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Channel constriction predicts pool-riffle velocity reversals across landscapes

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Key Points:

- 702 pool-riffle couplets from a large field dataset were analyzed using a mass and energy conservation-based velocity reversal criterion
- Velocity reversals are relatively infrequent, but comprise more than 50% of couplets with riffle-to-pool top width ratios greater than 1.2
- Velocity reversal pools were almost always found at width constrictions and riffles at width expansions, though to a lesser extent

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Abstract

Research regarding self-maintenance of pool-riffle river morphology has focused on hydraulics within individual pool-riffle couplets. Here we make a scientific leap from one site on river to 702 pool-riffle couplets across northern California to understand the frequency of the foundational velocity-reversal hypothesis. A geometrical, mass and energy conservation-based velocity reversal criterion was used to predict the occurrence of a velocity reversal. Only 18% of all couplets met the established criteria indicating a velocity reversal. At locations with riffle-to-pool bankfull width ratios greater than 1.2, more than 50% of couplets met velocity-reversal conditions. Velocity reversal pools were almost always (89%) associated with channel constrictions while riffles were typically (71%) associated with channel expansions, albeit less often. Therefore, across landscapes, it appears channel constrictions propagate velocity reversal maintenance. Phasing between width and depth variability is central to fluvial morphodynamics and ecology and must be considered in sustainable river eco-engineering.

Plain Language Summary

Deep pools and shallow riffles occur in most river systems and are formed through an interaction between the water flowing through a river and the sediment it carries and deposits. Several more technical hypotheses have been developed as to why pools and riffles form where they do. The original hypothesis, called the velocity reversal hypothesis, suggested that while pools commonly have slow moving water, at higher flood event flows, pools are subjected to greater velocities than riffles, which causes the removal of sediment at the stream bed. While this has been shown to only be true in certain circumstances, we sought to quantify how often velocity reversals do occur. Due to the large field dataset, this research presented a unique opportunity to understand how frequently a river process, such as a velocity reversal, occurs across a landscape. We found that velocity reversals are relatively uncommon and occur in only 18% of pool-riffle pairs. Where reversals do occur, the river narrows and then widens to a greater degree than other locations that are closer to the average width. We suggest that future studies need to focus on the prevalence of river processes in rivers for improved river restoration strategies.

1 Introduction

Seminal research about river hydraulic geometry determined that central tendencies of alluvial river size and shape are highly correlated with the discharge magnitude of frequent floods (Ferguson, 1986; Leopold & Maddock, 1953; Park, 1977; Parker, 1979). On the basis of that and derivative research, modern physical river science and eco-engineering are dominated by theories and practices emphasizing central tendency, ignoring data variability as noise (Chen et al., 2014; Doyle et al., 2007). However, rivers exhibit a large array of spatially correlated physical processes that depend on river size and shape varying downstream, thus not remaining constant at central-tendency dimensions (Kleinhans, 2010; Wilkinson et al., 2008; Wyrick & Pasternack, 2014). As near-census (~1 m resolution) topographic datasets equitably representing nested scales of variance become ubiquitous, river science must make a paradigm shift away from roots in central tendency toward one embracing coherent varying patterns. To highlight the importance of variability over central tendency, this study presents a novel analysis of a unique regional-scale field-derived geomorphic dataset.

Many rivers around the world exhibit variability in the form of alternating sequences of riffle and pool landforms. The velocity-reversal hypothesis was one of the seminal mechanisms proposed to explain pool-riffle couplet persistence, here termed self-maintenance (Keller, 1971; Tinkler, 1970; Yang, 1971). The velocity-reversal hypothesis posits that, compared to riffles, pools have lower near-bed flow velocities and shear stresses at low discharges, and greater near-bed velocities and shear stresses at bankfull discharge (i.e., flow that fill riverbanks). At the discharge triggering a velocity reversal, the largest sediment particle size that pools and riffles can transport equilibrates and reverses, thus depositing the largest clasts on the riffle, keeping riffles topographically high and pools low. This theory originally assumed steady, uniform flow, yet by definition riffles and pools have very different hydraulics (Keller, 1971). Keller's theory explores simple fluid effects of varying depth and slope between riffles and pools but ignores varying width (Keller, 1971). Generalizing Keller's theory and holding to the assumption of flow continuity between pool and riffle, a cross-sectional velocity reversal is assumed when pool cross-sectional area is sufficiently smaller than that of the downstream riffle (Caamaño et al., 2009; Keller, 1971).

