



Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems

Gary Brierley

The University of Auckland, New Zealand

Kirstie Fryirs

Macquarie University, Australia

Carola Cullum

University of the Witwatersrand, South Africa

Marc Tadaki

The University of Auckland, New Zealand

He Qing Huang

Chinese Academy of Sciences, China

Brendon Blue

The University of Auckland, New Zealand

Abstract

Assertions of a 'naughty world' (Kennedy, 1979) point to the importance of place-based knowledge in informing landscape interpretations and management applications. Building upon conceptual and theoretical insights into the geomorphic character, behaviour and evolution of rivers, this paper outlines an approach to the practice of fluvial geomorphology: 'reading the landscape'. This scaffolded framework of field-based interpretations explicitly recognizes the contingent nature of biophysical interactions within any given landscape. A bottom-up, constructivist approach is applied to identify landforms, assess their morphodynamics, and interpret the interaction and evolution of these features at reach and catchment scales. Reading the landscape is framed as an open-ended and generic set of questions that inform process-form interpretations of river landscapes. Rather than relying unduly on conceptual or theoretical representations of landscapes that suggest how the world 'should' ideally look and behave, appropriately contextualized, place-based understandings can be used to detect where local differences matter, thereby addressing concerns for the transferability of insights between locations and the representativeness of sample or reference sites. The approach provides

Corresponding author:

Gary Brierley, University of Auckland, 10 Symonds Street, Auckland City, Auckland 1142, New Zealand.

Email: g.brierley@auckland.ac.nz

a basis for scientifically informed management efforts that respect and work with the inherent diversity and dynamics of any given river system.

Keywords

catchment, evolution, landform, landscape, morphodynamics, river management, scale

I Introduction

Assertions of a ‘naughty world’ (Kennedy, 1979) point to the importance of place-based knowledge in developing understandings of landscape character and behaviour that can be used to inform planning or management decisions. It is increasingly recognized that the complexity of landscape systems (multiple causalities, feedbacks, lags, thresholds, non-linearity, emergent properties) generates inherent uncertainty, often producing surprising and/or unpredictable outcomes (Harrison, 2001; Phillips, 2004, 2011; Preston et al., 2011; Wohl, 2012). Such understandings build upon long-standing assertions in geomorphological inquiry (e.g. Richards, 1986; Richards and Clifford, 2011; Schumm, 1991; Simpson, 1963; Thorn, 1988). As landscape evolution is fashioned by spatial and temporal contingencies, geography and history conspire to create unique places, or ‘perfect landscapes’ (Phillips, 2007), which are often ‘naughty’ in one or more respects. In this complex, naughty world, how do we meaningfully incorporate difference in scientific interpretations of landscape form and function? How do we relate and integrate the particularities of site-specific process-form interactions to general (theoretical) principles? Recognizing that there are multiple interpretations and readings of landscapes, how can we best use available approaches and understandings to reliably inform management applications?

Recognizing that every location is potentially unique does not render generalizations meaningless. Regularities in time and space can still be observed as repeated patterns of landforms, and interpretations of these patterns can support efforts to meaningfully transfer understandings

from one location to another. The challenge lies in identifying where a general pattern holds true and how and when local differences may be important (see Burt, 2005; Richards et al., 1997). Theory (general understanding) informs local interpretations, but site-specific appraisals prompt insights into ‘differences’, allowing local ‘stories’ to emerge (Phillips, 2012).

Effective analysis of ‘perfect’ landscapes cannot be meaningfully formalized through prescriptive applications of ‘checklist’, ‘tick-box’ sets of rule-based procedures (Kondolf and Piégay, 2011; Newson and Large, 2006). Such rigidity belies the inherent diversity of landscapes and the overwhelming range of processes, interactions and controls that create the pattern of landforms at a particular locality. Standardized approaches to landscape classification sacrifice heterogeneity in order to generalize, treating landscape units as homogenous entities wherein all members of the same class are considered to be equivalent and interchangeable (Church, 2011). In these framings, all class members are treated as equally eligible candidates for sampling or monitoring sites, and knowledge and experience gained at these sites is assumed to apply equally well at all other sites in the same class. These assumptions idealize the world beyond recognition. Ironically, if management of biodiversity or geodiversity is an underlying goal, local ‘noise’ or ‘complications’ may represent the very attributes that we seek to protect (Fryirs and Brierley, 2009).

Unfortunately, procedures used to interpret the inherent diversity and variability of landscapes are seldom expressed formally. All too often, recourse is taken to instinctive and intuitive understandings of ‘experts’, whose experience and training commonly build upon what Sauer

(1956) refers to as an ‘innate morphologic eye’ for form and pattern (see also Church, 2013). Without a formal statement of procedures with which to develop place-based geomorphic understandings of landscapes, it is difficult to interrogate and communicate how interpretations have been made. In this paper, we document procedures that build upon conceptual and theoretical understandings of river character, behaviour and evolution to provide a systematic geomorphic approach to ‘reading the landscape’. A scaffolded, open-ended set of questions is used to identify landforms, assess their morphodynamics and interpret their interactions, evolution and likely future trajectories. Documentation of the approach used to perform these analyses presents a transparent basis from which to critique perspectives and understandings, facilitating training while potentially demystifying the process of expert judgement. Prior to outlining our approach to reading the landscape, we briefly comment upon the geomorphic foundations upon which it is based.

II Theoretical foundations upon which our approach to reading the landscape is based

Rhoads and Thorn (2011: 62) note that: ‘Geomorphologists pursue two primary goals: first, exploration of general principles that explain geomorphological processes, the ensuing landforms, and their interaction; and, second, explanation of the unique histories of individual landforms and landscapes.’ Our approach to reading the landscape considers the space between these two goals, articulating how the theory and practice of geomorphology intersect in the development of place-based understandings that can be used to inform management and planning decisions. Appreciation of generalized theoretical principles alongside particular, place-based environmental/historical contingencies underpins this perspective. All data are inherently theory-laden; theory cannot be built

without data, and it is not possible to make sense of data without theory (Church, 2011; Odoni and Lane, 2010; Rhoads and Thorn, 1993, 1996; Richards et al., 1997).

There is no single, ‘right’ way to read a landscape. Different readings can be made based on the questions asked, the methodology used to generate data (whether qualitative or quantitative), and the way data are analysed and interpreted. Our approach to reading the landscape is offered as a heuristic device, a pragmatic starting point for inquiries upon which different perspectives and interpretations may be integrated to develop explanations of biophysical interactions, to explore future scenarios, decide on management, planning and policy actions, and prioritize activities, among other things. The approach is grounded in theory that relates form and process at various spatial and temporal scales, providing a physical template for integrative analysis and interpretation of a range of ecological processes (e.g. Brierley and Fryirs, 2008; MacMillan et al., 2004; Stallins, 2006).

Fluvial geomorphologists have developed well-established understandings of how flow-sediment interactions and the associated balance of erosional and depositional processes create and rework river landforms (e.g. Brierley and Fryirs, 2005). Theoretically derived principles present significant insights into controls upon variability in channel geometry and planform (e.g. Eaton et al., 2004, 2010; Huang and Nanson, 2000; Nanson and Huang, 2008). These understandings typically build upon empirically derived relationships determined from field analyses or experiments performed under controlled sets of conditions. However, it is difficult to assess how reliably empirical relationships can be transferred from one location to another. For example, significant concerns remain regarding the appropriateness of sediment transport formulae that feed into many theoretical relationships. Local or historical factors, the configuration of a system, or particular sequences of events may generate significant variability in the outcome

of process interactions, such that general principles derived from experiments, theory or empirical observations may not apply in locations outside the circumstances in which they were derived. Hence, predictions from theoretical or empirical models cannot be extrapolated with certainty beyond the boundaries of their known reliability and representativeness (Lane, 2001).

