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Truths of the Riverscape: Moving beyond command-and-control to geomorphologically informed nature-based river management

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Abstract

Truths of the Riverscape refer to the use of geomorphological principles to inform sustainable approaches to nature-based river management. Across much of the world a command-and-control philosophy continues to assert human authority over rivers. Tasked to treat rivers as stable and predictable entities, engineers have 'fixed rivers in place' and 'locked them in time'. Unsustainable outcomes ensue. Legacy effects and path dependencies of silenced and strangled (zombified) rivers are difficult and increasingly expensive to address. Nature fights back, and eventually it wins, with disastrous consequences for the environment, society, culture and the economy. The failure to meet the transformative potential of nature-based applications is expressed here as a disregard for 'Truths of the Riverscape'. The first truth emphasises the imperative to *respect diversity*, protecting and/or enhancing the distinctive values and attributes of each and every river. A cross-scalar (nested hierarchical) lens underpins practices that 'know your catchment'. The second truth envisages management practices that *work with processes*, interpreting the behaviour of each river. This recognises that erosion and deposition are intrinsic functions of a healthy living river—in appropriate places, at appropriate rates. This premise underpins the third truth, *assess river condition*, highlighting the importance of what to measure and what to measure against in approaches that address the causes rather than the symptoms of unexpected river adjustment. The fourth truth *interprets evolutionary trajectory to determine what is realistically achievable* in the management of a given river system. Analysis of whether the river sits on a degradation or recovery pathway (i.e., condition is deteriorating or improving), alongside assessment of catchment-specific recovery potential, is used to foresight river futures. Viewed collectively, Truths of the Riverscape provide a coherent platform to develop and apply proactive and precautionary catchment management plans that address concerns for biodiversity loss and climate change adaptation.

Keywords: Fluvial geomorphology, Climate change adaptation, Biodiversity management, Command-and-control, Sustainable development, Catchment, Adaptive management, Precautionary principle, Conservation, Geoethics

"Science for its own sake usually means nothing more than science for the sake of the people who happen to be pursuing it. Knowledge which is unable to support action is not genuine—and how unsure is activity without understanding …

Rudolf L. C. Virchow (1821–1902)

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Introduction

Despite good scientific understanding of river systems, significant awareness of the issues to be addressed, and considerable expenditure and socio-cultural/political goodwill in the design and implementation of restoration programmes, river health is in a perilous state in many parts of the world (e.g., Albert et al. 2020; Best 2019; Reid et al. 2019; Su et al. 2021). Biodiversity losses, increasing flood- and drought-induced disasters, and failure to adapt to changing climates present a salutary reminder of the unsustainable outcomes of management practices and the unfulfilled promise and prospect of an era of river repair (Bernhardt and Palmer 2011; Brierley and Fryirs 2008; Palmer et al. 2010; Suding 2011; Tickner et al. 2020). In large part this reflects the persistence of the prevailing management ethos—a command-and-control mentality that asserts human authority over river systems (Holling and Meffe 1996).

Tasked to make river systems more manageable and predictable entities, engineering interventions emphasise concerns for river stability and hydraulic efficiency (e.g., Brookes 1985; Downs and Gregory 2014; Gilvear 1999; Newson et al. 1997; Newson and Large 2006; Sear 1994; Sear et al. 1995; Thorne et al. 1997). Channelisation programmes systematically simplify alluvial reaches, creating uniform, straightened channels (e.g., Petts 1984). Dams and weirs disrupt longitudinal connectivity, 'silencing' rivers (McCully 1996). Anthropogenic margins such as artificial levees and embankments (stopbanks) disconnect channels from floodplains (Belletti et al. 2020), 'strangling' rivers into increasingly lifeless and sterile forms (zombie rivers; Brierley et al. 2021a). Resulting path dependencies and legacy effects are expensive and increasingly difficult to revoke (Moore and Rutherfurd 2017). All too often, practices of a fast-emerging river restoration industry are little more than repackaged applications of a command-and-control philosophy under the label of 'environmentally sensitive engineering' (Kondolf 2011; Hewett et al. 2020), failing to engender self-sustaining, dynamically adjusting, healthy rivers (e.g., Bernhardt and Palmer 2011; Feld et al. 2011; Palmer et al. 2005, 2010, 2014). An alternative approach to river science and management is required.

Rather than fighting nature, nature-based solutions embrace a different mentality, conceptualising humans as part of nature, supporting sustainable development in ways that deliver multiple benefits for people and nature (Fryirs and Brierley 2021b; Garcia et al. 2021; Hooke 2020; Newson 2021; WWAP 2018). Working with the river in holistic, place-based (catchment-specific) applications contributes to the achievement of several United Nations (UN) Sustainable Development Goals (SDGs) to generate social, economic and environmental co-benefits that deliver various ecosystem services (e.g., Martin et al. 2020). Guidelines for design and uptake of nature-based solutions proposed by Albert et al. (2021) entail six planning steps: *Co-define setting*, *Understand challenges*, *Create visions and scenarios*, *Assess potential impacts*, *Develop solution strategies*, and *Realise and monitor*, with implementation guided by five principles: *Place-specificity*, *Evidence base*, *Integration*, *Equity,* and *Transdisciplinarity*. Aligned directly with this conceptualisation, this paper applies such thinking to the application of geomorphological principles to the development and delivery of management practices that work with the river.

Recognising that fragmented knowledge can only engender fragmented management, coherent, whole-of-system understanding is required to develop and enact practices that work with nature. Conceptualisations of landscapes and ecosystems as holistic, evolving, emergent and indivisible are firmly embedded in lived experiences of indigenous peoples (Fox et al. 2017; Hikuroa et al. 2021; Wilcock et al. 2013; Wilkinson et al. 2020). Parallel scientific framings apply a riverscapes ethos that incorporates understandings of the geo–eco-hydrological template of each river system—its dynamic physical habitat mosaic (Benda et al. 2004; Castro and Thorne 2019; Fausch et al. 2002; Johnson et al. 2020; Jungwirth et al. 2002; Polvi et al. 2020; Ward 1989; Wiens et al. 2002). Such conceptualisations recognise that the weakest link in life-cycle chains fashions the functionality and integrity of the ecosystem as a whole (Hilderbrand et al. 2005). Living rivers are disturbance-driven entities (Everard and Powell 2002). Each river system is unique—perfect in its own right (Phillips 2007). Emerging approaches to integrative river management appraise feedbacks *between* social and ecological processes, conceiving riverscapes as complex, dynamic, interacting social–ecological systems (e.g., Downs and Piégay 2019; Dunham et al. 2018; Frascaroli et al. 2021; Hand et al. 2018). Framed in this manner, a riverscapes ethos provides a holistic platform for biodiversity management, flood risk and climate change adaptation programmes (e.g., Tonkin et al. 2019).

Among many factors, the generation of catchment-specific knowledge presents a significant impediment to the design and uptake of nature-based approaches to river management. System complexity must be unravelled and interpreted in efforts to describe, explain and predict the inherent traits of a given riverscape (Brierley and Fryirs 2005; Brierley et al. 2021b). Geomorphic understandings of landscapes provide a foundation template for such endeavours (Brierley and Fryirs 2005; Downs and Gregory 2014; Thorp et al. 2006; Wohl 2005, 2015a, b). However, deriving catchment-specific geomorphic understandings is not always a straightforward task. As noted in the foundation textbook by Schumm (1991); *To*

Interpret the Earth: Ten Ways to be Wrong), geomorphology is not a linear, cause and effect science (see Brierley et al. 2021b; Grant et al. 2013). Complexities and challenges often conflict uncomfortably with management quests for simple, consistent, efficient, standardised and readily applicable practices (e.g., Lave 2012), which can result in a form of turbulence and trainwrecks as outlined by Benda et al. (2002) and Boulton et al. (2008). Prescriptive applications that build upon generalised (theoretical) understandings disrespect the distinctive properties and values of a given river system (Brierley et al. 2013). Management interventions that strive to make rivers the same engender unsustainable and inequitable outcomes (Simon et al. 2007; Tadaki et al. 2014).

The failure to meet the transformative potential of nature-based applications (Fryirs and Brierley 2021b; Newson 2021) is expressed here as a disregard for 'Truths of the Riverscape' (Table 1). These principles parallel Truths of the Shoreline proposed by Pilkey et al. (1978) in their critique of unsustainable and inequitable approaches to coastal management, wherein engineering measures strive to control beaches by keeping them in-place (see Neal et al. 2018). The 'Truths of the Riverscape' outlined in this paper provide a package of geomorphic principles to guide coherent approaches to river management:

- **Truth 1**: Respect diversity
- **Truth 2**: Work with process
- **Truth 3**: Assess river condition
- **Truth 4**: Interpret evolutionary trajectory to determine what is realistically achievable.

Principles that underpin **Truth 1**, *respect diversity*, support development of catchment-specific knowledge to look after distinctive values and attributes of each river system. *Working with processes* (**Truth 2**) applies

Table 1 Truths of the Riverscape

Truth 1: Respect diversity	
Discipline-bound knowledges assert theoretical framings of the river as it should be	Nested hierarchical principles underpin appropriately contextualised knowledge of the geo-eco-hydrological template of a river. A holistic riverscape approach generates and applies catchment-specific knowledges of the river as it is
Truth 2: Work with process	
Site/reach-scale applications, typically channel-centric, apply linear, cause-and-effect principles that conceptualise a river as a predictable entity in a dynamic equilibrium state (i.e., regime principles)	Process relationships conceptualise rivers as living, adjusting, disturbance-driven entities. Inherent uncertainties accompany understandings of rivers as non-linear, contingent and emergent entities that demonstrate complex response
Truth 3: Assess river condition	
Prescriptive, checklist, cookbook applications (one size fits all) generate a static appraisal of a river, conceived as a collection of bits	Open-ended methods meaningfully compare like-with-like in process-based appraisal of character and behaviour, emphasising concerns for the integrity of river systems
Truth 4: Interpret evolutionary trajectory to determine what is realistically achievable	
Site/reach scale applications are inappropriately contextualised in space and time	Interpretation of where each reach sits on a degradation or recovery pathway is used to scope realistically achievable visions, framing reach-scale moving targets in relation to recovery potential and (dis)connectivity relations at the catchment scale
Bring Truths together to inform management applications	
Reactive, cost-ineffective, ad hoc applications. Locked-in mentalities and legacy effects set path dependencies that are expensive and difficult (sometimes impossible) to revoke	Proactive and precautionary catchment plans respect diversity and work with processes to improve river condition. A conservation ethos works with recovery and strategically addresses threatening processes. Monitoring underpins adaptive management programmes that adjust as necessary
Limitations of a command-and-control perspective and imperatives of a nature-based approach to river management	

understandings of how and why a river looks and works as it does, defining the expected structure and range of behaviour (functionality) of a river. This underpins efforts to *assess river condition* (**Truth 3**) to ensure that appropriate criteria are used to compare like with like and identify underlying causes, not just the symptoms, of river condition. *Interpretation of evolutionary trajectory to determine what is realistically achievable* (**Truth 4**) assesses whether river condition is improving or continuing to deteriorate, and the recovery potential of the system. Insights derived from this package of Truths support proactive and precautionary catchment management plans that protect system-specific values and attributes, strategically address threatening processes and work with recovery to improve river condition (Table 1).

This paper applies a scaffolding approach that systematically documents understandings of each Truth, then brings together findings to support the development and implementation of proactive and precautionary catchment management plans. Various figures and tables provide an adaptable package of resources to support the development of geomorphologically informed river and catchment management.

Truth 1: Respect diversity

Truth statement: *Unless management practices respect diversity they fail to embrace place-based values, compromising biodiversity management and sustainability programmes. Failure to develop and apply management programmes at the catchment scale results in inequitable outcomes in spatial and temporal terms.*

Sustainable approaches to river management respect the geodiversity of river systems along the spectrum from bedrock-controlled to fully alluvial and wetland variants (discontinuous watercourses) (Fig. 1A; Table 2). While an energy-induced gradient of river types is clear (Fig. 1B), concerns for biodiversity management embrace the quirky and the unique, alongside typical or common attributes (Fryirs and Brierley 2009, 2021a). Exceptionalism and local differences matter: No two rivers are exactly the same and there is no magic number of river types (Brierley et al. 2013; Phillips 2007; cf., Rosgen 1994). Some rivers are naturally complex and heterogeneous (messy), others are relatively simple and homogeneous (Fryirs and Brierley 2009, 2021a). Some are inherently connected, others are not (Fryirs et al. 2007; Poole 2002). Some rivers operate as discontinuous (unchannelised) watercourses. Despite such long-standing knowledge, command-and-control approaches to river management pigeon-hole rivers into a select number of classes, applying carbon-copy principles that strive to make rivers the same (Hilderbrand et al. 2005; Tadaki et al. 2014). Discipline-bound, fragmented knowledges assert theoretical framings of rivers as they 'should' be. Conversely, nature-based approaches apply holistic, catchment-specific knowledge that works with each river as it is.

Building upon foundation work by Frissell et al. (1986), Naiman et al. (1992) and Poff (1997), a nested hierarchical framework provides conceptual and practical guidance to analyse and interpret river diversity (Brierley and Fryirs 2005; Gurnell et al. 2016; Table 3). In simple terms, river diversity at the granular scale reflects hydraulic interactions with available bed material, creating and reworking hydraulic units (also called biotopes or ecotopes; Newson and Newson 2000; Thomson et al. 2001). Process–form interactions at the landform (geomorphic unit) scale reflect the distribution and effectiveness of erosional and depositional processes in channel and floodplain compartments (**Truth 2**) (e.g., pool scour, bar deposition, levee formation; Brierley and Fryirs 2005; Fryirs and Brierley 2013, 2021a; Wheaton et al. 2015). Characteristic assemblages and patterns of geomorphic units at the reach scale provide the key platform for process-based river management (**Truth 2**) (Kellerhals et al. 1976; Fryirs and Brierley 2021a). Conceptualising rivers like the veins on a leaf, tributary-trunk stream relations drive the operation of source, transfer and accumulation zones at the catchment scale (Fig. 2b; Schumm 1977). What happens upstream impacts upon what happens downstream, and what happens off-site can have consequences on-site or elsewhere—it's just a matter of time (**Truth 4**). As drainage basins are the fundamental geomorphic and hydrologic unit (Chorley 1969), it is imperative to "know your catchment' (Brierley and Fryirs 2005).

Longitudinal profiles provide an elegant tool to frame and communicate catchment-scale patterns of river types (Fig. 2A, C) (e.g., O'Brien et al. 2017). Downstream changes in slope and valley setting (width) are key determinants of the distribution of flow energy (stream power) in river systems (e.g., Bizzi and Lerner 2015). Geological factors, alongside the discharge regime and anthropogenic impacts, influence the pattern of river types (Fig. 2b). Drainage network configuration and the balance of erosion or deposition along a longitudinal profile are key controls upon the type and distribution of geomorphic hotspots in a catchment (areas where river responses to disturbance are accentuated; Czuba and Foufoula-Georgiou 2014, 2015), and the relationships between on-site and off-site impacts (**Truth 4**).

