the Changjiang, the Huanghe, the Indus and the Zhujian, suggests that present-day average sediment discharge at basin outlets has remained constant throughout the Quaternary, even though episodes of uplift and climate oscillations (of the order of 10^4 years) have been experienced in upstream regions (Metivier and Gaudemer 1999). The record of these events may have been diluted or buffered by large floodplain areas, such that sediment delivery to the deltaic region provides an insensitive guide to the timing and consequences of upstream perturbations. As an interesting contrast, Goodbred (2003) indicates that during the Holocene there has been a tightly coupled relationship (over 3000 km distance) between disturbance events in mountain headwaters and sedimentation responses on deep sea fans, as interpreted from analyses of sedimentation rates in the Ganga–Brahmaputra delta region (Goodbred and Kuehl 1999). The contradictory nature of these basin-scale studies indicates the need to quantify connectivity at different spatial and temporal scales across a system. Deposits from 'disconnected' parts of river basins will provide patchy records, at best, of geological events in upstream regions. Hence, understanding of coupling/connectivity in a system is a critical consideration in interpretations of geological and climatic events through analyses of the sedimentary archive.

River responses to base-level change present an interesting contrast to these notions of downsystem functional (dis)connectivity. In general terms, base-level lowering enhances upsystem functional connectivity via propagation of coupling relationships, especially in tectonically active areas. Examples that demonstrate timescales of upsystem propagation and/or damping of river responses to base-level changes are reported by Blum and Tornqvist (2000). Similar types of upsystem response have been recorded in smaller systems in different parts of

Figure 1 Scales of landscape connectivity within a catchment (a) Blankets may impede surface–subsurface interactions along a channel and its floodplain. Form–process associations of landforms are examined at this scale; (b) Landslip and hillslope forming processes. Soil formation and material movement on/off hillslopes are examined at this scale; (c) Tributary–trunk stream, slope–valley floor, upstream–downstream and channel–floodplain linkages are examined at the between landscape compartment scale. These linkages can be longitudinal and lateral, and connected or disconnected depending on the distribution of buffers and barriers. In this diagram, fans and floodplains act as buffers to sediment conveyance from hillslopes to the channel network; (d) Land system and valley segment assemblages are put together to explain (dis)connectivity at the subcatchment scale. Various degrees of tributary–trunk stream, slope–valley floor, upstream–downstream and channel–floodplain (dis)connectivity occur depending on the landscape setting and the distribution of buffers and barriers. In this example, fans and floodplains disconnect various linkages in different parts of the catchment. The effect of a buffer depends on its position in the catchment and relative size; (e) Subcatchments are pieced together to explain the across-catchment variability in linkages and to calculate the effective catchment area (Fryirs *et al.* in press submitted). In this example, some tributaries are disconnected and a sediment slug acts as a barrier to sediment conveyance through to the mouth of the catchment

catchments associated with upstream migration of headcuts, especially in cut-and-fill landscapes, altering the pattern and rate of tributary–trunk stream and slope–channel coupling over time (e.g. Harvey 2002).

Interpretation of landscape responses to human disturbance

Analysis of differing forms of landscape (dis)connectivity also represents a major consideration in analysis of catchment responses to human disturbance. Early phases of settlement history (indeed, the foundation eras of civilization) often focused on valley floors (e.g. Wittfogel 1956). Hence, areas adjacent to the channel became the focal point for disturbance – the very area where 'mobile' sediments are stored in landscapes. The nature of these materials, and their proximity to major processes of reworking, ensured that these areas are especially sensitive to geomorphic adjustment (see Brierley *et al.* 2005). However, river responses to disturbance vary at differing positions in catchments, reflecting the nature of sediment stores on valley floors. Similarly, hillslope–channel connectivity tends to become less pronounced moving downstream (e.g. Lane and Richards 1997). These relationships vary markedly in different environmental settings. For example, landscape disconnectivity may be pronounced in low-relief settings that characterize much of the Australian landscape, accentuating the relative separation of hillslope and valley floor processes (Fryirs and Brierley 1999; Fryirs *et al.* submitted). Notions of landscape disconnectivity may partially account for the pronounced difference in disturbance response of channel zones following human removal of riparian vegetation and wood (Brierley *et al.* 2005), relative to the negligible landscape imprint associated with land use changes on hillslopes proposed by Butzer and Helgren (2005) in the same region (cf. Gale and Haworth 2005).

