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Letters to ESEX

An approach for measuring confinement and assessing the influence of valley setting on river forms and processes

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ABSTRACT: Valley setting and confinement (or lack thereof) are primary controls on river character and behaviour. Although there are various proxies for valley confinement, direct measures that quantify the nature and extent of confinement are generally lacking and/or inconsistently described. As such they do not lend themselves to consistent analysis over large spatial scales. Here we clearly define forms of confinement to aid in quantification of degrees of confinement. Types of margin that can induce confinement are differentiated as a valley margin, valley bottom margin, and/or anthropogenic margin. Such margins sometimes overlap and share the same location, and in other situations are separated, giving immediate clues as to the valley setting. We apply this framework to examples from Australia, United States and New Zealand, showing how this framework can be applied across the spectrum of river diversity. This method can help to inform interpretations of reach-scale river behaviour, highlighting the role of antecedent controls on contemporary forms and processes. Clear definitions of confinement are shown to support catchment-scale analysis of river patterns along longitudinal profiles, and appraisals of the geomorphic effectiveness of floods and sediment flux in catchments (e.g. process zone distribution, lateral sediment inputs and (dis)connectivity). Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: valley confinement; fluvial corridor; river planform; antecedence; river structure and function

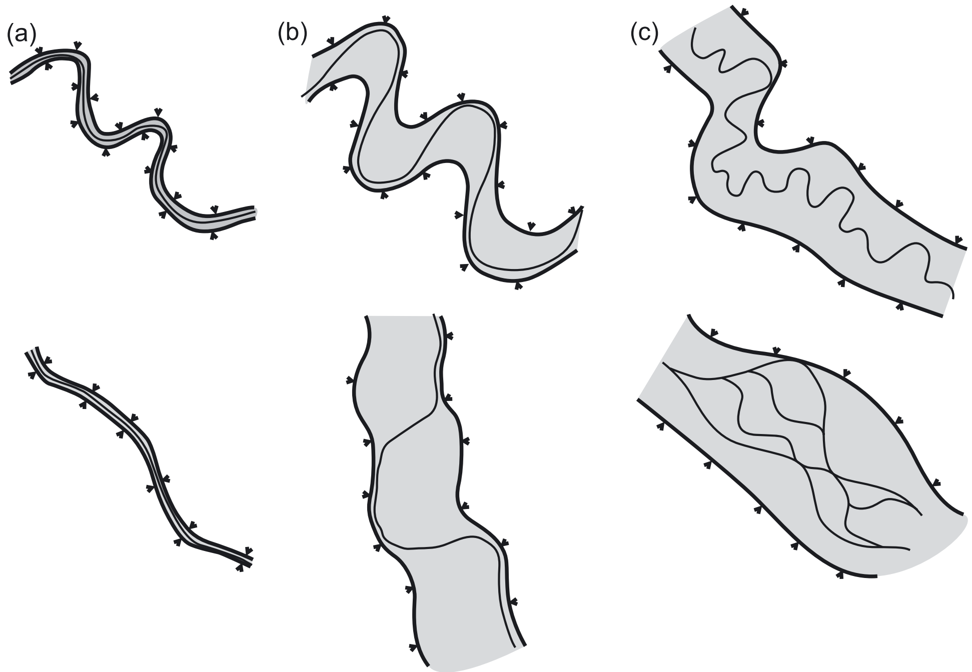
Introduction

Along with gradient, discharge and sediment regime, valley confinement is a primary control on river morphology. Definitions of valley setting are typically based on the distribution of genetic floodplain along river courses, defined by Nanson and Croke (1992) as the largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, built of sediment transported by the present flow-regime, and reformed by contemporary processes. Kellerhals and Church (1989), Rosgen (1994, 1996) and Polvi *et al.* (2011) use the entrenchment ratio, defined as the ratio of flood prone width (i.e. width of the valley over the genetic floodplain) to bankfull channel width as a measure of flow confinement. In application of the Rosgen (1994, 1996) channel classification framework, the flood-prone width is approximated as the width measured at an elevation that is twice the maximum depth of the bankfull channel. However, these are not direct measures of valley confinement. Alternatively, Lewin and Brindle (1977) use degrees of confinement to describe the extent to which bedrock influences valley confinement, but this approach is not quantified. Also, Schumm (1985), Brierley and Fryirs (2005) and Fryirs and Brierley (2013) use the position of the channel on the valley floor to define ranges of confinement that can be used to differentiate valley settings (Figure 1). Very few of these schemes work across the range of river diversity, or consider the relative role of bedrock versus other confining features (e.g. ancient alluvium, or anthropogenic features) in differentiating between river types (Fotherby, 2009; Fryirs and Brierley, 2010). The lack of a consistent and conceptually sound approach for the analysis of valley confinement limits our capacity to interpret the impact it has on reach-scale river behaviour and catchment-scale patterns of river types.

Previous authors have used quantitative measures as proxies for valley setting (e.g. Johansen *et al.*, 2013; Beechie and Imaki, 2014). However, these approaches do not adequately discriminate between situations in which the active channel is in contact with potential confining margins, and the type of confining margin the channel abuts against. The increasing availability of high resolution digital elevation models (DEMs) presents an opportunity for systematic analyses of these relationships (e.g. Leviandier *et al.*, 2012; Parker *et al.*, 2012; Roux *et al.*, 2015). However, before automated procedures become firmly embedded in the literature, it is important to give careful consideration to the conceptual framework within which forms of confinement are defined and assessed. This communication outlines a systematic approach to conceptualise and quantify valley confinement.