However, local variability is not always random or unpredictable, but is often governed by contextual constraints that are revealed in multi-scaled analyses. In geomorphic analyses of river systems, landscape features are characteristically analysed at the scale of individual particles, bedform-scale features (or hydraulic units), erosional and depositional landforms (also referred to as geomorphic units or elements), assemblages of landforms at the reach scale, process zones within a subcatchment (or catchment), and regional-scale characterizations such as physiographic or tectonic zones, ecoregions or biomes (e.g. Brierley and Fryirs, 2005; Frissell et al., 1986; Naiman et al., 1992; Rogers and O'Keefe, 2003). At each scale, the configuration of a river system can be analysed in terms of its composition (the kinds of elements it contains), its structure (how they are arranged in space) and its behaviour (how landforms are formed, reworked and adjust over time). Church (1996) refers to the 'tyranny of scales' in geomorphic inquiry, wherein short-term predictability of process-form responses at particle, bedform and reach scales must be framed in relation to long-term complexities and uncertainties of catchment-scale behaviour. Different controlling factors play different roles in different places, at different scales, over different timeframes, and at different times (Brierley and Fryirs, 2005; Church and Mark, 1980; Couper, 2004, 2007; Lane and Richards, 1997; Schumm and Lichty, 1965). As a result, significant challenges are faced in scaling up understandings of small-scale hydraulic processes to develop coherent appraisals of process-form relationships that shape patterns of landforms and their interactions

at reach and catchment scales (see Burt, 2005; Rhoads, 2005; Trudgill and Richards, 1997).

Small-scale hydraulic processes can be integrated with understandings at reach and catchment scales though the concept of 'process zones'. Different relationships between available energy (E) and the energy that is required to transport available sediment (E_{min}) exist in different parts of a catchment (Church, 1992; Huang et al., 2004; Schumm, 1977). In the steep, confined valley settings of *source* zones, where $E > E_{min}$, channels have excess energy to remove sediments, erosion is dominant, and the river has an imposed (forced) morphology that is set primarily by the valley slope (Montgomery and Buffington, 1997). A transition from erosion-dominated to deposition-dominated processes occurs in *transfer* zones, where $E \sim E_{min}$. A change in boundary conditions is evident, as sediment stores start to occur on the channel bed and floodplain pockets form in partly confined valley settings (Fryirs and Brierley, 2010; Jain et al., 2008). Flow and sediment flux fashion process-form relationships for these bedload and mixed load rivers. In *accumulation* zones, where $E < E_{min}$, freely adjusting alluvial channels adopt and adapt their own morphologies, altering the channel (water surface) slope for a given valley floor slope (Nanson and Huang, 2008). Adjustments to channel planform and geometry for these mixed and suspended load rivers accommodate alterations to flow and sediment conditions more readily than elsewhere in the catchment. Although a generalized downstream sequence of process domains (sensu Montgomery, 1999) from source through transfer to accumulation zones is often observed, marked discontinuities (or alternations) in the pattern of these zones may be evident in any given catchment (e.g. Poole, 2002).

As catchment-scale attributes and relationships vary markedly within differing geologic, climatic and topographic settings, observations and analyses of landscapes must be framed in relation to these contextual considerations. The

Table 1. Contextual considerations that underpin our approach to reading the landscape.

Subject area	Considerations
Landscape setting (geological controls)	<p>Where is the site relative to a plate boundary? What type of plate boundary is it? What is the extent and frequency of neotectonic activity? What is the geology of the area? Is this a glaciated landscape, a desert, a polar region, an urban environment, a tropical setting, the flanks of a volcano? Have there been any major disturbance events (e.g. volcanoes, earthquakes, cyclones)? How does the setting influence the erodibility/erosivity of this landscape, and associated flow–sediment fluxes?</p>
Hydrological conditions (climatic controls)	<p>What is the pattern of precipitation (seasonality, rain days (storminess), % snow, etc.)? What is the primary source of flow? What is the character of the discharge regime (annual flow, seasonal variability, interannual variability (coefficient of discharge))? What is the flood history of the catchment?</p>
Catchment morphometrics	<p>What is the catchment size? What is the catchment shape (elongation ratio, circularity, etc.)? Where and how often do tributaries join the trunk stream? How large are the tributary subcatchments? What is the drainage pattern of the (sub)catchment? What is the drainage density of the (sub)catchment? What is the relief ratio and hypsometric interval of the catchment? What is the topography of the catchment? What landscape units are there? What is the shape of the longitudinal profile? How do slope and discharge affect patterns of gross stream power along the longitudinal profile?</p>
Position in the catchment	<p>Where are you located within the catchment? Are you in a source, transfer or accumulation zone? What is upstream and downstream of this location?</p>
Valley setting	<p>What is the valley width/confinement? What is the shape of the valley? How connected are hillslopes to the valley floor? What sediments make up the valley floor (type, size and distribution in channels and on floodplains)? Is the river bedload, mixed load or suspended load?</p>
Vegetation and wood conditions	<p>What is the contemporary coverage of vegetation on the valley floor? What was the historical coverage of vegetation on the valley floor? What vegetation associations occur at different positions on the valley floor (instream, riparian, floodplain)? How does vegetation affect instream and floodplain roughness? Is wood present and what is its density?</p>
Human disturbance (anthropogenic controls)	<p>What is the land-use pattern in the catchment? How has land use changed over time? How has the settlement pattern of the catchment changed (e.g. population density and distribution; environmental history)? How have direct human activities modified the river (e.g. dams, stopbanks, gravel extraction, vegetation clearance, desnagging)? How have indirect human activities modified the river (e.g. vegetation clearance and changes to hydrology and sediment flux, interbasin transfers)?</p>

approach to reading the landscape outlined in this paper is framed initially as a top-down process that builds upon big-picture geomorphic understandings of river systems, prior to applying bottom-up (constructivist) principles that build upon field interpretations of landforms, tied specifically to appreciation of the importance of position in a catchment.

III Reading the landscape: a procedure to generate place-based understandings of river systems

Before reading the landscape in the field, background research on the study area is undertaken to understand the context in which local processes operate. GIS-based analyses frame the study site within a climate, vegetation, geology and topographic context (see Table 1). Virtual observation tools such as Google Earth[®] provide a powerful resource base with which to ground these familiarization exercises. Once in the field, reading the landscape is enacted through a structured set of observations, measurements, analyses and interpretations. Detective-style analyses bring together strands of inquiry in a multiple lines of evidence approach (Schumm, 1991).

Reading the landscape is framed around four steps (Figure 1; further details are provided in Fryirs and Brierley, 2013). This 'bottom-up', constructivist approach to geomorphic analysis of river systems identifies process-form relationships at the geomorphic unit scale, analyses landform assemblages at the reach scale, interprets how rivers adjust over time, and integrates these understandings at the catchment scale to interpret patterns of reaches, their (dis)connectivity and the evolutionary trajectory of the river. The last step includes analysis of how changes to one part of a system may (or may not) affect other parts of that system. Essentially, this framing of landscape analysis views geomorphic units as the building blocks of river systems (Brierley, 1996). Patterns and interactions among these features are interpreted at higher levels of

organization (i.e. at reach and catchment scales). Each stage of the approach is scaffolded to produce increasingly sophisticated knowledge of river form, process and evolution. In any new locality, baseline information generated in Step 1 is required before 'moving on' to Steps 2, 3 and 4. As the approach builds, increasing levels of experience and training are required to ensure the quality of the information and knowledge generated. This provides a framework for assigning levels of 'confidence' to the interpretations made, and for users to identify limitations or gaps in their own knowledge base and skills set.

Step 1: Identify and interpret landforms and their process-form relationships

Reading the landscape at the level of geomorphic units entails observations of which features are present, where they are situated with respect to the depth and strength of flows, determination of what types of sediments they are made of, and analysis of the frequency with which they are inundated, formed and/or reworked. Landform identification is the critical starting point in our approach to reading the landscape. Geomorphic units have characteristic geometries, sedimentology and bounding surfaces (i.e. erosional or depositional contacts) that reflect their formative processes (see Brierley, 1996; Brierley and Fryirs, 2005; Miall, 1985; Spedding, 2011).

