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Wood jam characteristics influence but do not fully explain wood jam morphologic functions

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Abstract In-stream wood jams alter their surrounding channel morphology, thus setting riverscape morphology and ecosystem function. While wood jams clearly scour pools, retain sediment, and influence bank erosion, there is a lack of observational evidence of how wood jam characteristics themselves control morphologic effects. Here, I analyzed field observations of hundreds of wood jams to test the hypothesis that wood jam characteristics can predict local morphologic effects such as sediment retention, bar forcing, and pool scour. I found mixed support for this hypothesis: While jam characteristics such as porosity, channel blockage ratio, thalweg occupation, and having rootwads and multiple trunks significantly predicted morphologic effect occurrence and magnitude, they only explained a small portion of the variance in those morphologic effects. While wood jam characteristics are relevant in controlling their overall morphologic functions, those functions are both inherently variable and likely affected by numerous other factors, such as reach-scale topography, the sediment transport capacity to supply ratio, and interactions with surrounding wood and vegetation. Wood function restoration may be more effective if it targets reach-scale objectives across dynamic wood jam assemblages, instead of individual jams.

Non-technical summary Accumulations of logs, or wood jams, in rivers shape the landforms around them, such as pools and mounds of sediment known as bars. I hypothesized that the characteristics of wood jams, such as how densely packed they are, where they are in the river channel, and how much of the channel they block, would determine the size and nature of their effects on the shape of the river channel bed. I tested that hypothesis by examining hundreds of river-made and human-made wood jams and measuring their effects on the channel around them. I found that wood jam characteristics do explain some of the wood jam effects on the channel bed. However, the effects wood jams have on the shape of the river around them vary widely and cannot be fully explained by wood jam characteristics alone. Other factors, such as the shape of the river upstream and the amount of sediment being transported down the river may also play substantial roles in determining how wood jams shape their riverine landscape. These results imply that efforts to restore wood to rivers may be more successful if they account for the variability in how wood jams shape their local riverine landscape.

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1 Introduction

Wood is a transient but influential component of the riverine landscape, or riverscape (Wohl et al., 2019, 2023). Wood jams, here defined as accumulations of three or more pieces of wood greater than 1 m long and 10 cm in diameter in contact, can influence local and reach-scale hydraulics by causing constricted, backwatered, jet, wake, or plunging flow (Addy and Wilkinson, 2019; Geertsema et al., 2020; Müller et al., 2022; Schalko et al., 2021; Zhang and Rutherfurd, 2020). These hydraulic influences increase hydraulic heterogeneity, diversifying patterns of erosion and deposition and thus producing varied topography (Buffington et al., 2002; Collins et al., 2012; Keller and Swanson, 1979; Latterell et al., 2006; Pagliara and Kurdistani, 2017; Pfeiffer and Wohl, 2018). How wood jams influence channel and floodplain topography defines their morphologic function. The morphologic functions of wood jams form the physical foundation of how wood influences not only geomorphic evolution, but also ecosystem character and function.

Past field observational studies of wood influences on in-stream morphodynamics tend to be limited to noting the correlation between wood presence and associated morphologic effects. Field observations of pools, bars, and sediment wedges apparently created by in-stream wood are abundant (e.g., Brummer et al., 2006; Buffington et al., 2002; Keller and Swanson, 1979; Latterell et al., 2006; Leung, 2019; Martens and Devine, 2023; Mikuś et al., 2013; Montgomery et al., 1995; Pfeiffer and Wohl, 2018; Wohl et al., 2022; Wohl and Scott, 2017), but tend to be made at the reach-scale and thus focus on the morphologic function of wood at that scale. Few field studies move beyond the correlation between wood and associated morphologic effects to examine the variability in wood-induced morphodynamics: Wood jams have generally been found to have a greater hydraulic and morphodynamic influence at lower porosities (Manners et al., 2007), greater channel blockage (Addy and

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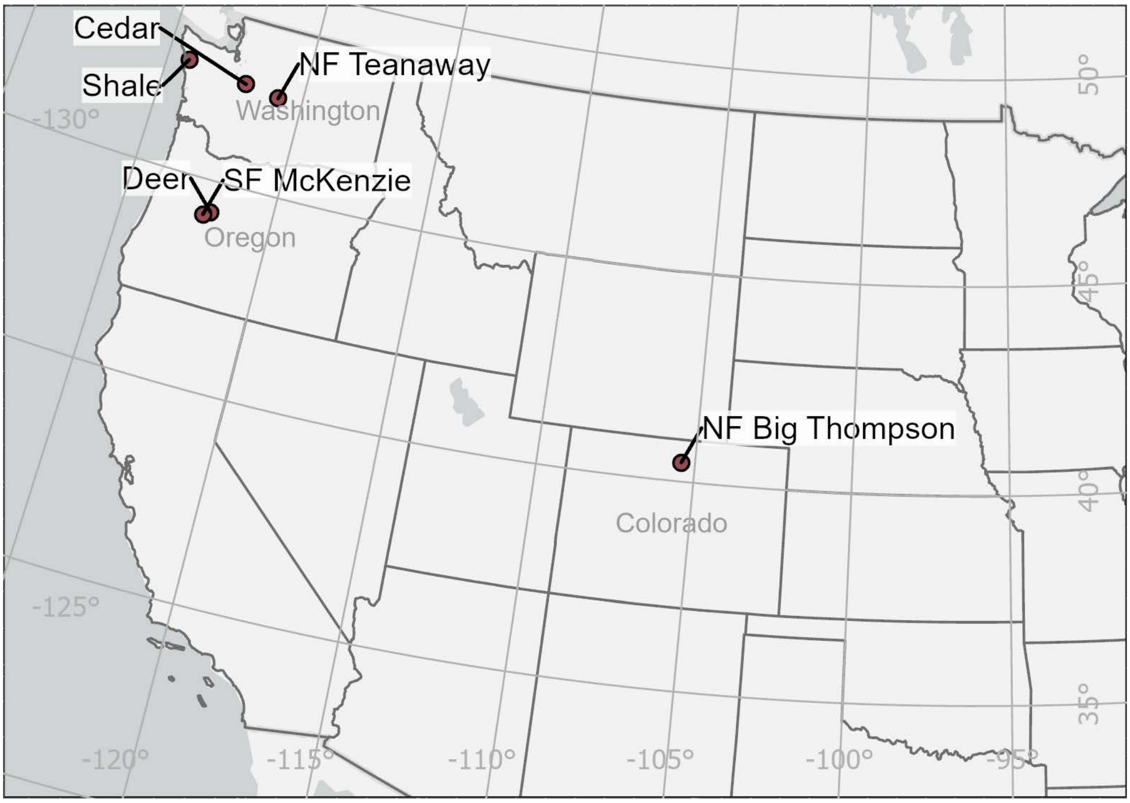

Figure 1 Map of study sites showing locations in the Western United States. NF is North Fork and SF is South Fork. Grid shows latitude and longitude lines.

Wilkinson, 2016; Livers and Wohl, 2021), at certain locations relative to banks and other wood jams (Zhang and Rutherfurd, 2020), and when jams have large, rootwad-attached logs and are perpendicular to flow (Kail, 2003; Martens and Devine, 2023; Ravazzolo et al., 2015; Seixas et al., 2020).

Our more detailed understanding of how wood-induced morphologic functions vary in response to wood and riverscape characteristics comes primarily from flume experiments. Experimental observations of both wood jams and single logs suggest that wood porosity, size relative to channel cross-sectional area, orientation, and rootwad presence control the magnitude of either scour or deposition (Cherry and Beschta, 1989; Gippel et al., 1996; Ravazzolo et al., 2022; Schalko et al., 2021; Schalko and Nepf, 2024; Svoboda and Russell, 2011; Wallerstein et al., 2001). While such studies provide much more detailed insights into the interactions between specific wood characteristics and morphodynamics than field studies, they cannot account for or describe the real riverscape complexity in hydraulics, sediment dynamics, and wood the way that field studies can.

