Fryirs Kirstie (Orcid ID: 0000-0003-0541-3384)

# Assemblages of geomorphic units: A building block approach to analysis and interpretation of river character, behaviour, condition and recovery

Kirstie Fryirs[1]* and Gary Brierley[2]

[1] Department of Earth and Environmental Sciences, Macquarie University, NSW, Australia.

[2] School of Environment, University of Auckland, Auckland, New Zealand

* Corresponding author: kirstie.fryirs@mq.edu.au

## Acknowledgements

We thank the Editors of this Special Issue for the invitation to write this paper in memory of Prof. Ken Gregory. We thank the Editor-in-Chief, Associate Editor and two other reviewers who provided insightful comments on this paper. The authors have no conflicts of interest to declare.

## Data availability statement

Data sharing not applicable – no new data generated.

## Author contributions

Kirstie Fryirs - conceptualisation; methodology, investigation, resources, writing – initial draft; writing – reviewing and editing.

Gary Brierley - conceptualisation; investigation, writing – initial draft; writing – reviewing and editing.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/esp.5264

# Assemblages of geomorphic units: A building block approach to analysis and interpretation of river character, behaviour, condition and recovery

## ABSTRACT

A geomorphic unit is a landform that has been created and reworked by a particular set of earth surface processes. Each geomorphic unit has a particular morphology and sediment properties. Characteristic assemblages and patterns of geomorphic units reflect the use of available energy at any particular location in the landscape. In river systems the mix and balance of erosional and depositional processes creates characteristic, and sometimes distinctive, patterns of geomorphic units at the reach scale. As geomorphic units make up all parts of every valley bottom, the analysis of geomorphic units provides a universal resource with which to undertake systematic geomorphic analysis of river systems. In the first instance, this tool helps to interpret river morphodynamics. Particular process-form associations determine what type of geomorphic unit is found where, how it is formed and/or reworked, and if/how that unit is related to adjacent units in the channel and/or floodplain. From this, particular assemblages of geomorphic units can be used to identify and map reach boundaries along a river course. Each reach has a particular set of process-form relationships that determine (and/or reflect) the range of behaviour and the capacity for adjustment of that section of river. Framed in a catchment context and in relation to evolutionary trajectory, interpretation of geomorphic unit assemblages, and how they change over time, informs analysis of river condition and the potential for geomorphic recovery of each reach. A scaffolding framework to conduct such analyses and interpretations provides an important bridge between expert manual analysis and machine learning analysis using Big Data, allowing for the identification and interpretation of the distinctive traits of each and every river system.

**Keywords:** landform, hydromorphology, morphodynamics, stream process, river management

# 1. INTRODUCTION

"*Thinking about landforms as natural kinds underlies the need for the description and classification of landforms to be more detailed, rigorous and genetically based*" (Gregory and Lewin, 2014; p42).

## 1.1 Overview and structure of this paper

The conduct and outcomes of geomorphic analysis of river systems have profound implications in scientific and management terms. Recognising the inherent diversity of river systems (Phillips, 2007), innate limitations are faced in application of unduly prescriptive approaches to analysis (e.g. Lave, 2009; Simon et al., 2007). Rather than over-simplistic cookbook approaches or check-lists, generic and open-ended frameworks are required to identify the distinctive attributes and traits of each and every river (MacMillan et al., 2000; Brierley et al., 2013; Fryirs and Brierley, 2021).

Landscape characterisation entails key decisions regarding the scale of analysis (i.e. the topographic grain; Church and Mark, 1980; Church, 1996; Evans, 2003; Smith and Mark, 2003; Mark and Smith, 2004; Schmidt and Andrew, 2005, Tarolli and Sofia, 2016). This determination has implications for the accuracy, reliability and meaning of outputs derived from both expert-manual and automated approaches to identification and mapping of geomorphic features (e.g. Macmillan et al., 2000; Drăguţ and Blaschke, 2006; Jasiewicz and Stepinski, 2013; Tarolli, 2014; Kennelly et al., 2021; Braun, 2021). In geomorphic analyses of river systems, an appropriate approach must be well-suited to analysis of all sections of river course, from source to sink, including both erosional and depositional forms. Such efforts provide insights into the heterogeneity and distinctiveness of a given riverscape while retaining the capacity to recognise, map and interpret patterns of attributes at broader scales. This paper shows how geomorphic units – instream and floodplain landforms that make up river courses – provide a universal resource to conduct such analyses.

While the foundation principles of geomorphic unit analysis are well established (Brierley, 1996; Brierley and Fryirs, 2005; Fryirs and Brierley, 2013, 2018; Wheaton et al., 2015; Gurnell et al., 2016a; Belletti et al., 2017), to date no systematic synthesis outlines and demonstrates the flexibility and practicality of this universal resource. This paper shows how a scaffolding approach, in which a range of techniques and steps are used to progressively build sophisticated understanding and knowledge, provides a logical basis to conduct geomorphic analyses and interpretation of all river systems (Brierley et al., 2021). The approach starts with geomorphic unit identification to characterise river forms. Building on this, analysis of reach-scale assemblages of geomorphic units is used to define and interpret river behaviour. The continuum of instream and floodplain geomorphic units reflects the catchment-scale balance of erosional and depositional processes from source to sink. This approach provides a coherent platform to analyse geomorphic river type (style) and interpret geomorphic condition and recovery potential. The discussion section outlines prospects for place-based analyses and interpretations of river systems in an era of big data and machine-learning applications. Unless conceptual framings that underpin such exercises are 'right', such that foundation knowledge is meaningful and accurate, semi-automated approaches to geomorphic analysis of river systems are unlikely to achieve their intended aims, goals and potential (cf. Bangen et al., 2014; Brown and Pasternack, 2019; Williams et al., 2020). It is contended that while automated geomorphic analyses using remote sensing imagery are increasingly used to undertake morphometric analyses of surface topography, fieldwork is still required to see below the surface to determine the sedimentary makeup of landforms and to fully reveal their erosional-depositional morphodynamics and evolution (e.g., Roering et al., 2013). The scaffolding framework that is developed and applied in this paper provides an important bridge between expert manual analysis and machine learning analysis using big data.

## 1.2 What are geomorphic units and assemblages of geomorphic units?

Geomorphic units are the building blocks of river systems (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013; Wheaton et al., 2015). They are the landforms that make up the channel (instream geomorphic units) and the floodplain. Each geomorphic unit has fundamental morphometric properties (Minar and Evans, 2008) that include a characteristic shape (geometry), sedimentary composition, and position on the valley bottom. A mix of these attributes can be used to map and identify geomorphic units, and classify them (Evans, 2012; Wheaton et al., 2015; Belletti et al., 2017; Phillips, 2017). In hierarchical approaches to geomorphic analysis of rivers, geomorphic units sit between hydraulic units and reaches (Gurnell et al., 1994; Brierley and Fryirs, 2005; Gurnell et al., 2016a; Fryirs et al., 2018a). In landscape ecology, equivalent features are referred to as tesserae or patches (Malanson, 1997; Wiens, 2002). In sedimentology, they are architectural elements, elements, morphostratigraphic units or morphogenetic units (Miall, 1985; Brierley, 1996).

Identification of types and patterns of geomorphic units is the key that helps to 'read the landscape' (Brierley et al., 2013; Fryirs and Brierley, 2013), unlocking and unravelling the range of process relationships that shape river morphodynamics (Gregory 1979; Brierley, 1996). As such, they underpin interpretations of river character, capacity for adjustment and evolution (e.g. Williams et al., 2020). Assessment of the types of geomorphic unit, the processes by which they were formed and/or reworked, and interactions between units at differing flow stages provides insight into the range of variability of a river reach - its behavioural regime. In turn, the ease of adjustment of different geomorphic units provides a measure of the sensitivity of a reach to different types of disturbance event (Downs and Gregory, 1995; Gregory 2004, 2006). In evolutionary terms, the preservation of different geomorphic units, either in the sedimentology or at different positions on the valley bottom, provides insight into how that river has adjusted over time (Kellerhals et al., 1996). Some reaches may reflect contemporary conditions, while others comprise units that have been inherited from conditions in the past (Brierley, 2010).

Individual geomorphic units can be unit or compound (Smith, 1974; Brierley, 1991a). Unit features are often products of single depositional or erosional events, whereas compound features reflect a range of flow conditions and a mix of deposition and erosion events. Unit features tend to have a relatively homogenous morphology and sedimentary composition, whereas compound features are comprised of smaller geomorphic units, and have a heterogeneous morphology and sedimentary composition. Unit features contain a limited variety of elementary forms or geomorphons (Minar and Evans, 2008; Jasiewicz and Stepinski, 2013) whereas compound units contain a greater variety of these shapes. Some geomorphic units, whether unit or compound, are fully alluvial. Flow with a particular range of energy interacts with available sediments to produce particular patterns of units (Hawkins et al., 1993). Some geomorphic units are predominantly erosional (e.g. pool formed by scour or chute channel caused by excavation). Others are primarily depositional (e.g. bedload bars in mid-channel or bank-attached locations, or suspended load deposits on instream islands or vertically accreted floodplains). In many instances, extraneous factors influence local flow hydraulics. For example, riparian vegetation (Corenblit et al., 2007a, b) and ecosystem engineers (e.g. beavers; Gurnell, 2014), log jams (whether natural or engineered) and obstructions such as bridge piers and revetments may act as structural elements (Wheaton et al., 2015). Elsewhere, channel boundaries are fixed, whether by bedrock, cemented terrace sediments or anthropogenic channel margins (e.g. artificial levees; stopbanks) or forced by obstructions such as wood (Gurnell et al., 2002; Wohl et al., 2019). In these situations, the prefix 'forced' is used to distinguish the important control that other elements of rivers may play upon the type and pattern of geomorphic units found along a reach (Brierley and Fryirs, 2005). As an example, a forced pool often has a different morphology and morphdynamics to an alluvial pool.

Although individual geomorphic units may be observed in a range of river types (e.g. pools are common along many variants), characteristic reach-scale patterns or assemblages of geomorphic units tend to occur along different types of rivers. When pieced together using a constructivist approach, the mix of units determines the structural character or mosaic of a river (Pringle et al., 1988; Brierley, 1996). Collectively, the assemblage of geomorphic units that make up a section of river describe, and reflect, reach scale morphodynamics.

## 1.3 Process-form associations of geomorphic units and interpretation of river behaviour

Each geomorphic unit has a process-form association (Lane and Richards, 1997). Gregory (1978) expresses the way that Processes (P) operate on Materials (M) over time (t) to produce landforms (F) as:

$$F = f\,(P, M)\,dt.$$

Each geomorphic unit is created and/or reworked by a mix of erosional and depositional processes at different flow stages. Processes that form and rework geomorphic units are dependent upon position and elevation on the valley bottom (e.g. instream or floodplain) and how this affects the distribution and use of flow energy along a reach. Energy use varies with slope and confinement (and associated total/unit stream power), sediment availability and calibre, and the form/extent of resistance elements along a reach (Gurnell, 2014; Gurnell et al., 2016b; Wheaton et al., 2015; Sholtes et al., 2018). Inverting this lens, correct identification of a geomorphic unit, using morphology, position, and sedimentary composition and calibre, provides the basis to interpret the mechanisms by which each unit was formed and/or reworked (Lane and Richards, 1997).

Many geomorphic units are genetically linked to adjacent units (Wyrick and Pasternack, 2014), wherein the processes that form and/or rework one unit are genetically linked to processes that form and/or rework the adjacent unit. For example, steps and pools are genetically linked along steep, bedrock-controlled rivers, and pools and riffles co-adjust along active meandering rivers. In channels with a high wood load, lateral or mid-channel bars may be forced where flow circulation around wood creates zones of deposition, or in partly confined settings pools may scour where bedrock forcing realigns the thalweg.

While the interpretation of the process-form association of each geomorphic unit provides an important understanding of the mechanisms by which each individual geomorphic unit is formed and/or reworked, it is the analysis of the full set of processes responsible for the assemblage of geomorphic units that produces interpretations of river behaviour at different flow stages (see below). This incorporates analysis of a river's capacity for adjustment in lateral, vertical or wholesale dimensions (Brierley and Fryirs, 2005). Different geomorphic units adjust in different ways and in different dimensions, and when assessed as an assemblage the geomorphic sensitivity of a reach can be interpreted (see Fryirs, 2017). Changes to the assemblage of geomorphic units along a particular reach over time indicate alteration to the behaviour and sensitivity of the river. Such analyses reveal phases of river evolution over geomorphic time (Hickin, 1983).

The analysis and characterisation of geomorphic units and their process-form associations, and interpretations of behaviour using assemblages for different river types, have been fully documented in other works such as Brierley and Fryirs (2005), Fryirs and Brierley (2013), Wheaton et al. (2015) and Belletti et al. (2017) and are not repeated here. Collectively, insights from these works summarise and record the continuum of geomorphic units along river courses.