Since Keller's original hypothesis, fluvial geomorphologists have debated the physics and natural occurrence of velocity reversals (Carling, 1991; Thompson, 2011). Improved and alternate theories and mechanisms about pool-riffle maintenance include energy expenditure minimization (Yang, 1971), energy expenditure convergence at pools and riffles (Heritage & Milan, 2004), flow convergence routing (MacWilliams et al., 2006), grain-size influenced self-maintenance (Bayat et al., 2017), jet flow (Thompson et al., 1998), turbulence (MacVicar & Roy, 2007; Thompson, 2007), or a combination of proposed maintenance processes (Thompson & Wohl, 2009). Due to the overwhelming evidence of other processes playing a role in pool-riffle maintenance in individual situations, the velocity reversal is likely only one of multiple maintenance processes within pool-riffle streams.

1.1 Investigating velocity reversals across landscapes

Most riffle-pool self-maintenance articles rely on a small number of pool-riffle couplets measured in either field, flume, or computational settings. Predominantly, only one to four couplets in one reach were explored. Methods and data among studies are not sufficiently comparable for meta-evaluation (Gonzalez & Pasternack, 2015). Recently, topo-bathymetric LiDAR and multi-dimensional hydrodynamic modeling have yielded a few studies of longer sequences of couplets, but still on individual rivers (Strom et al., 2016). Even after 50 years of work, the frequency of velocity reversal across a landscape is unknown. Notably, pool-riffle streams need not have any self-maintenance at all if pools and riffles are transient, or possibly streams could have a variety of self-maintenance mechanisms including velocity reversal. Meanwhile, aquatic ecology restoration languishes due to the lack of practical concepts and tools for designing dynamic yet self-sustainable alluvial riffle-pool sequences (Pasternack, 2020), though recent articles evaluate better ways to institute morphodynamic processes that rejuvenate rather than destroy such sequences (Brown et al., 2016; Chartrand et al., 2018; Schwartz et al., 2015). Still, the critical knowledge gap arising from the lack of meta-synthesis due to incommensurate study designs and insufficient regional and continental scales of analysis prevents translation of current riffle-pool scientific thinking to river engineering. For example, if riffle-pool self-maintenance differs by higher controls such as channel type or valley confinement, then self-sustainable river design should focus on them. Our investigation is the first to shift focus on a single pool-riffle formational mechanism from a few couplets to 702 couplets over a large region and ask the following two novel scientific questions: Question 1, at bankfull discharge, what is the frequency of cross-sectional velocity reversal conditions in pool-riffle couplets across a landscape; and Question 2, if any, which differences in reach or cross-sectional morphology explain the presence or absence of velocity reversal conditions?

2 Materials and Methods

2.1 General methodological approach

To address Question 1, we performed 171 reach-scale (~10-20 times bankfull width) cross-sectional bankfull surveys using a consistent methodology and careful sampling design (Byrne et al., 2020; also summarized in Section 2.3). Surveys were conducted throughout northern coastal California, which includes the Smith, Klamath, Trinity, and Eel River watersheds. Data included 702 pool-riffle couplets across diverse channel types (see Table S1 in Supplementary Information). Each couplet was evaluated using a mass and energy conservation-based velocity reversal criterion (Caamaño et al., 2009), which established a geometric methodology to predict the presence of a velocity-reversal (see Section 2.3), and the percentage of sites with velocity reversals was subsequently calculated.

For Question 2, we first analyzed 15 common bankfull channel attributes to determine which channel characteristics explain velocity reversal occurrence: reach-averaged depth, pool depth, riffle depth, residual pool depth, reach-averaged width, pool width, riffle width, reach-averaged width-to-depth ratio, riffle-to-pool bankfull width ratio, reach-scale coefficient of variation in depth, reach-scale coefficient of variation in width, median reach grain size, 84th percentile reach grain size, valley confinement distance, and stream order. For each attribute, Wilcoxon rank sum tests were used to assess differences between riffle-pool couplets with or without velocity reversal conditions.