Here, I seek to bridge the gap between experimental and field observational work on wood morphodynamic influences by exploring how a broad array of wood jam characteristics control wood-induced morphologic functions in the context of diverse riverscape geomorphic characteristics. By measuring wood jam morphologic effects and the characteristics that might influence them, I hope to advance our ability to predict the local morphologic function of wood jams (e.g., pool scour and bar deposition), helping to inform both our understanding of how wood jams regulate geomorphic evolution, but also our ability to restore wood function in degraded riverscapes.

While wood is commonly used in stream management, there is considerable focus on optimizing the use of placed wood to accomplish specific goals, including bank protection or erosion, pool scour, and sediment retention (Cashman et al., 2018; Ockelford et al., 2024; Roni et al., 2015). In many cases, wood jams are intended to achieve morphodynamic goals to specific magnitudes (e.g., pool depth sufficient to meet salmonid habitat requirements) and in specific places in the river corridor (Abbe et al., 2018; Addy and Wilkinson, 2016; Bureau of Reclamation and U.S. Army Corps of Engineers, 2015). Manners et al. (2007) highlighted over a decade ago the significant gap between the dominantly reach-scale nature of studies on wood morphologic effects and the structure-scale engineering that often guides wood restoration. That same gap exists today, and this paper seeks to take a step towards filling it. Here, I ask: Can I predict wood jam morphodynamic effects at the scale of individual wood jams using information about wood jam characteristics and the surrounding reach? And, if so, what wood jam characteristics are most important in making such predictions?

2 Methods

I surveyed wood jam characteristics and morphologic effects from 2019 to 2022 across six rivers in Washington, Oregon, and Colorado: North Fork Big Thompson River, CO, Deer Creek, OR, South Fork McKenzie River, OR, North Fork Teanaway River, WA, Shale Creek, WA, and Cedar River, WA (Figure 1). These gravel-bed rivers range in bankfull depth from 0.1 to 3.1 m, bank-

Table 1 List of wood jam characteristics metrics included in this study. If a metric was measured for the Cedar subset (n = 301), then it was evaluated in statistical models using the entire dataset (maximum n = 729). If a metric was not measured for the Cedar subset, then it was only evaluated in statistical models using the rest of the dataset (maximum n = 428). Please see Scott et al. (2019) for more detailed descriptions of WooDDAM variables measured here (i.e., all metrics except for blockage ratio, jam length, and key piece presence).

Metric (units or categories)	Description	Measured for Cedar subset
Location (decimal degrees)	Latitude and longitude from a handheld GPS or smartphone with precision on the order of 5 m	Yes
Bankfull width (m)	Width between bank tops for the reach surrounding each jam, measured with a laser rangefinder with precision on the order of 0.1 m	Yes
Bankfull depth (m)	Depth between the lowest bank top and the thalweg, measured with a laser rangefinder	No
Slope (%)	Slope of the channel bed surrounding each jam, measured with a laser rangefinder	No
Bed surface grain size (sand, gravel, cobble, boulder, bedrock)	Visual estimate of the dominant bed surface grain size in the reach surrounding the jam, following the Wentworth scale	No
Channel confinement (binary)	Whether the channel surrounding the jam is confined: yes if the wetted width at 2x the bankfull stage is less than 1.5x the bankfull width, otherwise no	No
Jam orientation (binary)	Whether the jam is oriented along or across the flow direction. Parallel if the bulk of the jam is longer (parallel to flow) than it is wide (perpendicular to flow).	Yes
Obstruction index (porosity, 1 – 3)	Visual estimate of jam porosity, categorized as 3 (0 – 25 % porosity), 2 (25 – 75 % porosity), or 1 (75 – 100 % porosity).	Yes
Rootwad presence (binary)	Whether the jam had key logs with attached rootwads	Yes
Multiple trunk presence (binary)	Whether the jam had key logs with either multiple trunks or large branches	Yes
Blockage ratio (%)	Ratio of jam width to channel bankfull width. Jam width was measured in the field as the cross-sectional width of the bulk of the jam (i.e., excluding logs that extended far from the rest of the jam) or using drone-derived orthorectified imagery (resolution of 2 – 8 cm) to measure the total width of the jam (i.e., possibly including outlier logs that may have been excluded in field measurements).	Yes
Jam length (m)	Streamwise length of the wood jam, measured similarly to jam width.	No
Key piece presence (binary)	Whether the jam included key pieces as defined by Fox and Bolton (2007) for the Cedar River, WA as those with rootwads and a volume over 10.48 m^3 (370 ft^3)	Yes (only in Cedar subset)

full width from 2.1 to 174 m (although 174 m was an outlier: the 95th percentile bankfull width was 64 m), and slope from 0.01 to 6.82%. Planforms represented in this dataset include broad, multi-channel anastomosing rivers exhibiting river-wetland corridor characteristics (South Fork McKenzie, Deer), dominantly one- to two-thread meandering to anabranching rivers with occasional reaches of river-wetland corridor (Cedar, Shale, North Fork Teanaway), and steep, confined, single-thread rivers with minimal meander migration (North Fork Big Thompson). For all but the South Fork McKenzie River, surveys included every jam within multiple segments on each river ranging from approximately 0.1 to 1 km in valley length. For the South Fork McKenzie, I chose a subset of jams that captured the variability in wood jam characteristics at that site.

All of these sites were the locations of wood restoration projects, although the surveyed jams include a mix of jams of both fluvial and anthropogenic origin. Along Shale Creek and the Cedar River, wood reintroduction largely took the form of a few well-anchored engineered log jams (ELJs) and the vast majority of surveyed jams were fluviogenic. Along the North Fork Big Thompson, logs were placed and often partially buried in clusters and generally consisted of discrete jams, although nearly all jams were anthropogenic. Along the North Fork Teanaway, bundles of loose logs were placed by helicopters and a few ELJs were constructed and stabilized using buried pilings and threaded steel rods; most of the wood in surveyed jams was anthropogenic, although most jams were formed by fluvial rearrangement of placed loose wood. Finally, along Deer Creek and the South Fork McKenzie, dozens of unanchored jams and hundreds more dispersed, loose logs were placed as part of widespread wood reintroduction, and while most jams were formed from human-placed