### 1.4 The continuum of geomorphic units

At any given position along a longitudinal profile a mix of erosional and depositional processes, controlled by catchment-scale patterns of impelling and resisting forces, results in textural segregation and trends in the dominance of bedload, mixed load and/or suspended load conditions (Schumm, 1977; Church, 2002). Alongside downstream patterns and transitions in valley confinement, this determines the sequence of confined, partly-confined and laterally-unconfined (alluvial) conditions and associated river types and diversity, as well as the types of geomorphic units that occur (Schumm, 1985; Fryirs et al., 2016; O'Brien et al., 2019; Khan et al., 2021a). For example, differing types of geomorphic units occur where channels begin to form and when bedrock channels become disrupted by clusters of coarse sediments that create a gradient of features along steep, confined streams (Hawkins et al., 1993; Montgomery et al., 1996; Montgomery and Buffington, 1997). Similarly, the longitudinal pattern of geomorphic units changes when there is sufficient accommodation space on the valley bottom for out-of-channel processes to occur, such that floodplain pockets form in partly confined valleys (Jain et al., 2008). Beyond this, a transition can occur from degradational to aggradational settings. Degrading channels that are incised or entrenched (Rosgen, 1996; Montgomery and Macdonald, 2002) with limited space to adjust tend to concentrate their energy on the channel bed, so erosional geomorphic units are dominant. Aggrading channels have the maximum degrees of freedom to adjust. They are able to deform their own boundaries, create their own slope, sinuosity and number of channels (Eaton et al., 2010; Mueller and Pitlick, 2013, 2014). These channels flow within floodplain deposits along both banks in laterally unconfined (fully alluvial) settings.

The availability of sediment and the potential for it to be deposited and/or transported in any given reach determines the types of geomorphic units that form and their position and distribution along a reach. Types of geomorphic units reflect a gradient of energy (stream power) and sediment load/calibre conditions (Downs and Gregory, 2014). This produces a continuum of geomorphic units, in both instream and floodplain zones.

Downstream changes in the assemblage of geomorphic units demarcate a shift in geomorphic river type and its behavioural regime. Importantly, these morphological transitions indicate a shift in the formation and/or reworking processes that characterise the geomorphic behaviour of the reach, and associated linkages between reaches. Differing assemblages of channel and floodplain features reflect these transitions in process relationships along river courses (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013; Nanson and Croke, 1992).

**Figure 1** illustrates the range of instream geomorphic units along a continuum of energy (as determined by flow and slope) and available sediment (primarily the calibre/texture and volume of material). The continuum of instream geomorphic units extends from 1) sculpted or erosional bedrock and boulder units, through 2) mid-channel depositional units, to 3) bank-attached depositional units, and 4) sculpted or erosional fine-grained units. Overlap in the environmental domains within which geomorphic units are found (and formed/reworked) means that the continuum is a simplification of reality and is not all-inclusive (Hawkins et al., 1993; Montgomery and Buffington, 1997). Indeed, some instream geomorphic units such as alluvial pools, islands, bank-attached benches and ledges, forced and compound features, sand and gravel sheets, scroll bars, chute channels, bedrock core bars etc. are missing from this continuum because they can form in a variety of different situations or as a result of local conditions (Brierley, 1991a; Brierley and Cunial, 1998; van Niekerk et al., 1999; Brierley and Fryirs, 2005; Fryirs and Brierley, 2013; Wheaton et al., 2015).

Erosional bedrock and boulder instream geomorphic units typically occur in steep, high-energy conditions where erosion dominates over deposition. These units are eroded from bedrock or are comprised of boulders that have been arranged and organised by flow

(Montgomery and Buffington, 1997). The continuum from waterfall, step-pool, cascade, rapid, bedrock pool and bedrock run reflects the transition from supply- to transport-limited conditions, with some finer boulder and cobble features occurring towards the lower energy end of this category (Hawkins et al., 1993).

In the transition to depositional instream geomorphic units, mid-channel forms are typically found under higher energy conditions than bank-attached variants. Depositional, mid channel geomorphic units occur where coarse sediments are moved infrequently and the channel is competence limited, or the sediment load is high and the channel is capacity limited (Knighton, 1998). A typical downstream continuum of mid-channel forms occurs from boulder mounds to expansion, longitudinal, diagonal and transverse bars comprised of cobbles, gravel and sand (Smith, 1974). Alluvial riffles and runs that tend to span the full channel width also occur in this category (Lisle, 1979). Depositional forms found in bank-attached positions reflect a further decline in energy and/or sediment load (Church and Jones, 1982). Lateral bars are attached to the channel banks along straighter sections of channel, while point bars occur on the inside of meander bends (Jackson, 1976). These bars are less frequently reworked than mid-channel forms (Church and Jones, 1982). Further down the continuum in low slope, low energy settings, instream geomorphic units may be sculpted or eroded from surrounding fine-grained, suspended load sediments (Fryirs and Brierley, 2013).

While the continuum presented in **Figure 1** provides a useful synthesis of the diversity of instream geomorphic units for their identification, it can also be used to assess how individual features or assemblages of features may adjust to altered energy and sediment load and/or calibre conditions (Church, 2002). By extension this provides insight into process-form associations and the behaviour of the river. For example, a decrease in sediment load along a low sinuosity river that is dominated by mid-channel longitudinal bars may result in a transformation in bar type towards bank-attached lateral bars. This reflects a shift in bar forms along that river, the processes occurring to produce those bar forms and the behaviour of the reach. Alternatively, mid-channel longitudinal bars may be transformed into diagonal bars as local sediment transport adjusts to flow conditions during braid bar development.

**Figure 2** illustrates typical floodplain geomorphic units along a continuum of energy (as determined by flow and slope), valley confinement and sediment calibre/texture (after Nanson and Croke, 1992). In high energy settings, coarse grained floodplains are typically dominated by vertical accretion and erosional processes such as floodplain stripping produce geomorphic units such as floodchannels and floodplain steps (Nanson, 1986). In medium energy settings a mix of geomorphic units and floodplain types are formed depending on whether the floodplain is formed by vertical or lateral accretion, and the type of reworking process that dominates. Levees, backswamps, cutoffs and palaeochannels result (Farrell, 1987; Brierley et al., 1997). In low energy settings, vertical accretion processes typically result in a range of backswamp, wetland, anabranch, valley fill and discontinuous watercourse units (Knighton and Nanson, 1993; Williams and Fryirs, 2020). Position on the floodplain is a key indicator of the type of floodplain geomorphic unit, and formation and reworking processes. For example, proximal floodplain geomorphic units and deposits (e.g. levees) often reflect quite different sets of process-form interactions relative to geomorphic units in distal floodplain areas (e.g. backswamps) (Fisk, 1944).

## 2 WHAT CAN ANALYSIS OF ASSEMBLAGES OF GEOMORPHIC UNITS BE USED FOR?

Analysis of assemblages of geomorphic units provides a powerful tool to interpret river type and behaviour, condition and recovery (Brierley and Fryirs, 2005). In conceptualising each of these components, such analyses can be unpacked to undertake reach-scale interpretations of landforms (individual geomorphic unit) that underpin assessments of patterns and sequences along longitudinal profiles, across catchments or across regions (Newson and Newson, 2000; Church 2002; Brierley and Fryirs, 2005; Phillips, 2017).

### 2.1 Analysing river type - Style indicators

Each river type (or River Style) has a characteristic and expected assemblage of geomorphic units that can be used as style indicators. An assemblage contains diagnostic geomorphic units that are core (or essential) to the river type, common or overlapping geomorphic units with like-river types, and ubiquitous units that occur in a large number of river types (Fryirs and Brierley, 2018). Using a biology analogy, this is analogous to the differentiation of species, such as *Homo sapiens* versus *Gorilla beringei*. *Homo sapiens* and *Gorilla beringei* have 98% of their DNA in common. However, 2% of diagnostic indicators (DNA) differentiate between these two species. Ubiquitous DNA is found across all living things. This same principle can be applied to identify different river types, highlighting core diagnostic indicators. Common geomorphic units in an assemblage may overlap with river types in adjacent settings on the spectrum of river diversity. Alternatively, if the type sits at an opposite end of the spectrum of river diversity, the assemblage of geomorphic units may be completely distinct and share no common units.

**Figure 3** provides a simple, conceptual basis to differentiate assemblages of geomorphic units that are expected for different river types. Diagnostic geomorphic units are isolated within a pink circle with pink text. Common units are shown as overlapping pink circles with blue text. Ubiquitous geomorphic units are shown within green circles with green text. This schematic representation provides a useful starting point to consider diagnostic, common and ubiquitous geomorphic units along the spectrum of river diversity. However, it does not cover the full spectrum of river diversity. Also, it does not indicate the full set of geomorphic units that make up the assemblage of each river type.

For example a confined, bedrock margin controlled, gorge river type (Fryirs and Brierley, 2018) has an assemblage of geomorphic units that comprises diagnostic units such as waterfalls and cascades, common units such as rapids, bedrock pools and bedrock riffles that overlap with other confined and partly confined river types, and ubiquitous units such as bedrock runs. This assemblage is completely different to that found along a laterally unconfined, anastomosing river type where sculpted fine grained geomorphic units (both instream and floodplain) are diagnostic and common.

In some instances, river types have a simple character and behaviour with a small number and a low richness of geomorphic units in their assemblage (Phillips, 2001, 2017; Fryirs and Brierley, 2009). For example a chain of ponds has a simple assemblage comprising ponds and valley fill (**Figure 3**). Other river types are complex with a variety (or high richness) of geomorphic units in their assemblage. For example a partly confined bedrock margin controlled river (Fryirs and Brierley, 2018) may have a mix of both bedrock and alluvial geomorphic units and a variety of mid-channel, bank-attached and floodplain geomorphic units in the assemblage (**Figure 3**).

A morphodynamic assessment of river type uses the assemblage of geomorphic units to interpret the process-form associations of each geomorphic unit in the assemblage and uses a scaffolding approach to interpret how the river is functioning or behaving under different flow magnitude-frequency conditions (Brierley, 1996). In the work of Brierley and Fryirs (2005, pg 143) river behaviour is defined as "adjustments to river morphology induced by a range of erosional and depositional mechanisms by which water moulds, reworks and reshapes fluvial landforms, producing *characteristic assemblages of landforms* at the reach scale". This is differentiated from river change which is defined as a wholesale shift in the character (i.e. assemblage of geomorphic units) of a reach such that a new river type occurs (Fryirs et al., 2012; Fryirs and Brierley, 2013). Associated with this wholesale shift in assemblage is a shift in the process-form associations operating and the behaviour of the reach at different flow stages.

Interpretation of river behaviour builds upon assessment of river character. Analysis of river character involves identifying shapes and boundaries between different topographic areas on the valley bottom (**Figure 4**) (c.f. MacMillan et al., 2000; Smith and Mark, 2003; Mark and Smith, 2004). These shapes are then assigned names using a taxonomy or naming convention (e.g. Wheaton et al., 2015; Fryirs and Brierley, 2018; **Figure 4**). The process-form association of each geomorphic unit is then used to determine how each is formed and/or reworked and whether erosional or depositional processes are responsible (**Figure 5A**). River behaviour is analysed and interpreted for the assemblage of geomorphic units that is active at three different flow stages – low flow, bankfull and overbank (Brierley and Fryirs, 2005; Fryirs, 2017; **Figure 5B**). Analyses consider how flow alignment at differing stages of inundation alters flow energetics, and therefore erosion-deposition dynamics, over different surfaces and geomorphic units. At low flow stage, bed material (re)organisation and low flow channel dynamics around geomorphic units is interpreted (**Figure 5B**). At bankfull stage, the process-form associations of all instream geomorphic units is interpreted, including genetically-linked processes and forcing processes (**Figure 5B**). The position of units whether on the channel bed or along banks is used to interpret how erosion and/or deposition processes determine channel size and shape (putting the bed and banks together; Brierley and Fryirs, 2005). At overbank stage when the floodplain is activated, analysis of the assemblage of floodplain geomorphic units interprets processes of floodplain formation and/or reworking (**Figure 5B**).

## 2.2 Analysing river condition - Condition indicators

Modification to the geomorphic condition (or health) of a river reach of a particular type (or style) is demarcated by alteration to the assemblage of geomorphic units without the reach losing its diagnostic ‘identity’ or changing type. This typically entails assessment relative to a reference or ‘expected’ condition that meaningfully compares like-with-like

(Fryirs et al., 2008, 2021; Fryirs, 2015; Rinaldi et al., 2017; Han and Brierley, 2021). In this context, the assemblage of geomorphic units used to identify river type becomes the expected benchmark or reference against which condition is assessed (e.g. O'Brien et al., 2017). Therefore, condition assessment tends to focus on the identification and interpretation of the presence, absence and abundance of geomorphic units that make up the assemblage. An observed over expected (O/E) approach can be adopted. Using the biology analogy referred to previously, assessments of health compare like-with-like (i.e. within species), whereby a doctor assesses the health of *Homo sapiens* and a vet the health of *Gorilla beringei*. If a human falls ill there will be a deterioration in the physiology of the body. If a virus is responsible, this may manifest as presence of coughing or sneezing and the loss (or absence) of appetite. The severity of the illness and the impact on a person's overall health could be dependent on the abundance of virus in the system.