In simple terms, instream geomorphic units tend to scale relative to channel width (e.g. Miall, 1985). In absolute terms, this scale may range from centimetres to tens of kilometres. However, it is dangerous to over-generalize here, as not all rivers are channelized, and a flexible approach to the designation of geomorphic units is required. Similarly, if floodplain features are present, they do not necessarily scale directly with the contemporary channel. Hence, geomorphic units may vary markedly both in terms of their absolute and relational (e.g. channel-floodplain) scale. These

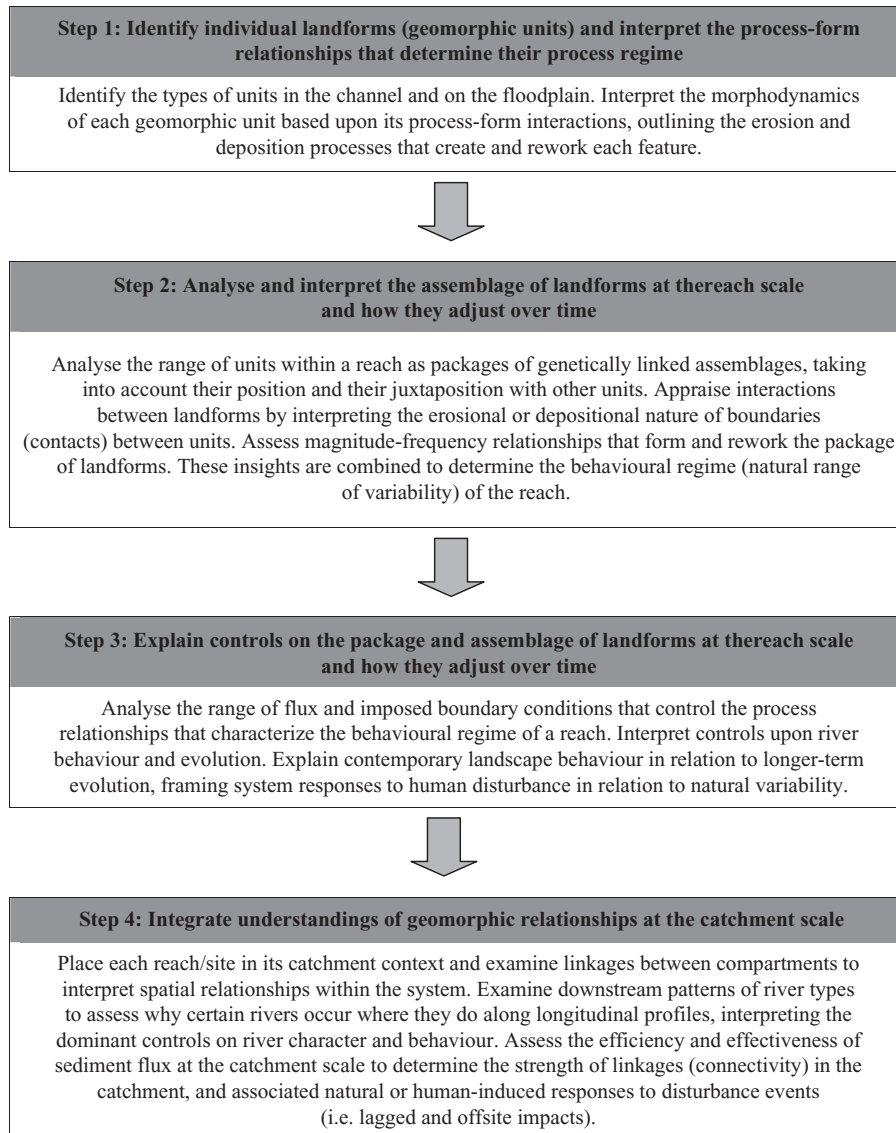


Figure 1. An approach to reading the landscape.

context (situation) specific relationships are recognized inherently in this approach.

Particular sets of processes form and rework geomorphic units under a given set of energy conditions at particular locations in a landscape (e.g. relative to channel geometry and valley alignment). Combinations of erosive and depositional processes that sculpt, create and rework channel and floodplain landforms

reflect magnitude-frequency relations and energy (stream power) conditions (Brierley and Fryirs, 2005). Essentially, this stage of analysis develops a conceptual model of the likely morphodynamics for each observed type of unit.

Fryirs and Brierley (2013) identify four categories of instream geomorphic units: (1) sculpted and erosional forms in bedrock or coarse substrate; (2) mid-channel depositional

units; (3) bank-attached depositional units; and (4) fine-grained sculpted geomorphic units. Each category tends to form and operate within a particular process domain that is defined by available stream power/energy, substrate size and sediment availability (Montgomery, 1999). Interpretation of formative processes relates field observations and measurements to theoretical knowledge of process-form associations for each type of geomorphic unit. Sediment analyses are used to differentiate among contentious equifinality variants (e.g. benches are indicative of channel contraction, while ledges are indicative of channel expansion; Brierley and Fryirs, 2005). Similar analyses are performed for floodplain geomorphic units, differentiating primary formative (depositional) processes from reworking (erosive) processes for high, medium and low energy floodplains (see Nanson and Croke, 1992).

The vegetation supported by different types of geomorphic units also offers clues about erosion and deposition processes and the magnitude and frequency of formative events. Depending on flow inundation and disturbance characteristics, different landforms tend to be characterized by particular vegetation associations. While erosive surfaces may support little vegetation, depositional surfaces offer greater opportunities for vegetative growth, which can then feed back to trap more and finer sediments (see Corenblit et al., 2007). The nature of vegetative cover can also indicate the time interval since a landform was last reworked. For example, surfaces that have been undisturbed for long periods of time are likely to support denser vegetation, and inputs of organic material may have stimulated soil formation. In some instances, the age of vegetation on relatively undisturbed features can be used to indicate the elapsed time since the last major flood. This helps to build a picture of the magnitude-frequency relationships that fashion the character and behaviour of a particular river (Steps 2–4 in the approach to reading the landscape).

Theoretical understandings of river systems at this scale of analysis reflect hydraulic considerations. This relates the flow energy that is available to do work along a river (i.e. entrain, mobilize and deposit bedload and suspended load materials) to how that energy is used to create and sustain geomorphic units (determined by the relationship between discharge, slope, the calibre/amount of material along the channel bed, and resistance elements). The energy available to do work along a river is a function of the balance of impelling and resisting forces. Theoretically, a range of equilibrium relationships driven by negative feedback mechanisms adjust to maintain a balance between slope, bed material size, channel size, etc. These relationships determine the consumption of energy at different positions along the longitudinal profile (especially energy that is required to overcome frictional resistance). Cross-sectional adjustments alter channel flow conditions, modifying flow resistance and sediment transport relations. In general terms, rivers adjust the balance of impelling and resisting forces such that the system is able to use available water (flow) to transport available sediment. The use of energy, in turn, is determined by valley confinement – the space within which the channel can adjust (Huang et al., 2004). If $E > E_{min}$, erosion ensues and sculpted instream geomorphic units dominate channel morphology. If $E = E_{min}$, the self-adjusting channel determines its own morphology, and associated patterns of resistance elements, thereby setting its own slope. If there is insufficient energy to mobilize available materials (i.e. $E < E_{min}$), deposition and bed aggradation ensue, and the river may be characterized by mid-channel sedimentation and floodplain development (dependent upon slope and valley width conditions).

All landscapes retain a history of their past, such that observed landforms may not have formed under the contemporary process regime (e.g. Brierley, 2010). Interpreting whether instream and floodplain geomorphic units were formed by the contemporary process regime, or

whether they are inherited products of former flow and sediment conditions, is a critical determination in reading the landscape. For example, how readily is the channel bed substrate entrained by the contemporary flow regime? Lag deposits from palaeofloods may exert a significant influence upon contemporary process-form interactions along a reach. Disjuncts in the sedimentary record or abandoned palaeolandforms such as palaeochannels or terraces provide insights into transitions in floodplain formation and reworking processes. The morphology, position and sediment attributes of terraces and palaeochannels can guide insight into past flow and sediment regimes (Steps 3 and 4 in reading the landscape; Figure 1). A high level of training may be required to make informed interpretations of the bounding surfaces and sediment composition of landforms.

Typical questions to ask in Step 1 of reading the landscape include:

Identify individual geomorphic units

- Based on the morphology (geometry), position in the landscape (channel or floodplain) and sedimentology of the feature, what is the type of geomorphic unit observed?
- Is this an erosional or depositional feature (i.e. does it have an imposed, forced morphology, or is it a free-forming, depositional landform)?
- Are instream landforms mid-channel, bank-attached or a combination thereof?
- If there is a floodplain, what features is it made up of?

Interpret process-form relationships to determine their process regime

- What flow hydraulic and sediment conditions are required to form the geomorphic unit? How is each geomorphic unit reworked?
- What do material properties and vegetation associations tell us about energy

conditions of formative flows and associated magnitude-frequency relationships for each landform? Are the units formed by the contemporary flow regime or are they legacies from previous conditions?