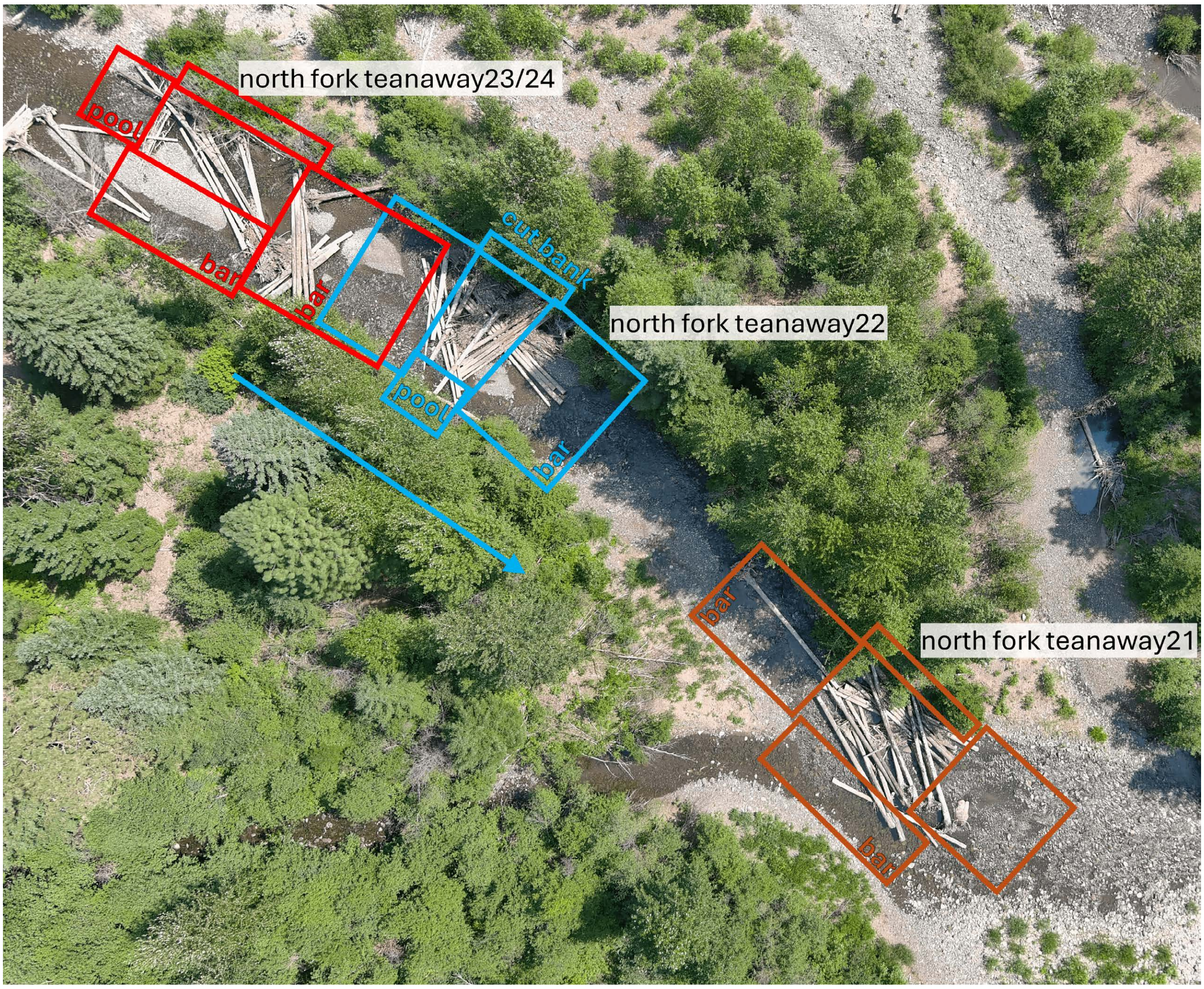

Figure 2 Drone photo from 30 July 2021, showing an example of quadrants and morphologic effects noted for 3 jams along the North Fork Teanaway. Where no morphologic effects were present, none are noted on this figure. Note that the upstream-most jam is channel-spanning, whereas the other two are not. Flow direction is shown by the blue arrow.

wood, they had nearly all been fluvially rearranged (for more details on the restoration to Stage 0 that occurred at these sites, see Flitcroft et al., 2022; Scott, 2024).

This dataset includes 546 unique wood jams on which I collected 729 independent observations of wood jam characteristics and associated morphologic effects. Two hundred of those 729 observations are repeat observations, the inclusion of which was intended to permit testing whether jam characteristics and morphologic effects would change in predictable ways through time. These repeat observations introduce the possibility of observation dependence. To ensure independence between observations necessary for statistical analysis, repeat observations were only included in the analyzed dataset if a flow of near or above bankfull stage occurred between observations of the jam and its morphologic effects. Based on documented change in jam and surrounding channel morphology (Kramer and Wohl, 2017; Scott et al., 2019), near or above bankfull flows are likely sufficient to move both wood and sediment, producing the possibility of an effectively new set of wood jam characteristics and morphologic effects.

Of the 729 wood jam observations, 301 (all unique jams with no repeat observations) came from a more focused study on the Cedar River in 2021, which involved measuring a reduced set of wood jam and morphologic effect metrics. For clarity, I refer to these 301 observations as the “Cedar subset” of the dataset.

I measured wood jam characteristics and flow magnitude between repeat surveys following the methodology of the Wood Jam Dynamics Database and Assessment Model (WooDDAM; Scott et al., 2019). Wood jam characteristics measurements included in this study are listed and described in Table 1. The Cedar subset had a reduced set of wood jam characteristics, as noted in Table 1.

For observations of wood jam morphologic effects for measurements other than the Cedar subset (n = 428), I measured such effects manually in the field in four quadrants around wood jams: upstream, downstream, and on the left and right sides of the jam (Figure 2). The downstream and upstream quadrants were defined as being directly upstream (where a backwater could occur) or downstream (where a potential wake could occur) from the bulk of each jam. Left and right quadrants were defined as being lateral (i.e., along the cross-stream direction on either side) to the bulk of each jam and not overlapping upstream or downstream areas. Within each quadrant, I noted the dominant in-channel morphologic effect (largest by planform area)

Figure 3 Examples of each type of morphologic effect surveyed in this study, including (**a**) a scour pool on the upstream side of jam shale1 on 14 July 2021, (**b**) a forced bar downstream of jam cedar10 on 9 September 2020, (**c**) a sediment wedge retained by jam shale9 on 15 July 2021, (**d**) a cut bank to the left of jam cedar11 on 6 February 2021, and (**e**) a scour pool downstream of jam deercreek73 on 3 August 2021.

as either a scour pool, forced bar, cut bank, or sediment wedge (examples of each shown in Figure 3). For jams whose bulk contacted or extended over the banks, left and right morphologic effects could only be cut banks, as morphologic effects atop floodplains were not measured. Where jams were so closely spaced as to have potentially overlapping zones of hydraulic influence, I inferred whether morphologic effects were the result of a single jam or multiple, then assigned those effects to the quadrants they fell in with regards to each nearby jam.

I used the following definitions of morphologic effects. Scour pools forced by wood jams here are defined as concave-up depressions in the channel bed whose geometry matches typical scour pool patterns observed around in-stream wood (Leung, 2019) and which are unlikely to have resulted from other structural forcing. Forced bars are defined here as convex-up depositional landforms adjacent to wood jams whose location and geometry would be difficult to explain in the absence of the inferred high-flow hydraulic effects of the wood jam (e.g., inferred wake zones, eddies, or backwaters). Sediment wedges are defined here as depositional wedges formed on the upstream side of channel-spanning wood jams that bury at least a portion of the upstream face of the jam. Cut banks are scalloped, near-vertical, recently eroded (i.e., unvegetated) banks around the flanks (left or right sides) of wood jams whose geometry and river corridor location would be difficult to explain in the absence of the inferred hydraulic effects of the wood jam (e.g., flow constriction against the bank).

For the dominant morphologic effect in each quadrant, I measured the magnitude of the effect either as the residual depth of scour pools, residual height of forced bars (i.e., the residual depth of the bar if it were conceptualized as an upside-down pool), the maximum horizontal distance between the existing cut bank top and a line connecting the upstream and downstream edges of the cut, and the height of sediment wedges from the downstream side of the jam to the surface of the wedge just upstream of the jam. I also noted the bed surface substrate size class in each quadrant for comparison against the reach-scale dominant bed surface substrate size class. For lateral morphologic effects (i.e., those on the left or right sides of the jam), I also measured the planform streamwise extent of the morphologic effect.

For the Cedar subset (n = 301), I measured morphologic effects manually in the field as only scour pool presence/absence, the residual depth of the deepest scour pool (regardless of position around the jam), and whether the jam retained spawning gravel (i.e., a specific criteria for sediment retention), without differentiating morphologic effects in each quadrant around the jam. Spawning gravel retention was defined as whether the wood jam retained or caused deposition of spawning gravel, defined as patches of bed surface sediment > 1.86 m^2 (20 ft^2) in which over 75% of the material is between 2.5 and 152.4 mm (0.1 to 6 in) in intermediate axis diameter, based on Chinook Salmon (*Oncorhynchus tshawytscha*) redd surveys along the Cedar River (Burton et al., 2000).

For the purpose of the statistical modeling presented below, I present models using both the full dataset (i.e., every wood jam for which a given response variable was measured, maximum n = 729), and for the dataset excluding the Cedar subset (maximum n = 428), which lacked the full set of jam characteristics and morphologic effect data. This splitting of the dataset allowed me to maximize my sample size for each statistical analysis without excluding predictor or response variables that were not measured for every jam. For spawning gravel retention, the only response variable unique to the Cedar subset, I was only able to model data from the Cedar subset (n = 301). Each model presented below is noted as either excluding the Cedar subset (to include variables not measured for the Cedar subset, maximum n = 428), or including the Cedar subset (including only variables measured in the Cedar subset as well as the rest of the dataset, maximum n = 729). Note that sample sizes for models presented here may not be the maximum sample size possible, as some variables (especially bankfull depth in deeper channels) were unmeasurable and regarded as missing data for some jam observations.