In geomorphic analysis of river systems, if the presence, absence or abundance of geomorphic units is unexpected, then condition is compromised and something is 'not quite right' or anomalous in the character and behaviour of the river (Montgomery and Macdonald, 2002). For example, in some cases the presence of a certain geomorphic unit is unexpected and would not occur in the characteristic assemblage used to identify the river type. In other cases a geomorphic unit that would be expected may be absent or missing from the assemblage. In some cases, the expected assemblage may be in place, but there is an under-abundance or an over-abundance of certain units that comprise the 'balance' of the expected assemblage, so the quantity of unit(s) is unexpected. This abundance indicator can be considered in one of two ways; as the number of different types of units that occur relative to expected (i.e. the O/E richness), or the number of repeats of each type of unit relative to expected (i.e. the O/E count).

The O/E richness abundance indicator may be used where a reach that is expected to have a relatively simple assemblage of geomorphic units with a low richness becomes more complex, either via disturbance or anthropogenic alteration. This shift in O/E richness suggests that the condition of the reach is compromised. For example, installing gravel or boulder bed control structures and large numbers of wood jams along a fine-grained river that is expected to have a relatively simple structure and where such features do not naturally occur will compromise the integrity and condition of that reach. Vice versa, if a reach that is expected to have a relatively complex assemblage of geomorphic units with a high richness becomes more simple, then the integrity and condition of that reach is compromised. Channelisation and homogenisation of active meandering or braided gravel bed rivers provides a classic example of this form of disruption.

The O/E count abundance indicator could be used to consider whether certain expected geomorphic units in the reach are over-represented in the assemblage. The reach is 'unbalanced' as repeated presence of some units overwhelms the assemblage in terms of their count. For example, the number of repeat longitudinal bars may overwhelm the assemblage at the expense of the abundance of alluvial pools along a reach of braided river. Both units are expected to occur along the reach, but their count is 'unbalanced' relative to expected.

**Figure 6** presents good, moderate and poor condition variants of a confined, bedrock margin controlled, occasional floodplain pockets river type to show how the assemblage of geomorphic units for an individual river type can be used to assess geomorphic river condition (Fryirs, 2015; Fryirs et al., 2021). The good condition variant (green circle) shows the expected assemblage of geomorphic units for this river type (transferred from **Figure 3**). The yellow circle shows the assemblage of geomorphic units for a moderate condition variant of this river type. The diagnostic units that define the river type are still present, but other units are evident in the assemblage (e.g. alluvial pools and lateral sand bars) while others are absent (e.g. bedrock riffles and rapids). The abundance richness of different geomorphic units has decreased. Also, the abundance count of bedrock runs and bedrock pools has decreased as sediment infills and smothers these features to create an abundance of alluvial pools and lateral sand bars. The diagnostic units are still present in the poor condition variant of this river type (red circle) but many units that are expected are absent from the assemblage (e.g. bedrock pools, riffles, runs and rapids). The reach has a lower bedrock core bar richness abundance relative to expected, and is overwhelmed with an abundance count of sand sheets that dominate the assemblage.

Although assessments of river condition are often undertaken at a particular point in time (i.e. the condition of the river today), this does not mean that the assessment disregards the dynamics of the system. A dynamic assessment of river condition uses the form-process associations of the geomorphic units and interpretation of reach behaviour to determine whether the current state is expected for that river type. The presence, absence and abundance of geomorphic units indicates a status in time relative to prevailing sediment regime conditions (i.e., whether the system is in a state that is dominated by erosion processes or deposition processes and whether this state reflects the expected character and behaviour of that river type). This interpretation is aided by determining what the assemblage of geomorphic units 'says' about the process zone function of the reach, i.e. whether the reach is currently behaving as a source zone, a transfer zone or accumulation zone, and whether this is the expected functional role of that reach (Schumm, 1977; Fryirs, 2015). If the state is expected, the reach is classed as being in good condition. The further away from expected the poorer its condition, on a sliding scale through moderate to poor. For the example in **Figure 6**, Reach A is currently operating as a transfer zone. The presence of bedrock pools and the absence of sand sheets indicates that the reach is transferring any sediment made available to it and there is a relative balance between sediment input and output along the reach. This is expected for this river type, and therefore this reach is in good condition. By contrast, Reach C is currently behaving as an accumulation zone. The absence of bedrock pools and the presence (and abundance) of sand sheet sediments indicates that the reach is in a dominantly depositional state and there is an imbalance between sediment input and output that is not expected for a reach of this river type. Therefore the condition of the reach is compromised and is classed as poor. The moderate condition reach has characteristics that are both expected and unexpected, with accompanying representations of erosion and deposition processes. This indicates an imbalance in the sediment regime that is compromising the condition of this reach.

### 2.3 Analysing river recovery - Recovery indicators

Assessing river recovery involves understanding whether the condition of a given reach is improving or deteriorating over a certain timeframe (typically a management timeframe of 50-100 years) (see Fryirs and Brierley, 2016; Fryirs et al., 2018b). Such assessment entails trajectory analysis and comparison of the assemblage of geomorphic units over a time series or between two sequential timeslices. Analysis of the assemblage of geomorphic units indicates what has adjusted over a given timeframe and the direction and pathway of adjustment that a reach has been on, is currently on, or has shifted onto – whether degradation, restoration or creation (see **Figure 7**; Brierley and Fryirs, 2005; Fryirs and Brierley, 2005, 2016). Detection of geomorphic units that return or disappear from the assemblage over time informs recovery assessment. Returning to the biology analogy, for *Homo sapiens* recovery from an illness may entail the return of something (e.g. appetite) or the disappearance of something else (e.g. nausea). For rivers, if restoration is occurring, geomorphic units are returning to the characteristic or expected assemblage over time, whereas if creation is occurring new geomorphic units are being added to the assemblage. This returning and disappearing may not occur equally nor at the same time or rate for reaches at different positions on the degradation, restoration or creation pathways. However, in all cases the diagnostic units that define the river type are not altered and the river maintains key attributes of that river type over time. However, if the time series analysis detects a completely new assemblage (i.e. one assemblage replaces another assemblage), river change has occurred, creating a new or different river type.

The potential for the river reach to recover is dependent on catchment boundary conditions and the (dis)connectivity of sediment flux between reaches (Brierley and Fryirs, 2009; Fryirs et al., 2009, 2012). Reach scale adjustments to the assemblage of geomorphic units may be reversible or irreversible. **Figure 7** shows a worked example for the confined, occasional floodplain pockets river type from **Figure 6**.

A dynamic assessment of river recovery uses the process-form associations of geomorphic units and interpretation of reach behaviour at each stage of the time series to detect changes in the erosion-deposition dynamics of a reach. From this, analyses assess how the return or disappearance of certain geomorphic units alters erosion-deposition dynamics. Fryirs et al. (2009) present such work as an analysis of response gradients, subsequently extending this analysis as an ergodic matrix (Fryirs et al., 2012). In many instances, certain key geomorphic units indicate or signpost that river recovery (or degradation) is underway, marking a turning point in the condition of the river (see Brierley et al., 2008; Fryirs and Brierley, 2016). Examples of recovery geomorphic units for different river types summarised in Fryirs et al. (2018b) include the emergence of bedrock or alluvial pools, formation of benches, stable bars or islands, and definition of low flow channels. A classic example is the detection of bank-attached, step-shaped features (**Figure 8**). A ledge is an erosional feature that has been excised or eroded from the floodplain by an incising and/or expanding channel, whereas a bench is a depositional feature deposited against the channel bank as the channel contracts (Fryirs and Brierley, 2013). Occurrence of a ledge in the assemblage indicates that the reach is likely on a degradation pathway, whereas if a bench is occurring then the reach is on a recovery pathway (Fryirs et al., 2018b). Benches are key indicator geomorphic units for detecting river recovery in previously incised and/or overwidened river reaches. Spotting when a bench is being formed, or when a ledge becomes a bench, indicates that a shift from dominance of erosional to depositional processes is underway, such that the reach may be at a turning point to recovery.

In other cases, analysis of the full geomorphic unit assemblage can be used to detect a change in the erosion-deposition dynamics of a reach. Returning to **Figure 7** as an example, if recovery from poor to moderate condition is occurring, then sand and gravel sheets will disappear and lateral bars and alluvial pools will (re)emerge in the assemblage. There may still be longitudinal bars in the assemblage. However, if recovery is occurring to a good condition, a much broader range of geomorphic units will (re)emerge and be (re)added to the expected assemblage. When this transition occurs, the erosion-deposition dynamics of the reach will be transformed from dominantly depositional where the behaviour of the reach is controlled by sediment competence and/or capacity limits, to dominantly erosional where the behaviour of the reach is characterised by the scour and removal of sediment from infilled pools, the reorganisation of within-reach sediment to create islands, and the (re)emergence of geomorphic units such as bedrock riffles, islands and rapids and sediment is transported out of the reach.

## 3. FUTURE RESEARCH NEEDS AND USES IN APPLIED FLUVIAL GEOMORPHOLOGY

Given the critical importance of geomorphic units as a central and universal tool with which to undertake geomorphic analysis of rivers, considerable attention has been given to development of approaches to their identification, definition, characterisation and mapping (MacMillan et al., 2000; Brierley and Fryirs, 2005; Fryirs and Brierley, 2013; Wheaton et al., 2015). Importantly, geomorphic units characterise all of the valley bottom – there is no blank space on a map (Evans, 2012; Wheaton et al., 2015). Everywhere is part of a geomorphic unit, although boundaries between features are sometimes ill-defined, gradual or fuzzy and inevitably adjust over time (MacMillan et al., 2000; Smith and Mark, 2003; Mark and Smith, 2004; Evans and Minar, 2008).

Interest in creating a comprehensive, coherent and systematic framework for identifying geomorphic units and interpreting their morphodynamics has prompted initiatives to develop automated procedures to map them using digital elevation models derived from remotely sensed datasets (Drăguţ, L., & Blaschke 2006; Wheaton et al., 2010a; Oguchi et al., 2011; Bangen et al., 2014; Wyrick and Pasternack, 2014; Wyrick et al., 2014; Bizzi et al., 2016; Brown and Pasternack, 2019; Williams et al., 2020). The enormous progress that has been made in this field offers considerable prospect to recurrently generate maps and data that can be used to characterise diversity, and interpret the morphodynamics, condition and evolutionary trajectory of river systems, and scaffold this analysis to produce sophisticated understandings of river systems (**Figure 9**). This can be undertaken at unprecedented scales (extent/frequency) and levels of resolution (e.g. Bizzi et al., 2019; Piégay et al., 2020; Boothroyd et al., 2021a, b;). However, with the lure of big data and machine learning applications to provide the answers (Reichstein et al., 2019), careful attention to testing, verification and reproducibility of data input, outputs, analyses and interpretations remains a concern (Wheaton et al., 2010a; Fryirs et al., 2019; Kennelly et al., 2021; Braun, 2021). Caution is also required to prevent the perception that the outputs can be used as a cookbook or a set of diagnostic keys, with the danger of misuse and misinterpretation by non-specialists (cf., Simon et al., 2007; Lave, 2009). To avoid such, it is critical that outputs are verified by interpretations based on traditional methods and training, giving due regard for accuracy and reliability (Gregory, 1979, 2004; Montgomery and Macdonald 2002; Brierley et al., 2021; Braun, 2021). This requires that sound foundational knowledge underpins application of analytical tools that make use of big data, striving to produce realistic and acceptable outputs that make sense on-the-ground (Evans, 2012; Roering et al., 2013).

Essentially, remotely sense analyses are skin-deep, unable to extract potentially vital information from beneath the surface to support analyses and interpretations of geomorphic units. Although inferences can be made by ‘reading the river’, confirmatory evidence is required to support reliable interpretations (Brierley et al., 2013; 2021). For example, 3-D analyses of bounding surfaces are required to reliably define the geometry of geomorphic units (in sedimentology these are referred to as elements, architectural elements, or morphostratigraphic units; Miall, 1985). Strategically positioned trenches provide insights that cannot be derived from 2-D pits (or core log data; Brierley, 1991b). To date, remotely sensed satellite or drone imagery are not directly tied to subsurface seismic techniques. For now, at least, fieldwork is often vital.

Operationalising the conceptual framings presented in this paper to quantify and statistically analyse clusters and assemblages of geomorphic units based on style, condition or recovery indicators is an enticing prospect and one that could provide a powerful tool for both scientists and managers (e.g. Coffman et al., 2011; Belletti et al., 2017). (Semi)automated mapping and classification of shapes (landforms) is now relatively straight forward (e.g. Passalacqua et al., 2010; Jasiewicz and Stepinski, 2013; Bangen et al., 2014; Tarolli et al., 2014; Demarchi et al., 2016; Minar et al., 2020). However, the identification and interpretation of geomorphic units is often open to debate and unanticipated units are sometimes evident, requiring additional information to make reliable explanations (Roering et al., 2013; Wheaton et al., 2010a, 2013, 2015). Regardless, there is significant potential to roll out such analyses across regions and for the full spectrum of river diversity to qualitatively and quantitatively analyse the types and assemblages of geomorphic units that are expected for different river types, and define characteristic or reference states (Fryirs et al., 2019; Gurnell et al., 2020). The identification of diagnostic, common and ubiquitous geomorphic units and their richness for different river types is possible (**Figure 9**). By extension, mapping and classification of geomorphic units can be conducted to quantitatively and statistically analyse the presence, absence and abundance of geomorphic units and develop observed versus expected ratios that could define states of river condition for different river types (**Figure 9**). Further, the mapping and classification of geomorphic units coupled with change detection techniques could be used to track geomorphic recovery over time and spot geomorphic units that are returning or disappearing from the assemblage and indicate that river recovery (or deterioration in condition) is occurring (**Figure 9**). Analysis of geomorphic hotspots (Czuba and Foufoula-Georgiou, 2015) can be substantively expanded through analyses of recovery trajectories linked to sediment cascades (e.g. Fryirs et al., 2018; Khan et al., 2021b; Tangi et al, subm). Such analysis can potentially help determine which geomorphic units are most representative or indicative of geomorphic river recovery (or degradation).