Truth 2: Work with process

Truth statement: *Unless management practices work with process they fail to work with the river, inhibiting prospects to sustain key values, attributes and functions of a living and dynamically adjusting system.*

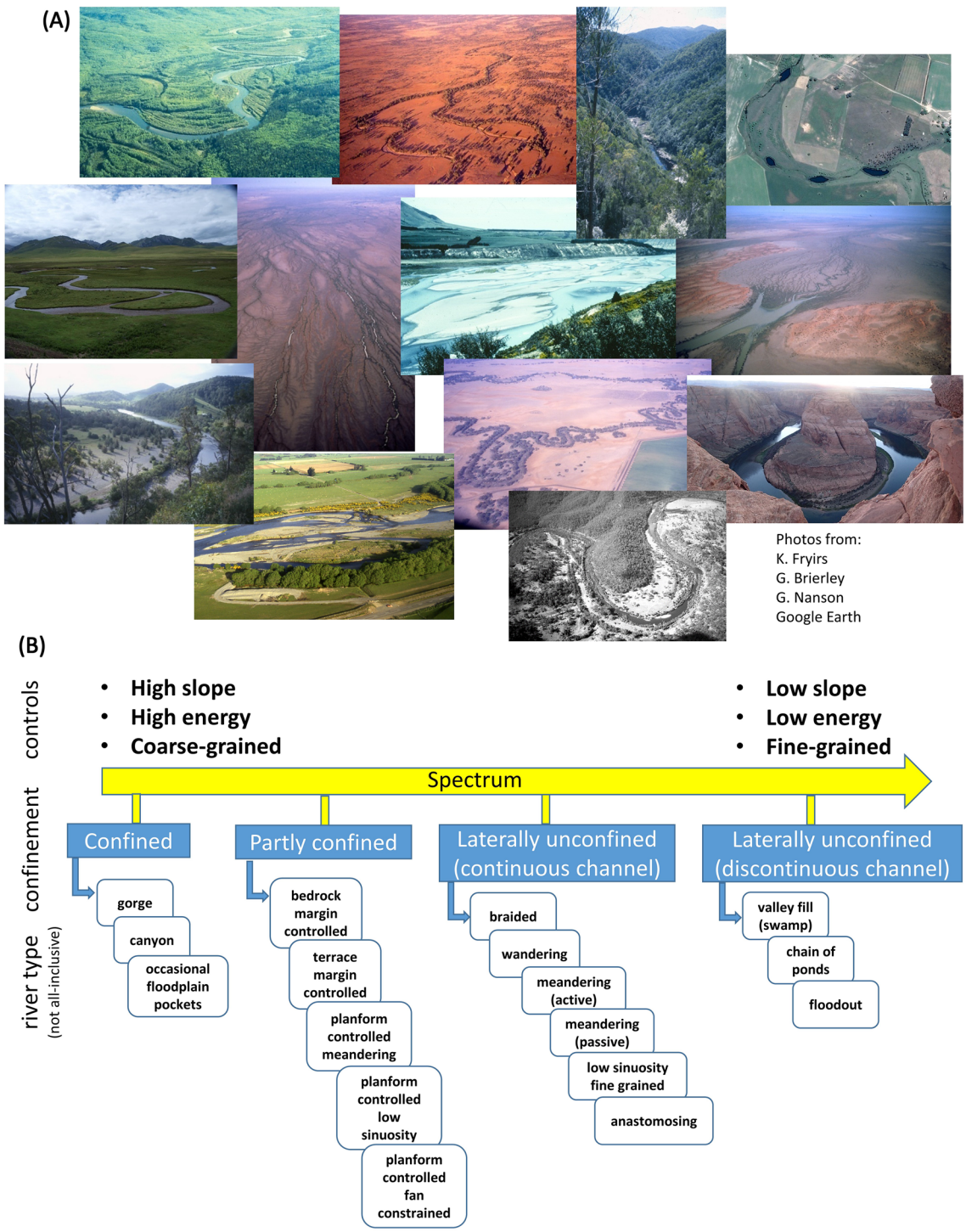

Fig. 1 Respect diversity. **A** Shows examples of river diversity, **B** conceptualises the spectrum of river diversity along an energy gradient

Nature-based applications recognise that rivers are disturbance-driven entities (Table 4). They are never static. Rather, each riverscape is a product of a suite of processes that operates across various spatio-temporal scales (Table 3). Accordingly, management practices are unlikely to be effective unless they build upon process-based understandings of a given river (Beechie et al. 2010; Rhoads 2020; Simon et al. 2007; Spink et al. 2009).

Table 2 Geomorphic principles that underpin management practices that respect diversity (**Truth 1**)

Work with the river as it is, not theoretical or digital representations of a river divorced from place-based understandings
Geography and history matter. Theory is good, but reality is better
Open-ended and flexible practices identify and look after key values of each and every river
Some rivers are inherently messy (heterogeneous), others are not. Some rivers are leaky, others are not. Not all rivers have a channel
A nested hierarchical framework of understanding derives and applies appropriately contextualised, cross-scalar, catchment-specific knowledge
Know your catchment. The catchment is the fundamental geomorphic unit. Like the veins on a leaf, the catchment feeds the river. What happens upstream impacts downstream—it's just a matter of time
Different types of river at the reach scale comprise differing assemblages of geomorphic units (also called hydromorphic or morphologic units)
Drainage network configuration and tributary-trunk stream interactions influence the pattern of geomorphic process zones, associated patterns of river types and (dis)connectivity relationships at the catchment scale
Listen to the river and learn from it. Catchment-specific understandings give due regard for diversity, variability, process, pattern and evolutionary traits

Table 3 Nested hierarchical (cross-scalar) approach to analysis of river systems (after Brierley and Fryirs 2005; Frissell et al. 1986; Gurnell et al. 2016; Naiman et al. 1992; Poff 1997)

Scale	Attributes	Significance (respect diversity)	Importance for other Truths
Ecoregion	Catchment styles (archetypes)	Biodiversity links to geodiversity Platform for planning and policy Appraise catchment-scale similarity/differences	Evolutionary traits (**Truth 4**)
Catchment	Hydrologically and geomorphologically constrained unit (veins on a leaf) Pattern of process zones Drainage network: Tributary-trunk stream and connectivity relationships	Fundamental geomorphic unit—holistic basis for land and water management	Proactive planning that incorporates knowledge of off-site impacts and legacy effects (**Truth 4**)
Reach (River Style)	Relatively uniform assemblage and pattern of geomorphic units Planform scale—channel–floodplain linkage	Geomorphic process zone (source, transfer, accumulation) Balance of flow/sediment flux (regime principles)	Magnitude–frequency relations (range of behaviour) (**Truth 2**) Form/capacity for adjustment (sensitivity) (**Truth 2**) Key scale for process-based analysis of river condition (**Truth 3**)
Geomorphic unit	Channel and floodplain landforms Channel geometry	Dynamic physical habitat mosaic	Morphodynamics—process–form linkage (bed before banks) (**Truth 2**) Magnitude–frequency relations (**Truth 2**)
Bed material size	Bedrock (forced) versus alluvial (freely adjusting) Flow–sediment interactions—Hydraulic units	Impelling-resisting forces - Biotopes	Ease of adjustment (rivers love sand) and bank strength (**Truth 2**)

Command-and-control management programmes apply linear, cause-and-effect principles to impose upon a reach a particular morphology with a particular process regime. Typically, channel-centric designs apply dynamic equilibrium (regime) principles, often divorced from understandings of process relationships at broader spatial and temporal scales. Such interventions fight the river and the river fights back. Eventually it wins! In contrast, nature-based framings work with the range of processes to create and regenerate the dynamic physical habitat mosaic of a healthy river (Florsheim et al. 2008; Maddock 1999; Piégay et al. 2005). Healthy river systems are entirely capable of looking after themselves, as erosional and depositional processes create and rework landforms (geomorphic units). Different types of river along the spectrum of river diversity shown in Fig. 1 set their own slope over different timeframes, as forms, patterns and effectiveness of resistance elements adjust in different ways (e.g., bed material organisation, scour to create step-pool sequences, number of channels and sinuosity, etc.).

Implicitly, the management imperative to 'work with river process' considers river behaviour at the reach scale, framing understandings of forms and rates of activity in their catchment context. Such assessments are inherently tied to perceptions of river condition (Truth 3)—the character (structure) and behaviour (function) that is considered to constitute a healthy river at a particular place

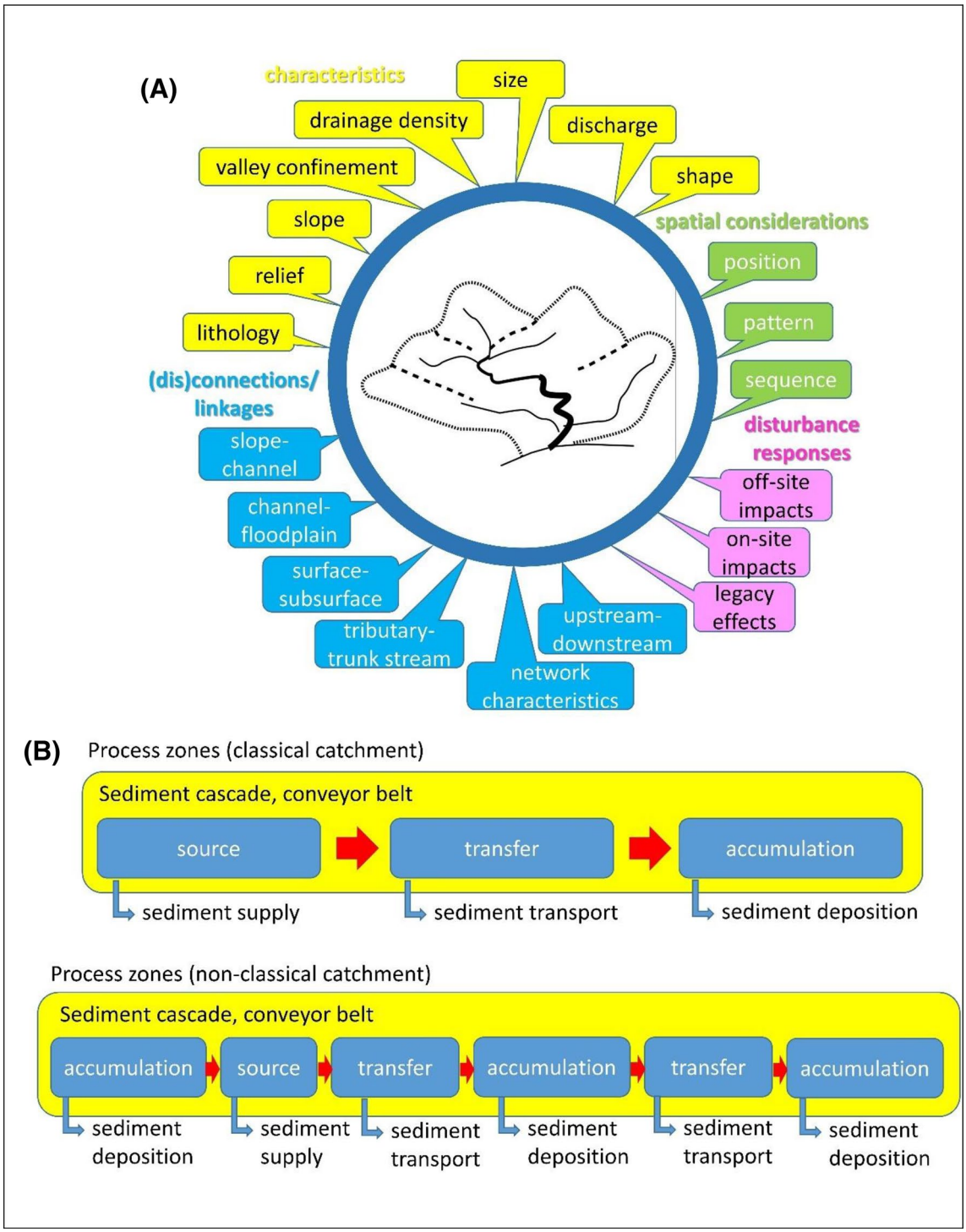

Fig. 2 Know your catchment. **A** Characteristics, linkages, spatial considerations and disturbance responses of catchments, **B** Patterns of process zones at the catchment scale, **C** Longitudinal profiles provide a tool to interpret and communicate controls on catchment-scale sequences and patterns of river types. This example is from the Middle Fork John Day, USA and has been modified from O'Brien et al. (2017) and Fryirs et al. (2019)

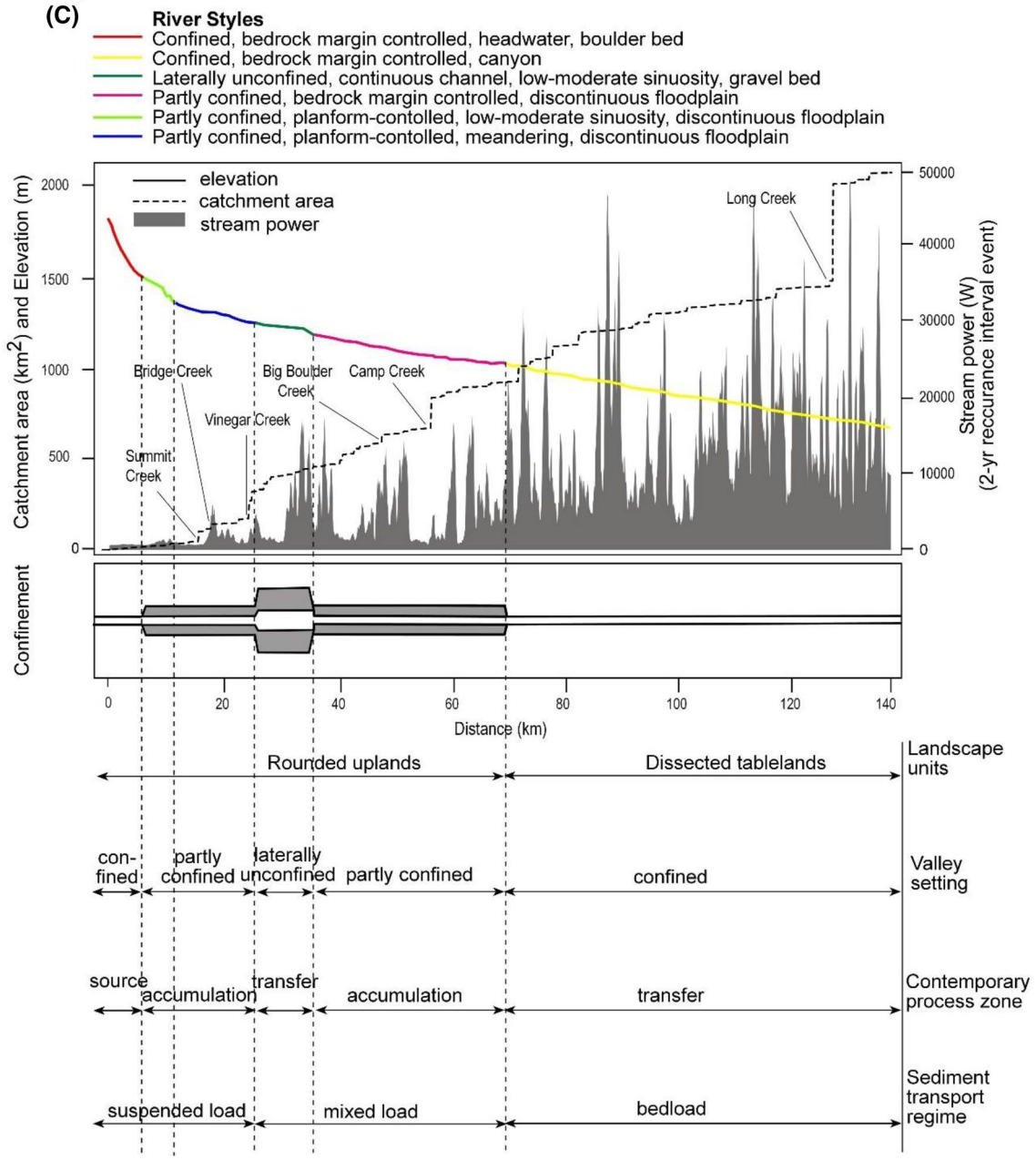

Fig. 2 continued

and time (e.g., Fryirs 2015). Erosion and sedimentation are integral parts of a healthy, living river—in the right place, at the right time/rate (Florsheim et al. 2008; Piégay et al. 2005). Similarly, riparian vegetation cover and wood loading are important attributes of a healthy river, so long as associated process interactions are appropriate for the type of river under investigation (Corenblit et al. 2007; Gurnell 2014). Viewed in this way, floods, droughts, erosion, sedimentation or vegetation 'problems' are entirely anthropocentric concerns. To the river itself, 'natural' disturbance events are important parts of river behaviour and functionality—the river is simply being a river. For example, floods form and regenerate alluvial soils and are important drivers of recovery processes in rehabilitation initiatives (**Truth 4**; Fryirs et al. 2018; Williams et al. 2020). The more management programmes promise 'protection' from flood-related 'problems', the greater the costs and potential consequences of disasters (e.g.,