I performed statistical analyses using the R statistical package (R Core Team, 2023) and the tidyverse package (Wickham et al., 2019) in RStudio (RStudio Team, 2020). To test which jam and reach characteristics (i.e., predictors) controlled wood jam morphologic effect presence and magnitude (i.e., responses), I first performed univariate comparisons and correlation analyses between each response and each predictor hypothesized to potentially control it. I used that univariate filtering to select only predictor variables with plausible correlations with each response, based on Wilcoxon rank-sum tests, Spearman correlation coefficients, and graphical and tabular examination. I then performed backward stepwise multiple regression (linear for continuous responses, namely morphologic effect magnitude, and logistic for binary responses, namely the presence of specific morphologic effects), creating a full model with all plausible predictor variables, then eliminating the least significant predictor variable until all remaining variables were significant at an alpha value of 0.1 (i.e., $p < 0.1$). I also considered 95% confidence intervals on model parameters and effect directions and magnitudes. I evaluated model assumptions for the full model and selected model and transformed response variables using a natural logarithm transformation when necessary to meet the assumption of homoscedasticity of error terms for multiple linear regressions.

3 Results

3.1 Wood jam and morphologic effect change through time

The inclusion of repeat observations was intended to permit testing the hypothesis that as jam characteristics change, jam morphologic effects would change accordingly. However, likely due to the low precision of wood jam characteristics observations (e.g., the use of categorical porosity measurements, see below), this dataset proved insufficient to test that hypothesis — very few wood jams experienced substantial change in the characteristics that ended up controlling morphologic effect occurrence and magnitude (e.g., only 27 of the 200 repeat observations showed change in blockage ratio, and only 14 showed change in obstruction index). However, jam morphologic effects did vary through time: 53 of the 200 repeat observations either experienced a change in their maximum scour pool depth or changed whether they scoured a pool and 49 of those observations similarly changed in terms of forced bar presence and/or height. This justifies the inclusion of these repeat observations in characterizing the variability in the morphologic effects that can result from wood jams, although it does not permit a sufficient sample size to test my original hypothesis that both jam characteristics and jam morphologic effects would change accordingly through time.

3.2 Patterns in wood jam morphologic effect occurrence and location

Jams usually had some morphologic effect in the generally wadeable, gravel- to cobble-bed streams surveyed here. Only 96, or 22% of the 428 jam observations for which all morphologic effects were surveyed lacked any morphologic effect. Of those 332 jams with morphologic effects, 154 (46%) simultaneously induced both depositional (forced bar or sediment wedge) and erosional morphologic effects and both pool scour and bar deposition were nearly equally common. Two hundred twenty eight jams (53%) forced at least one bar, and 242 (57%) scoured at least one pool. Twenty eight jams (7%) retained a sediment wedge, and 44 jams (10%) eroded a cut bank. Of the 301 jams on the Cedar River for which

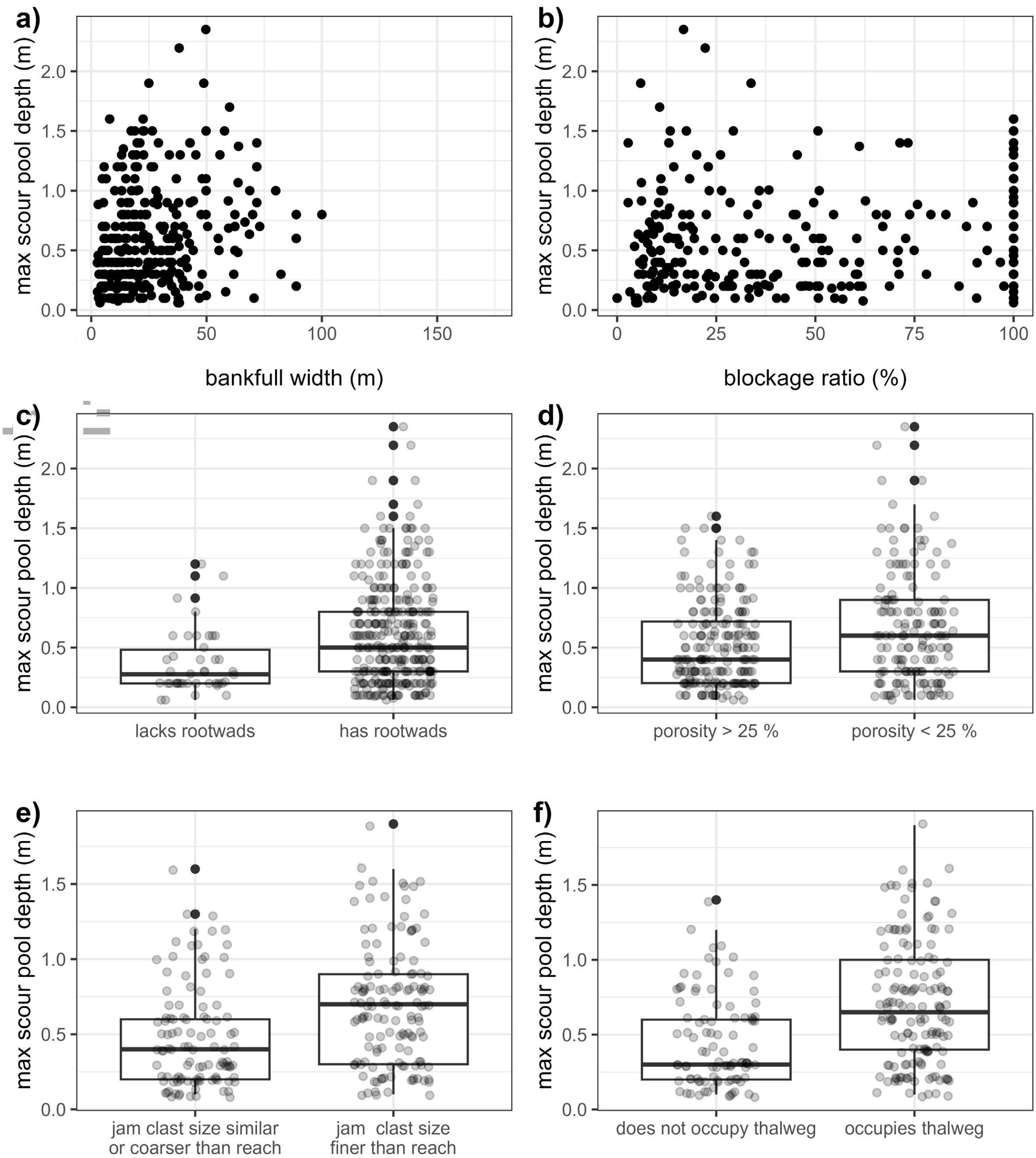

Figure 4 Univariate plots showing the relationship between maximum scour pool depth and (**a**) bankfull width, (**b**) blockage ratio, (**c**) rootwad presence, (**d**) obstruction index 2 or 1 versus 3, (**e**) jam clast size relative to reach clast size, and (**f**) thalweg occupation. For boxplots, whisker ends represent 1.5 times the interquartile range, box ends represent 25th and 75th quartiles, mid-line represents median, black points beyond box whiskers represent points outside the 1.5 times interquartile range (outliers), and grey jittered points show raw data.

I only measured pool scour and spawning gravel retention, 115 (38%) scoured at least one pool and 92 (31%) retained spawning gravel.