The importance of connectivity in management applications

The success of landscape management practices is ultimately determined by engagement of society in working towards sustainable environmental futures. In landscape terms, such measures are determined by the nature and extent of people–place (dis)connection. Reverence of place is a stepping-stone to success, as care/compassion tied to appreciation of identity and diversity promotes a harmonious relationship with which to approach management practice. Disharmony of people–place connection, as manifest through programmes that fail to 'work with nature', is indicative of the disconnection or decoupling of our relationship with the Earth (see Wohl 2004). Notions of landscape connectivity are critical considerations in measures that strive to recognize, and work with, system-specific dynamics.

Given the biophysical feedbacks inherent to healthy ecosystems, proactive river management will not be achieved unless local understanding of biophysical processes is framed within a catchment context, placing due regard on the (dis)connectivity between landscape compartments. For example, sediment transfer at the catchment scale is a critical consideration in the creation of catchment visions and associated river management plans. While sediment flux may represent a hazard in its own right, changes to the nature and pattern of geomorphic connectivity may impact significantly on the operation of other biophysical fluxes such as flow, nutrient and organic matter exchange and processing, and associated habitat availability and viability (e.g. Brierley *et al.* 1999). Principles such as the River Continuum Concept (Vannote *et al.* 1980), the Serial Discontinuity Concept (Ward and Stanford 1983), the Nutrient Spiralling Model (Newbold 1992), the Flood Pulse Concept (Junk *et al.* 1989), and the Hyporheic Corridor Concept (Stanford and Ward 1993) view ecological (dis)connectivity and biotic response as a function of physical stream structure at different spatial and temporal scales (Poole 2002). Concern for catchment-scale linkages, among many considerations, has led to the proposition that large-scale projects, although not always economically or socially feasible, may offer the greatest potential for effective river rehabilitation (Shields *et al.* 2003).

Prospective advances in applied geomorphology

As highlighted by Baker and Twidale (1991), landscape-scale analysis presents an ideal opportunity for the 're-enchantment of geomorphology', enhancing our capacity to move beyond local (landform) analyses to broader appreciation of interactions between landscape compartments. Environmental outcomes of overly engineered, site-specific practices present a salutary reminder of the patchy application of geomorphic thinking. If geomorphologists do not present coherent, whole-of-landscape perspectives, and work towards their integration in contemporary environmental management practice, who will?

Analyses of landscape relationships and modelling of biophysical fluxes lie at the heart of the geographic tradition in geomorphology. Embracing advances in modelling techniques and related fields of geophysical research, and placing such insights within the re-emergence of Earth System Science (and associated labels; see variable perspectives by Pitman (2005) and Clifford and Richards (2005)), highlights the imperative to ground predictions of landscape futures through field-based observation and measurement such that they have a direct relevance to any given place (cf. Church 2005; Summerfield 2005).

Field-based analytical skills that interpret landscape connectivity must be integrated into modelling analyses using DEM, GIS and associated techniques (e.g. Coulthard *et al.* 2005). When combined with an underlying sense of place, appreciation of diversity and difference, and associated insights into human relationships, these core geographic attributes place our discipline at the heart of environmental and natural resources management, in terms of policy, planning and on-the-ground initiatives. In order to meet these commitments, institutional changes are required to ensure that training in field, laboratory and modelling skills is maintained (or enhanced) as core components of Geography, with increased emphasis upon cross-disciplinary applications of landscape-scale research. More effective engagement with engineers and ecologists, among many disciplinary specialists, is required in working towards 'Integrative Environmental Solutions'.