- If depositional features are present, do they act as a sediment store or sink (i.e. over what timeframe are they likely to be reworked)?
- Is there any indication that human disturbance has altered the types of geomorphic units along a reach, or the magnitude-frequency relationships with which features are formed and reworked?

Step 2: Analyse the assemblage of landforms at the reach scale and interpret how they adjust over time (i.e. the behavioural regime of the river)

This step interprets river *behaviour*, as opposed to river *change*, which is interpreted in Step 3. River *behaviour* reflects ongoing geomorphic adjustments over timeframes in which flow/sediment regimes and vegetation interactions remain relatively uniform, such that a reach retains a characteristic set of process-form relationships (see Brierley and Fryirs, 2005). River *change* occurs when alterations to the balance between impelling and resisting forces induce a shift in the behavioural regime of a river that results in a different assemblage of geomorphic units and associated morphodynamic interactions.

Determination of reach boundaries is the key interpretative skill in Step 2 of reading the landscape. A reach is a length of river with a distinct assemblage of geomorphic units that reflect particular combinations of erosion and deposition processes (Brierley and Fryirs, 2005).

Two primary scales of interaction are considered in Step 2 of reading the landscape. First, boundaries between adjacent geomorphic units are interpreted to determine the nature of genetic (process) linkages between those landforms. For example, pools and riffles form

contemporaneously, while floodplains may (or may not) be formatively linked to the contemporary channel(s). In some instances, adjacent features are physically disconnected, reflecting an erosive event or a disjunct in time. For example, terraces are older than adjacent floodplain and channel forms. Inevitably, analyses are restricted to assessment of the preserved record, and interpretation of what has been removed. Note should be made of whether boundaries between geomorphic units are distinct, gradual, intercalated or otherwise.

Second, packages of geomorphic units that define the behavioural regime of the river at the reach scale are designated. Reaches at different positions in a landscape are characterized by different packages of landforms that are produced by differing sets of formative and reworking processes. A constructivist approach to analysis of geomorphic units allows interpretation of river diversity across the full spectrum from bedrock-controlled (forced) morphologies to fully self-adjusting (alluvial, laterally unconfined) variants. If a new variant of river is 'discovered', it is described and interpreted in its own right, rather than being forced into a predefined category into which it does not easily fit (see Brierley, 1996; Richards, 1986).

Reach-scale morphological attributes of a river reflect the nature and frequency of adjustments to bed material organization, bed/bank processes and processes that fashion assemblages of channel and floodplain geomorphic units, channel geometry and channel planform (see Brierley and Fryirs, 2005). In Step 2 of reading the landscape, a determination is made as to whether these features, and their process relationships, are products of the contemporary flow and sediment regime, or whether they have been influenced by (or inherited from) former conditions. The inferred 'natural range of variability' can be tested and reappraised through field observations and analyses undertaken in the same place at different times (e.g. following flood events) or in similar reaches at

different localities (i.e. ergodic reasoning; Fryirs et al., 2012). Theoretical and modelling applications can be used to assess the magnitude-frequency domains with which landforms are generated and reworked at the reach scale.

Particular packages of channel and floodplain features reflect the balance of impelling and resisting forces and associated flow/sediment interactions that fashion channel geometry and linkages to adjacent floodplains (if present). Some rivers are influenced primarily by recurrent low- to moderate-magnitude events, while others are formed by infrequent high-magnitude events. Changing environmental conditions and/or human interference may alter these relationships.

In reading the landscape, analysis of river behaviour is interpreted at low flow, bankfull flow and overbank flow stages (Fryirs and Brierley, 2013). While specific magnitude-frequency relations may vary markedly from system to system, meaningful differentiation can be made between the forms and rates (sensitivity) of river adjustment at each flow stage. Analysis of *low flow stage* river behaviour appraises adjustments to bed material organization and bedforms as flow covers the channel bed. River behaviour at *bankfull stage* reflects the conditions at which flow is contained within the channel without spilling onto the floodplain. Interpretations of river behaviour at this stage incorporate adjustments to the pattern and rate of erosion and deposition on the channel bed and banks, and associated formation and modification of the pattern of instream geomorphic units. To go overbank there must be well-defined channel banks, so behaviour can only be interpreted at this stage in settings with floodplains. The primary component of interpreting river behaviour at *overbank stage* entails assessment of the frequency of floodplain inundation, and process-form interactions that create and rework floodplain geomorphic units.

Typical questions to ask in Step 2 of reading the landscape include:

Analyse and interpret the assemblage of landforms at the reach scale

- What are the assemblages of channel and floodplain geomorphic units along the reach?
- What changes to landform assemblages and process relationships define reach boundaries? Why does this change occur where it does?
- How well defined are the boundaries of any given landform, and what does this say about the genetic (process) linkages to adjacent features?
- What is the mix of erosional and depositional geomorphic units along the reach? Is this a bedrock-dominated (forced) river, or is it a boulder, cobble, gravel, sand or fine-grained (silt-clay) system?

Analyse and interpret how the geomorphic unit assemblage adjusts over time (river behaviour)

- How does the river behave at low flow, bankfull and overbank flow stages? How are geomorphic units formed and reworked at different stages?
- Under what set of hydraulic conditions (balance of impelling and resisting forces, flow-sediment interactions) was each package of channel features formed and reworked? How frequently are different sediment (grain-size) fractions moved on differing surfaces? How do vegetative interactions influence process-form interactions along the reach?
- How do bed and bank processes adjust and how does this affect channel geometry (size and shape)? How do channel geometry, valley alignment and position of the channel on the valley floor affect the nature and pattern of instream and floodplain geomorphic units?

- If present, do floodplains occur as bedrock-controlled or planform-controlled pockets, or are they continuous along both banks of the channel (Fryirs and Brierley, 2010)? Is the floodplain relatively uniform (homogenous), or is it made up of an array of features such as levees, crevasse splays, floodchannels, palaeochannels, backswamps? Under what set of hydraulic conditions (stream power and the balance of impelling and resisting forces, flow-sediment interactions) was the package of floodplain features formed and reworked (see Nanson and Croke, 1992)?
- What do the floodplain geomorphic units tell us about river responses to infrequent, high-magnitude events? Do they provide evidence of variable flow alignment and associated energy conditions with stage?

Step 3: Explain controls on the assemblage of landforms at the reach scale and how they adjust over time

Step 3 in reading the landscape entails determination of primary controls upon the contemporary character and behaviour of the reach, appraising whether the package of geomorphic units is a product of the contemporary flow and sediment regime or whether landforms reflect former conditions. Controls on the range of variability of reach-level assemblages of geomorphic units are interpreted in relation to reach position within the catchment- and regional-scale controls such as geology, climate and human activities (Table 1). All rivers adjust and evolve, but the range of process adjustments and the ease/frequency with which adjustments occur vary from reach to reach. Many reaches have considerable capacity for adjustment, such that they are sensitive to disturbance events, while resilient reaches have limited capacity for adjustment. Hence, reaches respond to differing forms of disturbance event in different ways.

Some reaches may adjust among multiple states. River evolution may occur in response to progressive adjustments, an instantaneous event (e.g. a major flood or an earthquake) or longer-term changes to geologic and climatic conditions. In many instances, alterations to the boundary conditions under which rivers operate may bring about river change, whereby the assemblage of geomorphic units along a reach is modified and the behavioural regime of the river is transformed (i.e. the reach adopts a different set of process-form relationships; Brierley and Fryirs, 2005).

Theoretically, potential energy is the ultimate driving force of river evolution. An equilibrium state exists when a river's specific potential energy just satisfies the minimum need of the river for expenditure (i.e. $E = E_{min}$; Huang et al., 2004). However, this ideal state rarely exists. When $E > E_{min}$, a channel can readily expend excess energy by incising and/or widening if it can move more sediments. This requires doing additional work, thereby increasing energy expenditure. Different levels of energy and different environments create different resultant states, such that there is more than one possible resultant state in the case of $E > E_{min}$. Hence, although a range of riverscapes can be observed in steep mountainous areas, these rivers are generally stable over short timescales because their excess energy can be temporarily expended, but over longer timescales these river systems are unstable as incision slowly occurs. In the case of $E < E_{min}$, a river strives to gain additional energy to transport load by steepening its course or depositing some of its sediment load. Because these rivers normally occur under low slope conditions in relatively wide valleys, channels are unable to gain additional energy by steepening channel slope. In these instances, deposition of some of the sediment load yields additional resistance by inducing channel division, creating multiple channels (i.e. anabranching or anastomosing rivers; Nanson and Huang, 2008).