Scour pools were more common longitudinally, rather than along jam flanks (i.e., lateral pools). These longitudinal pools occur either upstream, likely from flow plunging under the jam (e.g., similar to pools observed by Schalko, 2020), or downstream of the jam, likely from flow plunging over the jam or jets emerging from underneath jams. Further, longitudinal scour pools tended to be slightly more common downstream of jams. Of the 242 jams for which I measured pool location and that scoured pools, 103 (43%) scoured lateral pools along their flanks and 178 (74%) scoured longitudinal pools either upstream or downstream of the jam. Of those 178 jams that scoured longitudinal pools, 92 (52%) scoured a pool upstream of the jam, 114 (64%) scoured a pool downstream of the jam, and 28 (16%) scoured pools both upstream and downstream.

Forced bars also tended to be more common longitudinally, likely either from upstream backwatering or the formation of downstream wake zones; upstream backwatering tended to be the more common mechanism of forcing such bars. Of the 228 jams that forced bars (this does not include the 28 jams with sediment wedges, although they are also likely formed from upstream

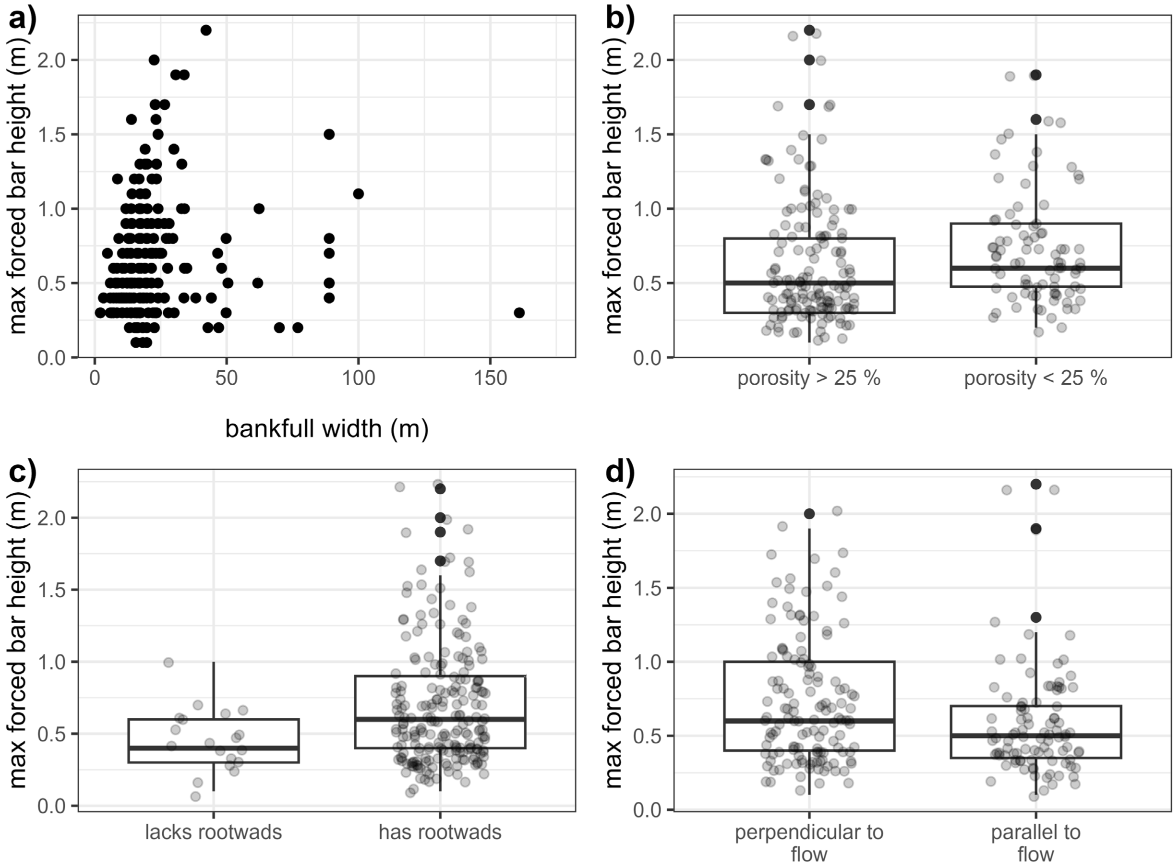

Figure 5 Univariate plots showing the relationship between maximum forced bar height and (**a**) bankfull width, (**b**) obstruction index 2 or 1 versus 3, (**c**) rootwad presence, and (**d**) jam orientation relative to flow. For boxplots, whisker ends represent 1.5 times the interquartile range, box ends represent 25th and 75th quartiles, mid-line represents median, black points beyond box whiskers represent points outside the 1.5 times interquartile range (outliers), and grey jittered points show raw data.

backwatering), 48 (21%) forced lateral bars along their flanks, and 202 (86%) forced bars longitudinally, either upstream or downstream of the jam. Of the 202 jams that forced longitudinal bars, 152 (75%) forced upstream bars, 85 (42%) forced downstream bars, and 35 (17%) forced both upstream and downstream bars.

3.3 Scour pool presence and depth

Pool scour is by no means a guaranteed result of a wood jam interacting with streamflow. Of the 729 total jams surveyed, only 357 (49%) had noticeable scour pools. Even a very high degree of blockage does not guarantee pool scour: Of the 164 jams that blocked 90% or more of the channel width, only 100 (61%) had scour pools. Likewise, particularly low porosity also does not guarantee pool scour: Of the 250 jams with an obstruction index of 3 (i.e., low porosity), only 158 (63%) scoured pools.

Scour pool presence was a function of jam porosity, blockage ratio, the presence of rootwads, and the bed surface substrate around the jam relative to the reach-average bed surface substrate. Pools were more likely to occur if jams had lower porosity, blocked more of the channel, had rootwads, and had bed substrate around them that was finer than the reach-average bed substrate size (Table S1). However, when modeled with a smaller dataset excluding the Cedar subset (n = 390), rootwads did not emerge as a significant predictor, indicating that they may have a less consistent influence on scour pool formation than other variables (i.e., a higher sample size is required to detect the signal of their influence) or may have simply had a disproportionately large impact on scour pool formation in the Cedar subset, which was included in the full model (n = 691).

The maximum scour pool residual depth around a wood jam (i.e., the depth of the deepest pool, if multiple existed), was a function of blockage ratio, rootwad presence, porosity, thalweg occupation, and bed surface substrate around the jam relative to the reach-average bed surface substrate. Pools tended to be deeper when jams blocked more of the channel, had lower porosity, had rootwads, occupied the channel thalweg (i.e., the deepest portion of the channel), and had bed substrate around them that was finer or similar in size to the reach-average bed substrate size (Table S1, Figure 4). Similar to the effect of rootwads in predicting scour pool presence, porosity did not emerge as a significant predictor in the smaller model of this response that excluded the Cedar subset, indicating that it may have a more variable or smaller effect on scour pool depth than wood jam characteristics such as blockage ratio and thalweg occupation.

Notably, I found it to be uncommon for wood jams to be able to scour pools in reaches dominated by coarse sediment (cobble or boulder-dominated bed surface

