The diversity of pool riffle morphologies

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Pool-riffle sediment and flow dynamics have been studied for many years, but there has been relatively little investigation on how field observations might be influenced by the variability of pool-riffle morphologies. In this letter we present a database of quantitative and qualitative measurements from sites where pool-riffle morphologies have been studied and apply two morphologic classifications that compare a) discharge and slope, and b) specific stream power and a representative coarse bed particle size. The classifications show that pool-riffles appear in different positions relative to mobility and morphologic transitions, which indicates that they occur within different flow and sediment regimes. Patterns in the distribution of studied pool-riffles show useful trends as well as an important diversity, the appreciation of which may help to clarify the importance of different flow and sediment transport phenomenon that underlie pool-riffle mechanics.

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The diversity of pool riffle morphologies

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Key points

- Pool-riffles presented in the literature have some features in common but also show an important diversity;
- Pool-riffles are often low mobility and show a morphologic gradient from meandering to forced pools as a function of specific stream power; and
- Observations or models from sites with unusual classifications may not apply to typical pool-riffle units.

Abstract

Pool-riffle sediment and flow dynamics have been studied for many years, but there has been relatively little investigation on how field observations might be influenced by the variability of pool-riffle morphologies. In this letter we present a database of quantitative and qualitative measurements from sites where pool-riffle morphologies have been studied and apply two morphologic classifications that compare a) discharge and slope, and b) specific stream power and a representative coarse bed particle size. The classifications show that pool-riffles appear in different positions relative to mobility and morphologic transitions, which indicates that they occur within different flow and sediment regimes. Patterns in the distribution of studied pool-riffles show useful trends as well as an important diversity, the appreciation of which may help to clarify the importance of different flow and sediment transport phenomenon that underlie pool-riffle mechanics.

Plain Language Summary

Pools and riffles are important for habitat and maintaining a balance between how much flow and sediment come into and leave a river reach. Despite their importance, researchers are still debating competing theories on how they form and maintain themselves, which makes it hard to protect or restore these important features. In this study we take the approach that we may all be right. We use the parable of people in the dark feeling different parts of an elephant and then getting into an argument about what this fantastical beast really looks like as motivation. We apply two classification approaches to try to tease out the overall shape of pool-riffle flow and sediment regimes using a database of prominent sites in the literature. We produce two diagrams that are useful for comparing and contrasting sites. They show that in our scientific pursuit some of us have studied extreme cases, so more like the tail or the trunk, while others have studied sites that are similar to the bulk of the others, and so more like the body of this proverbial fantastical beast. An appreciation of the diversity should help to resolve some debates and inspire new research.

Many gravel-bed rivers are characterized by an undulating bed morphology, with the deeper areas called pools and the shallower areas called riffles (Thompson & MacVicar, 2022). A range of theories on flow and sediment driven mechanisms to explain pool-riffle hydraulics, formation and maintenance have attempted to explain varied observations documented utilizing a wide range of differing study techniques. Prominent flow-driven mechanisms include the reversal hypothesis, whereby the location of maximal values of key hydraulic variables such as velocity may switch from riffles to pools as stage increases (Keller, 1971; Petit, 1987; White et al., 2010; Wilkinson et al., 2004), laterally concentrated flow driven by width variability (MacWilliams et al., 2006; Pasternack et al., 2018a; Sawyer et al., 2010), and spatial differences in turbulence generation driven by non-uniform topography (Clifford & French, 1993; MacVicar & Roy, 2007; Thompson, 1986; Thompson, 2006). De Almeida and Rodriguez (2011) critique this research by noting that the "mechanisms seem to operate under specific circumstances and that it is difficult to identify a universal process on the basis of flow variables alone," going on to demonstrate that some pool-riffle sequences may be maintained by a sediment driven process. Other researchers have argued that sediment routing around pools (Dietrich et al., 1979; Gregory et al., 1994; Milan, 2013), differences in sediment textures (Carling & Wood, 1994; Milan et al., 2001), or sediment structure (Sear, 1996; Hodge et al., 2013) may contribute to pool-riffle formation and maintenance. Despite these contributions, however, there has been relatively little investigation on how formative mechanisms might be influenced by the diversity of pool-riffle morphology.

Descriptions of pool-riffle morphology are notoriously inconsistent. Pool-riffles occur in meanders but also in straight channels (Leopold & Wolman, 1957). They can be forced by channel obstructions (Keller & Melhorn, 1978; Lisle, 1986), and valley wall irregularities (White et al., 2010), even forming in bedrock channels (Keller & Melhorn, 1978). To bring statistical rigor to the morphologic description, Richards (1976) defined riffles and pools in 1D as positive and negative residuals in elevation around larger trends, but perceived weaknesses in this method led to new definitions based on bedform differencing (O'Neill & Abrahams, 1984) and the residual depth of pools (Lisle & Hilton, 1992). 1D methods were admittedly deficient because they ignored lateral variability (O'Neill & Abrahams, 1984), and modern data acquisition has allowed new classification schemes that place pools and riffles within assemblages of geomorphic units (Fryirs & Brierley, 2021; Pasternack et al., 2018a; Wheaton et al., 2015;

Wyrick & Pasternack, 2014). In spite of this work, it remains difficult to ensure consistency in the identification of pool-riffle units and the selection of study sites. Channel width, gradient, sinuosity and bed material sizes vary widely between sites (Thompson & MacVicar, 2022) and quantification of variables such as sediment supply and channel equilibrium remain largely outside the scope of process based studies. Based on the principle of equifinality (Buffington & Montgomery, 2013), it is possible that river bed undulations commonly referred to as pool-riffles arise through multiple pathways.