Accurate measurements of valley confinement can be used to interpret both the contemporary range of river processes that occur on valley floors and the extent to which antecedent controls exert an influence on contemporary character and behaviour (Sidorchuk, 2003; Phillips, 2008; Brierley, 2010). Differences in valley confinement exert significant influence on the capacity for channel adjustment, whether vertically, laterally or wholesale; i.e. its degrees of freedom and sensitivity (Brierley and Fryirs, 2005). Different types of rivers in contrasting valley settings have different (in)abilities to adjust their channel morphology, planform and assemblage of geomorphic units (Hey, 1982; Montgomery, 1999; Brierley and Fryirs, 2005; Fotherby, 2009).

Bedrock rivers tend to occur in the incisional, degrading parts of landscapes, typically characterised by long-term sediment source or transfer zones. Structural and lithological controls are ubiquitous and valley confinement and shape produce an imposed array of forced channel morphologies (e.g. Baker and Pickup, 1987; Wohl, 1992; Montgomery and Buffington, 1998). Bedrock rivers lack a continuous alluvial bed and are confined by valley walls. Hence, bedrock exerts vertical and/or lateral constraints on river forms and processes. Unlike fully alluvial rivers, channel morphology of bedrock rivers reflects interactions between erosive processes and the resistance of the confining substrate (Wohl, 1998). Montgomery and Buffington (1998) differentiated amongst colluvial valleys with no fluvial channel, bedrock valleys (confined per Figure 1), and alluvial valleys that transport and sort sediment loads supplied from upslope but lack the transport capacity to routinely



Lewin & Brindle (1977)	third degree confinement	second degree confinement	first degree confinement
Kellerhals & Church (1989)	entrenched	–	alluvial
Schumm (1985)	confined	semi- controlled	alluvial
Rosgen (1994, 1996)	entrenched	moderately entrenched	alluvial
Brierley and Fryirs (2005) Fryirs and Brierley (2013)	confined	partly - confined	laterally - unconfined

Figure 1. Various definitions of valley confinement. Modified from Brierley and Fryirs (2005).

scour the valley to bedrock. Brierley and Fryirs (2005), among others, further differentiate these alluvial valleys into partly confined and laterally unconfined valley settings.

Rivers with discontinuous pockets of genetic floodplain are base-level confined such that bedrock is a key determinant on bed morphology. Lateral confinement determines the potential for floodplain pockets to form. In the River Styles framework, these are termed partly confined valleys (Brierley and Fryirs, 2005; Fryirs and Brierley, 2010). Differentiation of river types in these settings reflects the position of the channel relative to the valley margin, indicating how often and over what length of river course the channel impinges on that margin. In some settings, for example, rivers are confined by terraces and/or bedrock, limiting available space in which discontinuous pockets of genetic floodplain may form (Jain *et al*., 2006, 2008).

Alluvial rivers, by definition, have erodible beds and banks and are therefore not significantly influenced by valley confinement controls (Leopold *et al*., 1964; Eaton *et al*., 2010). Given the lack of confining media, a wide range of variability in river forms and processes may be evident. Despite their abundance and research efforts to appraise alluvial rivers and their process-form associations, the importance of confinement is underlined by the fact that there are many landscapes in which fully self-adjusting rivers make up only a small proportion of the total length of river courses.

Other than fully self-adjusting alluvial rivers, most rivers flow in valleys in which bedrock or other confining medium exerts some degree of lateral control on river character and behaviour (Fryirs and Brierley, 2010). Despite the pervasive influence of confining features on contemporary river forms and processes, there are no clearly defined conceptual approaches that can be used to quantify and systematically measure forms and extent of lateral confinement along river systems. This communication addresses this shortcoming.

The purpose of this communication is to provide clearer definitions of different types of confinement and present a tractable method with which investigators can calculate and apply these definitions across drainage networks and the spectrum of river diversity. Specifically, we define various forms of confinement, provide a systematic and consistent approach to identify, analyse and measure confinement, and illustrate the application of the proposed framework using examples from the Hunter catchment [New South Wales (NSW), Australia], various basins in the United States, and basins on the North Island, New Zealand.

Defining and Measuring Confinement Types

To calculate the degree of lateral confinement requires clear definitions of confinement and margins. We define confinement as the percentage of the length of a stream or river channel segment that abuts a confining margin on either bank. It is important to note that under this definition a channel is considered confined when one side of the channel abuts against a confining margin. The channel does not need to be confined along both banks (i.e. constricted) to be considered confined. This is critically important because the verb confine refers to 'restricting' or 'limiting' (in this case restricting the lateral adjustment of a channel). By contrast, to constrict refers to 'making narrower' and implies a measure that would be based on 'confinement' on both sides. We will return to the issue of constriction later. There are two practical upshots to promoting a confinement definition above constriction. The first is that in terms of percentages of streams and rivers making up a drainage network, the degree of confinement is a useful discriminating metric for the vast majority of the network. By contrast, constriction is only useful for discriminating the much smaller percentage of rivers that experience a high degree of confinement. The second practical advantage is that a confinement metric does not require a measure of channel width or valley width. While both are relatively straight-forward to measure at a particular transect of interest, estimating channel width and valley width is more difficult to measure accurately across an entire drainage network (especially from something like aerial imagery or a 10 m DEM). Moreover, the commonly used ratios of valley width to channel width can frequently fail to discriminate the situations in which the valley margin is actually restricting lateral movement of a channel.

We further differentiate confinement by adding an adjective before confinement, which refers to the type of margin that generates the confinement (defined later). Wheaton *et al*. (2015) defined various fluvial margins as borders or edges between distinct regions. In this context, several types of margin may impose important controls on river behaviour through confinement (Table I). The margins defined in Table I can, and frequently do, overlap in space. The extent of overlap defines both the valley setting and confinement context.