Analysis of river evolution is supported by interpretation of the boundaries between landforms and their sedimentary attributes. Inevitably, landscapes retain an incomplete record of past activities. Assessment of the preservation potential of deposits supports efforts to interpret what may be missing from the sediment record, and the erosional events that brought about removal of materials. Linking sediment sequences to their chronology is vital in determining phases and rates of activity. Some events or phases of geomorphic impacts leave a dominant imprint upon the contemporary landscape, essentially overriding (overprinting) the geomorphic signal of previous events (e.g. Brierley, 2010; Church and Slaymaker, 1989). In many instances, floodplain sediments provide an indication of past depositional environments. The key issue at this stage of analysis is explaining how and why channel and floodplain processes, and resulting river morphologies, have changed over time.

Determination of phases and trajectories of river evolution can be supplemented by process measurements to assess the rate and effectiveness of geomorphic process activity. From this, magnitude-frequency relationships can be derived to assess how much work is likely to be performed by an event of a given magnitude. Alternatively, modelling applications can be used to simulate real-world understanding as a basis to interpret process understandings, identify key controls upon process-form linkages, assess rates of activity and predict evolutionary trajectories (see Small and Doyle, 2012). Models may provide an idealized picture, based on physical principles and empirical relations, of process-form interactions. Observed deviations from this picture found in nature can then guide our process understanding and support further hypothesis development.

Typical questions to ask in Step 3 of reading the landscape include:

Explain controls on the package and assemblage of landforms at the reach scale

- What are the primary controls upon valley slope and width, and how do they influence river character and behaviour? Does the channel fit its valley, or is it underfit? When was the valley formed, under what set of controls?
 - Is there any evidence of changes to channel geometry? Is the bed stable? Has critical bank height been exceeded? Is the channel widening, contracting or is it about the same? Has channel-floodplain connectivity been altered, with associated adjustments to floodplain-forming processes?
 - How do sediment availability (calibre/volume) and the flow regime (prevailing energy conditions) affect river character and behaviour? What is the frequency of formative flow? How do slope, discharge and valley width affect the erosion-deposition balance and patterns of sediment stores/sinks along the reach?
 - Do channel geometry relationships conform to regime principles (e.g. Eaton et al., 2004)? If this is an alluvial, self-forming river, does channel planform type conform to predicted variants based upon theoretically defined combinations of slope, discharge, bed material size and bank strength conditions (e.g. Eaton et al., 2010; Parker et al., 2007)?
- channel bank deposits likely to have been produced by the contemporary river? Do terraces or palaeochannels provide insight into former phases of river activity?
- Is there any evidence to indicate whether evolutionary adjustments were progressive or whether exceedance of threshold conditions brought about dramatic/rapid change? Alternatively, was change lagged after the disturbance? What kinds of disturbance events brought about evolutionary adjustments to the river? Is river morphology largely an inherited artifact of a particular disturbance event (e.g. volcanic eruption, human channelization)? Are there any indicators of drivers of river evolution, such as flood debris (slackwater deposits), volcanic ash, fault scarp, mega landslides?
 - How has the nature, scale, extent and intensity of human influences affected the range of behaviour and evolutionary trajectory of the river? Has human disturbance simplified or diversified the range of geomorphic units? Do the various forms of human disturbance reinforce and accentuate change through positive feedback mechanisms, or do they counteract each other via negative feedback mechanisms? Has human disturbance altered the availability of energy in a reach, or the way in which that energy is used (i.e. alterations to the distribution and effectiveness of resistance elements)? Do adjustments merely reflect alterations to the rate of process activity (whether accelerated or decreased), or has the range and pattern of geomorphic processes been significantly modified by human disturbance? How have river management activities impacted upon the river, and over what timeframe?

Interpret river evolution

- Is there any evidence for evolutionary adjustments to river type, such as a discernible change to the assemblage of geomorphic units? Are features produced by the contemporary flow regime, or are they products of former conditions? For example, was the floodplain formed by an equivalent set of process interactions to those that fashion contemporary channel-floodplain linkages? Are

Step 4: Integrate understandings of geomorphic relationships at the catchment scale

Despite the uniformity of the underlying physics that shapes river character and behaviour, river systems demonstrate a remarkable array of biophysical interactions and evolutionary trajectories. Although we have developed a sophisticated understanding of the primary controls upon this diversity, variability and complexity, understanding of system-specific relationships is required to describe and explain process-form interactions and evolutionary trends for any given catchment. This includes assessment of lagged and offsite responses to disturbance events. Each site/reach must be viewed in its catchment context, assessing relationships to upstream and downstream considerations and the effectiveness and efficiency of flow-sediment (dis)connectivity (e.g. Fryirs, 2013; Fryirs et al., 2007, 2009; Harvey, 2002; Hooke, 2003). Step 4 of reading the landscape appraises these spatial and temporal considerations to assess how past events, that may have occurred elsewhere in the system, affect what is observed in any given reach today.

Patterns of river types along longitudinal profiles reflect the boundary conditions within which rivers operate at differing positions in a catchment. Key transitions in river character and behaviour are demarcated by patterns of sediment storage along river courses, whether as channel or floodplain features. Analysis of landform patterns provides insight into the balance of erosion and deposition processes along a river, and associated patterns of imposed (forced) and self-adjusting (alluvial) morphologies. These geomorphic relationships can be meaningfully interpreted at the catchment scale in relation to the energy levels of $E > E_{min}$, $E = E_{min}$ and $E < E_{min}$. Downstream patterns of rivers reflect changes in slope and valley width, and associated trends in stream power, discharge and sediment volume/calibre. Tributary-trunk stream

relationships and controls upon patterns of sediment stores exert a critical influence upon these catchment-scale interactions. Local-scale impacts must be differentiated from broader (catchment) scale controls.

Typical questions to ask in Step 4 of reading the landscape include:

Examine the downstream patterns of river types

- Does the downstream pattern of river types along the longitudinal profile conform to classical trends (e.g. Church, 1992; Schumm, 1977)? If not, why not?
- What sets the base level for the catchment, and any given reach? Is there any evidence of knickpoints and how do these affect the form of the longitudinal profile?
- What are the key controls upon river behaviour and evolution at the catchment scale? How do these factors interact, in space and time? Is the river well adjusted to its contemporary setting (slope, discharge regime, etc.) or are many attributes products of former geologic and climatic considerations? How can these analyses guide interpretation of likely future states?
- What are the primary disturbance events that drive spatial and temporal adjustments to river character and behaviour? Are these part of the contemporary process domain, or are they historical imprints (e.g. volcanic events, paraglacial sediments, responses to vegetation clearance)? Is there any evidence for particularly effective sequences (or concatenations) of events, or that magnitude-frequency relationships have changed over time?

Interpret the efficiency and effectiveness of sediment flux at the catchment scale

- How does the contemporary flow-sediment balance vary along the river

course and why? Is there any evidence that the reach-scale balance of flow and sediment flux (i.e. its storage function) has varied over time? How have human activities altered flow and sediment flux in the catchment? How and why have inputs and outputs changed? What is the role of geomorphically effective and/or ineffective tributaries?

- Are reaches hydrologically and geomorphologically well connected or disconnected? Are hillslopes connected to channels? Are tributaries and trunk streams connected? Have dams disconnected reaches? Are channels and floodplains connected? What blockages affect the catchment-scale sediment cascade?
- Are some reaches especially sensitive to change, with accentuated off-site impacts? If so, how and why? How do changes to one reach affect adjacent (or other) reaches, over what timeframes? How does catchment connectivity affect lagged and off-site responses?