Moving beyond the mapping and classification of geomorphic units, analysis of process-form associations and river behaviour is currently more challenging (Rhoads, 2006; Wheaton et al., 2010a). Agreement on the formation and/or reworking processes that create geomorphic units is helpful (Gregory and Lewin, 2014; Williams et al., 2020). However, appraisal of assemblages and interactions between units on the valley bottom, framed in contextual terms at the reach scale or along longitudinal profiles, is not always straightforward (Wyrick and Pasternack, 2014). Challenges remain in understanding the mutual and genetic interactions between slope, flow regime, sediment size, load and availability, vegetation cover, ecosystem engineers, anthropogenic and memory imprints for different geomorphic units. Without such information it is difficult to model and interpret process-form and behavioural traits that define the expected range of variability of different river types, the causes of different condition states or the triggers of river recovery. However, getting the geomorphic analysis and interpretation of assemblages of geomorphic units ‘correct’ is critical if such work is to be effectively and consistently used in eco-hydrology (habitat) and hydro-morphology (hydraulic) assessment, monitoring and management of a dynamic physical template (cf., Poff et al., 1997; Newson and Newson 2000; Wheaton et al., 2010b; Phillips 2017).

Automated monitoring of assemblages of geomorphic units offers prospect to undertake back sighting exercises to systematically analyse river responses to differing forms, sequences, magnitudes and frequencies of disturbance events and human impacts (Boothroyd et al., 2021a, b). With this understanding and knowledge in hand, geomorphologists can then begin and improve their forecasting work (Trofimov and Phillips, 1992; Wilcock and Iverson, 2003). There is a growing need to forecast how riverine processes and landforms (i.e. the dynamic physical template) are likely to respond to adjustments in water, sediment and vegetation interactions brought about by climate and/or land use change (Lane, 2013; Larkin et al., 2020). There is also a need to better identify and define sensitivity thresholds or tipping points of change (Fryirs, 2017), so that proactive and pre-emptive monitoring, planning and decision-making can take place. This goes to the heart of how we conduct geomorphic analyses of rivers in the 21st century (e.g. Ashmore, 2015; Blue and Brierley, 2016), as key evidence-bases, especially in relation to assessment of river condition and recovery, often drive river management practice and decision-making (Downs and Piegay, 2019; Fryirs et al., 2021).

Contextualising process relations at the assemblage of geomorphic units scale (i.e. the reach scale) in light of catchment-scale boundary conditions and associated insights into changing fluxes can guide the designation of ‘moving targets’ to support geomorphologically-informed management applications (Downs and Gregory, 2014; Brierley and Fryirs, 2016). Prospectively, such applications can understand and ‘work with each and every river’ (Brierley et al., 2013; Brierley, 2020; Fryirs and Brierley, 2021), use that knowledge for forecasting exercises to test the impact of different scenarios on geomorphic river adjustment, change, condition and recovery potential, and embed this in process-based river rehabilitation practice (Phillips, 2001; Gregory 2006; Beechie et al., 2010; Fryirs et al., 2021).

## 4. CONCLUDING COMMENT

Geomorphic analysis of river systems entails assessment of how and why a river looks and works as it does. Essentially, interpretations of river morphodynamics appraise the processes that create and rework geomorphic units, and the ways in which particular assemblages and patterns of these landforms make up a given landscape. In geomorphic terms, spatial and temporal variability in river morphology along every part of every valley bottom is a product of the mix and balance of erosional and/or depositional processes. Although geomorphic units are universal features, some are products of the last disturbance event, while others are inherited from the past. In this light, no analysis of river systems is complete unless due regard is given to the types of geomorphic unit found at a given locality, their relationship and interactions with adjacent units, the pattern of these units along a river course and consideration of how assemblages can adjust and change over time.

This paper has shown how assemblages of geomorphic units provide a flexible and adaptive tool to undertake geomorphic analyses of river systems. Foundation work in applications of a building block approach are used to describe and explain the types and pattern of geomorphic units that make up a particular section of river. Framed in an evolutionary context, assemblages geomorphic units can be used to assess the contemporary condition of a reach and evaluate whether the trajectory of river adjustment reflects deterioration or improvement in condition. Placed in a catchment context, alongside interpretation of likely pressures and/or threatening processes, future trajectories of river adjustment can be forecast. As this analytical lens incorporates layers of description and interpretation within a scaffolding framework, it provides an important bridge between expert manual analysis and machine learning analysis using big data, allowing for the identification and interpretation of core attributes and traits of each and every river system.

## References

Ashmore P. 2015. Towards a sociogeomorphology of rivers. *Geomorphology* **251**:149-156. https://doi.org/10.1016/j.geomorph.2015.02.020

Bangen SG, Wheaton JM, Bouwes N, Bouwes B, Jordan C. 2014. A methodological intercomparison of topographic survey techniques for characterizing wadeable streams and rivers. *Geomorphology* **206**:343-61. https://doi.org/10.1016/j.geomorph.2013.10.010

Beechie TJ, Sear DA, Olden JD, Pess GR, Buffington JM, Moir H, Roni P, Pollock MM. 2010. Process-based principles for restoring river ecosystems. *BioScience* **60(3)**:209-22. https://doi.org/10.1525/bio.2010.60.3.7

Belletti B, Rinaldi M, Bussettini M, Comiti F, Gurnell AM, Mao L, Nardi L, Vezza P. 2017. Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. *Geomorphology* **283**:143-57. https://doi.org/10.1016/j.geomorph.2017.01.032

Bizzi S, Demarchi L, Grabowski RC, Weissteiner CJ, Van de Bund W. 2016. The use of remote sensing to characterise hydromorphological properties of European rivers. *Aquatic sciences* **78(1)**:57-70. https://doi.org/10.1007/s00027-015-0430-7

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 Surface Processes and Landforms* **44(2)**:471-89. https://doi.org/10.1002/esp.4509

Blue B, Brierley G. 2016. 'But what do you measure?' Prospects for a constructive critical physical geography. *Area* **48(2)**:190-7. https://doi.org/10.1111/area.12249

Boothroyd RJ, Williams RD, Hoey TB, Barrett B, Prasojo OA. 2021a. Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change. *Wiley Interdisciplinary Reviews: Water* **8(1)**:e21496. https://doi.org/10.1002/wat2.1496

Boothroyd RJ, Nones M, Guerrero M. 2021b. Deriving planform morphology and vegetation coverage from remote sensing to support river management applications. *Frontiers in Environmental Science* **4(9)**:146. https://doi.org/10.3389/fenvs.2021.657354

Braun AC. 2021. More accurate less meaningful? A critical physical geographer's reflection on interpreting remote sensing land-use analyses. *Progress in Physical Geography: Earth and Environment* https://doi.org/10.1177/0309133321991814

Brierley GJ. 1991a. Bar sedimentology of the Squamish River, British Columbia; definition and application of morphostratigraphic units. *Journal of Sedimentary Research* **61(2)**:211-25. https://doi.org/10.1306/D42676D6-2B26-11D7-8648000102C1865D

Brierley GJ. 1991b. Floodplain sedimentology of the Squamish River, British Columbia: relevance of element analysis. *Sedimentology* **38(4)**:735-750. https://doi.org/10.1111/j.1365-3091.1991.tb01017.x

Brierley GJ. 1996. Channel morphology and element assemblages: A constructivist approach to facies modelling. In *Advances in Fluvial Dynamics and Stratigraphy*. Carling P, Dawson M (eds.) Wiley Interscience: Chichester; 263-298.

Brierley GJ. 2010. Landscape memory: the imprint of the past on contemporary landscape forms and processes. *Area* **42(1)**:76-85. https://doi.org/10.1111/j.1475-4762.2009.00900.x

Brierley GJ. 2020. *Finding the Voice of the River: Beyond Restoration and Management*. Springer Nature, UK. 179pp.

Brierley G, Cunial S. 1998. Vegetation distribution on a gravel point bar on the Wilson River, NSW: A fluvial disturbance model. *Proceedings of the Linnean Society of New South Wales* **120**:87-103.

Brierley GJ, Ferguson RJ, Woolfe KJ. 1997. What is a fluvial levee? *Sedimentary Geology* **114(1-4)**:1-9. https://doi.org/10.1016/S0037-0738(97)00114-0

Brierley GJ, Fryirs KA. 2005. *Geomorphology and River Management: Applications of the River Styles Framework*. Blackwell Publications, Oxford, UK. 398pp.

Brierley G, Fryirs K. 2009. Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. *Environmental Management* **43(6)**:1201-18. https://doi.org/10.1007/s00267-008-9266-4

Brierley GJ, Fryirs KA. 2016. The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. *River Research and Applications* **32(5)**:823-35. https://doi.org/10.1002/rra.2930

Brierley G, Fryirs K, Cullum C, Boulton A. 2008. Working with Change: The Importance of Evolutionary Perspectives in Framing the Trajectory of River Adjustment. In *River Futures: An Integrative Scientific Approach to River Repair*. Brierley GJ, Fryirs KA (eds.) Island Press, Washington DC; 65-81.

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. *Progress in Physical Geography* **37(5)**:601-21. https://doi.org/10.1177/0309133313490007

Brierley G, Fryirs K, Marçal M, Lima R. 2019. The use of the River Styles Framework as a tool to 'work with nature' in managing rivers in Brazil: Examples from the Macaé Catchment. *Revista Brasileira de Geomorfologia* **20(4)**:753-771. https://doi.org/10.20502/rbg.v20i4.1559

Brierley G, Fryirs K, Reid H, Williams R. 2021. The 'dark art' of interpretation in geomorphology. *Geomorphology* 107870. https://doi.org/10.1016/j.geomorph.2021.107870

Brown RA, Pasternack GB. 2019. How to build a digital river. *Earth-Science Reviews* **194**:283-305. https://doi.org/10.1016/j.earscirev.2019.04.028

Church M, Mark DM. 1980. On size and scale in geomorphology. *Progress in Physical Geography*. **4(3)**:342-90. https://doi.org/10.1177/030913338000400302

Church M. 1996. Space, time and the mountain–how do we order what we see. In Rhoads BL, Thorn CE. *The Scientific Nature of Geomorphology*, John Wiley and Sons, Chichester, pp.47-70.

Church M. 2002 Geomorphic thresholds in riverine landscapes. *Freshwater Biology* **47(4)**:541-57. https://doi.org/10.1046/j.1365-2427.2002.00919.x

Church M, Jones D. 1982. Channel bars in gravel-bed rivers. In *Gravel-bed Rivers: Fluvial Processes, Engineering and Management*. Hey RD, Bathurst JC, Thorne CR (eds.) John Wiley & Sons, Chichester; 291-338.

Coffman DK, Malstaff G, Heitmuller FT. 2011. *Characterisation of geomorphic units in the alluvial valleys and channels of Gulf coastal plain rivers in Texas, with examples from the Brazos, Sabine and Trinity Rivers, 2010*. Texas Water Development Board, Scientific Investigation Report 2011-5067. US Department of Interior and US Geological Survey. 31pp.

Corenblit D, Steiger J, Gurnell A, Tabacchi E. 2007. Darwinian origin of landforms. *Earth Surface Processes and Landforms* **32(13)**:2070-3. https://doi.org/10.1002/esp.1536

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-Science Reviews* **84(1-2)**:56-86. https://doi.org/10.1016/j.earscirev.2007.05.004

Czuba JA, Foufoula-Georgiou E. 2015. Dynamic connectivity in a fluvial network for identifying hotspots of geomorphic change. *Water Resources Research* **51(3)**:1401-21. https://doi.org/10.1002/2014WR016139

Demarchi, L, Bizzi, S, Piégay, H. 2016. Hierarchical object-based mapping of riverscape units and in-stream mesohabitats using LiDAR and VHR imagery. *Remote Sensing* **8(2)**:97. https://doi.org/10.3390/rs8020097

Downs PW, Gregory KJ. 1995. Approaches to river channel sensitivity. *The Professional Geographer* **47(2)**:168-75. https://doi.org/10.1111/j.0033-0124.1995.00168.x

Downs P, Gregory K. 2014. *River Channel Management: Towards Sustainable Catchment Hydrosystems*. Routledge, UK.