We define a confining margin as any section of channel bank (either bank) that abuts against a valley margin, valley bottom margin or anthropogenic margin (see Figure 2 and later). At the time of mapping, the margin constrains or retards a channel from adjusting laterally. For multi-threaded channels, if confining margins are present they will generally be found along the most laterally peripheral channels.

We define valley margins as the margin between a bedrock hillslope and the predominantly 'alluvial' sediment stores that make up the valley floor (see Figure 2). The valley margins themselves are a primary form of confinement. Valley margin confinement (C_V) is calculated as:

$$C_V = \left(\sum_{DS}^{US} CL_{EB}@H_S \Big/ CL_T \right) \times 100 \qquad (1)$$

Where C_V is the valley margin confinement; $CL_{EB}@H_S$ is the length of channel along either bank that abuts along a valley margin; CL_T is the total length of channel.

Most rivers flow between valley margins that are made up of some mix of active floodplains, inactive floodplains (i.e. terraces) and fans (both alluvial and colluvial), and occasionally other forms of alluvial or colluvial deposit. Therefore, the valley bottom comprises both the active channel and contemporary (or genetic) floodplain. The valley bottom margin can abut against the valley margin (as mentioned earlier) or other confining features such as terraces, fans, moraines and piedmonts (Figure 2). It is on the valley bottom that the contemporary river system is operating and for which contemporary river behaviour is interpreted, i.e. it is the 'effective valley width' (see Fryirs and Brierley, 2010). In some cases, the valley bottom margin is coincident with the valley margin and the valley margin sets the primary form of confinement. However, if fans, terraces and other non-valley bottom features are present in the valley, these features make up a valley bottom margin that differs from the valley margin and can provide a secondary form of confinement. Valley bottom confinement is calculated as:

$$C_{VB} = \left(\sum_{DS}^{US} CL_{EB}@C_M \Big/ CL_T \right) \times 100 \qquad (2)$$

Where C_{VB} is the valley bottom confinement; $CL_{EB}@C_M$ is the length of channel along either bank that abuts a confining margin.

If both valley margin confinement (C_V) and valley bottom confinement (C_{VB}) are known, the comparison of the two values

Table I. Examples of fluvial margins (see also Wheaton *et al.*, 2015)

Type of margin	Definition and identification
Confining margin (C_M)	Any section of channel margin (either side) that abuts against a valley margin or valley bottom margin (for natural settings) and/or anthropogenic margins (for human-impacted settings). The confining margin is not defined by what provides the confinement (e.g. levee versus bedrock valley wall), but instead by what the channel is currently abutting against.
Valley margin (C_V)	The valley margin comprises the valley bottom (defined later) and the inactive floodplains (i.e. terraces) and fans (both alluvial and colluvial). The valley margin is defined at the transition between the valley floor and bedrock hillslopes. This includes not just bedrock outcrops, but also regolith and soils derived from non-alluvial sources.
Valley bottom margin (C_{VB})	The valley bottom comprises the channel and the contemporary (active, genetic) floodplain. The valley bottom margin separates the valley bottom landforms from other valley floor landforms (e.g. fans and terraces) and hillslope landforms. Confined, partly confined and laterally unconfined valley settings are defined by the extent of the valley bottom margin (Brierley and Fryirs, 2005). The width between opposite valley bottom margins is referred to as the effective valley width (Fryirs and Brierley, 2010).
Anthropogenic margin (C_A)	An anthropogenic margin is an artificial (constructed) feature that is aligned with the channel boundary and constrains lateral adjustment of the channel in a valley setting where the channel would normally have capacity to adjust. Examples include embankments, fences, hedgerows, constructed levees, railroads, roads, pipes and walls, etc.
Channel margin (CL_{EB})	The channel margin is the edge of the active channel (in many systems this corresponds with a bankfull margin). The channel margin is the boundary between where regular fluvial flows take place and other areas (e.g. floodplains where less frequent fluvial flows take place; terraces, where historic fluvial flows took place; hillslopes where fluvial flows do not take place).

provides a useful diagnostic that can contrast the relative importance of valley features versus hillslope features in controlling behaviour. It is important to note that C_{VB} can equal C_V in systems that lack fans, terraces and other valley confining elements. However, C_{VB} will always be greater than or equal to C_V.

Anthropogenic margins include embankments, constructed levees, railroads, roads, pipes and walls and can act as confining margins in many rivers. These artificial margins provide a tertiary form of confinement. The extent and type of anthropogenic confining feature can be mapped and anthropogenic confinement (C_A) can be derived similar to C_{VB} and C_V:

$$C_A = \left(\sum_{DS}^{US} CL_{EB}@A_M \Big/ CL_T \right) \times 100 \qquad (3)$$

Where C_A is the anthropogenic confinement; $CL_{EB}@A_M$ is the length of channel along either bank that abuts an anthropogenic margin.