In this letter we use two morphologic classification diagrams to demonstrate that pool-riffles appear within a range of flow and sediment regime contexts. The diagrams are necessarily limited because hard thresholds likely do not exist (Ferguson, 1987), but they remain useful for comparing sites with each other and against theoretical transitions with respect to particle mobility and planform or bar morphology. The analysis utilizes a database of sites used to study pool-riffle formation and maintenance that was compiled by Thompson and MacVicar (2022). Not all data was available for all sites, which limited the analysis. Fortunately, there were enough to show that differences in flow and sediment regimes may help to explain why researchers arrived at quite different conclusions about the important physical mechanisms. In this letter we argue that we may all be right, and use as motivation the parable of people in the dark feeling different parts of an elephant and arguing about what this fantastical beast really looks like. The hope is that the comparison and justaposition of sites will allow a more nuanced discussion of pool-riffle form and process and so arrive more generally at a description of the common elephant.

To explain the methodology used in the current study, we will first review some quantitative classification systems. Leopold and Wolman (1957) compared channel planforms and proposed an empirical relation for a morphologic threshold slope (S_m) as a function of water discharge (Q [m^3/s]):

$$S_m = 0.012\, Q^{-0.44} \tag{1}$$

Channels where the measured slope $S > S_m$ were shown to have largely braided patterns while those with $S < S_m$ tended to meander. The product of these two terms is proportional to the stream power (Ω), or energy available in the flow, written as:

$$\Omega \;=\; \gamma Q S \tag{2}$$

where γ is the specific weight of water (~9.8kN/m^3). Building on this idea that the available energy is the primary determinant of morphology, Nanson and Croke (1992) classified channel floodplains based on the specific stream power (ω), written as:

$$\omega = \frac{\Omega}{W} \tag{3}$$

where W is the channel width.

Despite the utility of the available energy for determining channel pattern, the QS product represents only one side of the Lane balance, written as:

$$Q_b D \propto QS \tag{4}$$

where Q_b is the bed material flux and D is a representative particle size. This balance is thought to be fundamental for understanding channel pattern and metamorphosis (Church, 2006), with the left side relevant for estimating the energy required to overcome flow resistance and transport the sediment supplied to the river. Consideration of sediment size has been shown to improve the transition criterion in Equation 1 (Henderson, 1966), with Ferguson (1987), using a semi-theoretical hydraulic geometry relation from Parker (1979) and an assumption that the critical flow strength for bank erosion is proportional to D to argue that:

$$S_m \propto Q^{-0.5} D^{0.75} \tag{5}$$

Based on Figure 6.5 from Ferguson (1987) a discriminator for $D_{50} = 64$ mm could be written as:

$$S_{m64} = 0.061\, Q^{-0.5} \tag{6}$$

Recognizing the importance of sediment properties and the limitations of the Leopold and Wolman (1957) approach, van den Berg (1995) showed that transitions could be better anticipated by considering a morphologic specific stream power threshold (ω_m) based on the following proportionality:

$$\omega_m = c_m D_{50}^{0.42} \tag{7}$$

where c_m is a coefficient. Van den Berg (1995) calculated specific stream power with the valley slope rather than S and showed that a value of $c = 900$ could be used to distinguish single from multi-thread channels. Kleinhans and van den Berg (2011) further suggested a value of $c = 285$ to define an approximate transition in meandering rivers from those with scroll bars to those with chute cutoff bars. Ghunowa et al. (2021) modelled geomorphic thresholds using the D_{84} of the sediment based on the rationale that the variability of the coarse particle sizes has been shown to result in stronger relations for classification and roughness modelling (Ferguson, 1987, 2007; López & Barragán, 2008), and appears to be critical for bed degradation (MacKenzie et al., 2018) and the formation of riffles (Sear, 1996). Based on an equivalent roughness height approach from López & Barragán (2008), $k_s = 2.8D_{84} = 6.1D_{50}$ or $D_{84} \approx 2.2D_{50}$ and Equation 7 can be re-written as:

$$D_{84m} = 2.2\left(\frac{\omega}{c_m}\right)^{2.4} \tag{8}$$

where D_{84m} is the particle size at the morphologic transition for a given value of ω.