Second, standardized width and elevation of each pool and riffle were calculated in comparison to ten other equally spaced cross-sections in the same reach to describe the channel as narrower, wider, shallower, or deeper than mean channel reach dimensions. Along reaches with more than one pool-riffle couplet, depths and widths of all pool-riffle couplets were included in this calculation as well. Standardized width and elevation represent the deviation from mean channel conditions and allow comparison across sites. Wilcoxon rank sum tests were used to assess differences between pool-riffle couplets with or without velocity reversal conditions.

2.2 Study location

Northern coastal California is defined by a Mediterranean climate with hot, dry summers and cool, wet winters. Rivers in the region generally display flashy hydrographs and flow conditions are extremely responsive to storm events which can trigger substantial geomorphic work (Sloan et al., 2001). Rivers in the region also have relatively high sediment yields per square kilometer (Milliman & Syvitski, 1992). As part of a statewide investigation of reach-scale channel types in California, the 171 reach-scale surveys used in this study exist across a range of channel morphologies (see Supplementary Information). Regional rivers and their tributaries are important refugia for California salmon and steelhead populations (Olson et al., 2012; Power et al., 2015). With the exception of the Smith River, which remains undammed and largely unimpacted by humans, major anthropogenic influences in the basin include logging, mining, and cannabis cultivation in the predominant mountainous landscapes (Palmer, 2012). In the relatively low proportion of upland and coastal valleys, the landscape has been altered for agricultural or urban land uses.

2.3 Site selection and field surveys

Reach surveys were conducted at 171 locations within the study area. Drainage areas at these locations ranged from 1 to 1934 km^2, corresponding to first to fifth Strahler-order streams. Sites were selected as part of a larger California-wide channel type assessment, which strived to sample streams at diverse hydrogeomorphic locations across the state. The methodology used a two-tiered stratified sampling approach from 200-m segments of the National Hydrography Dataset version 2 (NHD) streamline layer (McKay et al., 2012; Byrne et al., 2020). The 171 reach surveys used here were part of a larger dataset with 1,012 survey sites. The purpose of the stratified sampling approach was to approximate the sediment supply and transport regimes at every 200-m stream segment in the state of California using statewide, available datasets. While the protocol was developed for the entire state, the protocol was applied within nine management regions: Klamath, North Coast, South Fork Eel, North Central Coast, Sacramento, San Joaquin-Tulare, South Central Coast, South Coast, Southeast California (Figure S1). In this way, we hoped to survey diverse channel locations and not just the most common and accessible streams. Due to California's diverse geology and climate only South Fork Eel, North Coast, and Klamath regional rivers, here termed northern, coastal California, were included here as to focus on predominantly cobble-gravel pool-riffle couplets subjected to similar hydrologic regimes (Lane et al., 2018). The following strategy documents the selection of diverse sites across the entire state of California, which the 171 sites used here made up less than 20% of the statewide dataset.

First, estimates of valley confinement and sediment supply were calculated as a proxy for potential sediment supply. Valley confinement, here defined as the distance from the nearest valley wall (Byrne et al., 2020), was estimated using ESRI's ArcMap as the perpendicular distance between an NHD streamline segment and valley walls on both sides of the segment. The value was calculated as the average of four cross-sections along each reach for every 200-m stream segment in California. Streams were then binned into confined, partly-confined, and unconfined segments based on valley confinement distances <100, 100-1,000, and > 1,000 m, respectively. California's diverse landscape includes numerous mountain ranges and unconfined valleys. The total number of streams is exponentially greater in the headwaters (first-order) of a drainage network, which, in California, predominantly occur in confined valley settings. Since the sampling protocol was developed for a channel type assessment, a purely random sampling strategy would not ensure that all types of systems are sufficiently represented to define a channel type. Therefore, the purpose of the logarithmic scale of confinement classification was to ensure that site selection was balanced across valley settings. Sediment supply was estimated using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991). At each site, RUSLE allowed for the incorporation of statewide datasets that represent rainfall-runoff erosivity, soil erodibility, slope characteristics, and land cover. Streams were binned into two groups based on sediment supply at a value of <225 and >225 t/km^2/year. This value was determined during protocol development for Byrne et al. (2020) and represented the approximate mean value of sediment supply in the Sacramento River basin. Binning methodologies remained the same for streams across California, but it should be noted that the value is an appropriate threshold for sediment supply in northern, coastal California streams as well (Kelsey, 1980). This methodology resulted in six upper-level bins. With respect to this study, streams in northern coastal California are predominantly confined (77%) and estimated to be subjected more often to higher sediment supply (56%), although characteristics of the coastal mountains are an important factor in sediment supply to streams (Kelsey, 1980).