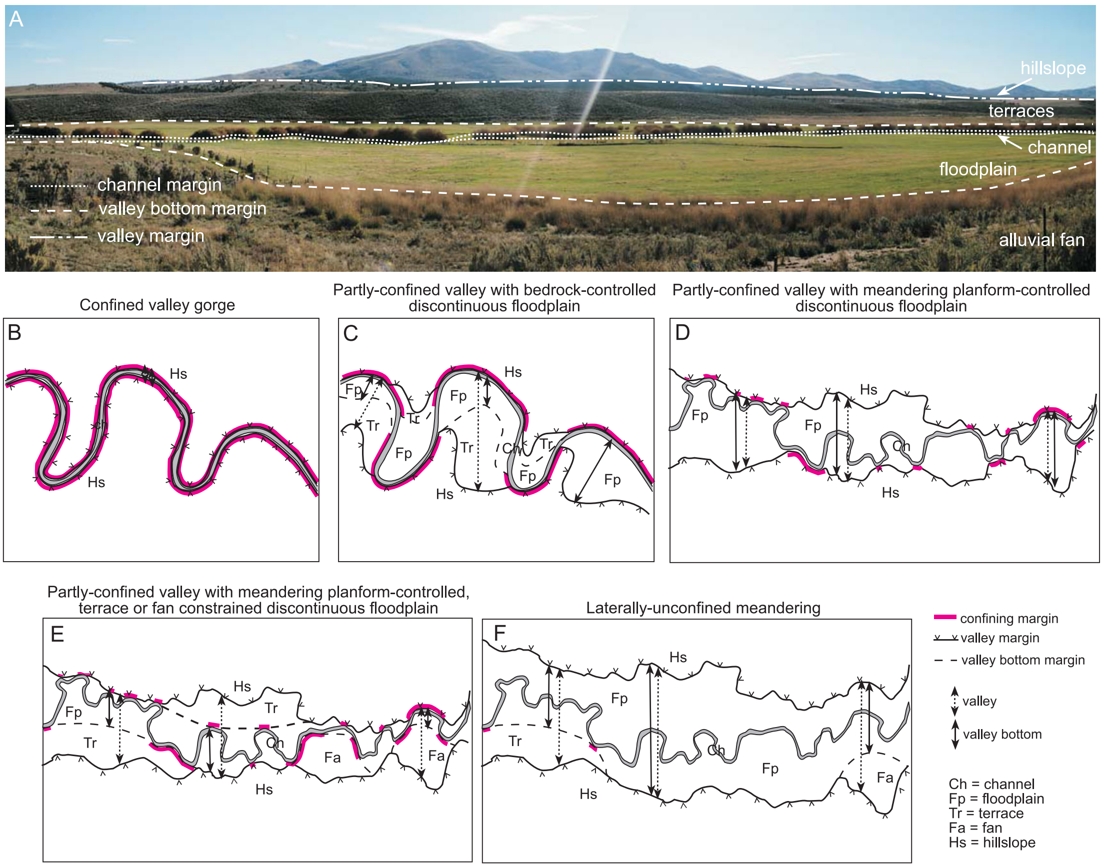


Figure 2. Identifying different forms of confinement across a range of river types. Modified from Wheaton *et al.* (2015).

In any segment of river where $C_A \geq C_{VB}$ (i.e. where natural confinement has been increased beyond natural valley bottom confinement), anthropogenic activity is exerting an artificial control on the river's natural capacity for lateral adjustment.

As an aside, measures of constriction are primarily useful in a confined or, occasionally, partly-confined valley setting to differentiate between different types of confined rivers, and are not the focus of this communication. However, two potential measures of constriction can be used to distinguish it from our three proposed measures of confinement that differentiate valley settings. Previous investigators (e.g. Schmidt, 1990) have defined a constriction ratio, $cR_{:}$, as:

$$cR_{:} = (w_c/\overline{w_{US}}) \tag{4}$$

Where w_c is the channel top width at the constriction, and $\overline{w_{US}}$ is the average upstream channel width. Schmidt (1990) used comparison of constriction ratios and expansion ratios (i.e. ratio DS of constriction), to describe the impact of constrictions imposed by tributary debris fans which choke portions of the Grand Canyon, USA, creating width constrictions that back water upstream, produce large rapids, and in the flow expansion downstream produce eddy-bars. These discrete points with elevated constriction ratios along an otherwise confined canyon define where rapids occur in debris-fan dominated canyons. These might be mapped as discrete points (i.e. constrictions), where constriction ratios are calculated and the degree of constriction is calculated.

By contrast, we can define a segment-based measure of constriction that is not dependent on a width measure and more analogous to our earlier measurements of confinement. We term this constriction proportion, c_P, and calculate its value over any segment as:

$$c_P = \left(\sum_{DS}^{US} CL_{BB} @ C_M \Big/ _{CL_T} \right) \times 100 \tag{5}$$

Where $CL_{BB} @ C_M$ is the length of channel that is 'confined' along both banks.

Constriction proportion can often be mapped continuously by segment. Lower constricted proportions over a reach may help discriminate confined valley segments that give rise to occasional floodplain pockets (i.e. lower percentage constriction). For example, many bedrock gorges have c_P approaching one, versus some of the debris-fan dominated canyons of the Colorado Plateau, USA, for example, which do give rise to occasional floodplain pockets.

Measurements of confinement (Equations 1, 2 or 3) and even constriction proportion (Equation 5) can be undertaken in a geographical information system (GIS) so long as the potential confining margins of interest are mapped, and the active channel margin itself is mapped. After establishing a buffer around these margins representing the precision of the mapping, the areas where an active channel margin intersects a potential confining margin (i.e. valley, valley bottom or anthropogenic), can be used to develop extents and measures of $CL_{EB} @ H_S$ or $CL_{EB} @ C_M$. Such margins can be field mapped or remotely mapped using aerial imagery or DEMs with a high enough resolution to identify valley bottoms [Roux *et al*. (2015) also map valley bottoms from topography]. The approach can be applied across whole networks to differentiate valley settings and river reaches. The calculations hold up for any reach segmentation length (i.e. CL_T), but will be sensitive to reach length and should scale to the size of the system. They are probably most useful for reach differentiation at 0.5 to 2 km reach scales.