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. https://doi.org/10.1016/j.geomorph.2019.03.021

Drăguţ L, Blaschke T. 2006. Automated classification of landform elements using object-based image analysis. *Geomorphology* **81(3-4)**:330-44. https://doi.org/10.1016/j.geomorph.2006.04.013

Eaton BC, Millar RG, Davidson S. 2010. Channel patterns: Braided, anabranching, and single-thread. *Geomorphology* **120(3-4)**:353-64. https://doi.org/10.1016/j.geomorph.2010.04.010

Evans IS. 2003. Scale-specific landforms and aspects of the land surface. In Evans IS, Dikau R, Tokunaga E, Ohmori H, Hirano, M. (Eds) *Concepts and Modelling in Geomorphology: International Perspectives*. Terrapub, Tokyo, pp61-84.

Evans IS. 2012. Geomorphometry and landform mapping: What is a landform? *Geomorphology* **137**:94-106. https://doi.org/10.1016/j.geomorph.2010.09.029

Farrell KJ. 1987. Sedimentology and facies architecture of overbank deposits of the Mississippi River, False River region, Louisiana. In *Recent Developments in Fluvial Sedimentology*. Etheridge FG, Flores RM, Harvey MD (eds.) Special Publication of the Society for Economic Palaentology and Minerology, Vol 39:111-121.

Fisk HN. 1944. *Geological investigation of the alluvial valley of the lower Mississippi River*: US Army Corps of Engineers. Mississippi River Commission ;78.

Fryirs KA. 2015. Developing and using geomorphic condition assessments for river rehabilitation planning, implementation and monitoring. *Wiley Interdisciplinary Reviews: Water* **2(6)**:649-67. https://doi.org/10.1002/wat2.1100

Fryirs KA. 2017. River sensitivity: A lost foundation concept in fluvial geomorphology. *Earth Surface Processes and Landforms* **42(1)**:55-70. https://doi.org/10.1002/esp.3940

Fryirs KA, Brierley GJ. 2005. *Practical Applications of the River Styles Framework as a Tool for Catchment-wide River Management: A Case Study from Bega Catchment, NSW, Australia.* Macquarie University, Sydney.

Fryirs K, Brierley GJ. 2009. Naturalness and place in river rehabilitation. *Ecology and Society* **14(1)**:20 http://www.ecologyandsociety.org/vol14/iss1/art20/

Fryirs KA, Brierley GJ. 2013. *Geomorphic Analysis of River Systems: An approach to Reading the Landscape*. John Wiley and Sons, Chichester; 345pp.

Fryirs KA, Brierley GJ. 2016. Assessing the geomorphic recovery potential of rivers: forecasting future trajectories of adjustment for use in management. *Wiley Interdisciplinary Reviews: Water* **3(5)**:727-48. https://doi.org/10.1002/wat2.1158

Fryirs KA, Brierley GJ. 2018. What's in a name? A naming convention for geomorphic river types using the River Styles Framework. *PloSOne* **13(9)**:e0201909. https://doi.org/10.1371/journal.pone.0201909

Fryirs K, Brierley GJ, Erskine WD. 2012. Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. *Earth Surface Processes and Landforms* **37(7)**:763-73. https://doi.org/10.1002/esp.3210

Fryirs KA, Brierley GJ, Hancock F, Cohen TJ, Brooks AP, Reinfelds I, Cook N, Raine A. 2018b. Tracking geomorphic recovery in process-based river management. *Land Degradation and Development* **29(9)**:3221-44. https://doi.org/10.1002/ldr.2984

Fryirs K, Brierley G, Marçal M, Peixoto MN, Lima R. 2019. Learning, Doing and Professional Development – The River Styles Framework as a tool to support the development of coherent and strategic approaches for land and water management in Brazil. *Revista Brasileira de Geomorfologia* **20(4)**:773-794. http://dx.doi.org/10.20502/rbg.v20i4.1560

Fryirs K, Hancock F, Healey M, Mould S, Dobbs L, Riches M, Raine A, 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. *PloSOne* **16(1)**:e0244719. https://doi.org/10.1371/journal.pone.0244719

Fryirs KA, Ralph TJ, Larkin ZT, Tooth S, Humphries M, McCarthy T, Hesse PP, Mosimanyana E. 2018a. A nested hierarchical perspective to enhance interpretations and communication in fluvial geomorphology for use in water resources management: Lessons from the Okavango Delta, Botswana. *The Geographical Journal* **184(2)**:192-207. https://doi.org/10.1111/geoj.12250

Fryirs K, Spink A, Brierley G. 2009. Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. *Earth Surface Processes and Landforms* **34(7)**:897-918. https://doi.org/10.1002/esp.1771

Fryirs KA, Wheaton JM, Brierley GJ. 2016. An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. *Earth Surface Processes and Landforms* **41(5)**:701-10. https://doi.org/10.1002/esp.3893

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 Interdisciplinary Reviews: Water* **6(5)**:e1372. https://doi.org/10.1002/wat2.1372

Gregory KJ, Lewin J. 2014. *The Basics of Geomorphology: Key Concepts*. Sage, London, UK. 225pp.

Gregory KJ. 1978. Fluvial processes in British basins: The impact of hydrology and the prospect for hydrogeomorphology In *Geomorphology: present problems and future prospects*. Embleton C, Brunsden D, Jones DKC (eds.) Oxford University Press, Oxford; 40-72.

Gregory KJ. 1979. Hydrogeomorphology: how applied should we become?.*Progress in Physical Geography* **3(1)**:84-101. https://doi.org/10.1177/030913337900300103

Gregory KJ. 2004. Human activity transforming and designing river landscapes: a review perspective. *Geographica Polonica* **77**:5-20.

Gregory KJ. 2006. The human role in changing river channels. *Geomorphology* **79(3-4)**:172-91. https://doi.org/10.1016/j.geomorph.2006.06.018

Gregory KJ, Lewin J. 2014. *The Basics of Geomorphology: Key Concepts*. Sage, London, UK. 225pp.

Gurnell A. 2014. Plants as river system engineers. *Earth Surface Processes and Landforms* **39(1)**:4-25. https://doi.org/10.1002/esp.3397

Gurnell AM, Angold P, Gregory KJ. 1994. Classification of river corridors: issues to be addressed in developing an operational methodology. *Aquatic Conservation: Marine and Freshwater Ecosystems* **4(3)**:219-31. https://doi.org/10.1002/aqc.3270040304

Gurnell AM, Piégay H, Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. *Freshwater Biology* **47(4)**:601-619. https://doi.org/10.1046/j.1365-2427.2002.00916.x

Gurnell AM, Corenblit D, García de Jalón D, González del Tánago M, Grabowski RC, O'hare MT, Szewczyk M. 2016b. A conceptual model of vegetation–hydrogeomorphology interactions within river corridors. *River Research and Applications* **32(2)**:142-63. https://doi.org/10.1002/rra.2928

Gurnell AM, Rinaldi M, Belletti B, Bizzi S, Blamauer B, Braca G, Buijse AD, Bussettini M, Camenen B, Comiti F, Demarchi L. 2016a. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. *Aquatic Sciences* **78(1)**:1-6. https://doi.org/10.1007/s00027-015-0424-5

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 Research and Applications* **36(8)**:1559-1578. https://doi.org/10.1002/rra.3673

Han M, Brierley G. 2021. Assessment of the geo-eco-hydrological condition of anabranching reaches in the Source Zone of the Yellow River, western China. *River Research and Applications* https://doi.org/10.1002/rra.3786

Hawkins CP, Kershner JL, Bisson PA, Bryant MD, Decker LM, Gregory SV, McCullough DA, Overton CK, Reeves GH, Steedman RJ, Young MK. 1993. A hierarchical approach to classifying stream habitat features. *Fisheries* **18(6)**:3-12. https://doi.org/10.1577/1548-8446(1993)018<0003:AHATCS>2.0.CO;2

Hickin EJ. 1983. River channel changes: Retrospect and prospect. *International Association of Sedimentologists Special Publication* **6**, 61-83. https://doi.org/10.1002/9781444303773.ch5

Jackson RG. 1976. Depositional model of point bars in the lower Wabash River. *Journal of Sedimentary Research* **46(3)**:579-94. https://doi.org/10.1306/212F6FF5-2B24-11D7-8648000102C1865D

Jain V, Fryirs K, Brierley G. 2008. Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. *Geological Society of America Bulletin* **120(1-2)**:127-41. https://doi.org/10.1130/B26092.1

Jasiewicz J, Stepinski TF. 2013. Geomorphons—a pattern recognition approach to classification and mapping of landforms. *Geomorphology* **182**:147-156. https://doi.org/10.1016/j.geomorph.2012.11.005

Kellerhals R, Church M, Bray DI. 1976. Classification and analysis of river processes. *Journal of the Hydraulics Division* **102(7)**:813-29. https://doi.org/10.1061/JYCEAJ.0004583

Kennelly PJ, Patterson T, Jenny B, Huffman DP, Marston BE, Bell S, Tait AM. 2021. Elevation models for reproducible evaluation of terrain representation. *Cartography and Geographic Information Science* **48(1)**:63-77. https://doi.org/10.1080/15230406.2020.1830856

Khan S, Fryirs KA, Ralph TJ. 2021a. Geomorphic controls on the diversity and patterns of fluvial forms along longitudinal profiles. *Catena* **203**:105329. https://doi.org/10.1016/j.catena.2021.105329

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 Surface Processes and Landforms*, https://doi.org/10.1002/esp.5213

Knighton AD. 1998. *Fluvial Forms and Processes: A New Perspective*. Arnold, London. 383pp.

Knighton DA, Nanson GC. 1993. Anastomosis and the continuum of channel pattern. *Earth Surface Processes and Landforms* **18(7)**:613-25. https://doi.org/10.1002/esp.3290180705

Lane SN, Richards KS. 1997. Linking river channel form and process: time, space and causality revisited. *Earth Surface Processes and Landforms* **22(3)**:249-60. https://doi.org/10.1002/(SICI)1096-9837(199703)22:3<249::AID-ESP752>3.0.CO;2-7

Lane SN. 2013. 21st century climate change: where has all the geomorphology gone? *Earth Surface Processes and Landforms* **38(1)**:106-110. https://doi.org/10.1002/esp.3362

Larkin ZT, Ralph TJ, Tooth S, Fryirs KA, Carthey AJR. 2020. Identifying threshold responses of Australian dryland rivers to future hydroclimatic change. *Scientific Reports* **10(1)**:1-15. https://doi.org/10.1038/s41598-020-63622-3

Lave R. 2009. The controversy over natural channel design: substantive explanations and potential avenues for resolution. *Journal of the American Water Resources Association* ***45*****(6)**:1519-1532. https://doi.org/10.1111/j.1752-1688.2009.00385.x

Lisle T. 1979. A sorting mechanism for a riffle-pool sequence. *Geological Society of America Bulletin* **90(7_Part_II)**:1142-57. https://doi.org/10.1130/GSAB-P2-90-1142

MacMillan RA, Pettapiece WW, Nolan SC, Goddard TW. 2000. A generic procedure for automatically segmenting landforms into landform elements using DEMs, heuristic rules and fuzzy logic. *Fuzzy Sets and Systems* **113(1)**:81-109. https://doi.org/10.1016/S0165-0114(99)00014-7

Malanson GP. 1993. *Riparian Landscapes*. Cambridge University Press, Cambridge, UK. 296pp.

Mark DM, Smith B. 2004. A science of topography: From qualitative ontology to digital representations. In Bishop M, Schroder, JF. (Eds). *Geographic Information Science and Mountain Geomorphology*, Springer, Chichester, pp.75-100.