Representing Q_b from the Lane balance in channel pattern classification systems remains difficult due to the challenge of quantification in real rivers. However, Dade & Friend (1998) and Church (2006) show that qualitative understanding of the sediment supply regime can be derived from a consideration of the dimensionless Shields parameter (τ^*). For example, channels with relatively fine bed material such that τ^* is greater than a threshold (τ_c^*) will have an abundance of sediment transported in suspension during floods and require high rates of supply to maintain equilibrium. In contrast, channels with relatively coarse beds such that $\tau^* < \tau_c^*$ will have low rates of sediment transported as bedload during floods and require low rates of sediment supply. The distance $\tau^* - \tau_c^*$ can thus be considered as a qualitative proxy for Q_b relative to the capacity of channels in equilibrium. Kleinhans & van den Berg (2011) calculated a critical specific stream power (ω_c) based on approximations about channel roughness, showing that:

$$\omega_c \propto D^{\frac{3}{2}} \tag{9}$$

For consistency with equation 5, Kleinhans & van den Berg (2011) used S_v rather than S in the Equation 9. A slightly different approach was taken by Phillips and Desloges (2015), who used S for both morphologic and mobility threshold calculations, the latter of which was calculated with the Parker et al. (2011) criterion, which follows the exponent in Equation 6 but has a different coefficient. Phillips and Desloges (2015) noted the occurrence of 'inherited oversteepened' channels that have an abundance of power but relatively low transport rates due to the legacy of coarse glacial sediments, supporting the use of $\tau^* - \tau_c^*$ or $\omega - \omega_c$ as a proxy for sediment transport relative to available energy, or sediment supply relative to capacity. In a similar direction, Ghunowa et al. (2021) adapted an equation derived by Ferguson (2005) for the specific stream power threshold for a size fraction of the sediment (ω_{cb}) by setting b to the D_{84} to obtain a model for a threshold particle size (D_{84c}), written as:

$$D_{84c} = \frac{1}{\tau_c^* \rho^+ g} \left(\frac{\kappa\omega}{2.30\rho[\log(30\tau_c^*\rho^+) - \log(emS)]} \right)^{\frac{2}{3}} \tag{10}$$

where κ is the von Karman coefficient for velocity profiles (~0.41), m is the empirical multiplier for D_{84} to estimate the bed roughness height (i.e. $k_s = mD_{84}$), ρ^+ = the submerged relative density of the sediment, and e is the base of the natural logarithm. The exponent on Equation 10 is consistent with the more general Equation 9. Assuming constants for ρ (1000 kg/m^3), ρ^+(1.6), m (2.8, López & Barragán, 2008), and τ_{cb} (0.045, Buffington & Montgomery, 1997), Equation 10 can be simplified to:

$$D_{84c} = c_c \omega^{\frac{2}{3}} \tag{11}$$

where c_c is a constant with a slight dependency on S. Assuming a relevant range of S from 0.0001 to 0.01, c_c will have a value between 3.6 and 6.5.

For the current study, we started with the database of sites used to research pool-riffle dynamics compiled by Thompson (2013) and updated by Thompson and MacVicar (2022) and added a few notable sites such as Solfatara Creek (Whiting & Dietrich, 1991), East Creek (Papangelakis & Hassan, 2016), and Durance River (Chapuis et al., 2015). The full list of sites and information is included in Appendix A. Q and D_{84} were not recorded by Thompson and MacVicar (2022), so the source papers were re-examined to obtain this information. Where possible, the bankfull flood Q_{bf} was used to represent Q. If this was not available, the 2-year flood (Q_2) was used, but in some cases neither value was available and the site was not further considered in the analysis. Sediment size estimates were also reported differently or incomplete. When D_{84} was reported for multiple locations along a reach, values at riffles were selected. Where D_{84} was not available, an assumption was made following the above discussion on equivalent roughness that $D_{84} = 2.2D_{50}$. Sites were classified based on whether the pool was reported to be freely formed or forced by an in-channel non-alluvial element such as a boulder or a tree. Site planform was classified a priori by Thompson and MacVicar (2022), as meandering or straight, with a third 'transitional' category added here where the channel was generally straight but the pool-riffle unit was in a bend, or the channel pattern was meandering but the pool-riffle unit was locally straight. The channel slope (S) was used for all calculations rather than S_v (the valley slope) because it was generally available in literature and previously used to derive Equations 1 and 10. The effect of the replacement of S_v with S on the bar morphology transitions was assumed to be minor relative to other uncertainties. A total of 59 sites were assessed, but due to missing data only 34 sites were compared on a plot of Q vs S with Equations 1 and 6 (Figure 1), and 32 on a plot of ω vs D_{84} with Equation 8 and 11 (Figure 2). Of the sites shown on Figure 2, only three required a relative roughness assumption to calculate D_{84} (#19 La Rulles; # 25 Quarme; and #45 Yuba), while the rest of the studies had reported D_{84} values.