Illustration of Application

To demonstrate the implications and generic nature of applying measures of confinement, we illustrate the contrast for a range of river types across the spectrum of river diversity and from different environmental settings in Australia, the United States and New Zealand (Figure 3).

Reaches of Wright Creek in the Lemhi River basin, USA, and the Waimata River, New Zealand are situated in a confined valley setting (Figures 3A and 3B). In these cases, bedrock or terraces occur along both channel banks over more than 90% of reach length. These rivers may have localised (occasional) floodplain pockets on the valley bottom at tributary confluences or areas of local valley widening (e.g. behind bedrock spurs), which are restricted to < 10% of reach length. In large part, contemporary channel planform is imposed by valley configuration with the margin made up of either bedrock or ancient, cemented alluvial deposits. For bedrock-controlled variants $C_V \geq 90\%$, whereas for terrace-controlled reaches $C_{VB} \geq 90\%$.

The Pages River and Williams River in the Hunter Catchment, NSW, Australia are situated in a partly confined valley setting (Figures 3C and 3D). In these two cases, bedrock valley margins occur along 10–90% of the channel length. Discrete, discontinuous floodplain pockets occur on alternating sides of the channel. However, the position of the channel relative to the valley margin differentiates these two rivers into bedrock-controlled and planform-controlled variants of partly confined rivers (Fryirs and Brierley, 2010). Pages River is a partly confined bedrock-controlled discontinuous floodplain river type. The C_V and C_{VB} are both between 50 and 90%. The channel is significantly constrained by the bedrock valley margin. Williams River is a partly confined planform-controlled discontinuous floodplain river type. For this example the C_V and C_{VB} are both between 10 and 50%. The channel is less constrained by the bedrock valley margin and the channel has some capacity to adjust laterally. In this case this lateral adjustment is manifest by the channel running along one valley margin, before shifting to the opposite valley margin. The channel has some capacity to adjust at these switch points. In the Williams River example, channel sinuosity (channel length along its axis/ valley length along its axis) is less than 1.5 and so this river type is considered a low sinuosity variant of the planform-controlled river type. Elsewhere, meandering variants of planform-controlled rivers also occur where channel sinuosity is > 1.5 (see Figure 3D and Fryirs and Brierley, 2010).

In other partly confined valley settings, the confining media is not bedrock. Two examples, one from Bear Valley Creek, Columbia Basin, USA and one from Takahue River, Northland, New Zealand are used to demonstrate how partly confined rivers can also be significantly controlled by secondary confining features (Figures 3E and 3F). In the case of Bear Valley Creek, the valley contains significant alluvial fan deposits that constrain the contemporary channel. In this case the $C_V \leq 10\%$, but C_{VB} is between 10 and 50%. The channel is significantly constrained by alluvial fans along the valley bottom margin and the channel has limited capacity to adjust laterally. Bear Valley Creek is a partly confined planform-controlled, fan-constrained discontinuous floodplain river type. In the case of Takahue River, significant flights of terrace deposits constrain the contemporary channel. In this case $C_V \leq 10\%$, but C_{VB} is between 50 and 90%. The channel is significantly constrained by terraces along the valley bottom margin and the channel has limited capacity to adjust laterally. Takahue River is a partly confined, terrace-constrained discontinuous floodplain river type.

Reaches of the Lemhi River in the Columbia Basin, and the Mississippi River, USA are situated in a laterally unconfined