The second lower-level tier of the stratified sampling technique was a surrogate for transport capacity with the combination of drainage area and slope at each NHD segment. Drainage area for a given 200-m segment was estimated using the Stream-Catchment dataset (Hill et al., 2016). Slope was calculated as the difference between the upstream and downstream 10-m elevations divided by the 200-m length. Two-dimensional distributions for drainage area and slope for each of the six upper-level bins were split into five lower-level bins using a k-means algorithm in the 'stats' package in the R programming language (R Core Team, 2017). All bins were sampled at least once for each of the two years that 60-site regional survey campaigns were conducted. This means that an upper level bin (e.g., confined-high sediment, confined-low sediment supply, etc.) would have at minimum five survey locations across a range of drainage area and slope per survey campaign. After initial allotment of five survey sites across all upper level bins, upper level bins with a larger proportion of 200-m segments across the entire drainage networks were sampled at a higher proportion. Bins were assigned sites in five site increments based on percentage of total streams within a given statewide survey region. In northern, coastal California this led to more sites in the confined, high sediment supply bin than any other bin. The goal of this proportional addition of sites to the stratified sampling approach was to survey streams of all geomorphic channel types while also being recognizant of the most common geomorphic settings throughout the networks.

While stratified sampling was conducted across the state, this study, as mentioned previously, only focused on pool-riffle couplets in the more similar geographic and climatic region of northern, coastal California. After binning was conducted for site selection, no further use of the bins was used in analysis. A total of 702 pool troughs and riffle crests were surveyed along the 171 stream reaches, in addition to ten equally spaced transects along each reach (Lane & Byrne, 2021; Byrne, 2021). Total survey lengths for all sites was approximately 15-times the estimated average bankfull width at the reach. At each transect, thalweg bankfull depth and width were recorded. A longitudinal stream survey also recorded elevation change between every other equally spaced transect and every pool trough and riffle crest. The following reach-scale attributes were calculated based on cross-sectional surveys: mean bankfull depth, mean bankfull width, coefficient of variation in bankfull depth, coefficient of variation in bankfull width, and mean bankfull width-to-depth ratio.

2.4 Criterion for cross-sectional velocity reversal

Caamaño et al. (2009) introduced a geometric criterion for the occurrence of a velocity reversal in a pool-riffle couplet based on mass and energy conservation given by:.

$$\frac{B_R}{B_P} - 1 > \frac{D_z}{h_{R_t}} \qquad (1)$$

Here, B_R and B_P represent riffle and pool bankfull top width, respectively. D_z represents residual pool depth, or the vertical distance between the upstream pool trough and downstream riffle crest, and h_{Rt} is bankfull depth at the downstream riffle crest. If equation (1) is true, then a velocity reversal must occur to conserve mass and energy through the simplified cross-sections. This criterion, here termed the Caamaño criterion, makes two key assumptions: the pool and riffle exhibit similar channel shapes at channel forming flows (here deemed bankfull discharge) and head losses, both from expansion and friction, are neglected (Caamaño et al., 2009).

2.5 Standardized stream dimensionality

Relationships between standardized width and elevation at a stream cross-section, which will vary along a reach, define whether a river is shallow or deep and narrow or wide at any cross-section in comparison to other reach cross-sections. The landforms are determined using standardized channel width (W_s) and standardized bed elevation (Z_s). Standardized channel width was calculated at each selected site for every surveyed channel cross-section using bankfull channel width measurements following:.

$$\boldsymbol{W_s = \frac{(w_t - w_r)}{\sigma_w}} \qquad (2)$$

Here, w_t is the transect bankfull width, w_r is the mean bankfull channel width at a given survey reach, and σ_w is the standard deviation in bankfull channel width at the same survey reach. Standardized channel bed elevation was also calculated at each cross-section where d_r is the reach averaged depth, d_t is the transect bankfull thalweg depth, and σ_d is the standard deviation of bankfull thalweg depths at all transects in the reach following:.

$$\boldsymbol{Z_s = \frac{(d_r - d_t)}{\sigma_d}} \qquad \mathbf{(3)}$$

After calculating W_s and Z_s for each transect along a reach, any given transect can be described as narrower (negative W_s) or wider (positive W_s) than mean channel width, as well as shallower (positive Z_s) or deeper (negative Z_s).