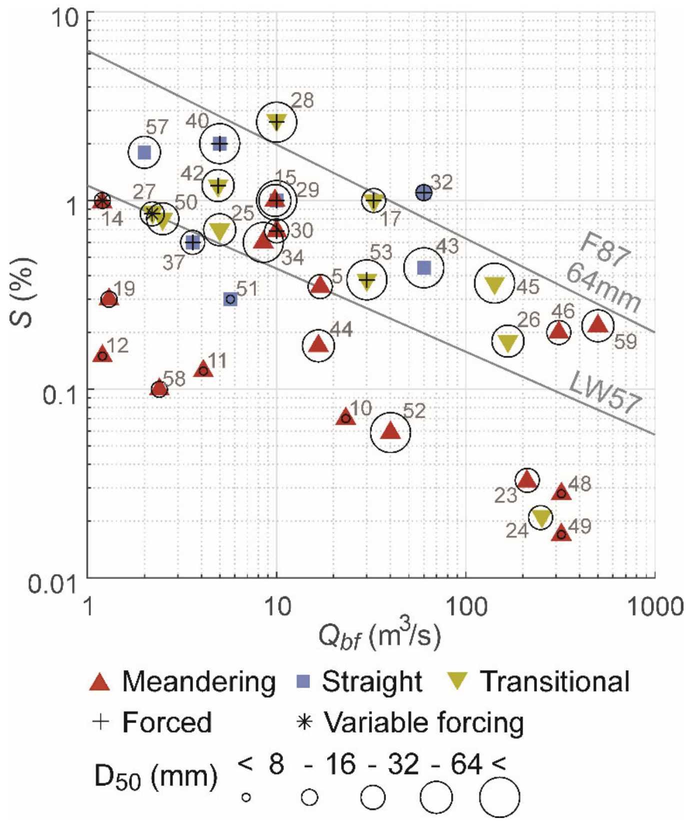

Figure 1 – Comparison of bankfull discharge (Q_{bf}) versus slope (S) for 34 pool-riffle study sites. Numbers refer to site numbers listed in Appendix A. Solid lines represent channel pattern transition from meandering to braided channels based on the empirical relation of Leopold and Wolman (1957) (LW57 - Equation 1) and a semi-empirical relation from Ferguson (1987) using D_{50} = 64 mm (F87 64mm - Equation 6).

Following the Leopold and Wolman (1957) approach for channel patterns, the plot of Q versus S shows some separation between identified pool-riffle subtypes (Figure 1). For example, only 5 of 17 meandering sites plot above Equation 1, while only 1 of 10 transitional and 2 of 7 straight sites plot below it. The plot also shows that forced pools tend to plot at or above Equation 1 and have $Q_{bf} < 35$ m^3/s, indicating that channel size is a limiting factor for their occurrence. The exceptional straight and transitional sites that plot below Equation 1 present classification difficulties. The straight reaches Tom MacDonald Ck (#37) and Majors Ck (#51) are unusual because they are located in the protected headwaters of old-growth redwood forest preserves (Chartrand et al., 2015; Hassan & Woodsmith, 2004). They were classified as straight but an abundance of in-channel wood could influence channel planform and the retention of sediment (Gurnell et al., 2002; Montgomery et al., 1996). The River Severn site D (#24) is straight but the longer reach is meandering. Though it is beyond the scope of the current work to re-examine all definitions used in the various studies, planform classification using minimum reach lengths and quantitative measures of sinuosity would help to resolve methodological uncertainties.

The difficulty of interpreting Figure 1 is a result of particle size trends. Ferguson (1987) describes that in some interpretations, Equation 1 can represent the mobility threshold for channels with D_{50} between 8 – 32 mm rather than a morphologic threshold. Channels with coarser particles may be single-thread at relatively high slopes, and 13 of 16 sites with $D_{50} > 32$ mm are located above Equation 1. The semi-empirical relation from Ferguson (1987) represented by Equation 6 does a better job of bounding the pool riffle-morphologies, with only 2 sites plotting above this line created with D_{50} = 64 mm. Some of the exceptions are known to be in disequilibrium due to dam construction. Site #32 (North Fork Poudre River), plots above Equation 6 despite relatively fine bed material, but the site is affected by an upstream reservoir that released large quantities of fine sediment that partially filled many pools (Wohl & Cenderelli, 2000). Site #52 (San Joaquin R.) plots well below Equation 1 despite a coarse bed material, but it too is affected by an upstream dam that has reduced the mean annual flood by an order of magnitude (Bray & Dunne, 2017). Thus while Figure 1 does help with some interpretation of the diversity of pool riffle morphologies, the confounding of particle size and mobility gradients with the morphology transitions make it problematic.