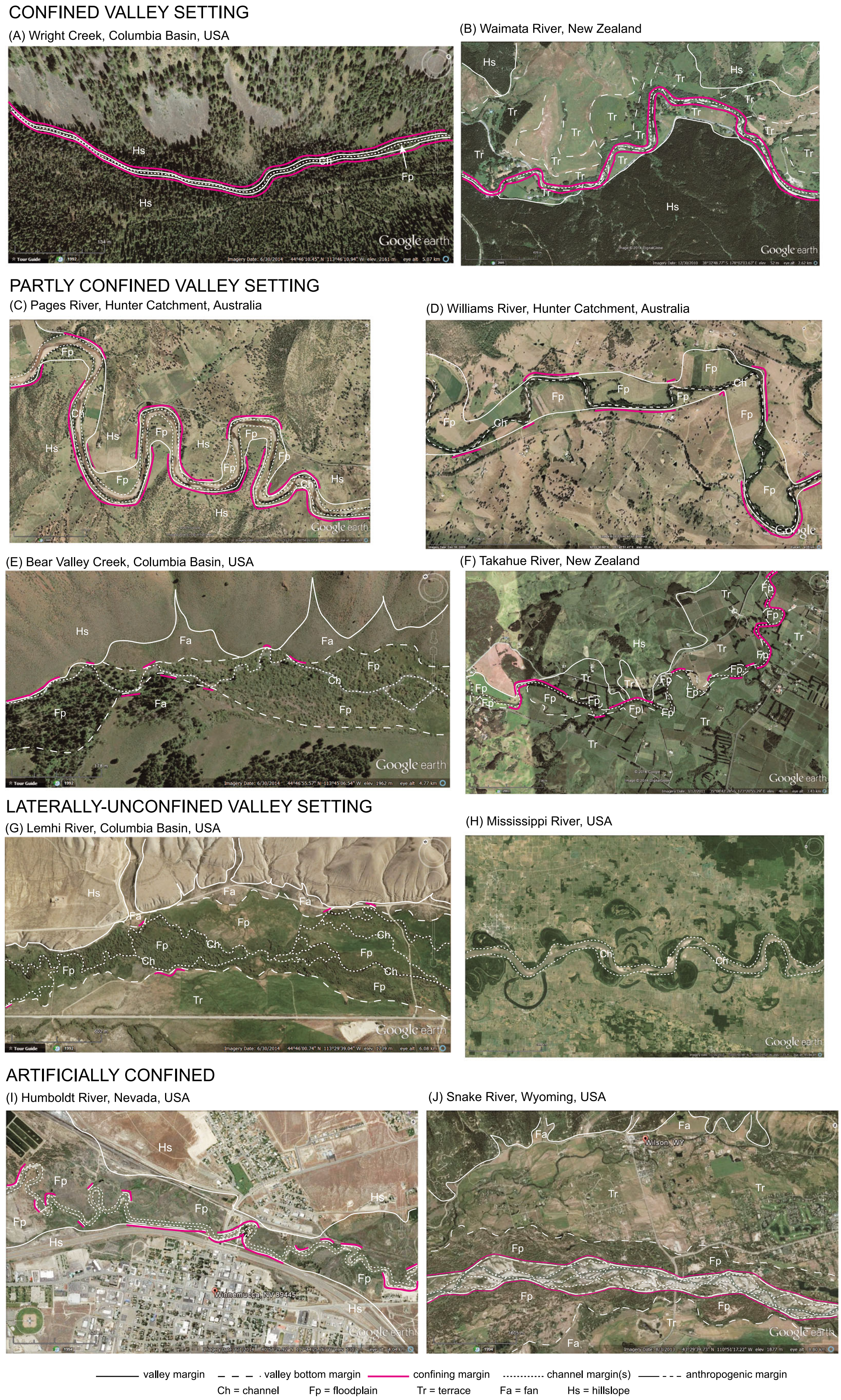


Figure 3. Examples of valley confinement analysis across a range of river types from Australia, New Zealand and the United States.

valley setting (Figures 3G and 3H). In these cases, bedrock or terraces or fans have almost no influence on channel planform and the capacity for adjustment. These alluvial rivers are laterally unconstrained, flowing atop their own deposits with continuous floodplains along both channel banks. Less than 10% of the channel margin abuts against the valley margin or valley bottom margin. Therefore, C_V and C_{VB} are both < 10%. The channel may locally hit a confining margin, but its influence is negligible. Banks are deformable, such that the channel is able to mould and rework its boundaries. In many instances channels have significant capacity to adjust on the valley floor. Rivers in laterally unconfined valley settings are differentiated in terms of planform attributes (number of channels, sinuosity, and lateral stability on the valley floor). The Lemhi River example is an anastomosing river type and the Mississippi is an active meandering river type.

In other cases, the river type may be readily identified as flowing within a partly confined or laterally unconfined valley, but contemporary forms and processes on the valley bottom are constrained by anthropogenic structures. These artificial confining features can add additional, tertiary layers of confinement to the channel. Along the Humboldt River in Winnemucca, Nevada, USA (Figure 3I), anthropogenic confinement in the form of roads and railroad grades further constrains a river that is in a partly confined valley setting. In this case C_{VB} remains between 10 and 50% but C_A adds additional confinement and occurs along > 50% of the reach. Along the Snake River in Wyoming, USA (Figure 3J), what was once a laterally unconfined braided river now contains flood control levees that run along almost the entire length of the channel margin. The C_A occurs along almost 100% of the reach length. While this essentially transforms this reach into a confined river, in this case the active channel is still wide enough to maintain braiding, but the formerly active floodplain is now artificially disconnected.

From these results, measures of valley margin and valley bottom confinement can be used to accurately characterise different valley settings and different river types (Table II). The approach adopted is generic and can be applied across a range of landscape settings.

Discussion

Contemporary river type and behaviour

In interpretations of contemporary river forms and processes, valley margin and valley bottom confinement sets one form of imposed boundary condition within which a river operates (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). Imposed boundary conditions from valley margins generally do not change over geomorphic timeframes (centuries to thousands of years) and impose some constraints upon the way in which energy can be used by the river to do geomorphic work (e.g. adjust river planform, form/rework floodplains) (Wolman and Miller, 1960; Nanson and Croke, 1992; Lecce, 1997; Knighton, 1999; Jain *et al.*, 2006, 2008). In addition, valley bottom confinement influences flow alignment at differing flow stages (i.e. topographic steering of flow), thereby dictating how flow energy is concentrated or dissipated, and the resultant patterns of sediment deposition and reworking on valley bottoms (Magilligan, 1992; Miller, 1995; Magilligan *et al.*, 2015).

Within these imposed conditions, hydrology, sediment regime and vegetation conditions (flux boundary conditions) act on the valley bottom to determine the range of process behaviour that is possible, and the range of types of rivers that can form in that setting (Brierley and Fryirs, 2005; Hough-Snee *et al.*, 2015). The extent to which various forms of confinement occur determines the degrees of freedom within which the river has the capacity to adjust (Phillips, 2008, 2010). Correctly interpreting the valley setting using measures of valley margin and valley bottom confinement is critical to correctly interpreting the contemporary character and behaviour of that river. Getting it wrong can lead to spurious interpretations of river behaviour. For example, a partly confined bedrock-controlled river, a partly confined meandering, planform-controlled river and a laterally unconfined meandering river all behave in significantly different ways (see Figures 2C, 2D, 2F and Figure 3).