3 Results: Velocity reversals are infrequent but predictable

Approximately 18% of all pool-riffle couplets surveyed across northern coastal California streams met the Caamaño criterion for the existence of cross-sectional velocity reversal conditions at bankfull stage (Figure 1a). The frequencies of velocity reversal conditions were greatest in pool-riffle couplets with the highest width variability including associated with plane bed (22% of couplets), pool-riffle (21% of couplets), and cascade/step-pool (20%) reach-averaged channel types (Supplementary Table S1). Frequencies were lowest in channel types with lower width variability including uniform (17%), step-pool (14%), and bed undulating (4%) locations. It should be noted that pool-riffle couplets were found in all stream types as documented here. While this seems counterintuitive to the channel type names, stream reaches were classified according to a multi-dimensional statistical approach (Byrne et al., 2020) based on the overall state of the reach, which could therefore include individual pool-riffle couplets within an otherwise "step-pool" or "cascade" dominated reach. An important scientific finding from the classification effort was the critical role of variability in width and depth through a reach compared to the role of the central tendency of these variables. For example, a confined, steep reach with a series of step-pool couplets could be interrupted by a single riffle-pool unit for any number of reasons. As the channel typing was done independently from the velocity reversal analysis, velocity reversal findings justify the channel typology as higher variability channel types exhibited higher percentages of pool-riffle couplets meeting the Caamaño criterion.