Table 4 Geomorphic principles that work with river process (**Truth 2**)

Don't fight the river. Locked-in mentalities that strive to control a river are unsustainable. Rivers that are fixed in place and locked in time are expensive to maintain. Nature fights back. Eventually it wins!
A living river ethos recognises rivers as disturbance-driven systems. Rivers are never static. Adjustment is the norm
A riverscape ethos works with the process regime that creates and regenerates the dynamic physical habitat mosaic
Erosion and sedimentation are integral parts of a healthy, living river – in the right place, at the right time and rate
Rivers create their own resistance (roughness) and are really good at using their own energy
Ecosystem engineers modify rivers for their own benefit, creating living rivers just as they like them
The balance of impelling and resisting forces, and the spatial distribution of unit stream power, influence the frequency of sediment movement through the system
River morphodynamics at the reach scale vary markedly for differing types of river, with significant differences in capacity for adjustment (sensitivity; rivers love sand) and range of variability (process regime). Different types of river adjust in different ways over differing timescales
The assemblage of geomorphic units along a reach reflects the suite of process–form interactions and magnitude–frequency relations that determine forms and rates of river adjustment (vertical, lateral and wholesale adjustment)
Different combinations of erosional and depositional processes occur at different flow stages, with marked variability in magnitude–frequency relations for different types of rivers. Some rivers are adjusted to extreme events, others are not
Channel geometry (size and shape) and channel–floodplain relationships (channel planform) are products of differing mixes of erosional and depositional processes on the bed and banks
Channels and floodplains tell different stories. When interpreting a river, it is important to get your head out of the channel
Reach-scale behaviour varies in differing process zones and is affected by (dis)connectivity relationships (controls upon the flow/sediment regime) at the catchment scale. Tributary-trunk stream relationships and network configuration control patterns of river reaches and the distribution of geomorphic hotspots
Controls upon process interactions vary at differing positions along a river (relative role of slope, valley width, discharge regime, stream power, sediment inputs (amount, calibre), bank strength, etc.). Different types of disturbance event, and upstream–downstream relationships, influence the pattern and range of variability of reaches along the river

Buffin-Belanger et al. 2015). As expressed by Bush et al. (1996, p 170), catastrophes often set the stage for bigger catastrophes. Building upon Truths of the Shoreline espoused by Pilkey et al. (1978), Bush et al. (1996, p 170) continue to assert: "… if you choose to live by the sea, … (it pays) to live by the rules of the sea."

Not all processes are necessarily healthy for a given river (**Truth 3**). Indeed, an imbalance in the mix and/or rate of process activity may threaten distinctive values of a given reach. For example, the loss of certain processes such as extreme flood events or the acceleration/suppression of process activity may be considered unhealthy. Work with process (**Truth 2**) builds directly upon **Truth 1**: Respect diversity. This recognises that different types of river adjust in different ways over differing timescales, with significant differences in capacity for adjustment and range of variability.

Controls upon process relationships are manifest at different scales (Table 3; Church 1996; Schumm and, 1965). Boundary, channel and valley scale elements induce different forms of roughness (resistance elements) (Fig. 3). At the granular scale, hydraulic interactions between water, sediment and vegetation reflect the balance between impelling and resisting forces at any given location (Fig. 3). Essentially, this reflects how moving water interacts with the boundaries against which it flows, overcoming frictional resistance such that impelling (gravitational) forces induce downslope-movement. As flow depth increases, the relative influence of boundary resistance decreases. Hence, the relationship between bed material size and flow depth is a key determinant of process interactions. Eventually, increases in flow depth/energy mobilise grains as bed resistance is exceeded (Fig. 3A, B). Forms and rates of channel adjustment reflect the deformability of channel boundaries (i.e., how alluvial each reach is). Rivers love sand, the most readily entrained and mobilised materials (Fig. 3A). In turn, bank material properties such as the cohesiveness of sediments (percentage fine-grained materials) and the role of riparian vegetation and wood are key determinants of the ease of channel adjustment (Eaton and Millar 2017).

Variability in boundary resistance along river courses reflects differences in bed material size/organisation, bank characteristics and channel geometry/planform. In simple terms this is determined by the smoothness of the flow boundary, and the relative influence of vegetation, bed/bank irregularities and anthropogenic structures. Various flora and fauna act as ecosystem engineers, modifying forms and patterns of resistance elements along river courses (Gurnell 2014; Law et al. 2017; Wheaton et al. 2019). In turn, channel size and alignment influence the ways in which energy is concentrated or dissipated (Fig. 3C). These factors influence when and where sediments are deposited, the landforms (geomorphic units) that are created and reworked, and the distribution of erosional and depositional processes that determine

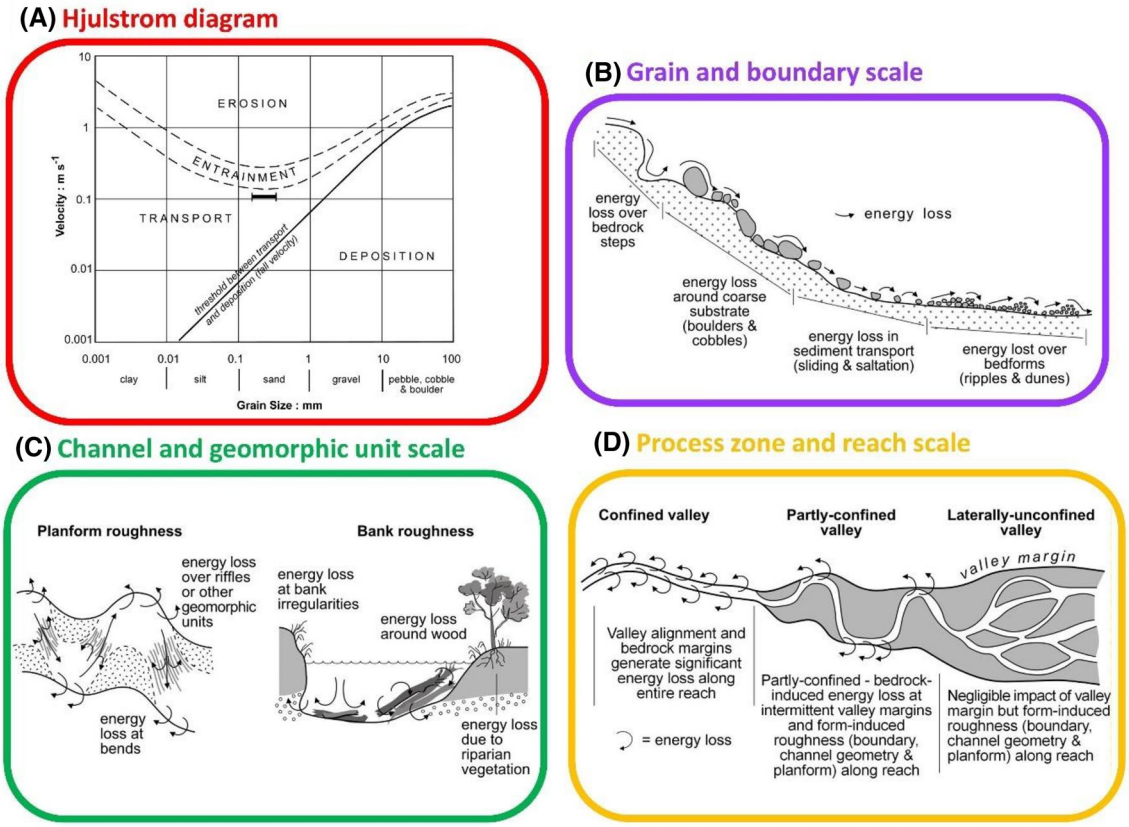

Fig. 3 Working with process: Impelling and resisting forces in river systems. **A** Hjulstrom diagram describes the relationship between bed material size and sediment entrainment, transport and deposition in rivers, showing that sands are the most readily mobilised materials in river systems (rivers love sand). **B** At the grain scale, interactions between the size and organisation of bed materials (boundary resistance) and flow (conditioned largely by slope and depth) influence the frequency of bed mobilisation and the distance materials are transported. **C** Channel geometry and planform influence the extent of the bed/bank surface against which flow interacts (and the form resistance thereof). **D** Valley scale resistance reflects the extent to which the channel abuts valley margins (or other lateral constraints such as terraces and anthropogenic structures) relative to planform-induced resistance

channel geometry and planform (Fryirs and Brierley 2021a). Valley width and confinement result in variable influence of bedrock or other margins (e.g., terraces, anthropogenic constraints) relative to influences of channel geometry and planform upon resistance (Fig. 3D). These considerations influence the extent to which morphodynamic interactions are forced (or imposed) by structural elements, relative to fully self-forming (alluvial) situations (Wheaton et al. 2015).

Alluvial channels adjust their boundaries to mobilise and transport available sediment (cf., Eaton and Millar 2017; Nanson and Huang 2017). In efforts to consume flow energy, rivers create their own resistance in the channel and riparian zone—the number and sinuosity of channels, their size and shape (Fig. 3B–D). Channel width–depth ratio exerts a critical influence upon concentration of flow energy. Marked differences for bedload, mixed load and suspended load rivers reflect variability in the ease of sediment conveyance and bank strength (Eaton and Millar 2017; Schumm 1977). In planform terms, boundary resistance varies markedly in relation to the surface area of single and multi-channelled rivers relative to non-channelised situations (valley fills and discontinuous watercourses). Alongside this, channel sinuosity is a measure of surface area and boundary/form resistance, setting the slope of the channel and influencing its ability to transport available sediments (Fig. 3C).

Inevitably, historical constraints and legacy effects exert a significant but variable influence upon process relationships in river systems (**Truth 4**). In simple terms, it is important to assess "how contemporary is my river?" When were sediments that make up the bed and banks last mobilised and deposited? How have weathering and pedogenic processes altered these materials over time? When was the valley formed, and what determines the slope and space within which the contemporary channel

adjusts? How have anthropogenic impacts altered process relationships along a given reach (in what ways, to what degree/extent, with what consequences)?

Geomorphic units are a key analytical tool with which to interpret the process regime of a given reach and the pattern of reaches along a river course (Fig. 4; Brierley and Fryirs 2005; Fryirs and Brierley 2013, 2021a). Channel and floodplain landforms are ubiquitous features of all rivers. The type and pattern of geomorphic units reflect a continuum of stream power (slope) and flow-sediment interactions along a river. In any given reach, the balance and distribution of impelling and resisting forces determines the pattern and frequency with which geomorphic units are created and reworked. Formative processes vary in intensity and effectiveness at different flow stages (e.g., low flow, bankfull, overbank), with marked variability in magnitude–frequency relations for different types of rivers. As noted on the Lane Balance diagram (Fig. 4A), any factor that alters the flow/sediment balance affects river morphodynamics and the relative effectiveness of erosional and depositional processes results in different types and patterns of geomorphic units. Interpreting assemblages of geomorphic units provides a basis to map types and patterns of river reach (i.e., define reach boundaries) and assess the character, behaviour, capacity for adjustment and range of variability of reaches that make up a river system (Brierley and Fryirs 2005; Fryirs and Brierley 2021a).

Rivers adjust in vertical, lateral and wholesale dimensions (Fig. 4B). Differing combinations of erosional and depositional processes along the bed and the banks create channels with different geometries and geomorphic attributes (e.g., irregular forms of bedrock rivers relative to symmetrical, asymmetrical and compound forms). As channels and floodplains tell different stories about the character, behaviour and evolution of a river, it is important to 'get your head out of the channel' when analysing the range of behaviour of a given reach, appraising forms and rates of floodplain formation and reworking processes (e.g., Nanson and Croke 1992).

Working with process requires insight into forms and rates of adjustment at different flow stages (Fig. 4C). Interpretation of river behaviour builds upon analysis of the capacity for adjustment and the range of variability of a given reach and assessing the magnitude–frequency dynamics of assemblages of geomorphic units at the reach scale (Fryirs and Brierley 2021a). Some river processes are only activated during extreme events, whereas others occur during frequent, lower magnitude flows. Some rivers are adjusted to extreme events, others are

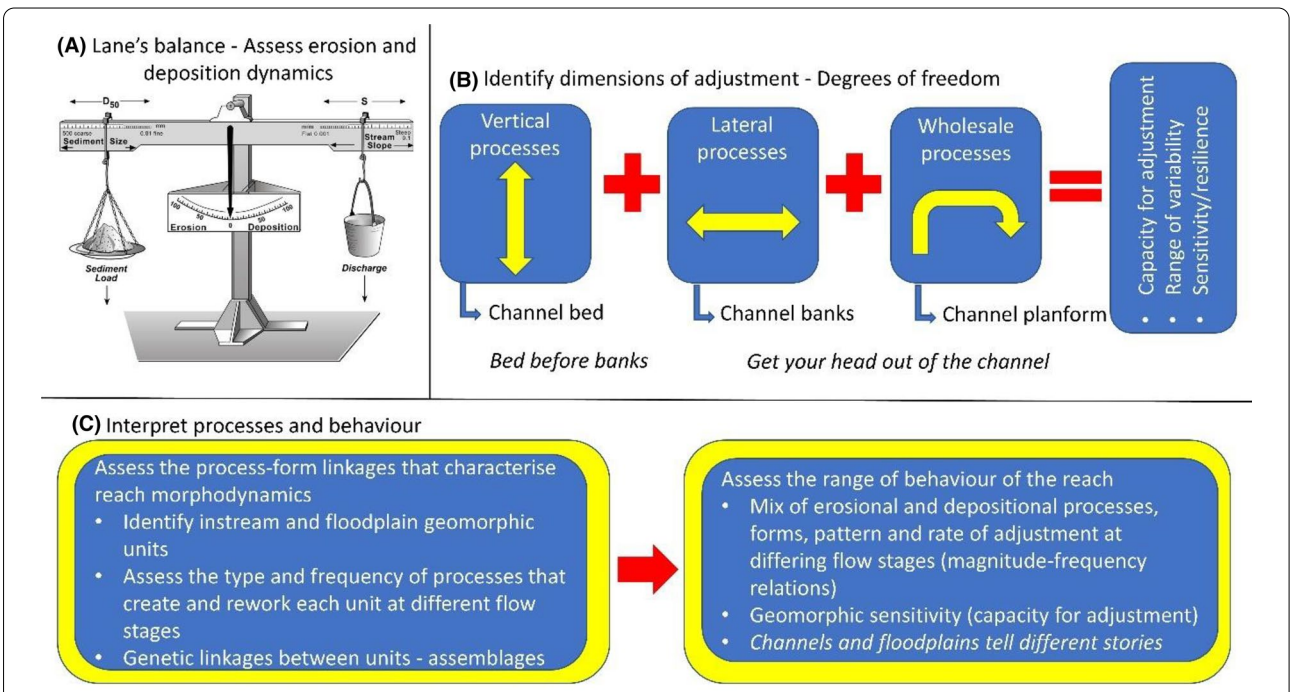

Fig. 4 Process–form linkages of geomorphic units determine and reflect river morphodynamics (and resulting channel geometry/planform) at the reach scale. **A** Lane Balance diagram helps to assess the balance of erosion and deposition at the reach scale. **B** Dimensions of adjustments and degrees of freedom determine the capacity for a river to adjust, its sensitivity and its range of variability. **C** Process–form associations of geomorphic units at different flow stages help to interpret river behaviour

not. Hence it is important to question the appropriateness and reliability of equilibrium-based regime principles in any given instance. Rivers do not always respond in predictable ways to a design flood (i.e., formative flows, often designated as bankfull discharge events; Eaton and Millar 2017; Davidson and Eaton 2018). Magnitude–frequency relationships of flood events, and complexities such as their duration and sequence (i.e., timing, flood history) determine their geomorphic effectiveness and the persistence of landscape changes that ensue (e.g., Costa and O'Connor 1995; Lisenby et al. 2018; Wolman and Gerson 1978). Much depends upon the geomorphic sensitivity of the system at the time of a given event (Brunsden and Thornes 1979; Downs and Gregory 2014; Fryirs 2017).