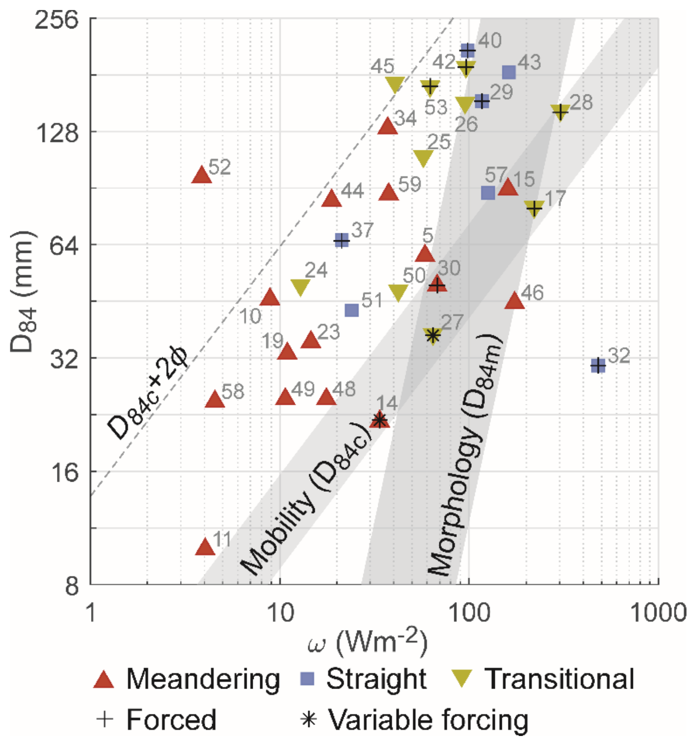

Figure 2. A comparison of specific stream power (ω) and bed particle size (D_{84}) for 32 pool-riffle study sites. Numbers refer to sites listed in Appendix A. Gray zones represent a family of mobility threshold curves (D_{84c}) based on Equation 11 with S varying from 0.0001 to 0.01, and a family of bar morphology transition lines (D_{84m}) based on Equation 7 with c_m varying from 285 – 900 to represent the transition from scroll to chute bars. A visual guidline to denote the rough envelope of particle sizes was added at $D_{84c} + 2\phi$, where ϕ represents particle size on the Krumbein scale (1951) modified by Parker and Andrews (1985) where $\phi = \log_2(D/D_o)$ and D_o is a reference diameter (1 mm) to ensure dimensional consistency.

The Kleinhans and van den Berg (2011) approach is advantageous because particle size is explicitly presented as a dependant variable and the mobility and morphology transitions are shown to have different slopes through the diagram (Figure 2). Grey bands represent approximate transition zones such that i) sediment supply is expected to be low or high relative to capacity if the measured D_{84} is coarser or finer, respectively, than the mobility transition zone (D_{84c}), and ii) bar dynamics are expected to be dominated by scroll or chute bars if the D_{84} is coarser or finer, respectively, than the morphologic transition zone (D_{84m}). The impact of the methodological choice to use S rather than accounting for channel sinuosity ($\zeta = S/S_v$) following Kleinhans & van den Berg (2011) is minor because it will rarely affect the classification even for the meandering channels where ζ is highest (~ 1.5). When pool-riffle sites from the literature are considered with respect to these transitions, it is apparent that $D_{84} \geq D_{84c}$ and $D_{84} \geq D_{84m}$ at most sites. Three sites known to be in disequilibrium due to dam construction stand out as exceptionally coarse (#45 and #52) and exceptionally fine (#32). In the Yuba River (#45), for example, bed coarsening was attributed to a reduction in sediment supply due to flow regulation (Sawyer et al., 2010). Bear Creek (#46) appears to be an outlier due to its position below D_{84c} at the upper limit of the D_{84m} range. It was for this site that de Almeida and Rodriguez (2011; 2012) showed that a partial mobility sediment transport model with a varying hydrograph was sufficient to form and maintain pools. The unusual location of the site on Figure 2 suggests that the high mobility and proximity to a morphologic transition may have contributed to model results and that the results should not be assumed to be transferable.

In contrast with the relative dearth of sites where $D_{84} < D_{84c}$, previous studies have examined an abundance of pool-riffle sites with low mobility and sediment supply (i.e. $D_{84} > D_{84c}$). The visual guideline at $D_{84c} + 2\phi$ confirms that there is an upper bound on particle sizes in 'typical' pool-riffles, the implication of which is that coarse particles are large enough that they are static in bankfull conditions but still small enough to be mobilized in extreme floods. These low mobility sites show a strong morphologic trend, with meandering systems generally appearing in sites with lower ω and smaller D_{84} (e.g. East Fork R. #10 and R. La Rulles #19, and Solfatara Ck #58) followed by transitional sites (e.g. R. Quarme #25 and R. N. Tyne #26) and straight channels with higher ω and larger D_{84} (e.g. N. St. Vrain Ck #29 and Rattlesnake Ck. #40). Transitional and straight channels are close to or within the morphologic transition with the exceptions of sites #37 #51, and #24, which appeared as morphologic exceptions on Figure 1. The classification of pool morphologies into three broad categories do thus agree with the idea that scroll bars and meandering are more common farther away from the morphologic transition with finer material and lower stream power. The significance for discussions of pool-riffle formation and maintenance is that, just like the transition in bar morphology, different processes are likely to be dominant in pool-riffles as the morpholgy transitions along this gradient.