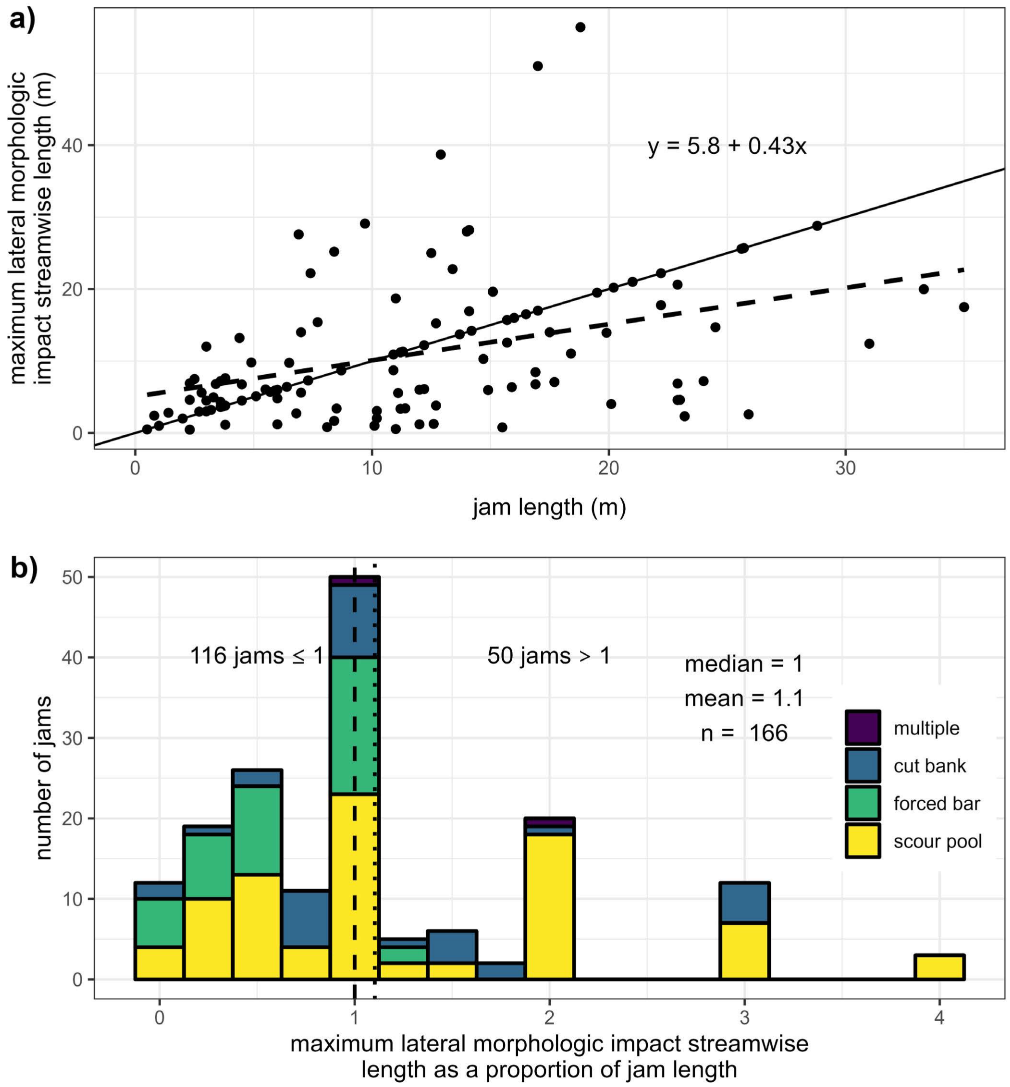

Figure 6 (**a**) Scatterplot of maximum lateral morphologic effect streamwise length versus jam length, with solid 1:1 line and dashed linear regression corresponding to the equation shown. (**b**) Histogram of wood jam count by maximum lateral morphologic effect streamwise length divided by jam length.

texture) without those jams having locally finer bed sediment where they scoured those pools. Of the 153 jams that scoured pools in coarse reach-average bed surface sediment (i.e., cobble or coarser), 124 of them (81%) had finer sediment where the pools were actually being scoured (this proportion increases to 90% when considering only the 86 jams that scoured pools deeper than 0.5 m).

3.4 Forced bar presence and height

Forced bar presence was less predictable than scour pool presence: After model selection, only the presence of rootwads significantly predicted bar presence (n = 428, p = 0.0024), although only with an overall accuracy of 57% (sensitivity of 19%, specificity of 92%). Jams with rootwads were found to be 2.50 times (95% confidence interval between 1.40 and 4.58) more likely to have forced bars. However, the accuracy of that relationship is only slightly better than random chance.

Forced bar height, similar to bar presence, was more difficult to predict than scour pool residual depth. After accounting for bankfull width (wider rivers tend to have larger bars), bars tend to be taller when jams are perpendicular to flow, have low porosity, and have rootwads (Table S2, Figure 5).

3.5 Sediment retention

Sediment retention, as measured here, is the occurrence of forced bars or sediment wedges around wood jams (i.e., depositional features, not the occurrence of jams preventing erosion that would have otherwise occurred in their absence, which could also be considered a form of sediment retention). While this is similar to forced bar presence (i.e., jams that only force a bar would have a positive response for both this model and the logistic model predicting forced bar presence), this metric relaxes the criteria for a jam having a measured morphologic effect, which may explain the greater number of significant predictors in this model. General sediment retention was more likely to occur if jams blocked more of the channel, were of moderate to low porosity, existed in a reach with dominantly gravel or finer bed surface sediment, and contained key pieces with multiple trunks, after accounting for the general trend of deeper channels being less likely to retain sediment (Table S3). Taken generally, wood jams that obstruct more of the flow and provide greater hydraulic roughness tended to be more likely to retain sediment.

3.5.1 Spawning Gravel Retention

A specific case of sediment retention is when wood jams induce the deposition of gravels within the size range thought to be acceptable for fish spawning. Here, examining only the subset of wood jams surveyed on the Cedar River for which I measured spawning gravel retention, I found that such retention was more likely around wood jams that had low porosity, had rootwads, and blocked a higher proportion of the channel, after accounting for the tendency of wider channels to be more likely to retain spawning gravel (Table S4).

3.6 Lateral morphologic effect length correspondence with jam dimensions

I examined whether wood jam morphologic effects along the sides of jams corresponded solely to wood jam dimensions (i.e., whether longer jams produce longer lateral morphologic effects) or to other wood jam characteristics. I found that lateral morphologic effects are commonly (70% of observations) limited by the length of wood jams, that is, less than or equal to the length of wood jams that create them (Figure 6a). While lateral morphologic effect length correlated with jam length (p value for Spearman correlation coefficient < 0.0001), other wood jam characteristics or reach characteristics did not reliably predict morphologic effect length. Of the 30% of jams with morphologic effects that stretched beyond the length of the jam, the majority were either cut banks or scour pools (Figure 6b).

4 Discussion

Here, I first discuss patterns in the occurrence and magnitude of wood jam morphologic effects and how those patterns fit into and perhaps expand our current understanding of wood influences on hydraulics and morphodynamics. I then offer my opinion on the implications of these findings for efforts to restore wood function to impaired riverscapes.

4.1 Patterns in wood jam morphologic effect occurrence and magnitude

Prediction of morphologic effect occurrence and magnitude at the scale of individual wood jams in this dataset is generally inaccurate. The statistical models presented here, from hundreds of wood jams and using a myriad of jam and channel characteristics to predict morphologic effects, show high accuracy for spawning gravel retention (78%), moderate accuracy for pool scour (64%) and sediment retention (65%) occurrence, and low accuracy for forced bar occurrence (57%). Statistical modeling only explained a small proportion of the variance of scour pool depth (R^2 = 0.20 – 0.22) and even less for forced bar height (R^2 = 0.09). That is, these observations poorly support my hypothesis that wood jam characteristics can predict wood jam morphologic effects in the context of channel characteristics.

That being said, I can glean some insights into how the factors measured here tend to influence wood jam morphologic effects, even if those effects are highly variable and difficult to predict. Of the wood jam characteristics measured here, only a select few emerged as relevant in regulating wood jam morphologic effects: porosity, blockage ratio, orientation relative to flow, interaction with the thalweg, or deepest portion of in-channel flow, and the presence of structurally complex or large elements, namely rootwads and branching or multiple trunks. For the set of jams for which I measured both key piece (i.e., large logs) and rootwad presence (i.e., the Cedar subset), these two variables were too well correlated (p value for X^2 test < 0.0001) to differentiate in statistical modeling, and thus it is plausible that the effects of rootwads could be in part explained by those logs tending to be larger. While this set of wood jam characteristics aligns well with past studies, the results presented here cover a notably large sample size and a variety of morphologic effects. In addition, thalweg occupation and multiple trunk presence have not, to my knowledge, previously emerged as controls on wood jam morphologic functions. Thalweg occupation highlights the importance of wood being able to interact with energetic flow to be able to shape the channel bed. Multiple trunk presence may reflect a similar characteristic to the interstitial complexity found to regulate wood jam hydraulic and bed sediment effects by Cashman et al. (2021). The importance of wood structural complexity also highlights that wood jams comprised of wood species with substantially different characteristics than those that dominate this dataset (primarily trees in the Pinaceae and Salicaceae families) may produce different patterns of morphologic effects.