Ultimately, reach-scale patterns of river types and their (dis)connectivity reflect the pattern of geomorphic process zones and linkages between them at the catchment scale (Brierley and Fryirs 2005, 2009; Downs and Piégay 2019; Montgomery 1999; Schumm 1977; Fig. 2). Hence, the catchment scale is the critical focus for geomorphologically informed approaches to proactive and precautionary planning. Two key process-based analyses inform this: appraisal of controls upon reach-scale responses to disturbance events, and interpretations of the ways in which geomorphic responses are mediated (conveyed) through the catchment (i.e., (dis)connectivity relationships; Fryirs et al. 2007; Fryirs 2013; Downs and Piégay 2019; Wohl et al. 2019). Sometimes geomorphic responses to disturbance events are accentuated in particular parts of catchments. Typically, these 'geomorphic hotspots' reflect reach scale sensitivity to disturbance and/or the ways in which drainage network configuration accumulates off-site impacts and legacy effects in particular parts of river systems (Czuba and Foufoula-Georgiou 2014, 2015; **Truth 4**). Hence it is important to assess how tributary-trunk stream relationships and network configuration influence patterns of river reaches and reach–reach (dis)connectivity (Fig. 2B).

Truth 3: Assess river condition

Truth statement*: Unless river condition is measured appropriately, it is not possible to assess whether river health is improving or deteriorating, the effectiveness of management actions cannot be appraised and management practices fail to learn from past experiences.*

Many researchers are uncomfortable with qualitative, subjective assertions in scientific assessment of river condition (e.g., Boulton 1999; Norris and Thoms 1999). Others are uncomfortable with approaches that apply blanket checklists and quantitative scoring and weightings to metrics across all river types without considering whether the measures being used and the weightings applied reflect river diversity (**Truth 1**) and expected process and behaviour of the river being assessed (**Truth 2**) (Fryirs 2015; Fryirs et al. 2008). Even more contentious circumstances are encountered when these understandings are viewed alongside socio-economic and cultural considerations (e.g., Blue 2018; Vollmer et al. 2018). However challenging, condition assessment is required to appraise improvement or deterioration in river health (Karr 1999). Conducted effectively, monitoring informs adaptive management programmes that learn from past experiences (Brierley et al. 2010; Downs and Kondolf 2002; Gilvear 1999; Hobbs and Norton 1996; Kondolf and Micheli 1995).

Command-and-control management tends to push aside concerns for river health and ecosystem services. If conducted at all, a 'one size fits all' approach to monitoring typically conceptualises a river as a collection of parts, often failing to assess underlying processes that are key determinants of river condition. A nature-based ethos appraises the functionality of the system as a whole (Table 5). Efforts that work with process (**Truth 2**) to improve condition treat the underlying causes of system degradation (Table 3; Fryirs 2015; Gurnell et al. 2020; Hobbs and Norton 1996; Rinaldi et al. 2015). Open-ended methods meaningfully compare like-with-like in process-based appraisals of system functionality and integrity, guiding practices that target underlying threats

Table 5 Geomorphic principles to assess river condition (**Truth 3**)

Think holistically at the ecosystem scale, recognising that there are too many species to save them one at a time. The weakest link in the chain—the least effectively functioning attribute—determines the viability of life cycles and the performance of the system as a whole. A healthy river is more than a collection of parts
Identify and address causes of deterioration, not merely their symptoms (e.g., bed before banks)
Compare like-with-like, carefully considering what to measure against. What is expected in process terms reflects the capacity for adjustment and the expected range of variability for the type of river under consideration
Tailor applications to the type of river, measuring the right things in the right places in the right way at the right time. Use geoindicators that give a reliable and relevant signal of condition for the type of river
Determine whether each reach is in a good, moderate or poor condition relative to expected, explaining underlying causes of deterioration so that structural or process attributes can be addressed to improve river condition

to river health. This allows meaningful transfer of insights to other reaches of the same river type.

Assessment of river condition defines the contemporary state of a river relative to an expected reference condition (Fryirs, 2015; Fig. 5). In geomorphic terms, an expected reference condition is based on the type of river and its character and behaviour under prevailing boundary conditions (Fryirs 2015; Fryirs et al. 2008; Stoddard et al. 2006). What is considered 'good' or 'poor' is relative to expected. This incorporates understandings of river diversity (**Truth 1**), the capacity for adjustment and the range of variability for each type of river (**Truth 2**) (Fig. 5).

Assertions of a living, dynamically adjusting river recognise that just as disturbance is expected and varies from situation to situation, 'what is expected' in structural and functional terms may vary markedly for different types of river. For example, a good thing in one place (e.g., bed scour and bank erosion at the outside of a bend along an active meandering river) may be a bad thing elsewhere (e.g., equivalent processes along a passive meandering river). Determination of appropriate reference conditions incorporates understandings of the timeframes over which processes occur and rivers adjust (Fig. 5). For example, a river may look and behave quite differently before, during and after a flood. The shifting baseline syndrome (Pauly 1995) asserts that what we measure against reflects the 'state' of a system at a particular moment in time, recognising that this state may be a pale reflection of earlier conditions (e.g., Park 1995). As noted by Dufour and Piégay (2009), fanciful assertions of wild, intact, pristine or natural (pre-disturbance) rivers do not provide a helpful basis against which contemporary condition can be meaningfully assessed in most instances (Castro and Thorne 2019; Fryirs and Brierley 2009; Montgomery 2008; Powers et al. 2019; Wohl 2013). Wherever irreversible change has occurred, contemporary river condition can only be realistically assessed in relation to how the river looks and behaves today. In these determinations, it is important to recognise that the future may be different and no analogue states are likely (Brierley and Fryirs 2005, 2016; Fryirs 2015). Situating analyses in context of river evolution (**Truth 4**) supports efforts to identify and manage causes of deterioration or triggers of improvement (Fig. 5).

Appropriate monitoring procedures tailor measures (geoindicators) to specific river types and expected morphodynamics, carefully considering where to measure and how often to measure to ensure that the analysis provides a reliable and relevant signal about contemporary river condition (Fig. 5; Blue and Brierley 2016; Fryirs 2015). Suitable measures detect underlying causes of deterioration, rather than merely the visible symptoms, thereby providing a basis to treat processes that are not functioning as expected (**Truth 2**; Fig. 5). For example, concerns for bank erosion cannot be addressed unless consideration is first given to whether the channel bed is unstable, and then whether bank erosion is expected for that type of river (e.g., Spink et al. 2009). If it is expected, where is it expected to occur and at what rate? If it is not expected, what is causing the problem?

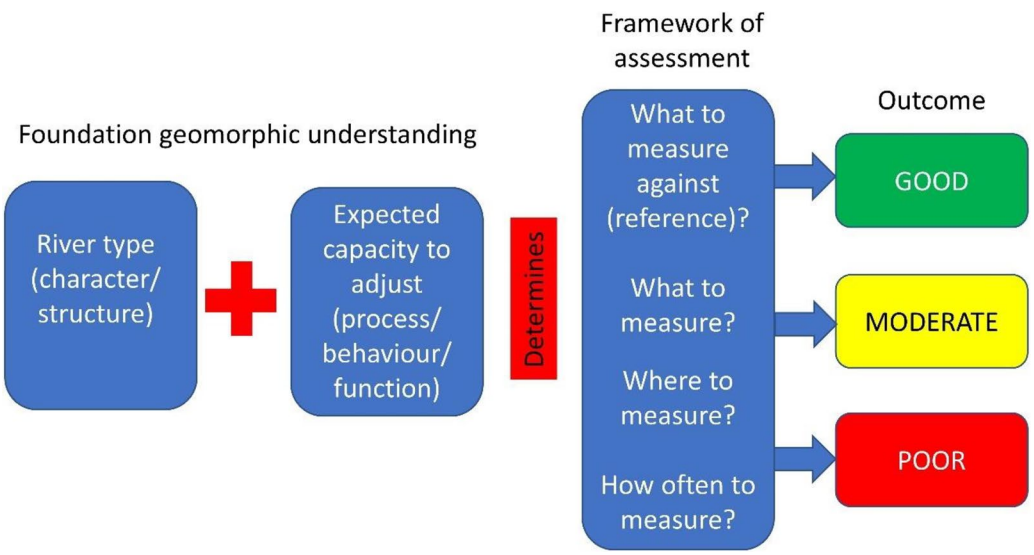

Fig. 5 Approach to assessment of geomorphic river condition (after Fryirs 2015)

Truth 4: interpret evolutionary trajectory to determine what is realistically achievable

Truth Statement: *Unless management practices are proactive and precautionary, they fail to incorporate understandings of recovery processes in working towards the best achievable character and behaviour of a river. Failure to inform the future is planning in the dark. Reactive measures are ineffective, expensive and inequitable, setting and accentuating unsustainable path dependencies that burden future generations.*

Just as rivers evolve, effective management practices adapt to changing circumstances. The scaffolded set of Truths outlined in this paper underpins determination of what is realistically achievable into the future, over a given timeframe (say, 50–100 years; Hobbs and Norton 1996). Typically, command-and-control practices emphasise immediate concerns for local/reach-scale issues, failing to contextualise system responses to changing circumstances in space or time (Gilvear 1999; Kondolf et al. 2001). Expensive, inequitable and unsustainable path dependencies ensue. In contrast, nature-based applications build upon analyses of the evolutionary trajectories of rivers at the catchment scale, assessing where each reach sits on a degradation or recovery pathway (Fryirs and Brierley 2016). Proactive management actions "Don't fight the site" (Brierley and Fryirs 2009), applying foresighting exercises to scope realistically achievable visions and designation of reach-scale moving targets (Brierley and Fryirs 2016; Table 6). Analyses of (dis)connectivity relationships interpret how responses to disturbance events are mediated through the catchment, and associated forms and timeframes of off-site impacts and legacy effects (Fryirs et al. 2009; Fryirs 2013).

To date, remarkably few comprehensive analyses document river adjustment and evolution at the catchment scale (Downs and Piégay 2019; Grabowski et al. 2014). Even fewer geomorphic studies foresight river futures (cf., Tangi et al. 2021). Assessment of recovery potential entails analysis of pressures and limiting factors operating in a system, interpreting legacy effects, sequences (concatenations) of disturbance events, and changing (dis)connectivity relations, among many considerations (Brierley and Fryirs 2005, 2009, 2016; Fryirs and Brierley 2016; Wohl et al. 2019). Conducted effectively, analysis of catchment-specific forms, rates and trajectories of geomorphic adjustment relate readily available remote sensing data to longer term environmental histories and field interpretations—the art of historical 'sleuthing' (e.g., Montgomery 2008; Khan et al. 2021; Piégay et al. 2020). Toolkits and resource bases such as Google Earth Engine provide near-instantaneous insight into the capacity for adjustment (sensitivity) and range of variability of a river (which reaches are adjusting, how and why), the role of disturbance events, and off-site consequences of adjustments (e.g., Boothroyd et al. 2021) that can be used to guide interpretations of evolutionary trajectory (**Truth 4**). The trajectory of adjustment reflects reach position within a catchment and responses to changing fluxes and (dis)connectivity relationships (**Truth 1**). Such is the primacy of the catchment scale in proactive and precautionary planning.

Table 6 Geomorphic principles that underpin interpretations of evolutionary trajectory to determine what is realistically achievable (**Truth 4**)

Catchment-specific drivers and controls upon forms and rates of river adjustment determine the evolutionary trajectory of a river. Such analyses relate river character and behaviour at the reach-scale to the pattern of river types and their (dis)connectivity relationships at the catchment scale
Some evolutionary adjustments are reversible (i.e., the reach operates within its range of variability). In other instances, irreversible change to a different type of river may occur
Reach scale sensitivity and (dis)connectivity relationships (the distribution of buffers, barriers, blankets and boosters) determine how legacies, path dependencies and lagged, off-site responses to disturbance events are conveyed through a catchment (the response gradient)
Changes to sediment sources and the flow/sediment regime impact upon the balance of impelling and resisting forces, the aggradational–degradational balance of the river, and associated trajectories and rates of river adjustment, in the past and future. Some reaches (types of river) are subject to progressive adjustment, others are characterised by threshold-induced change
Hotspots, threatening processes and reaches that are primed to change are important considerations in strategic approaches to proactive and precautionary planning
Legacy effects, the imprint of the past upon contemporary river character, behaviour and condition, vary markedly from system to system, now and into the future
Recovery takes different forms and works in different ways, shaped by different processes, for different types of river
The river recovery diagram provides a conceptual tool to appraise the condition of each reach today relative to the past, helping to assess how trajectories shape prospective futures
Recovery potential is shaped by system-specific pressures and limiting factors (e.g., reach sensitivity, legacy effects, changing (dis)connectivity relations, etc.), informing interpretations of whether flow/sediment budgets (and other considerations) will facilitate recovery and over what timeframe
Foresighting exercises scope prospective futures to derive a realistically achievable vision, using modelling exercises to predict the likelihood of differing scenarios

Brierley and Fryirs (2005) differentiate river responses to changes in imposed and flux boundary conditions. Imposed conditions refer to geologic/climatic factors such as earthquakes or volcanic eruptions that disrupt drainage basins. Flux boundary conditions refer to controls upon the flow/sediment regime and the associated balance of impelling and resisting forces along a river course. Anthropogenic impacts, alongside other forms of disturbance, often result in non-uniform traits that may counter or reinforce each other, accentuating or suppressing forms and rates of geomorphic process activity (Fryirs 2017). Reach-scale responses to disturbance events reflect the capacity for adjustment (sensitivity) of a river (**Truth 2**). Different rivers may respond in different ways to a flood event of a given magnitude (Schumm 1991). Similarly, a reach may respond to disturbance events in quite different ways at different stages of geomorphic adjustment (e.g., before, during and after conveyance of a sediment pulse; Fryirs et al. 2012). Sometimes a reach is primed to change as it sits close to a threshold condition, at other times it is not (Brewer and Lewin 1998; Schumm et al. 1987). Evolutionary appraisals relate contemporary reach morphodynamics to longer term trajectory (Brierley and Fryirs, 2005; Gilvear, 1999; Grabowski et al. 2014). Cumulative impacts reflect the summary response to catchment-specific circumstances (Schumm, 1991). While conceptualisations such as the Hjulstrom diagram (Fig. 3) and the Lane Balance diagram (Fig. 4) provide indicative guidance into the direction/pathway of system adjustment, quantification of rates of adjustment and estimations of the likelihood of particular outcomes is inherently uncertain. As the ancient dictum states, 'you can never step in the same river twice' (Heraclitus, c535–475 BC).