Miall AD. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews* **22(4):**261-308. https://doi.org/10.1016/0012-8252(85)90001-7

Minár J, Evans IS. 2008. Elementary forms for land surface segmentation: The theoretical basis of terrain analysis and geomorphological mapping. *Geomorphology* **95(3-4):**236-259. https://doi.org/10.1016/j.geomorph.2007.06.003

Minár J, Evans IS, Jenčo M. 2020. A comprehensive system of definitions of land surface (topographic) curvatures, with implications for their application in geoscience modelling and prediction. *Earth-Science Reviews:* 103414. https://doi.org/10.1016/j.earscirev.2020.103414

Montgomery DR, Abbe TB, Buffington JM, Peterson NP, Schmidt KM, Stock JD. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature* **381(6583)**:587-9. https://doi.org/10.1038/381587a0

Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* **109(5)**:596-611. https://doi.org/10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2

Montgomery DR, MacDonald LH. 2002. Diagnostic approach to stream cahnnel assessment and monitoring 1. *Journal of the American Water Resources Association* **38(1)**:1-6. https://doi.org/10.1111/j.1752-1688.2002.tb01530.x

Mueller ER, Pitlick J. 2013. Sediment supply and channel morphology in mountain river systems: 1. Relative importance of lithology, topography, and climate. *Journal of Geophysical Research: Earth Surface* **118(4)**:2325-42. https://doi.org/10.1002/2013JF002843

Mueller ER, Pitlick J. 2014. Sediment supply and channel morphology in mountain river systems: 2. Single thread to braided transitions. *Journal of Geophysical Research: Earth Surface* **119(7)**:1516-41. https://doi.org/10.1002/2013JF003045

Nanson GC. 1986. Episodes of vertical accretion and catastrophic stripping: A model of disequilibrium flood-plain development. *Geological Society of America Bulletin* **97(12)**:1467-75. https://doi.org/10.1130/0016-7606(1986)97<1467:EOVAAC>2.0.CO;2

Nanson GC, Croke JC. 1992. A genetic classification of floodplains. *Geomorphology* **4(6)**:459-86. https://doi.org/10.1016/0169-555X(92)90039-Q

Newson MD, Newson CL. 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography* **24(2)**:195-217. https://doi.org/10.1177/030913330002400203

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. *Journal of Maps* **13(2)**:369-81. https://doi.org/10.1080/17445647.2017.1313787

O'Brien GR, Wheaton JM, Fryirs K, Macfarlane WW, Brierley G, Whitehead K, Gilbert J, Volk C. 2019. Mapping valley bottom confinement at the network scale. *Earth Surface Processes and Landforms*. 2019 Jul;44(9):1828-45. https://doi.org/10.1002/esp.4615

Oguchi T, Yuichi SH, Wasklewicz T. 2011. Data sources. *Developments in Earth Surface Processes* **15**: 189-224. https://doi.org/10.1016/B978-0-444-53446-0.00007-0

Phillips JD. 2001. Human impacts on the environment: unpredictability and the primacy of place. *Physical Geography* **22(4)**:321-32. https://doi.org/10.1080/02723646.2001.10642746

Passalacqua P, Tarolli P, Foufoula-Georgiou E. 2010. Testing space-scale methodologies for automatic geomorphic feature extraction from lidar in a complex mountainous landscape. *Water Resources Research* **46(11)**:W11535 https://doi.org/10.1029/2009WR008812

Phillips JD. 2007. The perfect landscape. *Geomorphology* **84(3-4)**, 159-169. https://doi.org/10.1016/j.geomorph.2006.01.039

Phillips JD. 2017. Geomorphic and hydraulic unit richness and complexity in a coastal plain river. *Earth Surface Processes and Landforms* **42(15)**:2623-39. https://doi.org/10.1002/esp.4211

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 Surface Processes and Landforms* **45(1)**:157-88. https://doi.org/10.1002/esp.4787

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. *BioScience* **47(11)**:769-84. https://doi.org/10.2307/1313099

Pringle CM, Naiman RJ, Bretschko G, Karr JR, Oswood MW, Webster JR, Welcomme RL, Winterbourn MJ. 1988. Patch dynamics in lotic systems: the stream as a mosaic. *Journal of the North American Benthological Society* **7(4)**:503-524.

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. https://doi.org/10.1038/s41586-019-0912-1

Rhoads BL. 2006. The dynamic basis of geomorphology reenvisioned. *Annals of the Association of American Geographers* **96(1)**:14-30. https://doi.org/10.1111/j.1467-8306.2006.00496.x

Rinaldi M, Belletti B, Bussettini M, Comiti F, Golfieri B, Lastoria B, Marchese E, Nardi L, Surian N. 2017. New tools for the hydromorphological assessment and monitoring of European streams. *Journal of Environmental Management* **202**:363-78. https://doi.org/10.1016/j.jenvman.2016.11.036

Roering JJ, Mackey BH, Marshall JA, Sweeney KE, Deligne NI, Booth AM, Handwerger AL, Cerovski-Darriau C. 2013. 'You are HERE': Connecting the dots with airborne lidar for geomorphic fieldwork. *Geomorphology* **200**:172-183. https://doi.org/10.1016/j.geomorph.2013.04.009

Rosgen D. 1996. *Applied River Morphology*. Wildland Hydrology, Colorado. 843pp.

Schmidt J. Andrew R. 2005. Multi-scale landform characterization. *Area* **37(3)**:341-350. https://doi.org/10.1111/j.1475-4762.2005.00638.x

Schumm SA. 1977. *The Fluvial System*. The Blackburn Press, New Jersey, USA. 338pp.

Schumm SA. 1985. Patterns of alluvial rivers. *Annual Review of Earth and Planetary Sciences* **13(1)**:5-27.

Sholtes JS, Yochum SE, Scott JA, Bledsoe BP. 2018. Longitudinal variability of geomorphic response to floods. *Earth Surface Processes and Landforms* **43(15)**:3099-113. https://doi.org/10.1002/esp.4472

Simon A, Doyle MA, Kondolf MA, Shields Jr FD, Rhoads BR, 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 Journal of the American Water Resources Association **43(5)**:1117-31. https://doi.org/10.1111/j.1752-1688.2007.00091.x

Smith ND. 1974. Sedimentology and bar formation in the upper Kicking Horse River, a braided outwash stream. *The Journal of Geology* **82(2)**:205-23. https://doi.org/10.1086/627959

Smith B, Mark DM. 2003. Do mountains exist? Towards an ontology of landforms. *Environment and Planning B: Planning and Design* **30(3)**:411-27. https://doi.org/10.1068/b12821

Tangi M, Bizzi S, Fryirs K, Castelletti A. subm. A dynamic, network scale sediment (dis)connectivity model to reconstruct historical sediment transfer and river reach sediment budgets. *Water Resources Research.*

Tarolli P. 2014. High-resolution topography for understanding Earth surface processes: Opportunities and challenges. *Geomorphology* **216**:295-312. https://doi.org/10.1016/j.geomorph.2014.03.008

Tarolli P, Sofia G. 2016. Human topographic signatures and derived geomorphic processes across landscapes. *Geomorphology* **255**:140-161. https://doi.org/10.1016/j.geomorph.2015.12.007

Trofimov AM, Phillips JD. 1992. Theoretical and methodological premises of geomorphological forecasting. *Geomorphology* **5(3-5)**:203-211. https://doi.org/10.1016/0169-555X(92)90003-7

van Niekerk AW, Heritage GL, Broadhurst LW, Moon BP. 1999. Bedrock anastomosing channel systems: Morphology and dynamics of the Sabie River, Mpumulanga Province, South Africa. In *Varieties of Fluvial Form*. Miller AJ, Gupta A (eds.) John Wiley and Sons, Chichester; 33-51.

Wiens JA, 2002. Riverine landscapes: taking landscape ecology into the water. *Freshwater Biology*, **47(4)**:501-515. https://doi.org/10.1046/j.1365-2427.2002.00887.x

Wheaton JM, Brasington J, Darby SE, Sear DA. 2010. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms* **35(2)**:136-56. https://doi.org/10.1002/esp.1886

Wheaton JM, Brasington J, Darby SE, Merz J, Pasternack GB, Sear D, Vericat D. 2010b. Linking geomorphic changes to salmonid habitat at a scale relevant to fish. *River Research and Applications* **26(4)**:469-86. https://doi.org/10.1002/rra.1305

Wheaton JM, Brasington J, Darby SE, Kasprak A, Sear D, Vericat D. 2013. Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. *Journal of Geophysical Research: Earth Surface* **118(2)**:759-779. https://doi.org/10.1002/jgrf.20060

Wheaton JM, Fryirs KA, Brierley G, Bangen SG, Bouwes N, O'Brien G. 2015. Geomorphic mapping and taxonomy of fluvial landforms. *Geomorphology* **248**:273-95. https://doi.org/10.1016/j.geomorph.2015.07.010

Wilcock PR, Iverson RM. (Eds.). 2003. *Prediction in Geomorphology*. Geophysical Monograph 135. American Geophysical Union. Washington DC. 256pp.

Williams RD, Bangen S, Gillies E, Kramer N, Moir H, Wheaton J. 2020. Let the river erode! Enabling lateral migration increases geomorphic unit diversity. *Science of the Total Environment* **715**:136817. https://doi.org/10.1016/j.scitotenv.2020.136817

Williams RT, Fryirs KA. 2020. The morphology and geomorphic evolution of a large chain-of-ponds river system. *Earth Surface Processes and Landforms* **45(8)**:1732-48. https://doi.org/10.1002/esp.4842

Wohl E, Kramer N, Ruiz-Villanueva V, Scott DN, Comiti F, Gurnell AM, Piegay H, Lininger KB, Jaeger KL, Walters DM, Fausch KD. 2019. The natural wood regime in rivers. *BioScience* **69(4):**259-273. https://doi.org/10.1093/biosci/biz013

Wyrick JR, Pasternack GB. 2014. Geospatial organization of fluvial landforms in a gravel–cobble river: Beyond the riffle–pool couplet. *Geomorphology* **213**:48-65. https://doi.org/10.1016/j.geomorph.2013.12.040

Wyrick JR, Senter AE, Pasternack GB. 2014. Revealing the natural complexity of fluvial morphology through 2D hydrodynamic delineation of river landforms. *Geomorphology* **210**:14-22. https://doi.org/10.1016/j.geomorph.2013.12.013

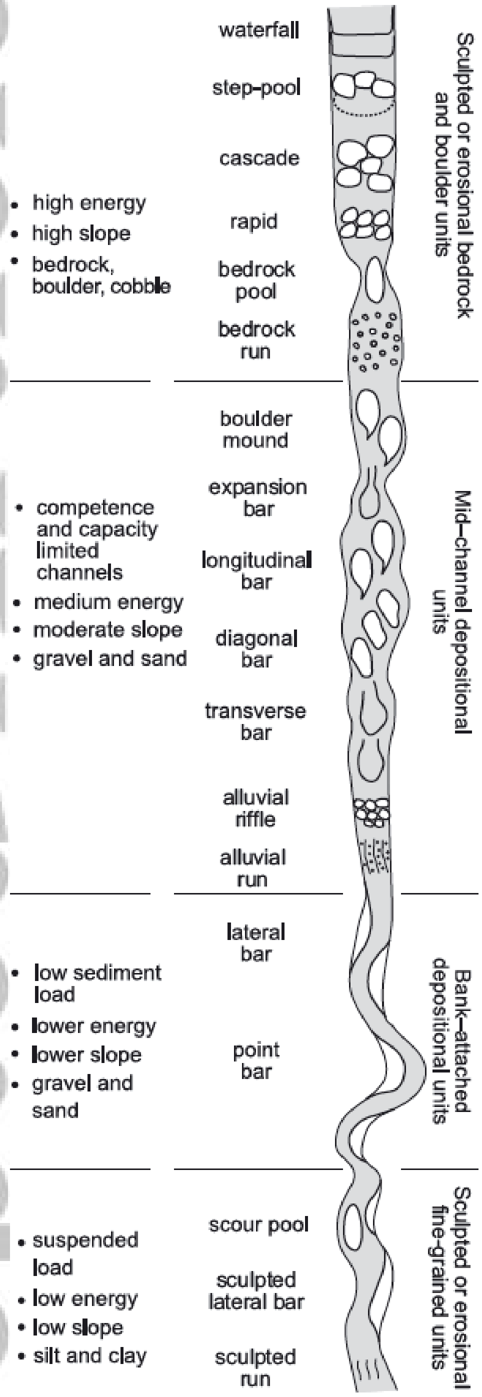
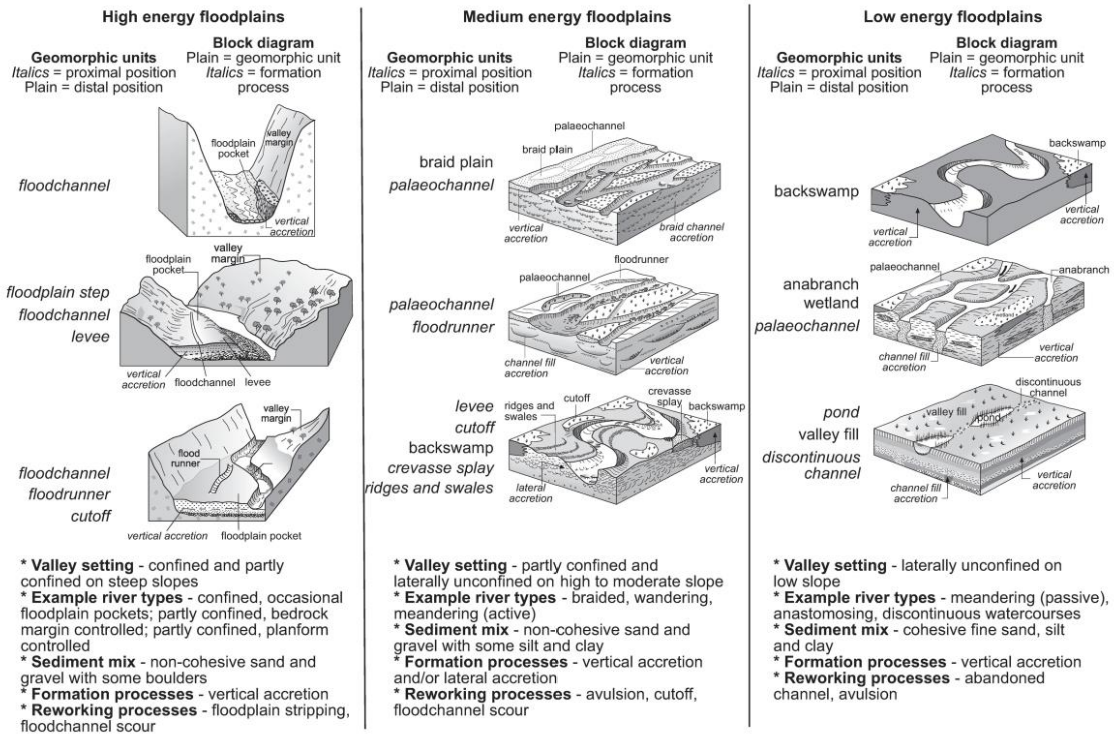


**Figure 1** The typical downstream continuum of instream geomorphic units. Modified from Fryirs and Brierley (2013).



* **Valley setting** - confined and partly confined on steep slopes
* **Example river types** - confined, occasional floodplain pockets; partly confined, bedrock margin controlled; partly confined, planform controlled
* **Sediment mix** - non-cohesive sand and gravel with some boulders
* **Formation processes** - vertical accretion
* **Reworking processes** - floodplain stripping, floodchannel scour

* **Valley setting** - partly confined and laterally unconfined on high to moderate slope
* **Example river types** - braided, wandering, meandering (active)
* **Sediment mix** - non-cohesive sand and gravel with some silt and clay
* **Formation processes** - vertical accretion and/or lateral accretion
* **Reworking processes** - avulsion, cutoff, floodchannel scour

* **Valley setting** - laterally unconfined on low slope
* **Example river types** - meandering (passive), anastomosing, discontinuous watercourses
* **Sediment mix** - cohesive fine sand, silt and clay
* **Formation processes** - vertical accretion
* **Reworking processes** - abandoned channel, avulsion

**Figure 2** A typical continuum of floodplain geomorphic units. Modified from diagrams in Fryirs and Brierley (2013), Brierley and Fryirs (2005) and Nanson and Croke (1992).