Acknowledgements

This research was supported by ARC Linkage Project and ARC Discovery Project Grants held by Gary Brierley and Kirstie Fryirs. Vikrant Jain holds a Macquarie University Research Fellowship. We thank Nick Preston, Ian Fuller and an anonymous reviewer for their comments on this manuscript.

References

Baker V R and Twidale C R 1991 The reenchantment of geomorphology *Geomorphology* 4 73–100

Blum M D and Tornqvist T E 2000 Fluvial response to climate and sea-level change: a review and look forward *Sedimentology* 47 (Supplement) 1–48

Brierley G J and Fryirs K 2005 *Geomorphology and river management: applications of the River Styles framework* Blackwell, Oxford

Brierley G J, Cohen T J, Fryirs K and Brooks A P 1999 Post-European changes to the fluvial geomorphology of Bega catchment, Australia: implications for river ecology *Freshwater Biology* 41 1–10

Brierley G J, Fryirs K, Outhet D and Massey C 2002 Application of the River Styles framework as a basis for river management in New South Wales, Australia *Applied Geography* 22 91–122

Brierley G J, Brooks A P, Fryirs K and Taylor M P 2005 Did humid-temperate rivers in the Old and New Worlds respond differently to clearance of riparian vegetation and removal of woody debris? *Progress in Physical Geography* 23 27–49

Brown E H 1975 The content and relationships of physical geography *Geographical Journal* 141 35–40

Butzer K W and Helgren D M 2005 Livestock, land cover, and environmental history: the Tablelands of New South Wales, Australia, 1820–1920 *Annals of the Association of American Geographers* 32 80–111

Caine N and Swanson F J 1989 Geomorphic coupling of hillslope and channel systems in two small mountain basins *Zeitschrift fur Geomorphologie* 33 189–203

Church M 2005 Continental drift *Earth Surface Processes and Landforms* 30 129–30

Clifford N and Richards K 2005 Earth system science: an oxymoron? *Earth Surface Processes and Landforms* 30 379–83

Coulthard T J, Lewin J and Macklin M G 2005 Modelling differential catchment response to environmental change *Geomorphology* 69 222–41

Fryirs K and Brierley G J 1999 Slope-channel decoupling in Wolumla catchment, New South Wales, Australia: the changing nature of sediment sources following European settlement *Catena* 35 41–63

Fryirs K and Brierley G J 2001 Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery *Geomorphology* 38 237–65

Fryirs K, Brierley G J, Preston N and Spencer J in press Landscape (dis)connectivity in the upper Hunter catchment, New South Wales, Australia *Geomorphology*

Fryirs K, Brierley G J, Preston N and Kasai M submitted Buffers, barriers and blankets: the (dis)continuity of catchment-scale sedimentary cascade *Catena*

Gale S J and Haworth R J 2005 Catchment-wide soil loss from pre-agricultural times to the present: transport- and supply-limitation of erosion *Geomorphology* 68 314–33

Goodbred Jr S L 2003 Response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstade *Sedimentary Geology* 162 83–104

Goodbred Jr S L and Kuehl S A 1999 Holocene and modern sediment budgets for the Ganges–Brahmaputra river system: evidence for highstand dispersal to flood-plain, shelf, and deep-sea depocenters *Geology* 27 559–62

Harvey A M 2001 Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity illustrated from the Howgill Fells, northwest England *Catena* 42 225–50

ISSN 0004-0894

Harvey A M 2002 Effective timescales of coupling within fluvial systems *Geomorphology* 44 175–201

Hooke J M 2003 Coarse sediment connectivity in river channel systems: a conceptual framework and methodology *Geomorphology* 56 79–94

Junk W J, Bayley P B and Sparks R E 1989 The flood pulse concept in river-floodplain systems *Special Publication of the Canadian Journal of Fisheries and Aquatic Science* 106 110–27