In conceptual terms, Brierley and Fryirs (2005) differentiate river behaviour (reach-scale adjustments that create a characteristic form; **Truth 2**) from river change (transition to a different type of river, such that reach-scale adjustments create a new or different characteristic form). While river behaviour reflects maintenance, regeneration and reworking of a particular assemblage of geomorphic units in a given reach (**Truth 2**), river change refers to processes and behaviour for a different assemblage of geomorphic units (Fryirs and Brierley 2021a). Differentiation of behaviour from change ensures that management aspirations work with the contemporary behavioural regime, recognising that what's gone before may not provide realistic guidance into what's possible into the future (Brierley and Fryirs 2005; Dufour and Piégay 2009; Hobbs and Norton 1996). Analyses of evolutionary trajectory help to set the baseline for assessing the contemporary state of adjustment and recovery potential of a river, determining whether adjustments are reversible (i.e., the reach operates within its range of variability) or irreversible (river change has occurred). If irreversible river change has occurred, past conditions no longer provide an appropriate guideline to determine what is realistically achievable today. Importantly, a change in river type for a given reach alters the flux boundary conditions under which other reaches operate (see Fryirs et al. 2012; Fryirs 2017). In some instances, other reaches can accommodate responses to changing boundary conditions such that they continue to operate as the same type of river; elsewhere, river change may be triggered (see Fryirs et al. 2012; Fryirs 2017). Building upon understandings of process–form relationships and catchment-scale linkages ((dis)connectivity) (**Truths 1 and 2**), geomorphologists can predict pathways and rates of adjustment/change for particular types of river under different sets of changing boundary conditions (e.g., changes to the flow/sediment regime or the types/effectiveness of resistance elements along a river). These relationships play out in very different ways, for example, in bedrock and partly confined rivers relative to the range of alluvial river types (Fig. 1).

Efforts to 'work with the river' assess whether river condition is improving or deteriorating over time (**Truth 3**). Recovery takes different forms and works in different ways for different types of river (Fryirs and Brierley 2016). Hence it is important to specify what recovery looks like for the system under investigation, assessing how it works, and how long recovery processes are likely to operate or be sustained into the future (Fryirs et al. 2018). Interpretation of recovery potential incorporates assessment of threatening processes, pressures and limiting factors (Fig. 6; Brierley and Fryirs 2005).

Assessing where each reach sits on a degradation or recovery pathway informs forecasting exercises (Fig. 7). Interpretations of likely reach responses to prevailing boundary conditions can distinguish situations in which the reach is likely to continue along a degradation pathway, whether recovery is possible and what it looks like, or if irreversible change is likely to occur (and the associated degradation, restoration and creation pathways thereof) (Brierley and Fryirs 2005, 2016). In management terms, identification of turning points is especially important, as small catalytic actions that work with and enhance/accelerate recovery can have major benefits in these instances (e.g., Fryirs et al. 2018).

Forms, patterns and rates of river adjustment/evolution reflect catchment-specific considerations (Fig. 7). In spatial terms (Fig. 7A), slope and valley setting and the associated quantity and use (dissipation) of flow energy (stream power), and relations to available sediment of a given calibre, determine the types, patterns and (dis)connectivity of reaches along a river (e.g., Lisenby et al.

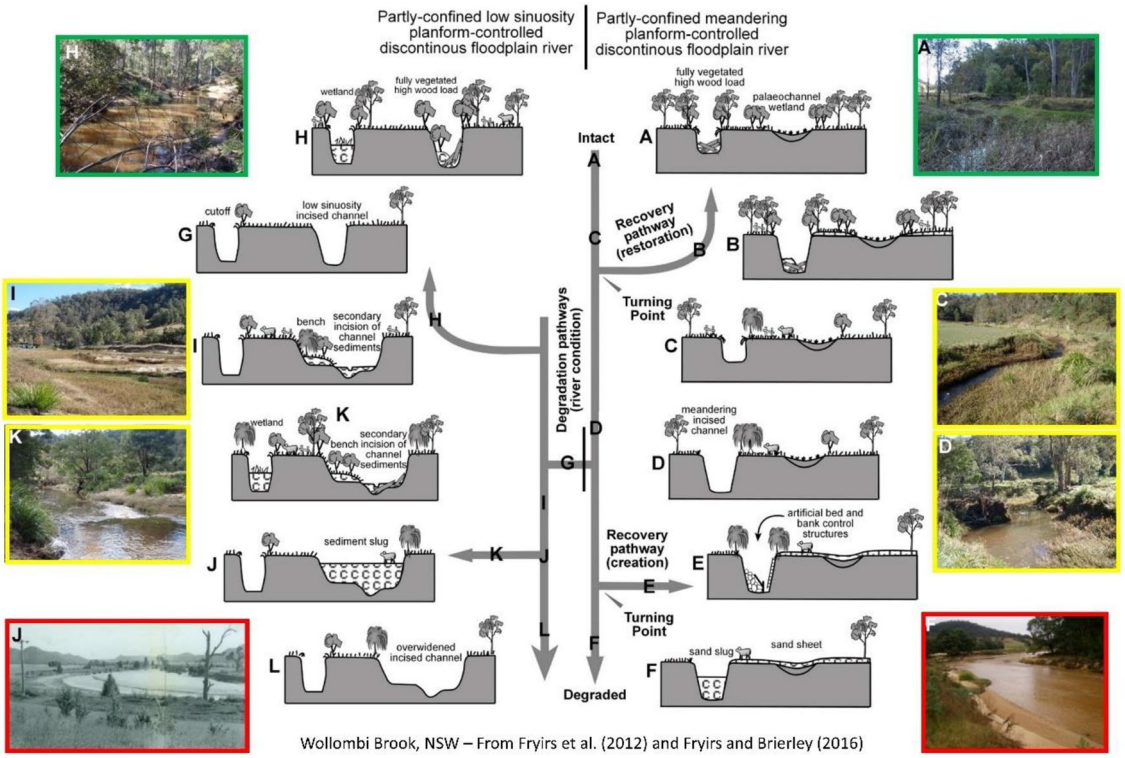

Fig. 6 River recovery diagram. This schematic conceptualisation situates the contemporary state/condition of a river in relation to its evolutionary trajectory (Brierley and Fryirs 2005; Fryirs and Brierley 2016). The vertical axis reflects deterioration in condition from top to bottom (i.e., from state A to D to F). Lateral axes reflect transition from degradation to recovery. If a reach has not moved far from its intact (best condition) state, restoration is possible (state B). If restoration back to the initial state is no longer possible, but river condition is improving (i.e., recovery is evident), the reach lies on a creation pathway (state E). The left hand side summarises responses if irreversible river change occurs (in this instance from a meandering to a low sinuosity partly confined river). Continued degradation is envisaged in states I, J and L, whereas state H shows recovery along a restoration pathway for this new type of river and state K shows recovery along a creation pathway. Green boxes are reaches in good geomorphic condition, yellow in moderate and red are in poor geomorphic condition (see **Truth 3**)

2020). These factors determine how system responses to changes to boundary conditions and responses to disturbance events are mediated through the system (Fryirs 2013; Fryirs et al. 2009, 2012). Process relationships and evolutionary traits reflect factors such as relief, drainage network configuration (tributary-trunk stream relationships), landscape dissection (drainage density), lithological controls upon sediment type, the discharge regime, legacy effects (landscape memory) and responses to anthropogenic disturbance (Fig. 2). The relative importance of these factors, among many others, varies from system to system, and changes over time. Valley setting and the associated degrees of freedom of a given river reach inform predictions of likely changes in river type. In large part, this reflects the extent/pattern of bedrock-forcing (i.e., how alluvial the reach is) (**Truths 1 and 2**). Hence, interpretation of where a reach sits in the spectrum of river diversity (Fig. 1) informs analysis of the likelihood of change and if change in river type does occur, what the river is likely to change into.

In temporal terms (Fig. 7B), the past shapes the present and the future to varying degrees, as legacy effects reflect catchment-specific considerations (Fig. 7A). Sequences of evolutionary adjustments reflect system responses to disturbance events, conveyed as timeslices in Fig. 7B. Purposefully no timeline is indicated on this figure, as system-specific characteristics determine whether a meaningful timeframe for management is expressed over weeks, months or hundreds of years. Although Fig. 7B is shown as a linear progression, threshold-exceeding events may disrupt evolutionary trajectories.

System responses to anthropogenic disturbance not only influence the contemporary river condition, they also set path dependencies that shape what is realistically achievable into the future (**Truth 3**). Building upon appraisal of whether a given reach lies on a degradation or a recovery pathway (Fig. 6), and assessment of the recovery potential of that reach, foresighting exercises can scope prospective future trajectories. Analyses of management choices in relation to the evolutionary

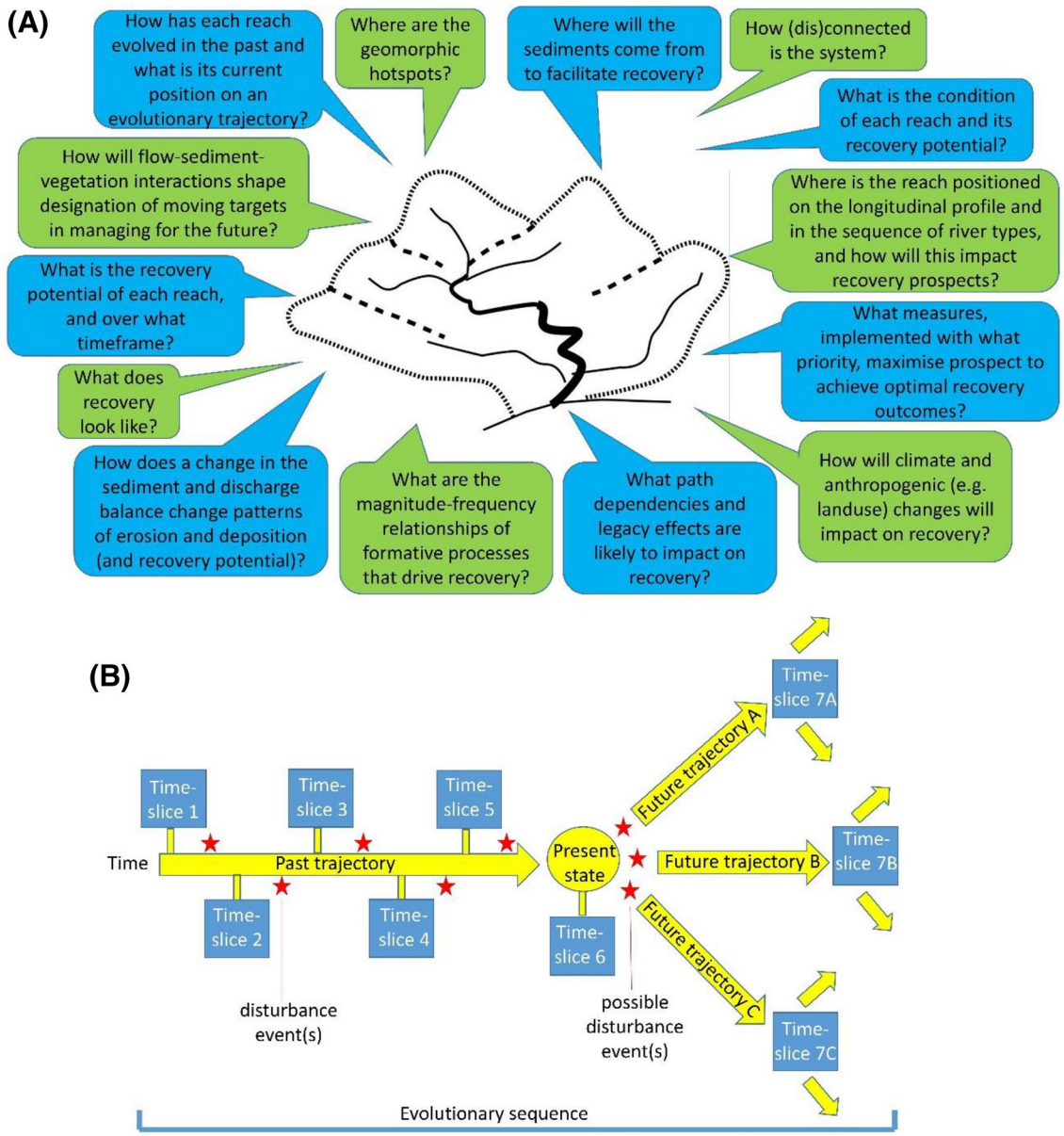

Fig. 7 Spatial and temporal components of evolutionary trajectory analyses inform interpretations of river recovery and determination of moving targets for management. **A** Sediment (dis)connectivity relations and changing sediment flux conditions at the catchment scale influence prospective river futures (Brierley and Fryirs 2016). **B** Evolutionary trajectory and future trajectory set moving targets for management (Poeppl et al. 2020)

trajectory of the river interpret potential changes to prevailing fluxes into the future. Alternative scenarios shown in Fig. 7B could be expressed as steady as she goes, command-and-control practices and nature-based (geomorphologically informed) management options (Marçal et al. 2017). These determinations are best viewed as moving targets, as inherent uncertainties will require differing forms of adaptation to best cope with changing circumstances into the future (Brierley and Fryirs 2016).

Adjusting the flow, sediment and vegetation levers and (dis)connectivity relationships for multiple scenarios helps to assess prospective future river morphodynamics (Brierley et al. 2021c; Fryirs et al. 2021; Fuller and Death 2018; Lisenby et al. 2020; Wohl et al. 2019). Changing relations between the flow and sediment regime (the aggradation—degradation balance of a given river reach) guides interpretations of how sediment availability and (dis)connectivity relationships will impact upon flow/

sediment regimes and associated recovery potential (e.g., Downs and Piégay 2019; Poeppl et al. 2020). For example, where will sediments come from to facilitate recovery and how is this likely to change over time (Fryirs and Brierley 2001; Tangi et al. 2021)? Modelling applications are required to quantify rates of adjustment and prospects to exceed threshold conditions, and the spatial ramifications thereof, assessing what can be done to mitigate prospects for system deterioration (e.g., Brierley et al. 2021c; Czuba and Foufoula-Georgiou 2014, 2015; Schmitt et al. 2016). Such analyses provide an evidence base to assess what can be done to trigger, enhance and maintain river recovery into the future, interpreting the timeframe over which management options can 'opt-out' as assisted recovery is no longer needed, because a system is self-healing (Kondolf 2011, 2012; Fryirs et al. 2018).

Discussion: bringing the Truths of the Riverscape together to inform catchment management plans

> *"Rivers … are the soul of the land through which they flow."*
> *Wade Davis, 2020, p14.*

River management is hard (Harris and Heathwaite 2012). Power relations underpin contestations among differing value sets of multiple stakeholders, regulators and knowledge providers: who is in-the-room, relative to the exclusion of 'others' determines what the plan or project looks like and associated perceptions of success or failure (Garcia et al. 2021; Jellinek et al. 2019; Perring et al. 2015; Rogers 2006). A sustainability lens takes heed of the Truths of the Riverscape. Nature-based framings work with river adjustment, change and evolution, explicitly acknowledging inherent uncertainties in planning for the future (Tables 1 and 7). Proactive and precautionary catchment plans respect diversity (**Truth 1**) and work with processes (**Truth 2**) to improve river condition (**Truth 3**), applying a conservation ethos that works with recovery and strategically addresses threatening processes (**Truth 4**). In environmental terms, compromise solutions are not the answer. What is half a habitat? Ecosystems cannot thrive and survive unless all components of lifecycles are viable.

Failure to plan is planning to fail. In the absence of proactive planning, reactive management fails to learn from what's gone before (Gilvear 1999). All too often, management programmes fail to hold steady at times of perceived crisis and adopt short-term reactive measures that authorities know do not work. Despite knowledge that such practices are not sustainable, many management responses continue to reassert human authority over rivers under the guise of notional stability, safety and resilience. Proactive and precautionary catchment plans require bravery, foresight and vision while embracing uncertainty (Fryirs and Brierley 2021b; Hillman and Brierley 2008) (Table 7). Experimentation is key to adaptive management, learning effectively from past experiences. It's okay to make mistakes, so long as lessons are heeded. Conversely, bumbling along blindly is disrespectful to what is known and what is possible. Resulting practices waste time, resources and opportunities, undermining societal confidence in the process of river repair.