IV Discussion

Building upon assertions proposed by Bauer et al. (1999), new approaches to geomorphic inquiry (or methodological sneakers) are required to develop understandings of ‘naughty worlds’ (Kennedy, 1979) or ‘perfect landscapes’ (Phillips, 2007). These applications must work with, but move beyond, reductionist approaches to landscape analysis, realistically framing and interpreting specific (local) instances in relation to generalizable understandings of trends and patterns (Rhoads, 2006; Richards and Clifford, 2008; Small and Doyle, 2012). Geomorphology is not only a reductionist (positivist) science in search of relationships or ‘laws’, but also an interpretive one for which multiple approaches are biophysically valid (Baker, 1999; Frodeman, 1995). Inevitably, different mindsets and approaches

to learning are required to successfully develop and integrate understandings of a particular locality with its own history with universal and timeless understandings derived from experimental investigations performed under known (repeatable) conditions. Viewed in this way, complementary approaches to analysis and understanding (i.e. geomorphic pluralism) are required to successfully interpret landscape form, function and evolution (Butzer, 1973; Jennings, 1973; Slaymaker, 2009).

This paper has advanced the case for ‘reading the landscape’ as a methodological practice in geomorphology, developing place-based understandings that meaningfully relate theory and practice. Reading the landscape is framed around ‘questioning’ and ‘interpretation’ rather than a tick-box set of potential answers. The approach is generic, open-ended and cross-scalar, allowing flexibility for interpretation and the development of new ideas about landscape form and process. As a structured way of applying general geomorphic theory to particular locations, the approach tailors theory to the particular instance rather than vice versa (see Montgomery, 2012). Rather than relying unduly on conceptual or theoretical representations of landscapes that suggest how the world ‘should’ ideally look and behave, appropriately contextualized, place-based understandings can be used to detect where local differences matter, thereby addressing concerns for the transferability of insights between locations and the representativeness of sample or reference sites.

Recognizing the potential implications of local differences challenges the application of standardized techniques that are designed to be simple to use in efforts to minimize ‘operator error’. However, prescriptive (unquestioning) use of these frameworks that overlook important local differences can potentially result in inappropriate management responses and adverse outcomes (see Lave, 2012; Milner et al., 2013; Roper et al., 2008; Trudgill and Richards,

1997). Similar dangers can also accompany the use of emerging technologies that deliver high-resolution, real-time data for observing and measuring natural phenomena (see Bishop et al., 2012; Brasington and Richards, 2007; Carbonneau and Piégay, 2012; Carbonneau et al., 2012; Church, 2010, 2011; Van Dam, 2012). While these large data sets offer immense opportunities for the development of local place-based knowledge, they also present a temptation to adopt standardized approaches at the expense of locally tailored interpretations.

The recognition that landscapes can be *read* and *interpreted* acknowledges that landscapes are not merely observed but are ‘invented’ (cf. Kennedy, 2006). The extent to which theoretical framings of field observations become institutionalized *in practice* prompts a concern for epistemological as well as ontological reflexivity: how can we meaningfully assemble geomorphological theory into particular place-contexts in ways which do not arbitrarily either exclude or presume a particular theoretical or observational perspective? Reading the landscape should not be understood as a universalizing epistemology or a mechanism to develop a ‘single knowable truth’. Rather, the approach is framed as a starting point for a pluralist activity that is not restricted to particular disciplinary or methodological framings. It is a heuristic device that supports and stimulates the generation of multiple hypotheses and interpretations that may be framed from a range of perspectives. Given its explicitly constructivist framing, our approach supports the *assembling* of landscape understanding through multiple propositions and explanations, embracing inherent uncertainties (see Beven and Alcock, 2012; Brown, 2004; 2010; Hillman and Brierley, 2008). Furthermore, the formal statement of procedures with which to ‘read a landscape’ makes the foundation for the approach transparent and therefore open to debate, thereby facilitating critical and robust analysis and transfer of knowledge.

Since approaches to geomorphic inquiry and their application to environmental management reflect particular epistemic cultures, questions must be raised as to whose frameworks should be used to interpret landscapes, and what qualifications and skills should be deemed appropriate, and why (e.g. Forsyth, 2003; Huggett and Perkins, 2004; McClain et al., 2012; Milner et al., 2013; Pedynowski, 2003). This points to the ‘skills agenda’ in physical geography – what is it we are training geomorphologists to *do* (see Tadaki et al., 2012)? Should geomorphologists value quantitative applications over and above anything else, or is there space for a different kind of ‘rigour’ in landscape analysis (see Church, 2005; Parsons, 2006; Sauer, 1956; Wainwright, 2012)? By understanding landscapes as interpreted, the need to teach and develop interpretation *skills* becomes more apparent, emphasizing concerns for mastery learning based upon thinking and questioning rather than rote-learning applications (see Castree, 2012; Castree et al., 2008; Day, 2012). Thus, professional short courses that are used to teach practitioners how to analyse landscapes must be accompanied by appropriate training in theoretical principles of the geomorphological dynamics of river systems. It is this package of skill sets that provides critical guidance with which to inform, interpret and contextualize field (or remotely sensed) observations.

Prospectively, reading the landscape presents a way that geomorphology can be open to ‘re-enchanted’ as well as (perhaps) developing radical or ‘outrageous’ hypotheses (see Baker and Twidale, 1991; Gregory and Goudie, 2011; Woodyer and Geoghegan, 2013). Intriguing challenges and opportunities are presented in relating geomorphological interpretations of landscapes to approaches that sit outside conventional scientific delineations (e.g. Dixon et al., 2013; Duncan and Duncan, 1988, 2010; Hillman et al., 2008; Lane et al., 2011; Wilcock et al., forthcoming; Wylie, 2007). These framings can support efforts

to engage with local communities and stakeholders (e.g. Rhoads et al., 1999). Viewed in this way, reading the landscape not only provides a platform to discuss landscape futures, it also helps to develop and redefine the management context of *how landscapes matter to people* (e.g. Cooke, 1987; Downs and Booth, 2011; Kondolf and Piégay, 2011).

V Conclusion

Reading the landscape appraises geomorphic relationships in any given catchment, striving to ensure that scientifically informed management efforts respect and work with the inherent diversity and dynamics of each system. Interpretative exercises apply detective-style investigations to differentiate among the myriad of factors that affect landscape character, behaviour and evolution. This place-based approach to geomorphic analysis of river systems accommodates environmental contingencies of river dynamics, arguing against a pure reductionist approach that either classifies streams into universal categories or assumes that understandings of general principles about the physics of rivers is sufficient to characterize any particular river. Meaningful *characterization* and *description* underpin effective *interpretation* and *explanation*, providing a rich set of baseline information with which to foresight likely future states. Emphasis is placed upon ‘what is there’ and ‘why it is there’, not what theoretically could be there under the right set of circumstances. Essentially, reading the landscape is presented as a vehicle, rather than a guidebook, with which to operationalize geomorphological interpretations and understandings of landscapes. Careful use of new and emerging technologies will play a critical role in enhancing these applications.

Acknowledgements

A Visiting Professorship awarded to Gary Brierley by the Chinese Academy of Sciences supported this research. Discussions with Zhaoyin Wang assisted efforts to formulate and articulate several of the ideas

conveyed in this manuscript. We are extremely grateful to Bruce Rhoads for his insightful, critical and constructive comments on this paper. Editorial comments by Nick Clifford and last minute suggestions by Jon Tunnickliffe supported the completion of this paper.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

- Baker VR (1999) Geosemiosis. *Bulletin of the Geological Society of America* 111: 633–645.
- Baker VR and Twidale CR (1991) The reenchantment of geomorphology. *Geomorphology* 4: 73–100.
- Bauer BO, Winkler JA and Veblen TT (1999) Afterword. A shoe for all occasions or shoes for every occasion: Methodological diversity, normative fashions, and metaphysical unity in physical geography. *Annals of the Association of American Geographers* 89: 771–778.
- Beven KJ and Alcock RE (2012) Modelling everything everywhere: A new approach to decision-making for water management under uncertainty. *Freshwater Biology* 57: 124–132.
- Bishop MP, James LA Shroder JF Jr, et al. (2012) Geospatial technologies and digital geomorphological mapping: Concepts, issues and research. *Geomorphology* 137: 5–26.
- Brasington J and Richards K (2007) Reduced-complexity, physically-based geomorphological modelling for catchment and river management. *Geomorphology* 90: 171–177.
- Brierley GJ (1996) Channel morphology and element assemblages: A constructivist approach to facies modelling. In: Carling P and Dawson M (eds) *Advances in Fluvial Dynamics and Stratigraphy*. Chichester: Wiley, 263–298.
- Brierley GJ (2010) Landscape memory: The imprint of the past on contemporary landscape forms and processes. *Area* 42: 76–85.
- Brierley GJ and Fryirs KA (2005) *Geomorphology and River Management: Applications of the River Styles Framework*. Oxford: Blackwell.
- Brierley GJ and Fryirs KA (2008) *River Futures: An Integrative Scientific Approach to River Repair*. Washington, DC: Island Press.