Forced pools in low mobility sites tend to appear as a cluster on Figure 2 with common characteristics such as coarse sediments (D_{84}~180 mm) and higher power (ω~100 W/m^2), and straight or transitional planforms. These sites include Moras Ck. #42; Blackledge R. #53;

Rattlesnake Ck. #40; N St Vrain #29. Their position relative to the morphologic transition suggests that scroll bars and meandering are uncommon and that forcing elements may be necessary to focus the stream power to induce scour. If this hypothesis is correct, pool-riffle frequency should correlate with the number of forcing elements (i.e. following Montgomery et al., 1995 and Thompson, 2001), and removal of forcing elements should reduce pool relief and frequency (Lisle, 1980; Wood-Smith and Buffington, 1996). Interestingly, Thompson and Fixler (2017) noted that the Blackledge pool formed in a plane-bed reach due to the introduction of a large wood (LW) piece, and recent unpublished changes show a loss of pool depth and volume following wood displacement. MacVicar and Roy (2011) similarly documented pool evolution in Moras Creek after a tree trunk shifted position. Edge cases may also be relevant despite the lack of clear forcing mechanisms. At Morse Ck (#43) for example, Wilkinson et al. (2008) noted that bridge embankments were forcing one of the pools in a series, while the Yuba River (#45) is too wide (W = 50-200 m) for individual logs or boulders to scour pools, but pool-riffles are thought to be nested within valley landform variation (Pasternack et al., 2018b). The characteristic of a forced or non-alluvial narrowing of either the channel or the valley is thus commonly associated with deep and persistent pools in coarse low-mobility systems.

Within the mobility threshold band, the trends in morphology are less clear, with a mix of meandering (#30 N St Vrain, #14 Flynn Ck. and #15 Kingledoors Burn) and transitional (#27 Highland Water and #17 Jacoby Ck). Other sites are located relatively close to this mobility band including the seminal site at #5 Dry Creek and the straight riffle pool #57 East Creek. Though the effect of channel size is not explicitly represented on Figure 2, these are all sites with relatively low discharge ($Q_{bf} \leq 15$ m3/s) and at or above Equation 1 in Figure 1. N St Vrain Ck is a useful example for comparison of the dynamics for these threshold type channels because of three sites on this river located within a 1 km reach (#28, #29 and #30) that plot in different locations on Figure 2. Site #30 is the furthest upstream and the studied pool-riffle was forced by a large boulder, but a freely formed pool-riffle was located immediately downstream. This site is at the low power limit of the morphologic transition range and has $D_{84} \approx D_{84c}$, indicating that coarse sediment supply is approximately equal to capacity and that both meandering and forcing can result in a pool in this context. Site #29 is the middle site and fits within a cluster of coarse forced pool morphologies as discussed previously. While there is some evidence of lateral mobility, pools are only associated with forcing elements in this area of the channel. Site #28 is the furthest downstream where a large boulder helps to force the pool-riffle unit, but the site was considered transitional due to secondary high-flow channels and a step-pool reach located immediately downstream, characteristics that fit with a site where chute bars are dominant and bed material is relatively mobile. Mixed planform classes can thus occur at sites with $D_{84} \approx D_{84c}$ but individual pools-riffle units may be transient. Figures 1 and 2 can thus be used to help interpret morphologic differences between sites.

Pool-riffle relief and bed-material size are known to decrease following an increase in sediment supply, with subsequent re-emergence structure following a sediment supply decrease (Lisle, 1982; Madej, 2001; Wohl and Goode, 2007). There are few high supply sites in the literature (i.e. where $D_{84} < D_{84c}$), and while their scarcity does not prove they cannot exist, it does indicate that much commonly cited pool-riffle characteristics such as a coarse riffle and pool head may be a function of low mobility. Changes can also occur to hydrology, for example in urbanized watersheds where stream power can increase with imperviousness. For example, a high frequency of competent floods led to frequent mobility of particle sizes as large as the D_{90} in an urban creek with pools and riffles (Papangelakis et al., 2019). The result was some exceptionally coarse riffles at high ω and $D_{84} > D_{84c}$ (Ghunowa et al. 2021), but coarsening will be limited by the availability of sufficient material, which in this case was glacial lag material in the floodplain. A study of channel evolution showed that avulsions sometimes occurred due to chute formation, the coarsest available material was mobilized, and riffles could be completely removed during floods to expose the underlying till (Bevan et al., 2018), changes which could be anticipated by modelling how increases in stream power would push the site towards the limits of the morphologic and mobility transitions.

These figures could also be used to aid channel restoration efforts. For example, the lack of natural analogs indicates that pool-riffle restoration should not be attempted at high mobility sites where $D_{84} < D_{84c}$. In such cases, pools are likely to fill with sediment and designs will be unstable, as has been shown in the review of in-stream restoration projects by Miller & Kochel (2009). Coarse material may be used to recreate a low mobility site where $D_{84} > D_{84c}$ by installing riffles or structures such as rock vanes, but there are limits to how large the coarse material should be if we are to mimic the natural dynamic morphology of these structures, and the installation of low mobility riffles does not preclude them failing as a result of a highly mobile sediment supply. The transition from meandering to forced pool-riffle could also be used to help parameterize the design. Forced pools are common in relatively straight channels at sites where $50 \leq \omega \leq 200$ W/m^2 and $Q_{bf} < 30$ m^3/s, but applying this concept outside the range where natural channel analogs exist could lead to higher risk designs. A restoration was attempted at Wilket Creek in Toronto, for example, where a moderately sinuous forced pool-riffle sequence was constructed in a high-power system (ω = 300 W/m^2, Q_{bf} = 38 m^3/s) (Papangelakis and MacVicar, 2021) and angular riffle material increased D_{84} from 120 to 250 mm post restoration - characteristics that place it at the upper limit of the morphologic transition on Figure 2 in a region with no natural pool-riffle analogs. The design has arrested the degradation at the site, but a sediment discontinuity has been introduced such that upstream aggradation and downstream erosion is ongoing (Papangelakis and MacVicar, 2021). Consideration of Figure 1 and 2 will allow designers to better place potential designs within the diversity of natural analogs, but more research is required before it can be recommended for design application.