Insights derived in using the Truths of the Riverscape underpin catchment-specific determinations of what is realistically achievable (Fig. 8). Working with the river assesses what is manageable, where, how, and with what priority (Brierley and Fryirs 2005; Schmidt et al. 1998; Table 7). A clear action plan identifies conservation goals and works with recovery to articulate what does (or does not) need to be done. Clear documentation of the underlying rationale and evidence base for any actions provides a basis to audit the extent to which decisions are made in the interests of the river, assessing whether the best available science and advice has been used or pushed aside. A conservation ethos protects key values and attributes and strategically addresses threatening processes (a stitch in time). Integrative plans and actions at local, catchment and eco-regional scales rebuild lost linkages in river systems (e.g., Erős et al. 2019; Fuller and Death 2018; Kondolf et al. 2006). It is important to recognise that in some instances the contemporary river may be the best that it can be. In many instances, applications of command-and-control practices to develop particular resources or protect particular assets/infrastructure create situations in which there is limited potential for comprehensive uptake of nature-based solutions. However, notable improvement in ecological conditions and socio-cultural relations to the river may be possible. Prospects for repair are especially limited for sacrificial reaches with low recovery potential (Bouleau 2014). Elsewhere, passive restoration techniques that enhance recovery engender optimal outcomes in environmental and cost-effective terms, leaving the river alone as far as practicable, allowing it to do the work—to look after itself (Fryirs and Brierley 2016; Fryirs et al. 2018, 2021; Kondolf 2011, 2012; Wheaton et al. 2019).

There is cause for considerable optimism in efforts to develop proactive, catchment-specific analyses. New and emerging technologies are changing the way practitioners observe, monitor and analyse river systems (e.g., Boothroyd et al. 2021; Brown and Pasternack 2019; Piégay et al. 2020; Reichstein et al. 2019). Available techniques allow objective quantification of geomorphic attributes at low cost, high resolution, and at large (global) scales, commonly applying open source tools that use freely available data (e.g., Guillon et al. 2020). Big data,

Table 7 Guiding principles for proactive and precautionary catchment plans that heed lessons learnt from the Truths of the Riverscape

Co-craft a visionary but realistically achievable vision
River management is a collective responsibility—an ongoing commitment, not a project. Healthy rivers are products of healthy societies. Unless those who live and work along the river want to look after it, management interventions are unlikely to be successful and sustainable
Be bold, preparing well for the future: Failure to plan is planning to fail. Without a proactive plan, management is inherently reactive, failing to hold steady at times of perceived crisis
Act and learn together, sharing perspectives and experiences along the way. Unless assessment tools and frameworks are co-developed with practitioners who use them, they are likely to be ignored or mis-applied. If struggling to translate, it's too late!
A coherent package of actions has a clear purpose and rationale, striving to achieve the best possible state (character and behaviour), and avoids measures or practices that work against each other
Work with the river as it is, determining what is manageable, where, how, and with what priority. Goals must be realistically achievable under prevailing conditions, recognising that in many instances the river is the best that it can be. Many legacy effects and path dependencies are difficult, if not impossible, to revoke
Incorporate future variability into management plans, recognising uncertain outcomes of potential adjustments through flexible, open-ended and dynamic goals (moving targets)
Hold steady at times of perceived crisis. Avoid ill-conceived, reactive measures that have limited prospects for success, often with negative long-term consequences
Carefully consider treatment response, working with recovery in a conservation-first approach to management
Develop and apply a rational approach to prioritisation with an accompanying evidence base
Protect and/or enhance key values/attributes, remembering that prevention is more effective, and cheaper, than cure
Carefully diagnose problems, avoiding piecemeal solutions and blanket applications. Tailored, process-based treatments tackle issues at source, at the scale of the problem (right place, right time). Inappropriate measures in the wrong place won't fix the problem (e.g., bed before banks)
Appraise thresholds of possible/probable concern, identifying what can be done to mitigate system deterioration or collapse. Strategically address threatening processes before they become more costly (a stitch in time), identifying risks/threats and tipping points and assessing how to manage them
Work with recovery to facilitate cost-effective management, avoiding wasteful expenditure (opportunity costs). Targeted interventions get the best 'bang for the buck' (return on investment). Sometimes small expenditure/efforts can make a big difference. Targeted interventions at carefully selected locations can have positive trickle-down consequences, as catalytic actions facilitate system-wide recovery (e.g., headcut management)
Get the sequence of actions 'right', avoiding and/or minimising negative off-site impacts (i.e., don't transfer problems elsewhere). In tackling one problem, don't create others. Don't fight the site—appropriately frame reach-scale applications in their catchment context, rebuilding lost linkages (connectivities) to support ecosystem functionality at the catchment scale
Recognise that repair may not be possible in 'sacrificial' reaches with low recovery potential
Know when to opt-in and when to opt-out. Whenever possible, apply passive management measures that work with the river and allow it to self-heal. Leave the river alone as far as practicable, allowing it to do the work—to look after itself. Passive restoration is a conscious choice to apply minimal intervention measures or the do-nothing option. Move the pump shed, not the river
Apply adaptive management principles
Be proactive, not reactive. Be ready when called upon
Learn effectively. Failing to learn from past experiences is a good way to keep making the same mistakes, unnecessarily repeating disasters and compromising riverine values
Effective monitoring programmes generate reliable and relevant signals about the condition and health of the river
Recurrently reappraise management objectives and approaches in light of experience and lessons learnt (successes and failures). Learn from experience, documenting, evaluating and reporting effectively
Make effective use of best available information. Ask the right questions—don't let technology drive the questions. Question persistently. If something doesn't make sense, don't do it
Develop and apply a carefully scaffolded information base (a living database), using clear language to establish common ground to inform integrative practices, identifying gaps and avoiding practices that re-invent the wheel
Experiment effectively. Learn from examples of good practice and promote them. Document failures so others can learn from them
Use process-based understandings (archetypal histories) to transfer and upscale understandings and applications to achieve big-picture (collective and cumulative) impacts
Respect and restore uncertainty, recognising that the future will be different in ways that we do not and cannot necessarily know. Expect the unexpected—surprises are inevitable … it all depends

automated monitoring programmes, machine learning algorithms and modelling exercises support contextualisation of place-based (catchment-specific) actions in relation to regional and broader-scale applications (e.g., Bizzi et al. 2019; Demarchi et al. 2017; Rowland et al. 2016; Schwenk et al. 2017). Enhanced predictive capacity of an increasingly data-rich science presents unprecedented opportunities to support coherent, strategic,

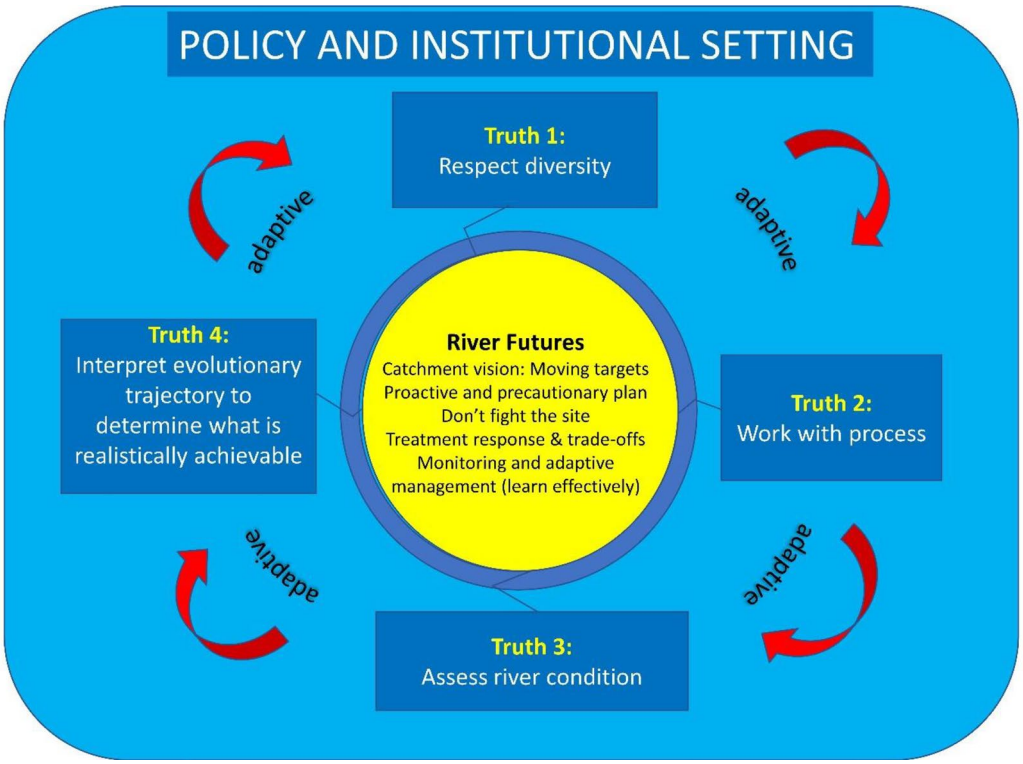

Fig. 8 Using lessons learnt from Truths of the Riverscape to determine what is realistically achievable in proactive and precautionary catchment management plans

geomorphologically informed approaches to river management. Lack of suitable data is no longer a limiting factor in the development of proactive catchment action plans that build upon carefully scaffolded packages of geomorphic information (e.g., Brierley and Fryirs 2005; Fryirs et al. 2021). Alongside these developments, design criteria are now in-hand to implement and adapt low-cost restoration practices that apply process-based solutions that work at the scale of the problem (e.g., Ciotti et al. 2021; Wheaton et al. 2019). Comprehensive flood management plans as part of climate change adaptation programmes increasingly frame economic benefits of enhanced buffering capacity and managed retreat alongside ecologically framed re-naturalisation and re-wilding initiatives in freedom space and space to move interventions (e.g., Biron et al. 2014; Buffin-Belanger et al. 2015; Piégay et al. 2005).

Ultimately, the adoption and use of principles embedded within the Truths of the Riverscape reflect political and societal attitudes to the environment—the workings of institutions, and associated policy and governance arrangements (the outer, all-encompassing box in Fig. 8). Although remarkable information and insight present unprecedented capacity to apply geomorphologically informed approaches to manage all river systems, realities on-the-ground attest to the ineffectiveness of contemporary practices and decision-making. A growing chasm exists between what is known and the practical use that is made of that knowledge (cf., Dark Knowledge; Jeschke et al. 2019). This attests to the 'real' river management problem—the mindset and aspirations which underpin the ways in which rivers are managed, the aims and intent with which scientific insights are used to inform policies, and associated institutional framings and governance arrangements (Wilcock 1997; Rogers 2006).

In light of these considerations, the challenge for researchers is to be prepared and ready when called upon (Table 7). For example, development of resource bases and large-scale databases that consolidate what is known, at-scale are not yet readily available, nor OpenAccess for use (e.g., see Fryirs et al. 2021). Alongside this, systematic generation of 'archetypal histories' of evolutionary trajectories of river systems subject to differing forms of disturbance are not yet in-hand. Such resource bases are needed to collectively enact and transform practice and improve river health on-the-ground (cf., Downs and Piégay 2019).

A geoethical approach emphasises concerns for the conduct of science, and the ways in which scientific findings are generated and used (e.g., Cronin 2021; Mogk

and Bruckner 2020). Co-development of constructive solutions (plans, policies, on-the-ground actions) with clear, strategic aims and an underlying rationale, with demonstrable return for investment and effort, underpins the design and uptake of scientifically informed, nature-based approaches to river management. In simple terms, a river-centric approach, wherein "if it harms the river don't do it" provides a foundation premise upon which transformative practices can be envisaged and enacted (Brierley 2020; RiverofLife 2019; Salmond et al. 2019). It's time to move beyond excuses, creating futures for which we can be proud, rather than apologetic.

In summary, despite excellent data availability and good understanding of river systems, and strong agreement on what should ethically be done, the river management 'industry' is yet to take full advantage of this potential. In many parts of the world, management processes, practices and philosophies have so far failed to respond effectively to lessons learnt from the Truths of the Riverscape. To the authors of this paper, two key issues must be addressed to transform this situation. First, different approaches to 'work' at the science-management interface are required to influence and embed best available knowledge and understanding in policy, legislation and strategic plans. If managers, decision-makers and policymakers who are notionally acting in the interests of society choose not to apply proactive and precautionary principles and participatory practices, they should be accountable for the outcomes that ensue. In negotiating limitations, trade-offs and compromises, short-term gains/benefits for some must be contextualised in relation to long-term (ongoing) consequences for all.

Second, envisaging and enacting healthy river futures embraces lessons learnt from Truths of the Riverscape. In geomorphic terms, locally owned and enacted practices build upon co-designed participatory practices that work with process-based understandings of river condition and evolutionary trajectory to co-create and implement plans of action that respect river diversity (character and behaviour) and seek to attain and maintain the best achievable state and functionality of each river system. The geomorphology community has a responsibility to carefully document and communicate what it knows and how this knowledge could be used or applied (e.g., Fryirs et al. 2021). This requires clear articulation of distinctive values and attributes in geoecological terms, explaining underlying controls to predict realistically achievable futures, incorporating this knowledge into catchment management plans and enacting those plans in practice. A move from rhetoric to action is needed—walking the walk, not just talking the talk. Co-ordinated leadership within the geomorphology community is required to 'make this happen'. Prospectively, a Riverscapes Consortium of geomorphic practitioners could develop and facilitate strategic partnerships, support networks and professional development/accreditation programmes in the quest to influence, develop and implement policy. Skillset development and commitment to succession planning is also needed to develop a community of researchers, practitioners and influencers, and support the next generation of river warriors (Freeman 2013; Fryirs and Brierley 2021b). Critically, if/when policy and legislation are in-place, it will be 'expected' that coherent and agreed-upon understandings and plans are in-hand to facilitate immediate uptake of transformative practices. As yet, the geomorphology community is not ready for this. Among numerous considerations, we owe it to our rivers to do this.

Conclusion

The underlying motivation for this paper lies in a moral and geoethical quest for social and environmental justice in sustainable management of healthy rivers in an era of climate change adaptation. We are yet to learn the lessons from history. Command-and-control approaches to river management are not sustainable. Although path dependencies have been set for decades or longer, and we have good knowledge of the consequences, we continue to perpetuate harmful practices, despite scientific guidance to the contrary. Continuing to make the same mistakes exacerbates inequities for future generations.

The four Truths of the Riverscape outlined in this paper use geomorphic principles to demonstrate how approaches to river management can (and must) move away from a command-and-control approach that asserts human authority over rivers. An alternative nature-based approach conceptualises humans as part of nature, developing and applying understandings of riverscapes as living and emergent entities. To date, management practices are yet to respond effectively to implications and imperatives of the Truths of the Riverscape. Many places are yet to adopt approaches that respect the inherent diversity of river systems, work with their formative processes, assess their condition in meaningful ways, and use understandings of evolutionary trajectory to work with recovery principles in the design and prioritisation of proactive and precautionary catchment management plans. Working with nature, working with the river embraces uptake of ALL principles outlined in this paper—not selection of convenient or straightforward elements. A holistic, river-centric focus embraces the quest for integrity—in biophysical and socio-cultural terms—envisaging sustainable ways of living with, and adapting to rivers as living and emergent entities. Future prospects reflect the ways we choose to live with rivers—and each other.