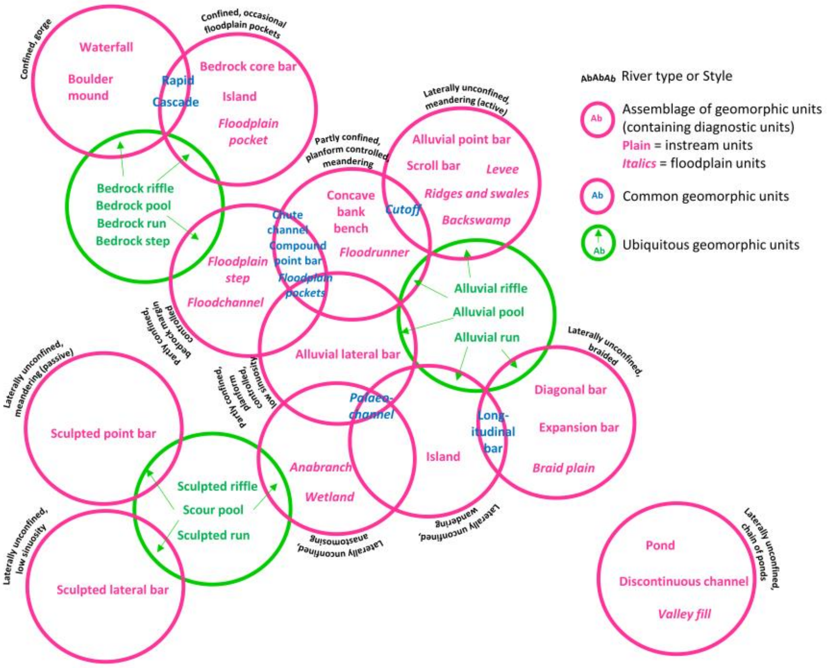


**Figure 3** Assemblages of geomorphic units for different river types or styles. Each river type contains a characteristic and expected assemblage of geomorphic units that contains diagnostic, common and ubiquitous units. Note that italicised names are floodplain geomorphic units and plain names are instream geomorphic units.

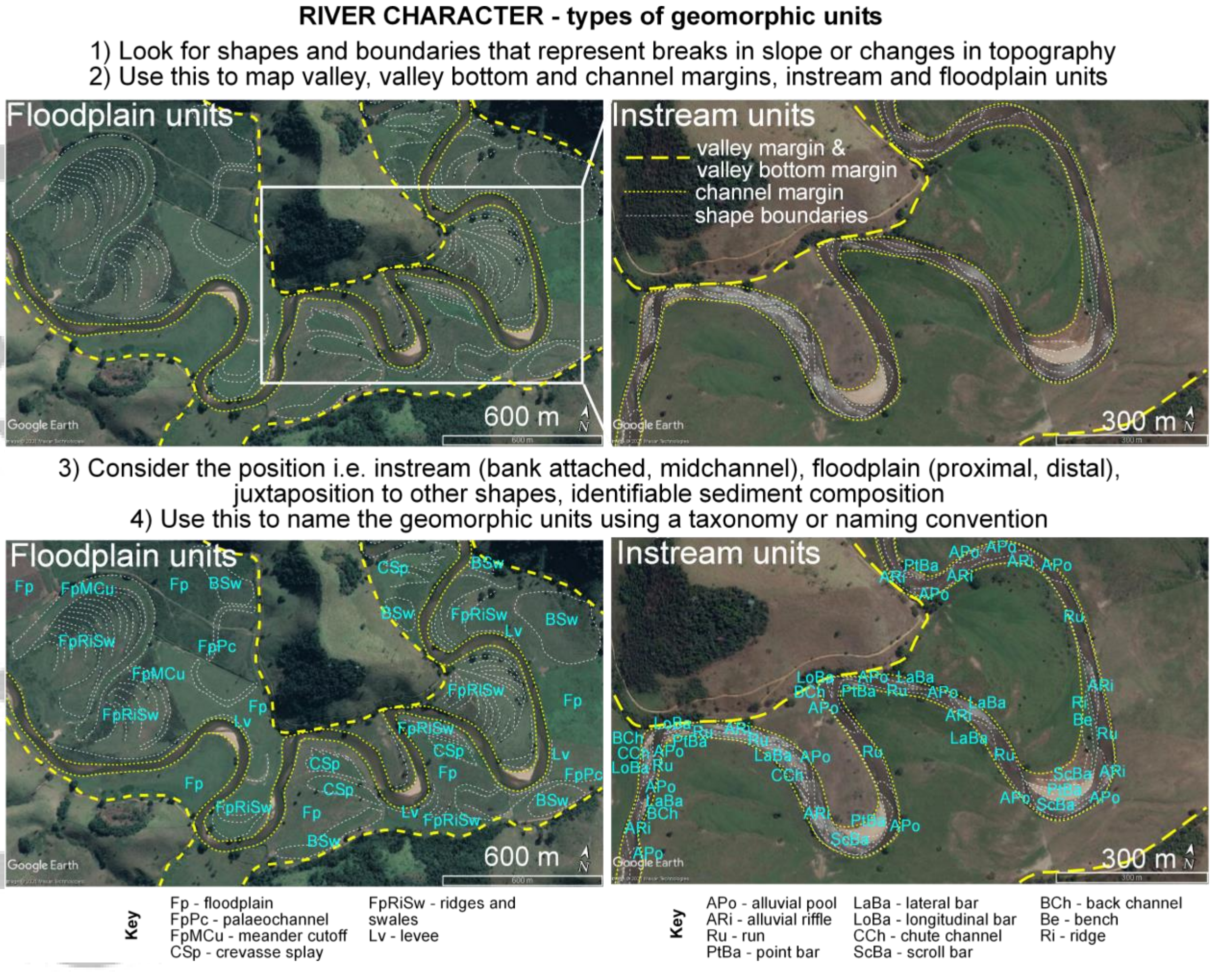


**Figure 4** Steps used to analyse river character using geomorphic units, for the instream and floodplain zones. The example is from the Macae River, Brazil documented in Brierley et al. (2019) and Fryirs et al. (2019). Base maps from Google Earth.

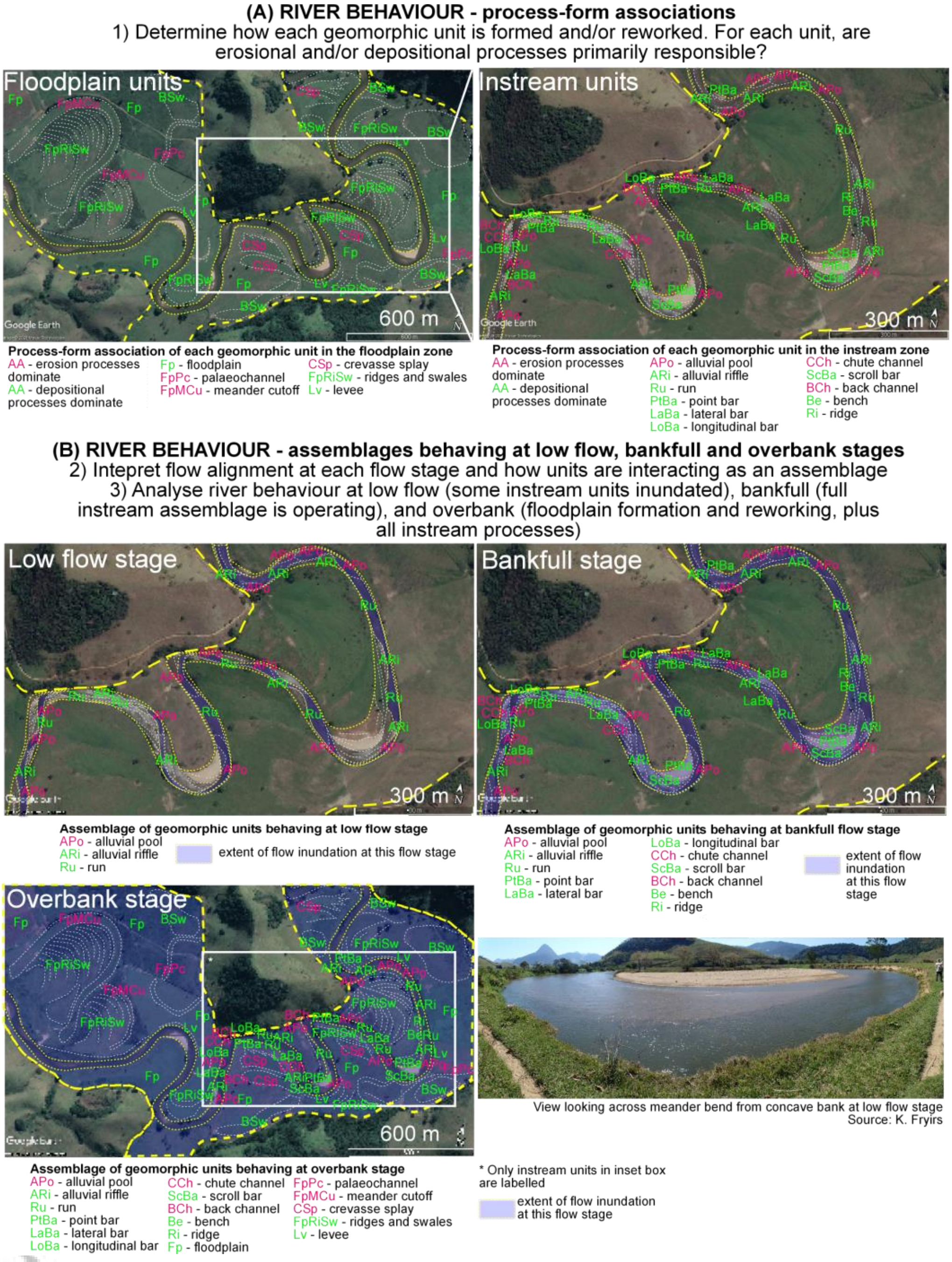


**Figure 5** Steps used to analyse river behaviour using geomorphic units, starting with (A) determination of process-form associations of geomorphic units and (B) interpretation of how assemblages of geomorphic units are formed and reworked at low flow, bankfull and overbank stage. The example is from the Macae River, Brazil documented in Brierley et al. (2019) and Fryirs et al. (2019). Base maps from Google Earth. Photograph from K. Fryirs.