Lane S N and Richards K S 1997 Linking river channel form and process: time, space and causality revisited *Earth Surface Processes and Landforms* 22 249–60

Metivier F and Gaudemer Y 1999 Stability of output fluxes of large rivers in South and East Asia during the last 2 million years: implications on floodplain processes *Basin Research* 11 293–303

Michaelides K and Wainright J 2002 Modelling the effects of hillslope–channel coupling on channel hydrological response *Earth Surface Processes and Landforms* 27 1441–57

Milliman J D and Syvitski P M 1992 Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers *Journal of Geology* 100 525–44

Montgomery D R 2001 Geomorphology, river ecology, and ecosystem management in **Dorava J M, Montgomery D R, Palcsak B B and Fitzpatrick F A** eds *Geomorphic processes and riverine habitat* American Geophysical Union, Washington DC 247–53

Newbold J D 1992 Cycles and spirals of nutrients in **Calow P and Petts G E** eds *The rivers handbook* Blackwell, Oxford 379–408

Newson M D 1992 Geomorphic thresholds in gravel-bed rivers – refinement for an era of environmental change in **Billi P, Hey R D, Thorne C R and Tacconi P** eds *Dynamics of gravel-bed rivers* Wiley, Chichester 3–15

Phillips J D 1992a The end of equilibrium? *Geomorphology* 5 195–201

Phillips J D 1992b Nonlinear dynamical systems in geomorphology: revolution or evolution? *Geomorphology* 5 219–29

Pitman A 2005 On the role of geography in earth system science *Geoforum* 36 137–48

Poole G C 2002 Fluvial landscape ecology: addressing uniqueness within the river discontinuum *Freshwater Biology* 47 641–60

Roehl J W 1962 Sediment source areas, delivery ratios and influencing morphological factors *International Association of Scientific Hydrology Publication* 59 202–13

Schumm S A 1977 *The fluvial system* John Wiley and Sons, New York

Schumm S A and Rea D K 1995 Sediment yield from disturbed earth systems *Geology* 23 391–94

Shields F D Jr, Copeland R R, Klingeman P C, Doyle M W and Simon A 2003 Design for stream restoration *Journal of Hydraulic Engineering* 129 575–84

Stanford J A and Ward J V 1993 An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor *Journal of the North American Benthological Society* 12 48–60

Stoddart D R 1987 To claim the high ground: geography for the end of the century *Transactions of the Institute of British Geographers* 12 327–36

Summerfield M A 2005 The changing landscape of geomorphology *Earth Surface Processes and Landforms* 30 779–81

Vannote R L, Minshall G W, Cummins K W, Sedell J R and Cushing C E 1980 The river continuum concept *Canadian Journal of Fisheries and Aquatic Sciences* 37 130–7

Wainright J and Mulligan M 2004 Pointers for the future in **Wainright J and Mulligan M** eds *Environmental modelling. Finding simplicity in complexity* Wiley, Chichester 389–96

Walling D E 1983 The sediment delivery problem *Journal of Hydrology* 65 209–37

Ward J V 1989 The four-dimensional nature of lotic ecosystems *Journal of the North American Benthological Society* 8 2–8

Ward J V and Stanford J A 1983 Serial discontinuity concept of lotic ecosystems in **Fontaine T D and Bartell S M** eds *Dynamics of lotic systems* Ann Arbor Science, Ann Arbor MI 29–42

Wilcock P R and Iverson R M 2003 Prediction in geomorphology in **Wilcock P R and Iverson R M** eds *Prediction in geomorphology* American Geophysical Union Geophysical Monograph 135 American Geophysical Union, Washington DC 3–11

Wittfogel K A 1956 The hydraulic civilisations in **Thomas Jr W L** ed *Man's role in changing the face of the Earth* University of Chicago Press, Chicago IL 152–64

Wohl E 2004 *Disconnected rivers: linking rivers to landscapes* Yale University Press, New Haven CT