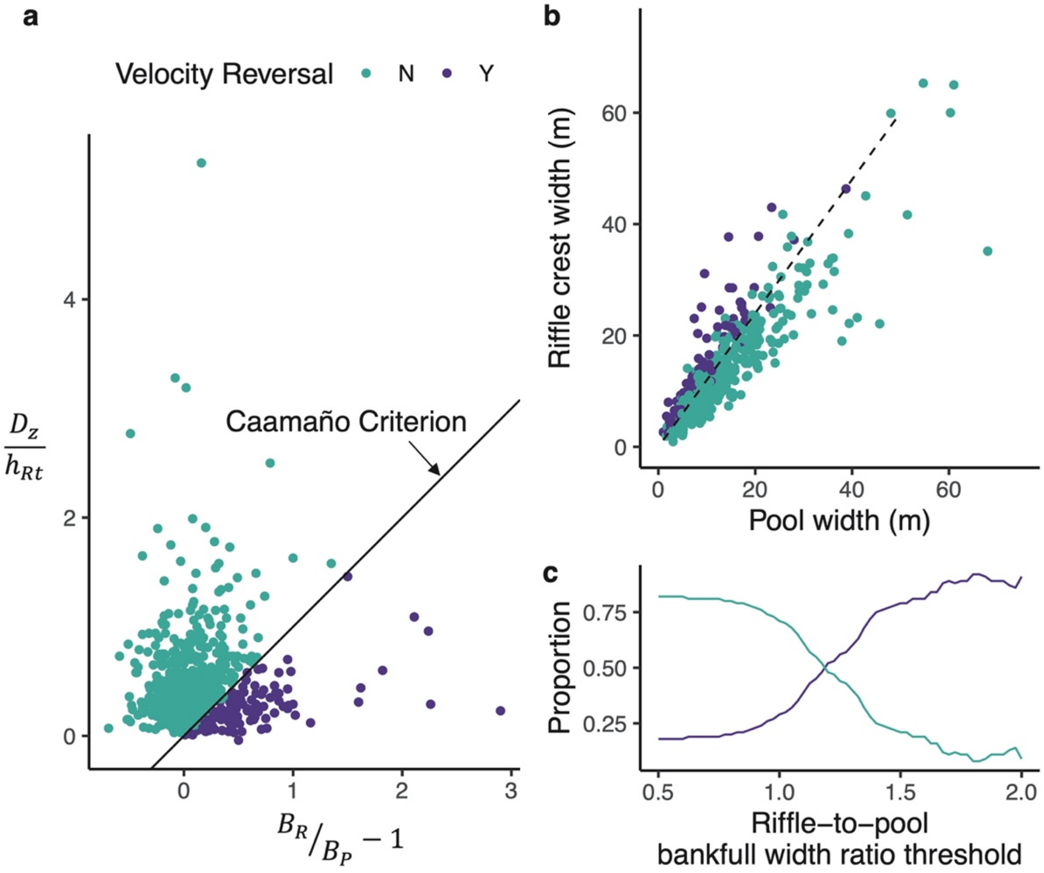

Figure 1. (a) Results of Caamaño Criterion analysis of 702 pool-riffle couplets in northern coastal California; (b) relationships between riffle and pool bankfull width in association with velocity reversal conditions and riffle-to-pool bankfull width ratio of 1.2 (dashed line); and (c) the proportion of couplets exhibiting velocity reversal conditions at or above a given riffle-to-pool bankfull width ratio.

Based on the Wilcoxon rank sum tests, the strongest non-standardized predictor of velocity reversal occurrence was riffle-to-pool bankfull width ratio, which indicated that velocity reversals are more common than not in pool-riffle couplets with a ratio greater than 1.2 (Figure 1b;c). The relationship between riffle-pool bankfull width ratio and velocity reversal occurrence is logical based on the defining test criterion accounting for width variability but deviates strongly from the mechanistic expectation in Keller's physical explanation which emphasized depth differences. The large number of couplets used in this study provides a basis for what is likely a relatively stable width ratio value in this region. Velocity reversal conditions also occurred in reaches with lower bankfull width-to-depth ratios, greater width variability, and smaller median grain size, while also exhibiting smaller residual pool depths as previously hypothesized (Caamaño et al., 2009), smaller pool widths, and greater riffle depths ($p < 0.05$;

Supplementary Information Table S2). No significant differences in the occurrence of velocity reversals were found between valley confinement settings, which suggests that velocity reversal presence is a localized feature rather than a feature dependent on broader topographic landscape patterns. However, unconfined streams were sampled at a lower proportion in the mountainous terrain of northern coastal California, so this distribution might change in other landscapes. Yet, unconfined rivers are often extremely altered and thus difficult to sufficiently sample with reasonably natural riffle-pool conditions.

All distributions of standardized elevation and width were significantly different between couplets that did and did not exhibit velocity reversal conditions ($p < 0.05$; Supplementary Information Table S2) (Figure 2). While velocity reversals tended to occur at locations with standardized elevations closer to reach averages, a clearer deviation in standardized width characterized velocity reversal locations. Width constriction, or cross-sectional width less than mean reach width, was most highly associated with velocity reversal locations as compared to any other channel attribute analyzed. Of all couplets surveyed, 60% of pools occurred at reach locations that were constricted while 53% of riffles occurred at locations that were wider than the mean reach width. At locations predicted to exhibit velocity reversals, 89% of pools occurred in constricted locations while 71% of riffles occurred in wide locations. This suggests that a width constriction is almost always required for a velocity reversal to occur, and an equivalent widening relative to mean reach width is common but not always needed.