The analysis presented in the current study is in many ways preliminary due to the empirical nature of the transitions and the 'found' nature of the data. Morphologic transitions are not precise due to their empirical and approximate derivation and even intensely researched mobility thresholds have been found to vary widely in field cases (Buffington & Montgomery, 1997). Planform classifications did not consider factors such as wood, temporal fluctuations in sediment supply, flow regulation, and we did not have objective measures of meandering, forcing, or pool morphology. Nevertheless, it does appear that Figures 1 and 2 can be used to group and differentiate pool-riffle sites depending on their positions relative to mobility and morphologic transitions. The two figures are complementary because of their explicit representations of discharge and particle size, respectively. Pool-riffles that have been described in the literature thus have certain features in common but show an important diversity. Some sites may represent an extreme case and so, if we can return to the analogy that was the motivation for this study, more like the trunk or tail of this proverbial elephant. They are still valuable because they describe a real case, but the importance of process-level observations at such a site should not be extrapolated to others in very different flow and sediment regime contexts. Pools in one site may be inextricably linked with planform meandering, others may rely on non-alluvial forcing elements such as a log or a boulder to scour out coarse bed material, while others may form as a type of sedimentary wave where the bed is highly mobile. Future research should consider this context of diverse sites as we work to untangle the mechanisms that underlie pool-riffle formation and maintenance.

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Open Research

Data and software to reproduce the figures are available through the Borealis Canadian Dataverse Repository (MacVicar & Thompson, 2022, doi: 10.5683/SP3/R3PSAP. Data is stored in the ascii text file (MacVicarThompsonGRL.csv) that can be analyzed by the Matlab programs (v. R2020a, no specialized toolboxes required).

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Appendix A

Table 1 – Flow and morphologic data from field study sites of pool-riffle processes

#	River	Reach	Q_{bf} (m3/s)	S (%)	W (m)	D_{50} (mm)	D_{84} (mm)	Pool Type [x]	Plan-form [y]	Reference
1	Rio Grande	1	n/a	0.08	95	n/a	n/a	FF	S (S)	Lane and Borland 1954
2	Brissell Bk.	1	n/a	4	3	n/a	n/a	-	S (-)	Wolman and Eiler 1958
3	Bronte Cr.	1	n/a	0.6	14.5^{+}	n/a	n/a	FF	M (S)	Dolling 1968

4	Hawkesbury R.	1	n/a	n/a	400$^+$	n/a	n/a	Fo	M (M)	Dury 1970
5	Dry Cr.	1	17	0.35	10$^+$	21$^+$	60	FF		Keller 1971
6	Dry Cr.	1	4.5	0.35	22.5$^+$	n/a	n/a	-	-	Jackson et al 2015
7	Knapp Cr.	1	n/a	0.5	8$^+$	46	n/a	FF	M (M)	Milligan et al. 1976
8	R. Fowey	1	n/a	0.32$^+$	7.5$^+$	64	n/a	FF	S (S)	Richards 1976b
9	Colorado R.	1	n/a	n/a	53.5$^+$	0.3	n/a	Fo	S (S)	Dolan et al. 1978
10	E. Fork R.	1	23.2	0.07	18	1.3	46	FF	M (M)	Andrews 1979
11	Fall River	1	4.1	0.125$^+$	12.5$^+$	1	10	FF	M (M)	Anthony and Harvey 1979
12	Muddy Cr.	1	1.2	0.15	5.5	n/a	n/a	FF	M (M)	Dietrich et al. 1979
13	Kaskaskia R.	1	n/a	0.13	30	22$^+$	n/a	FF	M (V)	Bhowmick and Demissie 1982
14	Flynn Cr.	1	1.2	1	3.5$^+$	10.5$^+$	22	V	M (M)	Jackson and Beschta 1982
15	Kingledoors Burn	1	9.8	1.0	6	40	90	FF	M (M)	Milne 1982
16	Boulder Cr.	1	n/a	0.6	n/a	n/a	n/a	Fo	M (M)	O'Connor et al. 1986
17	Jacoby Cr.	1	32.6	1.0$^+$	14.5$^+$	31$^+$	80	Fo	M (V)	Lisle 1986
18	Skirden Beck	1	n/a	0.48	12	48$^+$	n/a	FF	M (V)	Thompson 1986
19	R. La Rulles	1	1.3	0.3	3.5$^+$	15	33$^\wedge$	FF	M (M)	Petit 1987
20	R. Severn	0	n/a	0.027$^+$	80	22.5$^+$	n/a	FF	M (M)	Carling 1991
21		1	n/a	0.065	36.1	n/a	n/a	-	-	
22		2	n/a	0.059	30.8	n/a	n/a	-	-	
23		3	212	0.032	43.6	19.4	35	FF	M(M)	
24		4	250	0.02	37	30.5	51	FF	M(S)	
25	R. Quarme	1	5	0.7	6	50	110$^\wedge$	FF	M (S)	Clifford and Richards 1993
26	R. N. Tyne	1	167	0.18	31	58	175	FF	M (V)	Sear 1996
27	Highland Water	1	2.2	0.85	2.8	19	37	V	S (S)	Gregory et al. 1994
28	N. St. Vrain Cr.	1	10	2.6	8.4	81	144	Fo	S (M)	Thompson et al. 1996
29		2	10	1.0	8.4	77	154	Fo	S(S)	
30		3	10	0.69	10	24	50	Fo	M (M)	
31	Little Rouge R.	1	n/a	n/a	9$^+$	36	58	FF	M (S)	Robert 1997
32	N. Fk. Cache La Poudre R.	1	60	1.1	13.5$^+$	10.5$^+$	31	Fo	S (V)	Wohl and Cenderelli 2000
33	Issaquah Cr.	1	1.4	n/a	n/a	27$^+$	51	FF	M (M)	DeVries et al. 2001
34	R. Rede	1	8.5	0.6	13.5$^+$	95$^+$	131	FF	M (M)	Milan et al. 2001
35	R. Lune	1	n/a	n/a	n/a	n/a	n/a	FF	M (M)	Cao et al. 2003