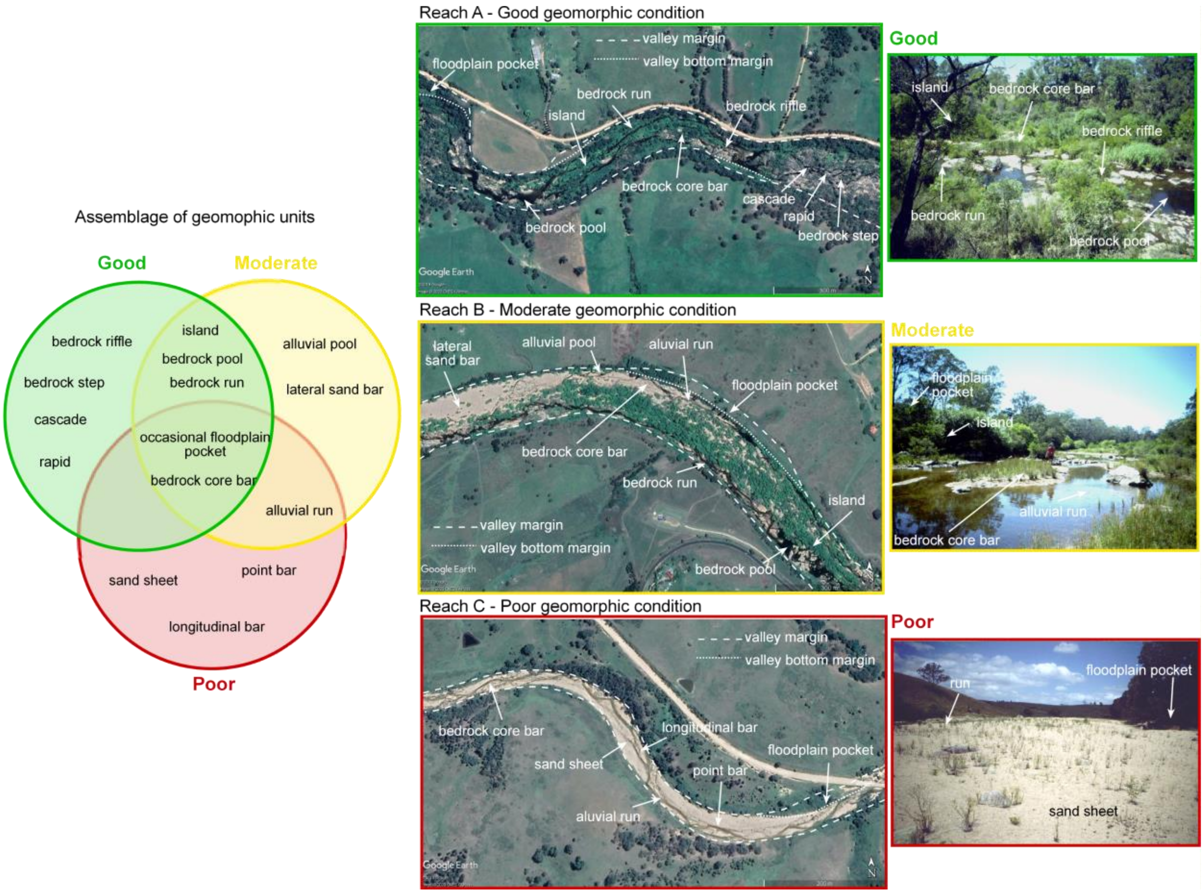


**Figure 6** Demonstration of how the assemblage of geomorphic units for an individual river type can be used to assess geomorphic river condition. This example is for a Confined, bedrock margin controlled, occasional floodplain pockets river type. Text in the three-way overlap zone of Venn diagram are the diagnostic units for this river type. Source of aerials: Google Earth. Source of photos: K. Fryirs.

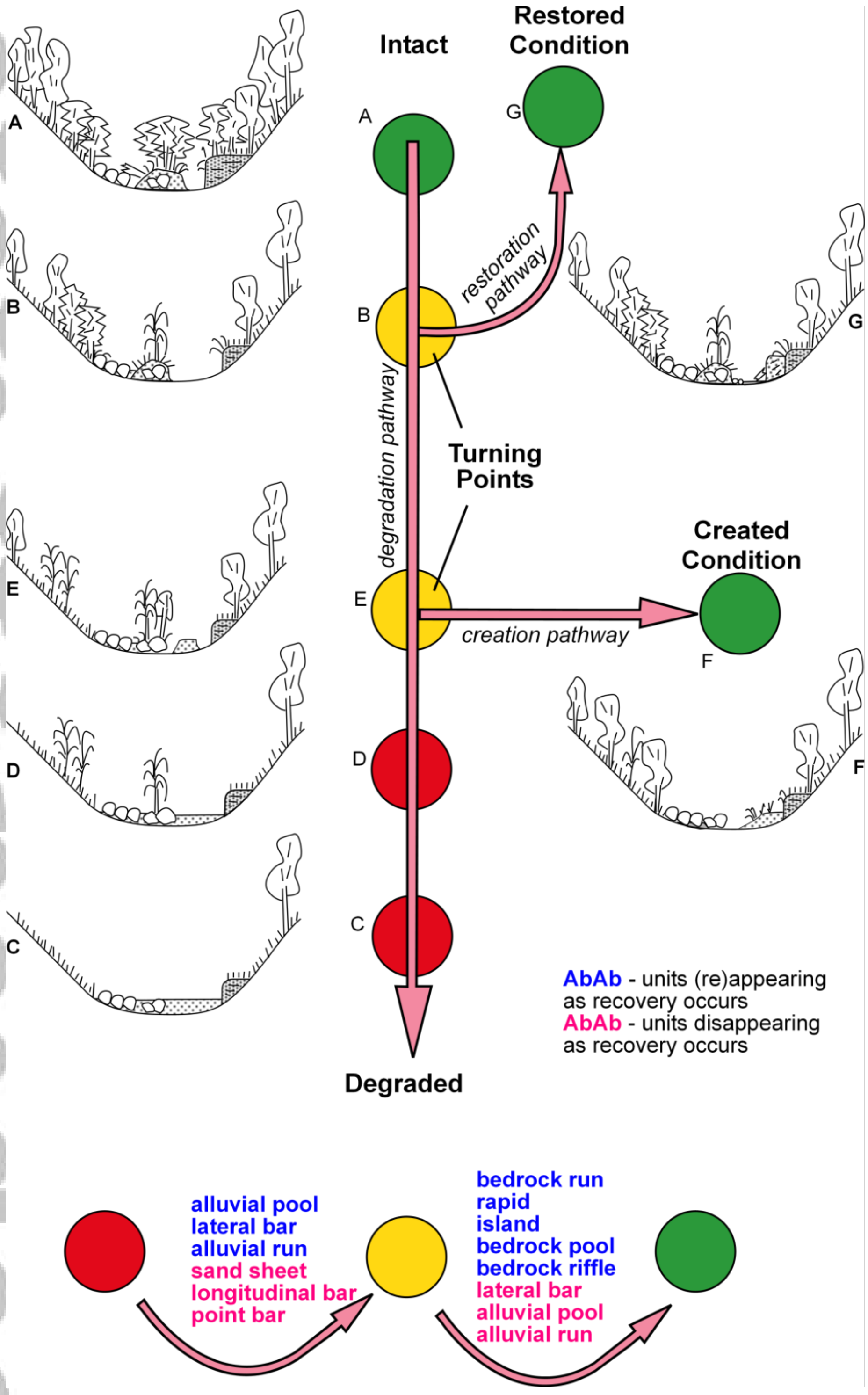


**Figure 7** Returning and disappearing geomorphic units for the confined, occasional floodplain pockets river type as recovery occurs and geomorphic condition improves (modified from Fryirs and Brierley, 2005). Green dots are reaches in good geomorphic condition, yellow are in moderate condition and red in poor geomorphic condition.

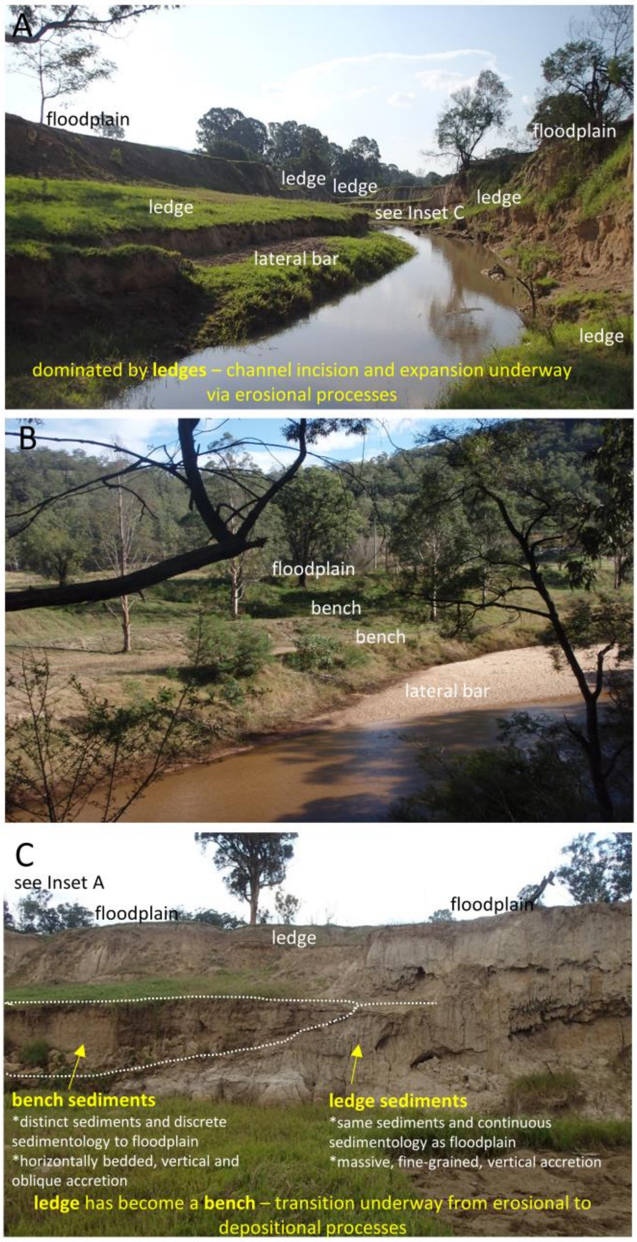


**Figure 8** Ledges and benches as geomorphic unit indicators of degradation and recovery and changing erosion-deposition dynamics. Source of photos: K. Fryirs. (A, C) Craven Creek NSW, (B) Macdonald River, NSW.

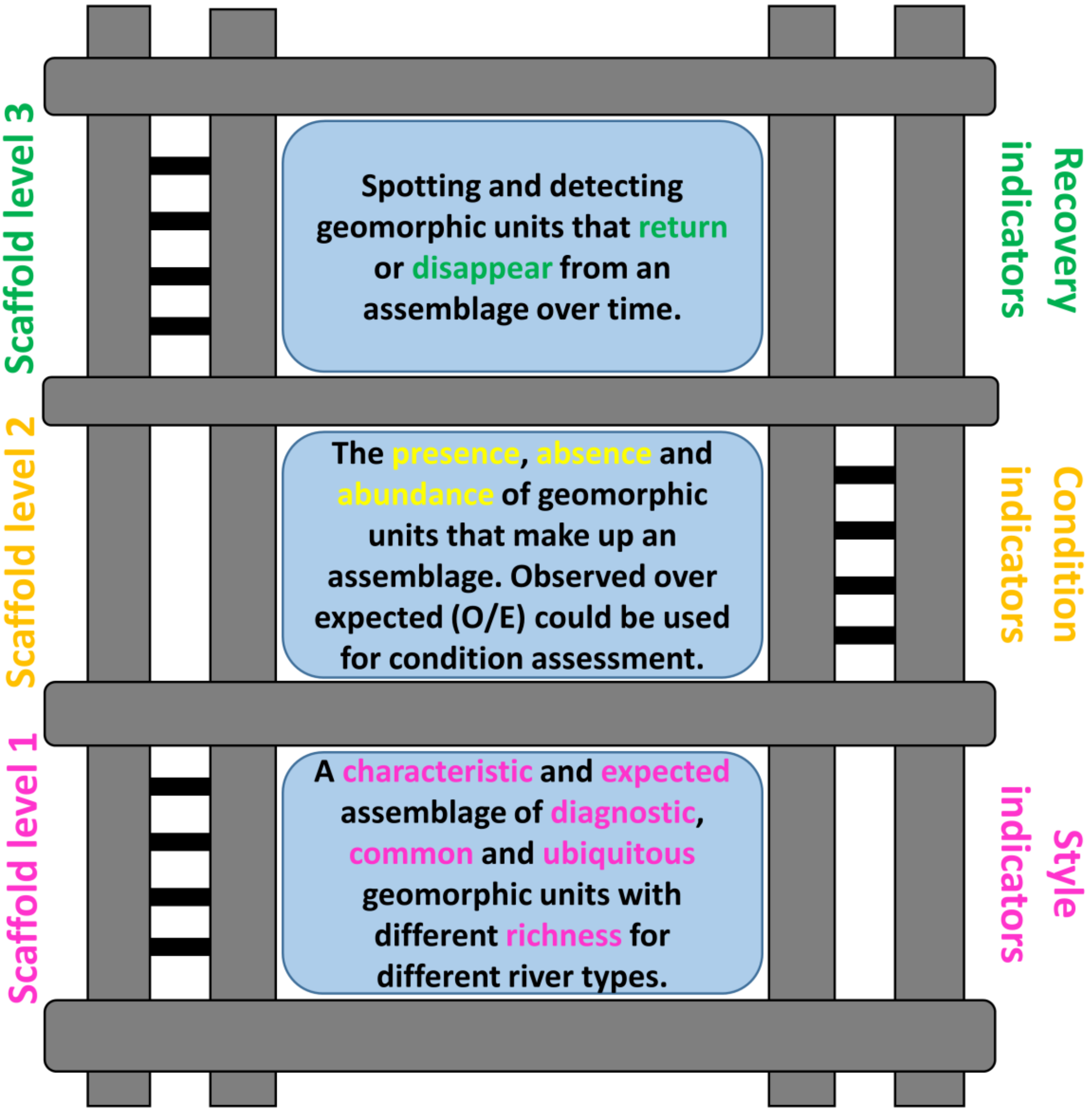


**Figure 9** A scaffolded approach to geomorphic assessment and interpretation of river style, condition and recovery based upon analysis of geomorphic units and their assemblages.

Graphical Abstract

# Assemblages of geomorphic units: A building block approach to analysis and interpretation of river character, behaviour, condition and recovery

Kirstie Fryirs[1]* and Gary Brierley[2]