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References

Albert JS, Destouni G, Duke-Sylvester SM, Magurran AE, Oberdorff T, Reis RE, Winemiller KO, Ripple WJ (2020) Scientists' warning to humanity on the freshwater biodiversity crisis. Ambio 50(1):85–94
Albert C, Brillinger M, Guerrero P, Gottwald S, Henze J, Schmidt S, Ott E, Schröter B (2021) Planning nature-based solutions: principles, steps, and insights. Ambio 50(8):1446–1461
Beechie TJ, Sear DA, Olden JD, Pess GR, Buffington JM, Moir H, Pollock MM (2010) Process-based principles for restoring river ecosystems. Bioscience 60(3):209–222
Belletti B, de Leaniz CG, Jones J, Bizzi S, Börger L, Segura G, Castelletti A, Van de Bund W, Aarestrup K, Barry J, Belka K, Zalewski M (2020) More than one million barriers fragment Europe's rivers. Nature 588(7838):436–441
Benda LE, Poff NL, Tague C, Palmer MA, Pizzuto J, Cooper S, Stanley E, Moglen G (2002) How to avoid train wrecks when using science in environmental problem solving. Bioscience 52:1127–1136
Benda L, Poff NL, Miller D, Dunne T, Reeves G, Pess G, Pollock M (2004) The network dynamics hypothesis: how channel networks structure riverine habitats. Bioscience 54(5):413–427
Bernhardt ES, Palmer MA (2011) River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation. Ecol Appl 21(6):1926–1931
Best J (2019) Anthropogenic stresses on the world's big rivers. Nat Geosci 12(1):7–21
Biron PM, Buffin-Bélanger T, Larocque M, Choné G, Cloutier CA, Ouellet MA, Ouellet MA, Demers S, Olsen T, Desjarlais C, Eyquem J (2014) Freedom space for rivers: a sustainable management approach to enhance river resilience. Environ Manage 54(5):1056–1073
Bizzi S, Lerner DN (2015) The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. River Res Appl 31(1):16–27
Bizzi S, Piégay H, Demarchi L, Van de Bund W, Weissteiner CJ, Gob F (2019) LiDAR-based fluvial remote sensing to assess 50–100-year human-driven channel changes at a regional level: the case of the Piedmont Region, Italy. Earth Surf Proc Land 44(2):471–489
Blue B (2018) What's wrong with healthy rivers? Promise and practice in the search for a guiding ideal for freshwater management. Progr Phys Geogrs 42(4):462–477
Blue B, Brierley G (2016) 'But what do you measure?' Prospects for a constructive critical physical geography. Area 48(2):190–197
Boothroyd RJ, Williams RD, Hoey TB, Barrett B, Prasojo OA (2021) Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change. Wiley Interdiscipl Rev 8(1):e21496
Bouleau G (2014) The co-production of science and waterscapes: the case of the Seine and the Rhône Rivers, France. Geoforum 57:248–257. https://doi.org/10.1016/j.geoforum.2013.01.009
Boulton AJ (1999) An overview of river health assessment: philosophies, practice, problems and prognosis. Freshw Biol 41(2):469–479
Boulton AJ, Piégay H, Sanders MD (2008) Turbulence and train wrecks: using knowledge strategies to enhance the application of integrative river science in effective river management. In: Brierley GJ, Fryirs KA (eds) River futures: an integrative scientific approach to river repair. Island Press, pp 28–39
Brierley GJ (2020) Finding the voice of the river: beyond restoration and management. London, Palgrave Macmillan
Brewer PA, Lewin J (1998) Planform cyclicity in an unstable reach: complex fluvial response to environmental change. Earth Surf Proc Land 23(11):989–1008
Brierley GJ, Fryirs KA (2005) Geomorphology and river management: applications of the river styles framework. Wiley, Hoboken
Brierley GJ, Fryirs KA (eds) (2008) River futures: an integrative scientific approach to river repair. Island Press, Washington
Brierley G, Fryirs KA (2009) Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. Environ Manage 43(6):1201–1218
Brierley GJ, Fryirs KA (2016) The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. River Res Appl 32(5):823–835
Brierley G, Reid H, Fryirs K, Trahan N (2010) What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. Sci Total Environ 408(9):2025–2033
Brierley G, Fryirs K, Cullum C, Tadaki M, Huang HQ, Blue B (2013) Reading the landscape: integrating the theory and practice of geomorphology to develop place-based understandings of river systems. Prog Phys Geogr 37(5):601–621
Brierley G, Tadaki M, Hikuroa D, Blue B, Šunde C, Tunnicliffe J, Salmond A (2019) A geomorphic perspective on the rights of the river in Aotearoa New Zealand. River Res Appl 35(10):1640–1651
Brierley GJ, Hikuroa DCH, Friedrich H, Fuller IC, Brasington J, Hoyle J, Tunnicliffe J, Allen K, Measures R. (2021a) Why we should release New Zealand's strangled rivers to lessen the impacts of future floods. The Conversation, 22 Feb

Brierley G, Fryirs K, Reid H, Williams R (2021b) The dark art of interpretation in geomorphology. Geomorphology 390:107870. https://doi.org/10.1016/j.geomorph.2021.107870
Brierley G, Tunnicliffe J, Bizzi S, Lee F, Perry G, Poeppl R, Fryirs K (2021c) Quantifying Sediment (Dis) Connectivity in the Modeling of River Systems. Treatise in Geomorphology, Elsevier
Brookes A (1985) Traditional engineering methods, physical consequences and alternative practices. Prog Phys Geogr 9(1):44–73
Brown RA, Pasternack GB (2019) How to build a digital river. Earth Sci Rev 194:283–305
Brunsden D, Thornes JB (1979) Landscape sensitivity and change. Trans Inst Br Geogr, 463–484
Buffin-Bélanger T, Biron PM, Larocque M, Demers S, Olsen T, Choné G, Ouellet MA, Cloutier CA, Desjarlais C, Eyquem J (2015) Freedom space for rivers: an economically viable river management concept in a changing climate. Geomorphology 251:137–148
Bush DM, Pilkey OH, Neal WJ (1996) Living by the rules of the sea. Duke University Press, Durham
Castro JM, Thorne CR (2019) The stream evolution triangle: integrating geology, hydrology, and biology. River Res Appl 35(4):315–326
Chorley RJ (1969) The drainage basin as the fundamental geomorphic unit. In: Chorley, R.J. (Editor). Water, Earth and Man
Church M (1996) Space, time and the mountain–how do we order what we see. In: Rhoads BL, Thorn CE (eds) The scientific nature of geomorphology. Wiley, New York, pp 147–170
Ciotti DC, Mckee J, Pope KL, Kondolf GM, Pollock MM (2021) Design criteria for process-based restoration of fluvial systems. Bioscience 71(8):831–845
Corenblit D, Tabacchi E, Steiger J, Gurnell AM (2007) Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth Sci Rev 84(1–2):56–86
Costa JE, O'Connor JE (1995) Geomorphically effective floods. Geophys Monogr Am Geophys Union 89:45–45
Cronin VS (2021) Geoethics as a common thread that can bind a geoscience department together. Geol Soc 508(1):55–65. https://doi.org/10.1144/SP508-2019-256
Czuba JA, Foufoula-Georgiou E (2014) A network-based framework for identifying potential synchronizations and amplifications of sediment delivery in river basins. Water Resour Res 50(5):3826–3851
Czuba JA, Foufoula-Georgiou E (2015) Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. Water Resour Res 51(3):1401–1421
Davidson SL, Eaton BC (2018) Beyond regime: a stochastic model of floods, bank erosion, and channel migration. Water Resour Res 54(9):6282–6298
Davis W (2020) Magdalena. River of Dreams. The Bodley Head, London
Demarchi L, Bizzi S, Piégay H (2017) Regional hydromorphological characterization with continuous and automated remote sensing analysis based on VHR imagery and low-resolution LiDAR data. Earth Surf Proc Land 42(3):531–551
Downs P, Gregory K (2014) River channel management: towards sustainable catchment hydrosystems. Routledge, Milton Park
Downs PW, Kondolf GM (2002) Post-project appraisals in adaptive management of river channel restoration. Environ Manage 29(4):477–496
Downs PW, Piégay H (2019) Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect. Geomorphology 338:88–104
Dufour S, Piégay H (2009) From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. River Res Appl 25(5):568–581. https://doi.org/10.1002/rra.1239
Dunham JB, Angermeier PL, Crausbay SD, Cravens AE, Gosnell H, McEvoy J, Moritz MA, Raheem N, Sanford T (2018) Rivers are social–ecological systems: time to integrate human dimensions into riverscape ecology and management. Wiley Interdiscip Rev Water 5(4):e1291
Eaton B, Millar R (2017) Predicting gravel bed river response to environmental change: the strengths and limitations of a regime-based approach. Earth Surf Proc Land 42(6):994–1008
Erős T, Kuehne L, Dolezsai A, Sommerwerk N, Wolter C (2019) A systematic review of assessment and conservation management in large floodplain rivers–actions postponed. Ecol Ind 98:453–461
Everard M, Powell A (2002) Rivers as living systems. Aquat Conserv Mar Freshwat Ecosyst 12(4):329–337. https://doi.org/10.1002/aqc.533
Fausch KD, Torgersen CE, Baxter CV, Li HW (2002) Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes: a continuous view of the river is needed to understand how processes interacting among scales set the context for stream fishes and their habitat. Bioscience 52(6):483–498. https://doi.org/10.1641/0006-3568(2002)052[0483:LTRBTG]2.0.CO;2
Feld CK, Birk S, Bradley DC, Hering D, Kail J, Marzin A, Melcher A, Nemitz D, Pedersen ML, Pletterbauer F, Pont D, Friberg N (2011) From natural to degraded rivers and back again: a test of restoration ecology theory and practice. Adv Ecol Res 44:119–209
Florsheim JL, Mount JF, Chin A (2008) Bank erosion as a desirable attribute of rivers. Bioscience 58(6):519–529
Fox CA, Reo NJ, Turner DA, Cook J, Dituri F, Fessell B, Jenkins J, Johnson A, Rakena TM, Riley C, Turner A, Wilson M (2017) "The river is us; the river is in our veins": re-defining river restoration in three Indigenous communities. Sustain Sci 12(4):521–533
Frascaroli F, Parrinello G, Root-Bernstein M (2021) Linking contemporary river restoration to economics, technology, politics, and society: perspectives from a historical case study of the Po River Basin, Italy. Ambio 50(2):492–504
Freeman MC (2013) Training the Next Generation of River Warriors. Bioscience 63(6):499–500. https://doi.org/10.1525/bio.2013.63.6.12
Frissell CA, Liss WJ, Warren CE, Hurley MD (1986) A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environ Manage 10(2):199–214
Fryirs KA (2013) (Dis) Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf Proc Land 38(1):30–46
Fryirs KA (2015) Developing and using geomorphic condition assessments for river rehabilitation planning, implementation and monitoring. Wiley Interdiscip Rev Water 2(6):649–667. https://doi.org/10.1002/wat2.1100
Fryirs KA (2017) River sensitivity: a lost foundation concept in fluvial geomorphology. Earth Surf Proc Land 42(1):55–70
Fryirs K, Brierley GJ (2001) Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. Geomorphology 38(3–4):237–265. https://doi.org/10.1016/S0169-555X(00)00093-3
Fryirs KA, Brierley GJ (2009) Naturalness and place in river rehabilitation. Ecol Soc. 14(1)
Fryirs KA, Brierley GJ (2013) Geomorphic analysis of river systems: an approach to reading the landscape. Wiley, Hoboken
Fryirs KA, Brierley GJ (2016) Assessing the geomorphic recovery potential of rivers: forecasting future trajectories of adjustment for use in management. Wiley Interdiscip Rev Water 3(5):727–748
Fryirs KA, Brierley GJ (2021a) Assemblages of geomorphic units: a building block approach to analysis and interpretation of river character, behaviour, condition and recovery. Earth Surf Proc Land. https://doi.org/10.1002/esp.5264
Fryirs K, Brierley G (2021b) How far have management practices come in 'working with the river'? Earth Surf Proc Land 46(15):3004–3010
Fryirs KA, Brierley GJ, Preston NJ, Kasai M (2007) Buffers, barriers and blankets: the (dis) connectivity of catchment-scale sediment cascades. CATENA 70(1):49–67
Fryirs KA, Arthington A, Grove J (2008) Principles of river condition assessment. In: Brierley GJ, Fryirs KA (eds) River futures. An integrative scientific approach to river repair. Island Press, Washington DC., pp 100–124
Fryirs K, Spink A, Brierley G (2009) Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. Earth Surf Proc Land 34(7):897–918
Fryirs K, Brierley GJ, Erskine WD (2012) Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. Earth Surf Proc Land 37(7):763–773
Fryirs KA, Brierley GJ, Hancock F, Cohen TJ, Brooks AP, Reinfelds I, Cook N, Raine A (2018) Tracking geomorphic recovery in process-based river management. Land Degrad Dev 29(9):3221–3244
Fryirs KA, Wheaton JM, Bizzi S, Williams R, Brierley GJ (2019) To plug-in or not to plug-in? Geomorphic analysis of rivers using the River Styles Framework in an era of big data acquisition and automation. Wiley Interdiscip Rev 6(5):e1372