36	Madden Cr.	1	n/a	0.19	9	n/a	n/a	FF	M (M)	Daniels and Rhoads 2003
37	Tom McDonald Cr.	1	3.6	0.6	10	18$^+$	66	Fo	M (S)	Hassan and Woodsmith 2004
38	Sandy Cr.	1	n/a	0.87	72.5$^+$	208	690	Fo	S (S)	Jansen and Brierley 2004
39	Steavenson R.	1	n/a	1.3	6$^+$	75$^+$	n/a	FF	S (S)	Wilkinson et al. 2004
40	Rattlesnake Cr.	1	5	2	10$^+$	88$^+$	210	Fo	S (S)	Harrison and Keller 2007
41	R. Dane	1	n/a	n/a	17.5$^+$	n/a	n/a	FF	M (M)	Hooke 2007
42	Moras Cr.	1	4.9	1.2	6	60	190	Fo	M (S)	MacVicar and Roy 2011
43	Morse Cr.	1	60	0.44	16	90$^+$	184	FF	S (S)	Wilkinson et al. 2008
44	Red R.	1	16.6	0.17	14.8$^+$	54$^+$	84	FF	M (M)	Caamano et a. 2009
45	Yuba R.	1	142	0.37$^+$	126$^+$	79$^+$	173$^\wedge$	FF	M (S)	Sawyer et al. 2010
46	Bear Cr.	1	310	0.2	35$^+$	30	45	FF	M (M)	de Almeida and Rodrigues 2011
47	Mulde R.	1	n/a	0.024$^+$	50$^+$	10.5$^+$	25	FF	M (S/M)	Vetter 2011
48		2	320	0.028	50$^+$	n/a	25	FF	M (S/M)	
49		3	320	0.017	50$^+$	n/a	25	FF	M (S/M)	
50	Bury Green Bk.	1	2.5	0.8	4.7$^+$	35$^+$	49	FF	M (V)	Hodge et al. 2013
51	Majors Cr.	1	5.7	0.3	7$^+$	7	43	FF	M (S)	Chartrand et a. 2015
52	San Joaquin R.	1	40	0.059	60	65$^+$	97	FF	M (M)	Bray and Dunne 2017
53	Blackledge R.	1	30	0.38	18	79	169	Fo	M (S)	Thompson and Fixler 2017
54	Kaj R.	1	n/a	n/a	9$^+$	34$^+$	n/a	FF	M (S)	Najafabadi et al. 2018
55	Madeira/Mississippi R.	1	n/a	n/a	n/a	0.2$^+$	n/a	V	M (M)	Gibson et al. 2019
56	Babolroud R.	1	n/a	0.003	18.5$^+$	43$^+$	63	FF	M (S)	Najafabadi and Afzalimehr 2019
57	East Cr.	1	2	1.8	2.8	49	88	FF	S (S)	Papangelakis & Hassan (2016)
58	Solfatara Cr.	1	2.4	0.1	5.2	12	25	FF	M	Whiting and Dietrich (1993)
59	Durance R.	1	500	0.23	290	40	89	FF	M	Chapuis et al. 2015

Notes: [+]average of recorded range; ^D_{84} estimated as $2.2D_{50}$; x Pool types are classified as free-formed (FF), forced (Fo) or variable (V); y Planform is classified as meandering (M) or straight (S) for the reach, with local study site in parentheses.