- Brown JD (2004) Knowledge, uncertainty and physical geography: Towards the development of methodologies for questioning belief. *Transactions of the Institute of British Geographers* 29: 367–381.
- Brown JD (2010) Prospects for the open treatment of uncertainty in environmental research. *Progress in Physical Geography* 34: 75–100.
- Burt T (2005) General/particular. In: Castree N, Rogers A and Sherman D (eds) *Questioning Geography*. Oxford: Blackwell, 117–130.
- Butzer KW (1973) Pluralism in geomorphology. *Proceedings of the Association of American Geographers* 5: 39–43.
- Carbonneau P and Piégay H (2012) *Fluvial Remote Sensing for Science and Management*. Chichester: Wiley.
- Carbonneau P, Fonstad MA, Marcus WA, et al. (2012) Making riverscapes real. *Geomorphology* 137: 74–86.
- Castree N (2012) Progressing physical geography. *Progress in Physical Geography* 36: 298–304.
- Castree N, Fuller D, Kent A, et al. (2008) Geography, pedagogy and politics. *Progress in Human Geography* 32: 680–718.
- Church M (1992) Channel morphology and typology. In: Calow P and Petts GE (eds) *The Rivers Handbook*. Oxford: Blackwell, 126–143.
- Church M (1996) Space, time and the mountain – how do we order what we see? In: Rhoads BL and Thorn CE (eds) *The Scientific Nature of Geomorphology*. Chichester: Wiley, 147–170.
- Church M (2005) Continental drift. *Earth Surface Processes and Landforms* 30: 129–130.
- Church M (2010) The trajectory of geomorphology. *Progress in Physical Geography* 34: 265–286.
- Church M (2011) Observations and experiments. In: Gregory KJ and Goudie A (eds) *The SAGE Handbook of Geomorphology*. London: SAGE, 121–141.
- Church M (2013) Refocusing geomorphology: Field work in four acts. *Geomorphology*. doi: 10.1016/j.geomorph.2013.01.014.
- Church M and Mark DA (1980) On size and scale in geomorphology. *Progress in Physical Geography* 4: 342–390.
- Church M and Slaymaker O (1989) Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature* 337: 452–454.
- Cooke RU (1987) Geomorphology and environmental management. In: Clark MJ, Gregory KJ and Gurnell AM (eds) *Horizons in Physical Geography*. Basingstoke: Macmillan, 270–287.
- Corenblit D, Tabacchi E, Steiger J, et al. (2007) Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. *Earth Science Reviews* 84: 56–86.
- Couper PR (2004) Space and time in river bank erosion research: A review. *Area* 36: 387–403.
- Couper PR (2007) Fluvial geomorphology and semiotics: A Wittgensteinian perspective of the ‘divide’ between human and physical geography. *Transactions of the Institute of British Geographers* 32: 279–294.
- Day T (2012) Undergraduate teaching and learning in physical geography. *Progress in Physical Geography* 36: 305–332.
- Dixon DP, Hawkins HM and Straughan ER (2013) Wonder-full geomorphology: Sublime aesthetics and the place of art. *Progress in Physical Geography* 37(2): 227–247.
- Downs PW and Booth DB (2011) Geomorphology in environmental management. In: Gregory KJ and Goudie A (eds) *The SAGE Handbook of Geomorphology*. London: SAGE, 78–104.
- Duncan J and Duncan N (1988) (Re)reading the landscape. *Environment and Planning D: Society and Space* 6: 117–126.
- Duncan N and Duncan J (2010) Doing landscape interpretation. In: Delyser D, Herbert S, Aitkin S, et al. (eds) *Handbook of Qualitative Research in Human Geography*. London: SAGE, 225–248.
- Eaton BC, Church M and Millar RG (2004) Rational regime model of alluvial channel morphology and response. *Earth Surface Processes and Landforms* 29: 511–529.
- Eaton BC, Millar RG and Davidson S (2010) Channel patterns: Braided, anabranching and single-thread. *Geomorphology* 120: 353–364.
- Forsyth T (2003) *Critical Political Ecology: The Politics of Environmental Science*. London: Routledge.
- Frissell CA, Liss WJ, Warren CE, et al. (1986) A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management* 10: 199–214.
- Frodeman R (1995) Geological reasoning: Geology as an interpretive and historical science. *Bulletin of the Geological Society of America* 107: 960–968.
- Fryirs K (2013) (Dis)connectivity in catchment sediment cascades: A fresh look at the sediment delivery

- problem. *Earth Surface Processes and Landforms, State of Science Series* 38: 30–46.
- Fryirs K and Brierley GJ (2009) Naturalness and place in river rehabilitation. *Ecology and Society* 14: 20.
- Fryirs K and Brierley GJ (2010) Antecedent controls on river character and behaviour in partly-confined valley settings: Upper Hunter catchment, NSW, Australia. *Geomorphology* 117: 106–120.
- Fryirs K and Brierley GJ (2013) *Geomorphic Analysis of River Systems: An Approach to Reading the Landscape*. Chichester: Wiley.
- Fryirs K, Brierley GJ and Erskine WD (2012) Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. *Earth Surface Processes and Landforms* 37: 763–773.
- Fryirs K, Brierley GJ Preston NJ, et al. (2007) Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena* 70: 49–67.
- Fryirs K, Spink A and Brierley GJ (2009) Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. *Earth Surface Processes and Landforms* 34: 897–918.
- Gregory KJ and Goudie A (2011) Introduction to the discipline of geomorphology. In: Gregory KJ and Goudie A (eds) *The SAGE Handbook of Geomorphology*. London: SAGE, 1–20.
- Harrison S (2001) On reductionism and emergence in geomorphology. *Transactions of the Institute of British Geographers* 26: 327–339.
- Harvey A (2002) Effective timescales of coupling within fluvial systems. *Geomorphology* 44: 175–201.
- Hillman M and Brierley GJ (2008) Restoring uncertainty: Translating science into management practice. In: Brierley GJ and Fryirs KA (eds) *River Futures: An Integrative Scientific Approach to River Repair*. Washington, DC: Island Press, 257–272.
- Hillman M, Brierley GJ and Fryirs KA (2008) Social and biophysical connectivity of river systems. In: Brierley GJ and Fryirs KA (eds) *River Futures: An Integrative Scientific Approach to River Repair*. Washington, DC: Island Press, 125–145.
- Hooke JM (2003) Coarse sediment connectivity in river channel systems: A conceptual framework and methodology. *Geomorphology* 56: 79–94.
- Huang HQ and Nanson GC (2000) Hydraulic geometry and maximum flow efficiency as products of the principle of least action. *Earth Surface Processes and Landforms* 25: 1–16.
- Huang HQ, Chang HH and Nanson GC (2004) Minimum energy as the general form of critical flow and maximum flow energy and for explaining variations in river channel pattern. *Water Resources Research* 40: W04502.
- Huggett R and Perkins C (2004) Landscape as form, process and meaning. In: Matthews JA and Herbert DT (eds) *Unifying Geography: Common Heritage, Shared Future*. London: Routledge, 224–239.
- Jain V, Fryirs K and Brierley GJ (2008) Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. *Geological Society of America Bulletin* 120: 127–141.
- Jennings JN (1973) ‘Any Millenniums Today, Lady?’ The geomorphic bandwagon parade. *Australian Geographical Studies* 11: 115–133.
- Kennedy BA (1979) A naughty world. *Transactions of the Institute of British Geographers* 4: 550–558.
- Kennedy BA (2006) *Inventing the Earth*. Malden, MA: Blackwell.
- Kondolf GM and Piégay H (2011) Geomorphology and society. In: Gregory KJ and Goudie A (eds) *The SAGE Handbook of Geomorphology*. London: SAGE, 105–117.
- Lane SN (2001) Constructive comments on D Massey ‘Space-time, “science” and the relationship between physical geography and human geography’. *Transactions of the Institute of British Geographers* 26: 243–256.
- Lane SN and Richards KS (1997) Linking river channel form and process: Time, space, and causality revisited. *Earth Surface Processes and Landforms* 22: 249–260.
- Lane SN, Odoni N Landström C, et al. (2011) Doing flood risk science differently: An experiment in radical scientific method. *Transactions of the Institute of British Geographers* 36(1): 15–36.
- Lave R (2012) Bridging political ecology and STS : A field analysis of the Rosgen wars. *Annals of the Association of American Geographers* 102: 1–17.
- McClain ME, Chícharo L Fohrer N, et al. (2012) Training hydrologists to be ecohydrologists and play a leading role in environmental problem solving. *Hydrology and Earth System Sciences* 16: 1685–1696.
- MacMillan RA, Jones RK and McNabb DH (2004) Defining a hierarchy of spatial entities for environmental analysis and modeling using digital elevation models (DEMs). *Computers, Environment and Urban Systems* 28: 175–200.