In bedrock-controlled variants, the planform shape of the valley is the dominant control on channel position (e.g. Figure 2C). Bedrock spurs often produce a sinuous valley alignment that forces the channel to abut bedrock along a significant proportion of its length (making it a low sinuosity channel) (Fryirs and Brierley, 2013). The bedrock spurs force the channel to shift to the opposite bank on bends producing very limited capacity to adjust.

Along the partly confined, meandering planform-controlled river, a straighter, more irregularly-shaped valley occurs and the channel hugs a confining margin for some distance and then shifts to the opposite confining margin, creating discontinuous pockets of floodplain (e.g. Figure 2D; Fryirs and Brierley, 2010). The confining media is often alluvial fans or terraces that steer the channel to the opposite side of a valley (e.g. Figure 2E). Where meandering can occur, the dominant channel adjustment processes include downstream translation of bends and stabilisation against confining media (Lewin and Brindle, 1977). Boxed or sinusoidal meander patterns may occur (Lewin and Brindle, 1977). In all these partly confined rivers, the assemblage of instream geomorphic units will often be forced, producing forced, bedrock pools, for example (Fryirs and Brierley, 2013). This river type has limited capacity to adjust.

Along the laterally unconfined river, the channel is readily able to adjust as the channel margins are unconstrained and do not abut against confining margins (e.g. Figures 2F and 3H). Continuous floodplains are formed along both channel banks. Free-forming instream geomorphic units are able to form with regularly spaced pool-riffle sequences common. Meander migration, growth, extension and cutoffs are common. This river type has significant capacity to adjust on the valley bottom.

Table II. Measures of valley margin and valley bottom confinement used to differentiate valley settings and river types

Valley-setting (river type)	Valley margin confinement	Valley bottom confinement	Dominant confining medium
Confined (bedrock-controlled)	$C_V \geq 90\%$	$C_{VB} \geq 90\%$	Bedrock
Confined (fan or terrace controlled)	$C_V \leq 10\ \%$	$C_{VB} \geq 90\%$	Terrace or fan
Partly confined (bedrock-controlled)	$C_V = 50–90\%$	$C_{VB} = 50–90\%$	Bedrock
Partly confined (planform-controlled)	$C_V = 10–50\ \%$	$C_{VB} = 10–50\%$	Bedrock
Partly confined (fan or terrace constrained)	$C_V = 10–50\%$	$C_{VB} = 10–50\%$	Terrace or fan
Laterally unconfined	$C_V \leq 10\%$	$C_{VB} \leq 10\%$	None
Anthropogenic	Any range ($C_A > C_V$)	Any range ($C_A > C_{VB}$)	Riverworks, roads, infrastructure, etc.

Note: this does not cover all river types or all possible combinations within ranges.

Interpreting antecedent control on contemporary capacity to adjust

Various forms of confinement are a direct product of antecedent controls that set the conditions within which contemporary floodplain formation and reworking processes operate (Fryirs and Brierley, 2010). The control exerted by confinement can be differentiated into a number of 'layers of imprint or antecedence' that can be interpreted to gain a full picture of why certain types of channels and floodplains (river types) form where they do (Brierley and Fryirs, 2005; Phillips, 2008; Fryirs and Brierley, 2010).

The antecedent imprint or 'geomorphic memory' varies from floodplain pocket-to-pocket, or reach-to-reach, reflecting the extent to which geological, climatic or anthropogenic controls are present (Ferguson and Brierley, 1999; McDowell, 2001; Fotherby, 2009; Brierley, 2010). In most cases, several layers of confinement may exert control in a given valley. These layers include geological control (e.g. valley margins), within which impacts of climatic controls are embedded (e.g. old alluvial sediment stores), and onto which a human imprint (e.g. anthropogenic margins) may be manifest (Fryirs and Brierley, 2010). This can be considered as primary, secondary and tertiary forms of confinement (e.g. Fryirs and Brierley, 2010). The nature of the confining media and its resistance to reworking can be usefully described and classified in this manner. Inevitably, our approach to assessing confinement from remotely sensed data may not detect situations where confining media (e.g. terraces) are buried or where boundaries are subtle and show no surface expression (Hoyle *et al.*, 2008; Fryirs and Brierley, 2010). To improve accuracy in these situations, field verification is required to identify these sorts of buried margins. Caution is always required in verifying the output produced, ensuring it reflects the on-ground reality. However, the differentiation provided is useful for determining the extent to which a river is confined and the extent to which the confining medium exerts a control on the channel boundary and therefore its capacity to adjust laterally.

Geological controls refer to the structural and lithological characteristics of a valley that dictate the ease with which rocks are weathered and eroded, the rate at which valleys develop, and the configuration of those valleys. Long-term landscape evolution, operating over millions of years, also impacts on valley formation and configuration (Miller, 1995; Nott *et al.*, 1996; Fryirs, 2002; Bishop, 2007). Valleys with varying morphologies and varying amounts of accommodation space are produced (Miller, 1995; Seidl *et al.*, 1996; Tooth *et al.*, 2002). Geological controls exert an influence on valley width, shape and alignment, and is identified here as the valley margin. Here, the valley margin is defined as an imposed, primary confining feature. In valleys where the channel abuts against the valley margin, there is limited capacity to adjust as the processes of lateral (or vertical) adjustment are controlled by weathering and erosion rates of adjacent bedrock.