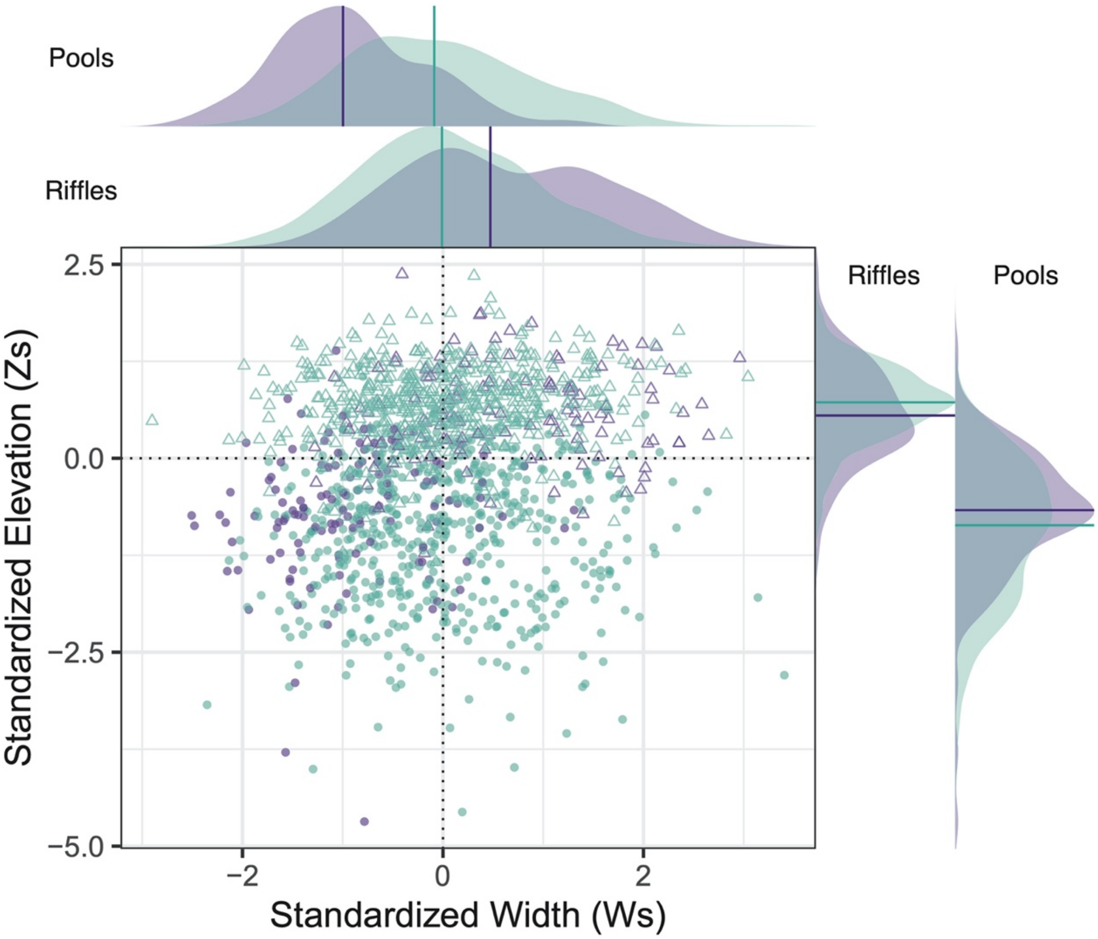

Figure 2. Distribution of field-identified pools (circles) and riffles (triangles) in terms of standardized width and elevation as well as velocity reversal (purple) and no velocity reversal (teal) locations. Purple and teal solid lines represent median standardized width and elevation for pools and riffles under velocity reversal and no velocity reversal conditions.

4 Understanding maintenance mechanisms within physical-temporal context

Our results display a clear linkage between form and process and demonstrate that dimensional variability of a river channel is critically linked to a formational mechanism. Based on the frequency of constrictions observed here, statistically observable channel constriction is more often a requisite channel attribute for velocity reversal conditions than is width expansion. Previous research in alluvial rivers has suggested that pools exist at channel width constrictions and riffles at expansions (Chartrand et al., 2018; White et al., 2010). Even in bedrock-influenced rivers, channel constriction is associated with pool location (Wohl & Legleiter, 2003). Beyond a specific channel maintenance mechanism, width variability has been linked to extremal hypotheses that have been proposed as the foundational mechanisms of dynamic equilibrium in alluvial rivers (Tranmer et al., 2019). Given that a velocity reversal is only one proposed mechanism for pool-riffle maintenance, realization of extremal hypotheses of dynamic equilibrium is likely to be achieved by different processes (e.g., jet flow, turbulence, flow convergence routing, etc.) at different locations along a river because of the numerous external forcings to which rivers are subjected. For example, a reach may include one pool-riffle couplet that is being maintained by a velocity reversal while another pool-riffle couplet may be the product of jet flow created by large woody debris within the channel.