That scour pools rarely occurred in coarse channel bed sediment indicates the importance of local fine sediment deposits in enabling pool scour in coarse-bedded riverscapes (e.g., those in which incision and narrowing prevents fine sediment retention). This finer bed surface sediment could either be present due to scour through an armor layer or from the local deposition of fine sediment immediately surrounding the jam, which was then scoured to form a pool (e.g., Figure 7). Either way, this indicates the importance of the presence of fine sediment in the riverscape in achieving scour pools around wood jams. For systems so incised as to have exposed bedrock or exclusively coarse clasts (i.e., not just an armored layer), fine sediment retention is likely necessary prior to jams being able to scour pools.

The importance of reach-average bed surface texture in predicting the occurrence of sediment retention may stem from the importance of some combination of wood jams requiring adequate sediment supply to generate depositional features or lower reach-average sediment transport capacity making it more likely for wood jams to be able to retain sediment in their vicinity. However, slope, bankfull width, and confinement, all indicators of potential unit stream power, did not correlate significantly with sediment retention, which I would have expected if reach-scale sediment transport capacity was a dominant control (Wohl and Scott, 2017). I also note that this dataset has few sand-bed observations and

Figure 7 Photo taken 29 July 2021 of a wood jam on the North Fork Teanaway River (ID north fork teanaway23/24) that has both induced upstream gravel deposition over a formerly cobble bed, then scoured a pool into that deposited sediment. Arrow indicates flow direction, and blue oval outlines the scour pool on the upstream side of the jam.

wood jam morphologic effects in lower-gradient. Sand-bed rivers may exhibit more predictable patterns than were observed here.

The wood jam characteristics that make jams accelerate flow to cause scour also commonly decelerate flow to create depositional backwaters or wakes, increasing hydraulic and sediment transport capacity heterogeneity around wood jams. This is shown here by three findings: (1) very similar wood characteristics predict both sediment retention and pool scour, (2) numerous wood jams create both scour and depositional features, and (3) wood jam morphologic effects show considerable variability in their location around jams, indicating that slowed or accelerated flow can occur in varied locations. This matches observations from flume experiments (Leung, 2019; Schalko and Nepf, 2024) that similarly find both scour and deposition around wood structures. These findings support the general idea that wood jams do not simply increase the potential for erosion or deposition alone, but instead diversify the flow field (Matheson et al., 2017) and, through extension, the morphology of the riverscape itself (Gurnell et al., 2005), not only through time (Galia et al., 2024), but also around individual jams.

Factors external to a given wood jam appear to explain more of the variance in wood jam morphodynamic functions than wood jam characteristics themselves (at least, those measured here; other unmeasured factors, such as the presence of gaps beneath jams, may also be important; Follett et al., 2021). These other factors may include channel cross-sectional and planform geometry, the ratio of sediment transport capacity to supply, the local influence of vegetation, the influence of nearby wood jams, and the sequencing of geomorphic change (e.g., sediment deposition being required prior to pool scour, as documented above). These factors all vary in time and space as the riverscape and wood stored within it evolve. Even if all of these factors were readily measurable, their inherent dynamism would make it difficult to use them to predict the morphologic effects of wood jams for more than a short period of time.

The importance of external factors is also highlighted by the finding that morphologic effects tended to be about as long or shorter than jams themselves, instead of correlating with jam characteristics. This contrasts with flume findings for isolated wood jams or logs that generally show lateral and downstream hydraulic and morphologic effects that extend far beyond the planform extent of the wood structure that causes them (Schalko et al., 2021; Schalko and Nepf, 2024). I hypothesize that this contrast is due to the generally complex hydraulics of the wadeable, wood-rich rivers studied here, with branching, bending, and converging flow, complex banks, and multiple wood structures that hydraulically interact. This hypothesis draws from field and flume observations that suggest that the interaction of multiple wood structures regulates their morphologic effects (Schalko et al., 2024; Zhang et al., 2019; Zhang and Rutherfurd, 2020).

I also note that this dataset comes from a limited bioclimatic range of mainly wadeable, gravel-bed rivers of the Pacific Northwest, United States. While the physical processes of jam-induced hydraulics and morphodynamics should be well-transferable across regions, sand-bed rivers may exhibit more predictable relationships between jam characteristics and morphologic effects. The relationship between jam characteristics and morphologic function in much larger rivers may also differ from those observed here.

4.2 Implications for wood restoration

River restoration success is a function of how human alterations change riverscape processes and the objectives we set for the magnitude and direction of that change (Dufour and Piégay, 2009). Setting precise objectives or design criteria for the morphologic function of individual wood jams may be infeasible given that those functions are controlled by factors generally outside the control of restoration design. Rather, it may be more feasible to target reach-scale restoration of wood morphologic function across numerous jams or assemblages of transient wood in which the variations among individual wood jams could be more readily averaged out. To exemplify this, I summarize the portion of this dataset describing anthropogenic jams on Shale Creek (eight ELJs) and the NF Teanaway River (46 jams, a mix of anchored ELJs and unanchored jams). Placed wood was intended to diversify the in-stream environment by creating pool habitat for salmonids (Shale) and retain sediment to cause reach-scale aggradation that could reverse anthropogenic incision (both sites). Of the eight jams along Shale Creek, seven (88%) scoured pools, but only three (38%) retained sediment. Of the 46 jams at NF Teanaway, 31 (67%) retained sediment as intended. Both projects can broadly be described as successful if their objectives only regard reach-scale wood function, but that success would not be nearly as evident if such objectives were set at the scale of individual jams.

Even if restoration targets reach-scale wood morphologic function, designing placed wood to have specific characteristics (e.g., high blockage ratio, low porosity, structural complexity from rootwads and branches, etc.) only moderately increases the likelihood of achieving a predictable morphologic function. Influential external factors, such as reach-scale sediment transport capacity, vegetation establishment, and hydraulic effects of other jams and channel topography all may be affected by placed wood and feedback on wood function itself (Collins et al., 2012; Gurnell and Bertoldi, 2020). In addition, wood is a transient component of riverscapes, decaying, breaking, and changing over short timescales, even when anchored in place (Andersen et al., 2016; Merten et al., 2013; Sass, 2009; Scherer, 2004; Spänhoff and Meyer, 2004; Wohl et al., 2019, 2023). Thus, as time passes after restoration, wood morphologic function will depend less and less on as-built wood characteristics and more on the assemblage of wood set by the wood regime. This all makes it difficult to sustainably restore wood morphologic function through the careful design of placed wood characteristics alone. While placed wood intended to produce specific, local effects (e.g., bank protection or scour mitigation) certainly must be carefully designed at the jam scale, that same careful design is insufficient and may be counter to achieving the heterogeneity and dynamism that are necessary for resilient riverine ecosystem function (Hiers et al., 2016).

Extrapolating from the results presented here and past work on wood dynamics, I propose four key factors specifically required (i.e., in addition to typical design criteria for process-based restoration) for successful restoration of wood morphologic function: (1) restoration should target wood morphologic function at the reach scale, across wood assemblages instead of individual jams, (2) placed wood should either have or be able to develop characteristics that tend to produce substantial morphologic effects, such as blocking a large proportion of the channel and having low porosity, (3) because those characteristics by no means guarantee wood morphologic function, wood design should account for the variability of wood-induced morphodynamics by intentionally including redundancy, allowing for a substantial amount of placed wood to function differently than intended, and (4) design should ideally ensure a long-term supply of wood, or a wood regime that enables the formation and maintenance of jams as the riverscape changes and wood breaks down. Recent efforts that successfully use wood to influence reach-scale geomorphic evolution, such as low-tech process-based restoration and restoration to a Stage 0 condition tend to include the first three of these factors (Flitcroft et al., 2022; Grabowski et al., 2019; Scott, 2024; Wheaton et al., 2019; Williams et al., 2020). However, even those efforts often do not restore the wood regime, something that may take decades to centuries of watershed-scale stewardship (Martens et al., 2019; Stout et al., 2018). Given that long timescale, it is likely that long-term wood restoration will require adaptive management or stewardship in the form of periodic wood supplementation.