Inset within valleys, climatic factors influence the rate of sediment and discharge supply, and vegetation cover, producing rivers with differing morphologies. If palaeo-deposits are preserved within a valley, and are unable to be reworked, inherited morphologies influence subsequent process-form associations in that valley. For example, terrace, fan and piedmont materials that were deposited under former flow and sediment regimes can continue to influence the type and lateral stability of contemporary channels (Sidorchuk, 2003; Wasklewicz *et al.*, 2004; Rodriguez *et al.*, 2005; Macklin and Lewin, 2008). The persistence of secondary confining features adds additional layers of confinement to contemporary form-process associations occurring on the valley bottom (Brunsden, 1993; Fryirs and Brierley, 2010; Keen-Zebert *et al.*, 2013). In valleys where the channel abuts against secondary confining features, there is still limited capacity to adjust, but the boundaries of the channel may be more erodible depending on the composition of the materials that make up the confining features. In most cases, these margins will be more erodible than the valley margin (Hoyle *et al.*, 2008).

A human imprint can also add to confinement. In many valleys, anthropogenic influences of river forms and processes are pervasive (Lewin, 2013). Structures associated with development, urbanization, and river 'training' have added artificial confining anthropogenic margins along rivers that are, in many cases, the dominant control on the capacity for river adjustment (Fotherby, 2009). Roads, bridges, bank protection works, etc. add a tertiary level of confinement in these systems. These attributes can act as local, point sources of confinement or they are more pervasive, extensive forms of confinement. We refer to these margins as anthropogenic confining features. In almost all cases, these margins significantly suppress the contemporary capacity for adjustment of a river.

Valley confinement as a control on patterns of rivers, evolutionary trajectory, sediment flux and the geomorphic effectiveness of floods

Valley confinement acts as a primary control on many fluvial geomorphic processes that occur on (and along) valley bottoms. In particular, the downstream sequence of valley settings is a key control on longitudinal patterns of hydrology and sediment flux, as well as dictating the pattern of river types and associated instream and floodplain geomorphic unit structure (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013).

The pattern of river types along longitudinal profiles is, in significant part, a function of the extent of valley confinement. Having a capacity to quantify broad-scale (network/catchment-framed) patterns of confinement (and associated type of margin) using a continuous variable (e.g. Equations 1 or 2) provides a key step in delineation of boundary conditions such that reaches with consistent structure and function can be differentiated (Brenden *et al.*, 2008; Fryirs and Brierley, 2013; Wheaton *et al.*, 2015).

Differences in valley width and confinement are a key control on spatial patterns of erosion and deposition during geomorphically effective floods (Miller, 1995; Magilligan *et al.*, 2015). Wide valleys can attenuate the peak discharge for a given event, as decreased velocity of overbank flow results in temporary storage of some of the runoff (Woltemade and Potter, 1994). Even for a given discharge, narrow valleys have higher stage, stream power, and shear stresses than wide valleys (Miller, 1995). These conditions are often reflected in floodplain forming processes and resultant geomorphic structures (i.e. assemblages of floodplain geomorphic units) (Nanson and Croke, 1992; Loczy *et al.*, 2012; Keen-Zebert *et al.*, 2013). Significant transitions in instream river character and behaviour may also accompany changes to valley confinement (e.g. McDowell, 2001).

When measures of confinement are combined with valley width, useful interpretations of the future trajectory of change and how a river may evolve can also be made (Fryirs and Brierley 2010; Brierley and Fryirs, 2015). For example a laterally unconfined river in a narrow valley has greater potential to evolve and change towards a partly confined river if the channel shifts on the valley floor, and the channel does not need to shift far. However, a laterally unconfined river in a wide valley is less likely to transition to a partly confined river over time.

The capacity for sediment storage and fluvial reworking along a reach is influenced by topographic controls such as slope and valley confinement. For example, the differentiation of geomorphic process zones (source, transfer and accumulation) along rivers can be related to the amount of 'accommodation space' available in valleys (Schumm, 1977). Also, knowing what type of margin is causing confinement can also provide important clues about lateral sediment inputs (and (dis)connectivity) to the valley floor (Rice, 1999; Fryirs, 2013; Kuo and Brierley, 2013). Useful indications of the extent of hillslope-channel coupling can be generated from analyses of where the channel abuts a valley margin, therefore providing colluvial inputs to a channel. This will differ significantly to sediment inputs from margins that cut into other types of valley bottom margins, i.e. alluvial fan or terrace materials.

Ultimately, the distribution of valley confinement within a given catchment exerts a primary influence upon flow and sediment flux relationships. For example, gorges (confined valley settings) act as boosters that link discontinuous parts of catchments (Fryirs *et al.*, 2007). Alternatively, choke points influence patterns of accommodation space in landscapes (and associated potential for sediment storage) (Fryirs *et al.*, 2007). Effective analyses of reach-scale valley confinement are most appropriately framed in relation to such catchment-scale considerations.

Finally, the future prospects for deriving continuous, network-scale assessments of confinement are very promising. Automated tools to systematically analyse and quantify catchment-scale patterns of valley confinement may yield new insights about the organisation of river systems. However, such understandings should not be applied in a prescriptive, uncritical manner. In light of pronounced variability in river systems, it is important that open-ended, flexible conceptual frameworks sit at the foundations of such applications (Brierley *et al.*, 2013; Fryirs and Brierley, 2013).

Conclusion

Valley confinement is one of the most fundamental controls on river character and behaviour. Numerous authors have acknowledged the importance of valley confinement under various guises (entrenchment ratio; valley width to bankfull width ratio). Here we provide clear definitions of confinement and provide a systematised approach to analysis that can be used to delineate valley settings along river courses and quantify the extent and nature of valley confinement along individual reaches. Differentiating between forms of confinement can be used to assess the valley setting within which a river occurs and the extent to which confining media provide levels of control (and antecedence) on a river's capacity to adjust. Such understandings aid interpretations of a range of issues relating to catchment-scale water and sediment fluxes.

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