- Miall AD (1985) Architectural element analysis: A new method of facies analysis applied to fluvial deposits. *Earth Science Reviews* 22: 261–308.
- Milner VS, Gilvear DJ and Willby NJ (2013) An assessment of variants in the professional judgement of geomorphologically based channel types. *River Research and Applications* 29(2): 236–249.
- Montgomery DR (1999) Process domains and the river continuum. *Journal of the American Water Resources Association* 35: 397–410.
- Montgomery DR (2012) Faith in floods: Field and theory in landscape evolution before geomorphology. *Geomorphology*. doi: 10.1016/j.geomorph.2012.10.006.
- Montgomery DR and Buffington JM (1997) Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* 109: 596–611.
- Naiman RJ, Lonzarich DG Beechie TJ, et al. (1992) General principles of classification and the assessment of conservation potential of rivers. In: Boon PJ, Calow P and Petts GE (eds) *River Conservation and Management*. Chichester: Wiley, 93–123.
- Nanson GC and Croke JC (1992) A genetic classification of floodplains. *Geomorphology* 4: 459–486.
- Nanson GC and Huang HQ (2008) Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. *Earth Surface Processes and Landforms* 33: 923–942.
- Newson MD and Large ARG (2006) ‘Natural’ rivers, ‘hydromorphological quality’ and river restoration: A challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms* 31: 1606–1624.
- Odoni NA and Lane SN (2010) Knowledge-theoretic models in hydrology. *Progress in Physical Geography* 34: 151–171.
- Parker G, Wilcock PR Paola C, et al. (2007) Quasi-universal relations for bankfull hydraulic geometry of single-thread gravel-bed rivers. *Journal of Geophysical Research* 112: F04005.
- Parsons AJ (2006) Whither geomorphology (re-)revisited. *Earth Surface Processes and Landforms* 31: 1595–1596.
- Pedynowski D (2003) Science(s) which, when and whose? Probing the metanarrative of scientific knowledge in the social construction of nature. *Progress in Human Geography* 27: 735–752.
- Phillips JD (2004) Laws, contingencies, irreversible divergence and physical geography. *The Professional Geographer* 56: 37–43.
- Phillips JD (2007) The perfect landscape. *Geomorphology* 84: 159–169.
- Phillips JD (2011) Emergence and pseudo-equilibrium in geomorphology. *Geomorphology* 132: 319–326.
- Phillips JD (2012) Storytelling in earth sciences: The eight basic plots. *Earth Science Reviews* 115: 153–162.
- Poole GC (2002) Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. *Freshwater Biology* 47: 641–660.
- Preston N, Brierley GJ and Fryirs KA (2011) The geographic basis of geomorphic enquiry. *Geography Compass* 5: 21–34.
- Rhoads BL (2005) Process/form. In: Castree N, Rogers A and Sherman D (eds) *Questioning Geography*. Oxford: Blackwell, 131–150.
- Rhoads BL (2006) The dynamic basis re-envisioned: A process perspective on geomorphology. *Annals of the Association of American Geographers* 96: 14–30.
- Rhoads BL and Thorn CE (1993) Geomorphology as science: The role of theory. *Geomorphology* 6: 287–307.
- Rhoads BL and Thorn CE (1996) Observation in geomorphology. In: Rhoads BL and Thorn CE (eds) *The Scientific Nature of Geomorphology*. Chichester: Wiley, 21–56.
- Rhoads BL and Thorn CE (2011) The role and character of theory in geomorphology. In: Gregory KJ and Goudie A (eds) *The SAGE Handbook of Geomorphology*. London: SAGE, 59–77.
- Rhoads BL, Wilson D and Urban M (1999) Interaction between scientists and nonscientists in community-based watershed management: Emergence of the concept of stream naturalization. *Environmental Management* 24: 297–308.
- Richards K (1986) Fluvial geomorphology. *Progress in Physical Geography* 10: 401–420.
- Richards K and Clifford NJ (2008) Science, systems and geomorphologies: Why LESS may be more. *Earth Surface Processes and Landforms* 33: 1323–1340.
- Richards K and Clifford NJ (2011) The nature of explanation in geomorphology. In: Gregory KJ and Goudie A (eds) *The SAGE Handbook of Geomorphology*. London: SAGE, 36–58.
- Richards KS, Brooks SM Clifford NJ, et al. (1997) Realism in geomorphology. In: Stoddart DR (ed.) *Process and Form in Geomorphology*. London: Routledge.
- Rogers KH and O’Keefe J (2003) River heterogeneity: Ecosystem structure, function and management. In: Du Toit JT, Rogers K and Biggs HC (eds) *The Kruger*

- Experience: Ecology and Management of Savanna Heterogeneity*. Washington, DC: Island Press, 189–218.
- Roper BB, Buffington JM Archer E, et al. (2008) The role of observer variation in determining Rosgen stream types in northeastern Oregon mountain streams. *Journal of the American Water Resources Association* 44: 417–427.
- Sauer CO (1956) The education of a geographer. *Annals of the Association of American Geographers* 46: 287–299.
- Schumm SA (1977) *The Fluvial System*. New York: Wiley.
- Schumm SA (1991) *To Interpret the Earth: Ten Ways to be Wrong*. New York: Cambridge University Press.
- Schumm SA and Lichty RW (1965) Time, space and causality in geomorphology. *American Journal of Science* 263: 110–119.
- Simpson GG (1963) Historical science. In: Albritton CC (ed.) *The Fabric of Geology*. Reading: Addison-Wesley, 24–48.
- Slaymaker O (2009) The future of geomorphology. *Geography Compass* 3: 329–349.
- Small MJ and Doyle MW (2012) Historical perspectives on river restoration design in the USA. *Progress in Physical Geography* 36: 138–153.
- Spedding N (2011) Landform. In: Agnew J and Livingstone DN (eds) *The SAGE Handbook of Geographical Knowledge*. London: SAGE, 465–475.
- Stallins JA (2006) Geomorphology and ecology: Unifying themes for complex systems in biogeomorphology. *Geomorphology* 77: 207–216.
- Tadaki M, Salmund J Le Heron R, et al. (2012) Nature, culture, and the work of physical geography. *Transactions of the Institute of British Geographers* 37: 547–562.
- Thorn CE (1988) *An Introduction to Theoretical Geomorphology*. Boston, MA: Unwin Hyman.
- Trudgill S and Richards K (1997) Environmental science and policy: Generalizations and context sensitivity. *Transactions of the Institute of British Geographers* 22: 5–12.
- Van Dam RL (2012) Landform characterization using geophysics – recent advances, applications, and emerging tools. *Geomorphology* 137: 57–73.
- Wainwright SP (2012) Science studies in physical geography: An idea whose time has come. *Progress in Physical Geography* 36: 786–812.
- Wilcock D, Brierley GJ and Howitt R (forthcoming) Ethnogeomorphology. *Progress in Physical Geography*.
- Wohl E (2012) The complexity of the real world in the context of the field tradition in geomorphology. *Geomorphology*. doi: 10.1016/j.geomorph.2012.12.016.
- Woodyer T and Geoghegan H (2013) (Re)enchanted geography? The nature of being critical and the character of critique in human geography. *Progress in Human Geography* 37(2): 195–214.
- Wylie J (2007) *Landscape*. Abingdon: Routledge.