The hierarchical nesting of channel forms, as well as differences in hydrologic and sediment regimes, further complicate linkages between form and flow (Chartrand et al., 2018; Pasternack et al., 2018; Pittaluga et al., 2014). This study only examines estimated conditions at bankfull flow, but there is no requirement that all pool-riffle couplets must be maintained at bankfull flow conditions (Sawyer et al., 2010) or that forms and processes will not vary across flows (Thompson & Wohl, 2009). While the conceptualization of bankfull flow has driven understanding of rivers and bankfull channel form, it is rooted in a paradigm that over-emphasizes central tendency. Bankfull flow has been shown to be a good approximation for effective discharge (Lenzi et al., 2006), especially in temperate rivers, but research suggests that river channel morphology is a product of all flows rather than the effective discharge (Pittaluga et al., 2014). In addition to the magnitude of channel forming floods, the complexity of mountain rivers can produce nested structures that are likely to adjust river bedforms in different ways (Pasternack et al., 2021). Pool-riffle couplets may exhibit velocity-reversal conditions at different flow conditions (Strom et al., 2016), changes in flow and sediment supply may lead to alteration of pool-riffle couplets and associated processes (Caamaño et al., 2009; Chartrand et al., 2018; Morgan and Nelson, 2021), or a stochastic forcing (e.g. large woody debris) may create a pool at a higher flow that persists at lower flows such as bankfull (Buffington et al., 2002). Due to river channel complexity, the relative abundance of velocity reversals may or may not necessarily peak at near-bankfull flow conditions. Even if bankfull discharge is assumed to equate to effective discharge, it does not necessarily mean that a given formational process will always be most prevalent at effective discharge. While this research has shown the benefit of linking form to process across a landscape, reconciliation of river form must also be done across flows with the understanding that forms and associated processes will change across the landscape as well.

Formational processes of pool-riffle couplets may also change under different management strategies. Pool-riffle morphology creates important heterogeneity of lotic habitats (Brown & Brussock, 1991; Gelwick, 1990), therefore, human alteration of rivers leading to channel change may alter couplet form and the associated formational process. For example, heavily impacted and often incised streams in the agricultural Central Valley of California exhibit low width-to-depth ratios (Byrne et al., 2020). Because velocity reversal streams were found to have lower width-to-depth ratios, it may be that degraded, incised streams tend to have a greater proportion of velocity-reversal maintained couplets. Incised streams can exhibit lower habitat quality due to smaller pool depths (Shields et al., 1994), and this may be a result of velocity-reversal maintenance producing smaller residual pool depths, which was found here. Knowledge of how pool-riffle formations differ based on different formational processes could point to the shifting of processes under different management scenarios.

This study does not address the full range of hydro-morphodynamic processes that occur in California's rivers; it focuses on one, important mechanism. This study assumes that pool-riffle couplets that meet the Caamaño criterion will likely exhibit a cross-sectional velocity reversal. Caamaño et al. (2009) show that the criterion is accurate for the selected pool-riffle couplets. In an independent test of the Caamaño criterion using two-dimensional hydrodynamic modeling, Jackson et al. (2015) found that it accurately predicted reversal occurrence for a number of incrementally altered terrains, but it did not perform well for subtle terrain having a weak reversal. For the present study, it is statistically unlikely that the criterion is one hundred percent correct for our large sample size with a wide range of topographic patterns. A limitation of this study is that we could not field verify these conditions or monitor individual sites over time; California is also in the midst of an exceptional drought yielding few floods and many study sites are difficult to access. Yet, the larger aim of this study, that is to understand the frequency of a formational river processes over a large area, was achieved here with a novel methodology based on previous literature. Such quantitative studies with large sample sizes should continue to be developed and investigated to understand river management, especially if restoration of rivers across entire stream networks is to be an achievable goal.

5 Conclusions

The frequency of formational fluvial processes is not well quantified. In this study, we used a large regional field dataset in combination with a previously established mass and energy conservation-based velocity reversal criterion to estimate the frequency of a formational mechanism across a landscape for the first time. We found that velocity reversals are predicted to occur relatively infrequently within pool-riffle couplets across northern, coastal California and preferentially occur at channel width constrictions, presented here as statistically narrow portions of the channel. Further, we found that a threshold of bankfull riffle-to-pool width ratio existed at which pool-riffle couplets are more likely than not to be subjected to a velocity reversal, which is likely to be stable for the region based upon the large sample size. This study showed that novel methodologies can be used to better understand the frequency of formational channel mechanisms across different landscape settings and channel types. However, further investigations may show different results due to different landscape characteristics, variable flow conditions, and different levels of impairment. To add more complexity, this study indicates that a singular maintenance mechanism is not likely to be the only relevant mechanism within a river reach and perhaps not even at a single pool-riffle couplet. This finding highlights the importance of river variability over central tendency in describing formational mechanisms. In summary, more complete understanding of the interplay of river channel formational mechanisms through reaches and landscapes is critically needed to inform river management, restoration efforts, and engineering strategies.

Acknowledgments, Samples, and Data

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