Fryirs K, Hancock F, Healey M, Mould S, Dobbs L, Riches M, Brierley G (2021) Things we can do now that we could not do before: developing and using a cross-scalar, state-wide database to support geomorphologically-informed river management. PLoS ONE 16(1):e0244719
Fuller IC, Death RG (2018) The science of connected ecosystems: what is the role of catchment-scale connectivity for healthy river ecology? Land Degrad Dev 29(5):1413–1426
García JH, Ollero A, Ibisate A, Fuller IC, Death RG, Piégay H (2021) Promoting fluvial geomorphology to "live with rivers" in the Anthropocene Era. Geomorphology 380:107649
Gilvear DJ (1999) Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. Geomorphology 31(1–4):229–245
Grabowski RC, Surian N, Gurnell AM (2014) Characterizing geomorphological change to support sustainable river restoration and management. Wiley Interdiscip Rev Water 1(5):483–512
Grant GE, O'connor JE, Wolman MG (2013) A river runs through it: conceptual models in fluvial geomorphology. In: Shroder J, Wohl E (eds) Treatise on geomorphology. Fluvial geomorphology, vol 9. Academic Press, San Diego, pp 6–21
Guillon H, Byrne CF, Lane BA, Sandoval Solis S, Pasternack GB (2020) Machine learning predicts reach-scale channel types from coarse-scale geospatial data in a large river basin. Water Resour Res 56(3):e2019WR026691
Gurnell AM (2014) Plants as river system engineers. Earth Surf Proc Land 39(1):4–25
Gurnell AM, Rinaldi M, Belletti B, Bizzi S, Blamauer B, Braca G, Buijse AD, Bussettini M, Camenen B, Comiti F, Ziliani L (2016) A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquat Sci 78(1):1–16
Gurnell AM, Scott SJ, England J, Gurnell D, Jeffries R, Shuker L, Wharton G (2020) Assessing river condition: a multiscale approach designed for operational application in the context of biodiversity net gain. River Res Appl 36(8):1559–1578
Hand BK, Flint CG, Frissell CA, Muhlfeld CC, Devlin SP, Kennedy BP, Crabtree RL, McKee WA, Luikart G, Stanford JA (2018) A social–ecological perspective for riverscape management in the Columbia River Basin. Front Ecol Environ 16(S1):S23–S33
Harris GP, Heathwaite AL (2012) Why is achieving good ecological outcomes in rivers so difficult? Freshw Biol 57:91–107
Hewett CJ, Wilkinson ME, Jonczyk J, Quinn PF (2020) Catchment systems engineering: an holistic approach to catchment management. Wiley Interdiscip Rev 7(3):e1417
Hikuroa D, Brierley GJ, Blue B, Tadaki M, Salmond A (2021) Restoring sociocultural relationships with rivers: experiments in fluvial pluralism from Aotearoa New Zealand. In: Cottet M, Morandi B, Piegay H (eds) River restoration: social and policy perspectives from practice and research. Wiley, Chichester
Hilderbrand RH, Watts AC, Randle AM (2005) The myths of restoration ecology. Ecol Soc. 10(1)
Hillman M, Brierley G (2008) Restoring uncertainty: translating science into management practice. In: Brierley GJ, Fryirs KA (eds) River futures. An integrative scientific approach to river repair. Island Press, Washington, pp 257–272
Hobbs RJ, Norton DA (1996) Towards a conceptual framework for restoration ecology. Restor Ecol 4(2):93–110
Holling CS, Meffe GK (1996) Command and control and the pathology of natural resource management. Conserv Biol 10(2):328–337
Hooke JM (2020) Changing landscapes: five decades of applied geomorphology. Geomorphology 366:106793
Jellinek S, Wilson KA, Hagger V, Mumaw L, Cooke B, Guerrero AM, Erickson TE, Zamin T, Waryszak P, Standish RJ (2019) Integrating diverse social and ecological motivations to achieve landscape restoration. J Appl Ecol 56(1):246–252
Jeschke JM, Lokatis S, Bartram I, Tockner K (2019) Knowledge in the dark: scientific challenges and ways forward. Facets. https://doi.org/10.1139/facets-2019-0007
Johnson MF, Thorne CR, Castro JM, Kondolf GM, Mazzacano CS, Rood SB, Westbrook C (2020) Biomic river restoration: a new focus for river management. River Res Appl 36(1):3–12
Jungwirth M, Muhar S, Schmutz S (2002) Re-establishing and assessing ecological integrity in riverine landscapes. Freshw Biol 47(4):867–887. https://doi.org/10.1046/j.1365-2427.2002.00914.x
Karr JR (1999) Defining and measuring river health. Freshw Biol 41(2):221–234
Kellerhals R, Church M, Bray DI (1976) Classification and analysis of river processes. J Hydraul Div ASCE 102(7):813–829
Khan S, Fryirs K, Bizzi S (2021) Modelling sediment (dis) connectivity across a river network to understand locational-transmission-filter sensitivity for identifying hotspots of potential geomorphic adjustment. Earth Surf Proc Land 46(14):2856–2869
Kondolf GM (2011) Setting goals in river restoration: when and where can the river "heal itself." Stream Restor Dyn Fluvial Syst 194:29–43. https://doi.org/10.1029/2010GM001020
Kondolf GM (2012) The Espace de Liberte and restoration of fluvial process: when can the river restore itself and when must we intervene. In: Boon PJ, Raven PJ (eds) River conservation and management. Wiley, Chichester, pp 225–242
Kondolf GM, Micheli ER (1995) Evaluating stream restoration projects. Environ Manage 19(1):1–15
Kondolf GM, Smeltzer MW, Railsback SF (2001) Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. Environ Manage 28(6):761–776
Kondolf GM, Boulton AJ, O'Daniel S, Poole GC, Rahel FJ, Stanley EH, Wohl E, Bång A, Carlstrom J, Cristoni C, Huber H, Nakamura K (2006) Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecol Soc. 11(2).
Lave R (2012) Fields and streams: stream restoration, neoliberalism, and the future of environmental science, vol 12. University of Georgia Press, Athens
Law A, Gaywood MJ, Jones KC, Ramsay P, Willby NJ (2017) Using ecosystem engineers as tools in habitat restoration and rewilding: beaver and wetlands. Sci Total Environ 605:1021–1030
Lisenby PE, Croke J, Fryirs KA (2018) Geomorphic effectiveness: a linear concept in a non-linear world. Earth Surf Proc Land 43(1):4–20
Lisenby PE, Fryirs KA, Thompson CJ (2020) River sensitivity and sediment connectivity as tools for assessing future geomorphic channel behavior. Int J River Basin Manag 18(3):279–293
Macklin MG, Lewin J (2019) River stresses in anthropogenic times: large-scale global patterns and extended environmental timelines. Progr Phys Geogr 43(1):3–23
Maddock I (1999) The importance of physical habitat assessment for evaluating river health. Freshw Biol 41(2):373–391
Marçal M, Brierley G, Lima R (2017) Using geomorphic understanding of catchment-scale process relationships to support the management of river futures: Macaé Basin, Brazil. Appl Geogr 84:23–41
Martín EG, Giordano R, Pagano A, van der Keur P, Costa MM (2020) Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. Sci Total Environ 738:139693
McCully P (1996) Silenced rivers: the ecology and politics of large dams. Zed Books, London
Mogk DW, Bruckner MZ (2020) Geoethics training in the earth and environmental sciences. Nat Rev Earth Environ 1(2):81–83
Montgomery DR (1999) Process domains and the river continuum 1. JAWRA J Am Water Resour Assoc 35(2):397–410
Montgomery DR (2008) Dreams of natural streams. Science 319(5861):291–292
Moore HE, Rutherfurd ID (2017) Lack of maintenance is a major challenge for stream restoration projects. River Res Appl 33(9):1387–1399. https://doi.org/10.1002/rra.3188
Naiman RJ, Lonzarich DG, Beechie TJ, Ralph SC (1992) General principles of classification and the assessment of conservation potential in rivers. In: Boon PJ, Calow P, Petts GE (eds) River conservation and management. Wiley, New York, pp 93–123
Nanson GC, Croke JC (1992) A genetic classification of floodplains. Geomorphology 4(6):459–486
Nanson GC, Huang HQ (2017) Self-adjustment in rivers: evidence for least action as the primary control of alluvial-channel form and process. Earth Surf Proc Land 42(4):575–594
Neal WJ, Pilkey OH, Cooper JAG, Longo NJ (2018) Why coastal regulations fail. Ocean Coast Manag 156:21–34

Newson MD, Large AR (2006) 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. Earth Surf Proc Land 31(13):1606–1624
Newson MD, Newson CL (2000) Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. Prog Phys Geogr 24(2):195–217
Newson MD, Hey RD, Bathurst JC, Brookes A, Carling PA, Petts GE, Sear DA (1997) Case studies in the application of geomorphology to river management. Wiley, Hoboken
Newson MD (2021) 'Fluvial geomorphology and environmental design': restitution for damage, rehabilitation, restoration or rewilding? Earth Surf Process Landforms.
Norris RH, Thoms MC (1999) What is river health? Freshw Biol 41(2):197–209
O'Brien GR, Wheaton J, Fryirs K, McHugh P, Bouwes N, Brierley G, Jordan C (2017) A geomorphic assessment to inform strategic stream restoration planning in the Middle Fork John Day Watershed, Oregon, USA. J Maps 13(2):369–381
Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Sudduth E (2005) Standards for ecologically successful river restoration. J Appl Ecol 42(2):208–217
Palmer MA, Menninger HL, Bernhardt E (2010) River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? Freshw Biol 55:205–222
Palmer MA, Hondula KL, Koch BJ (2014) Ecological restoration of streams and rivers: shifting strategies and shifting goals. Annu Rev Ecol Evol Syst 45:247–269
Park G (1995) Nga Uruora. The groves of life. Victoria University Press, Wellington
Pauly D (1995) Anecdotes and the shifting baseline syndrome of fisheries. Trends Ecol Evol 10(10):430
Perring MP, Standish RJ, Price JN, Craig MD, Erickson TE, Ruthrof KX, Whiteley AS, Valentine LE, Hobbs RJ (2015) Advances in restoration ecology: rising to the challenges of the coming decades. Ecosphere 6(8):1–25
Petts GE (1984) Impounded rivers: perspectives for ecological management. Wiley, Hoboken
Phillips JD (2007) The perfect landscape. Geomorphology 84(3–4):159–169
Piégay H, Darby SE, Mosselman E, Surian N (2005) A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River Res Appl 21(7):773–789. https://doi.org/10.1002/rra.881
Piégay H, Arnaud F, Belletti B, Bertrand M, Bizzi S, Carbonneau P, Dufour S, Liébault F, Ruiz-Villanueva V, Slater L (2020) Remotely sensed rivers in the Anthropocene: state of the art and prospects. Earth Surf Proc Land 45(1):157–188
Pilkey Jr OH, Neal WJ, Pilkey Sr, OH, 1978. From Currituck to Calabash: Living with North Carolina's Barrier Islands. North Carolina Science and Technology Research Center, Research Triangle Park, NC, p. 228 (1980; Second Edition); 1982, reprinted by Duke University Press, Durham, NC, 245p
Poeppl RE, Fryirs KA, Tunnicliffe J, Brierley GJ (2020) Managing sediment (dis) connectivity in fluvial systems. Sci Total Environ. 736:139627
Poff NL (1997) Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. J N Am Benthol Soc 16(2):391–409
Polvi LE, Lind L, Persson H, Miranda-Melo A, Pilotto F, Su X, Nilsson C (2020) Facets and scales in river restoration: nestedness and interdependence of hydrological, geomorphic, ecological, and biogeochemical processes. J Environ Manag 265:110288
Poole GC (2002) Fluvial landscape ecology: addressing uniqueness within the river discontinuum. Freshw Biol 47(4):641–660
Powers PD, Helstab M, Niezgoda SL (2019) A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. River Res Appl 35(1):3–13
Reichstein M, Camps-Valls G, Stevens B, Jung M, Denzler J, Carvalhais N (2019) Deep learning and process understanding for data-driven Earth system science. Nature 566(7743):195–204
Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol Rev 94(3):849–873
Rhoads BL (2020) River dynamics: geomorphology to support management. Cambridge University Press, Cambridge
Rinaldi M, Surian N, Comiti F, Bussettini M (2015) A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology 251:122–136
RiverOfLife M, Poelina A, Bagnall D, Lim M (2020) Recognizing the Martuwarra's first law right to life as a living ancestral being. Trans Environ Law 9(3):541–568
Rogers KH (2006) The real river management challenge: integrating scientists, stakeholders and service agencies. River Res Appl 22(2):269–280
Rosgen DL (1994) A classification of natural rivers. CATENA 22(3):169–199
Rowland JC, Shelef E, Pope PA, Muss J, Gangodagamage C, Brumby SP, Wilson CJ (2016) A morphology independent methodology for quantifying planview river change and characteristics from remotely sensed imagery. Remote Sens Environ 184:212–228
Salmond A, Brierley G, Hikuroa D (2019) Let the rivers speak: thinking about waterways in Aotearoa New Zealand. Policy Q 15(3):45–54. https://doi.org/10.26686/pq.v15i3.5687
Schmidt JC, Webb RH, Valdez RA, Marzolf GR, Stevens LE (1998) Science and values in river restoration in the Grand Canyon: there is no restoration or rehabilitation strategy that will improve the status of every riverine resource. Bioscience 48(9):735–747. https://doi.org/10.2307/1313336
Schmitt RJ, Bizzi S, Castelletti A (2016) Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity. Water Resour Res 52(5):3941–3965
Schumm SA (1977) The fluvial system. Wiley
Schumm SA (1991) To interpret the earth: ten ways to be wrong. Cambridge University Press, Cambridge
Schumm SA, Lichty RW (1965) Time, space, and causality in geomorphology. Am J Sci 263(2):110–119
Schumm SA, Mosley MP, Weaver W (1987) Experimental fluvial geomorphology. Wiley, New York
Schwenk J, Khandelwal A, Fratkin M, Kumar V, Foufoula-Georgiou E (2017) High spatiotemporal resolution of river planform dynamics from Landsat: the RivMAP toolbox and results from the Ucayali River. Earth Space Sci 4(2):46–75
Sear DA (1994) River restoration and geomorphology. Aquat Conserv Mar Freshwat Ecosyst 4(2):169–177
Sear DA, Newson MD, Brookes A (1995) Sediment-related river maintenance: the role of fluvial geomorphology. Earth Surf Proc Land 20(7):629–647
Simon A, Doyle M, Kondolf M, Shields FD Jr, Rhoads B, McPhillips M (2007) Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel response. JAWRA J Am Water Resour Assoc 43(5):1117–1131
Spink A, Fryirs K, Brierley G (2009) The relationship between geomorphic river adjustment and management actions over the last 50 years in the upper Hunter catchment, NSW, Australia. River Res Appl 25(7):904–928
Stoddard JL, Larsen DP, Hawkins CP, Johnson RK, Norris RH (2006) Setting expectations for the ecological condition of streams: the concept of reference condition. Ecol Appl 16(4):1267–1276
Su G, Logez M, Xu J, Tao S, Villéger S, Brosse S (2021) Human impacts on global freshwater fish biodiversity. Science 371(6531):835–838
Suding KN (2011) Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annu Rev Ecol Evol Syst 42:465–487
Tadaki M, Brierley G, Cullum C (2014) River classification: theory, practice, politics. Wiley Interdiscip Rev Water 1(4):349–367
Tangi M, Bizzi S, Fryirs K, Castelletti A (2021) A dynamic, network scale sediment (dis) connectivity model to reconstruct historical sediment transfer and river reach sediment budgets. Water Resour Res, e2021WR030784
Thomson JR, Taylor MP, Fryirs KA, Brierley GJ (2001) A geomorphological framework for river characterization and habitat assessment. Aquat Conserv Mar Freshwat Ecosyst 11(5):373–389
Thorne C, Hey R, Newson M (1997) Applied fluvial geomorphology for river engineering and management. Wiley, Hoboken
Thorp JH, Thoms MC, Delong MD (2006) The riverine ecosystem synthesis: biocomplexity in river networks across space and time. River Res Appl 22(2):123–147

Tickner D, Opperman JJ, Abell R, Acreman M, Arthington AH, Bunn SE, Cooke SJ, Dalton J, Darwall W, Edwards G, Harrison I, Young L (2020) Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. Bioscience 70(4):330–342
Tonkin JD, Poff NL, Bond NR, Horne A, Merritt DM, Reynolds LV, Olden JD, Ruhi A, Lytle DA (2019) Prepare river ecosystems for an uncertain future. Nature 570:301–303
Vollmer D, Shaad K, Souter NJ, Farrell T, Dudgeon D, Sullivan CA, Fauconnier I, MacDonald GM, McCartney MP, Power AG, McNally A, Regan HM (2018) Integrating the social, hydrological and ecological dimensions of freshwater health: the Freshwater Health Index. Sci Total Environ 627:304–313
Ward JV (1989) The four-dimensional nature of lotic ecosystems. J N Am Benthol Soc 8(1):2–8
Wheaton JM, Fryirs KA, Brierley G, Bangen SG, Bouwes N, O'Brien G (2015) Geomorphic mapping and taxonomy of fluvial landforms. Geomorphology 248:273–295
Wheaton JM, Bennett SN, Bouwes NW, Maestas JD, Shahverdian SM (Eds.). (2019). Low-tech process-based restoration of Riverscapes: design manual. Version 1.0. Utah State University Restoration Consortium. Logan, UT. Available at: http://lowtechpbr.restoration.usu.edu/manual
Wiens JA (2002) Riverine landscapes: taking landscape ecology into the water. Freshw Biol 47(4):501–515
Wilcock P (1997) Friction between science and practice: the case of river restoration. EOS Trans Am Geophys Union 78(41):454–454. https://doi.org/10.1029/97EO00286
Wilcock D, Brierley G, Howitt R (2013) Ethnogeomorphology. Prog Phys Geogr 37(5):573–600
Wilkinson C, Hikuroa DC, Macfarlane AH, Hughes MW (2020) Mātauranga Māori in geomorphology: existing frameworks, case studies, and recommendations for incorporating Indigenous knowledge in Earth science. Earth Surf Dyn 8(3):595–618
Williams RD, Bangen S, Gillies E, Kramer N, Moir H, Wheaton J (2020) Let the river erode! Enabling lateral migration increases geomorphic unit diversity. Sci Total Environ 715:136817
Wohl E (2013) Wilderness is dead: whither critical zone studies and geomorphology in the Anthropocene? Anthropocene 2:4–15
Wohl E, Lane SN, Wilcox AC (2015a) The science and practice of river restoration. Water Resour Res 51(8):5974–5997
Wohl E, Bledsoe BP, Jacobson RB, Poff NL, Rathburn SL, Walters DM, Wilcox AC (2015b) The natural sediment regime in rivers: broadening the foundation for ecosystem management. Bioscience 65(4):358–371
Wohl E, Brierley G, Cadol D, Coulthard TJ, Covino T, Fryirs KA, Grant G, Hilton RG, Lane SN, Magilligan FJ, Meitzen KM, Sklar LS (2019) Connectivity as an emergent property of geomorphic systems. Earth Surf Proc Land 44(1):4–26
Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palmer MA, Poff NL, Tarboton D (2005) River restoration. Water Resour Res, 41(10)
Wolman MG, Gerson R (1978) Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf Process 3(2):189–208
WWAP (United Nations World Water Assessment Programme) UN-Water (2018) The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. UNESCO, Paris

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