My original aim for this work was to partially fill the knowledge gap between our reach-scale understanding of wood jam morphodynamic functions and our desire to engineer those functions at the much more precise scale of individual wood jams, highlighted over a decade ago by Manners et al. (2007). I wonder if that aim was unreasonable. Instead of showing how wood characteristics can reliably predict wood function, I have come to appreciate from this effort that the morphologic effects of individual wood jams are highly variable and difficult to predict. This has led me to speculate that wood function restoration may be more successful when it both targets a scale larger than that of individual jams and also intentionally plans for a high degree of variability in how placed wood may shape the riverscape. This may be especially appropriate for wood restoration aimed at enhancing riverine ecosystems, which depend more on reach-scale geomorphic evolution than the specific functions of individual jams.

5 Conclusion

Here, I present a dataset of hundreds of observations of wood jam characteristics, channel characteristics, and associated wood jam morphologic effects. Through statistical analysis of this dataset, I find that certain wood jam characteristics, notably porosity, blockage ratio, obstruction of the thalweg, and the presence of structurally complex or large elements, namely rootwads and branching or multiple trunks, help explain some of the substantial variance in wood jam morphologic effects. However, a bigger picture takeaway from this analysis is that wood jam morphologic effects are highly variable and difficult to predict from wood jam and local channel characteristics alone. This highlights the importance of reach- and watershed-scale geomorphic context in understanding wood function, as well as the inherent high degree of variability of that function in dynamic riverscapes.

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Data and Codes Availability

All data used in the analyses presented here are available in the Dryad repository (https://doi.org/10.5061/dryad.pvmcvdnvw).

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Conflict of Interest Disclosure

The author has no competing interests.

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References

Abbe, T., Hrachovec, M., and Winter, S. *Engineered Log Jams: Recent Developments in Their Design and Placement, with examples from the Pacific Northwest, U.S.A.* Elsevier, 2018. doi: 10.1016/B978-0-12-409548-9.11031-0.

Addy, S. and Wilkinson, M. An assessment of engineered log jam structures in response to a flood event in an upland gravel-bed river: Engineered Log Jam Assessment. *Earth Surface Processes and Landforms*, 41(12):1658–1670, 2016. doi: 10.1002/esp.3936.

Addy, S. and Wilkinson, M. E. Representing natural and artificial inchannel large wood in numerical hydraulic and hydrological models. *Wiley Interdisciplinary Reviews: Water*, 6(6), 2019. doi: 10.1002/wat2.1389.

Andersen, D. C., Stricker, C. A., and Nelson, S. M. Wood decay in desert riverine environments. *Forest Ecology and Management*, 365:83–95, 2016. doi: 10.1016/j.foreco.2016.01.023.

Brummer, C. J., Abbe, T. B., Sampson, J. R., and Montgomery, D. R. Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. *Geomorphology*, 80(3-4):295–309, 2006. doi: 10.1016/j.geomorph.2006.03.002.

Buffington, J. M., Lisle, T. E., Woodsmith, R. D., and Hilton, S. Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Research and Applications*, 18(6):507–531, 2002. doi: 10.1002/rra.693.

Bureau of Reclamation and U.S. Army Corps of Engineers. National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure. Technical report, 2015.

Burton, K., Foley, S., and Mavros, B. Cedar River Chinook Salmon (Oncorhynchus tshawytscha) Redd Survey Report, 2000: Spawning Habitat Characteristics, Spatial and Temporal Redd Distributions, and the Incidence of Spawning Sockeye in the Vicinity of Incubating Chinook. Technical report, Prepared for Seattle Public Utilities, Seattle, WA, 2000.

Cashman, M. J., Wharton, G., Harvey, G. L., Naura, M., and Bryden, A. Trends in the use of large wood in UK river restoration projects: insights from the National River Restoration Inventory: Trends in the Use of Large Wood in UK River Restoration Projects. *Water and Environment Journal*, 33(3), 2018. doi: 10.1111/wej.12407.

Cashman, M. J., Harvey, G. L., and Wharton, G. Structural complexity influences the ecosystem engineering effects of instream large wood. *Earth Surface Processes and Landforms*, 46(10): esp.5145, 2021. doi: 10.1002/esp.5145.

Cherry, J. and Beschta, R. Coarse Woody Debris and Channel Morphology: A Flume Study. *Journal of the American Water Resources Association*, 25(5):1031–1036, 1989. doi: 10.1111/j.1752-1688.1989.tb05417.x.

Collins, B. D., Montgomery, D. R., Fetherston, K. L., and Abbe, T. B. The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, 139-140:460–470, 2012. doi: 10.1016/j.geomorph.2011.11.011.

Dufour, S. and Piégay, H. From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. *River Research and Applications*, 25(5): 568–581, 2009. doi: 10.1002/rra.1239.

Flitcroft, R. L., Brignon, W. R., Staab, B., Bellmore, J. R., Burnett, J., Burns, P., Cluer, B., Giannico, G., Helstab, J. M., Jennings, J., Mayes, C., Mazzacano, C., Mork, L., Meyer, K., Munyon, J., Penaluna, B. E., Powers, P., Scott, D. N., and Wondzell, S. M. Rehabilitating Valley Floors to a Stage 0 Condition: A Synthesis of Opening Outcomes. *Frontiers in Environmental Science*, 10: 892268, 2022. doi: 10.3389/fenvs.2022.892268.

Follett, E., Schalko, I., and Nepf, H. Logjams with a lower gap: Backwater rise and flow distribution beneath and through logjam predicted by twobox momentum balance. *Geophysical Research Letters*, 48(16), 2021. doi: 10.1029/2021GL094279.

Fox, M. and Bolton, S. A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State. *North American Journal of*

Fisheries Management, 27(1):342–359, 2007. doi: 10.1577/M05-024.1.

Galia, T., Poledniková, Z., and Škarpich, V. Impact of large wood on sediment (dis)connectivity in a meandering river. *Geomorphology*, 453:109153, 2024. doi: 10.1016/j.geomorph.2024.109153.

Geertsema, T. J., Torfs, P. J. J. F., Eekhout, J. P. C., Teuling, A. J., and Hoitink, A. J. F. Woodinduced backwater effects in lowland streams. *River Research and Applications*, 36(7):1171–1182, 2020. doi: 10.1002/rra.3611.

Gippel, C., O'Neill, I., Finlayson, B., and Schnatz, I. Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. *Regulated Rivers: Research & Management*, 12:223–236, 1996.

Grabowski, R. C., Gurnell, A. M., BurgessGamble, L., England, J., Holland, D., Klaar, M. J., Morrissey, I., Uttley, C., and Wharton, G. The current state of the use of large wood in river restoration and management. *Water and Environment Journal*, 33(3): 366–377, 2019. doi: 10.1111/wej.12465.

Gurnell, A. M. and Bertoldi, W. Extending the conceptual model of river island development to incorporate different tree species and environmental conditions. *River Research and Applications*, 36(8):1730–1747, 2020. doi: 10.1002/rra.3691.

Gurnell, A. M., Tockner, K., Edwards, P., and Petts, G. Effects of deposited wood on biocomplexity of river corridors. *Frontiers in Ecology and the Environment*, 3(7):377–382, 2005. doi: 10.1890/1540-9295(2005)003[0377:EODWOB]2.0.CO;2.

Hiers, J. K., Jackson, S. T., Hobbs, R. J., Bernhardt, E. S., and Valentine, L. E. The Precision Problem in Conservation and Restoration. *Trends in Ecology & Evolution*, 31(11):820–830, 2016. doi: 10.1016/j.tree.2016.08.001.

Kail, J. Influence of large woody debris on the morphology of six central European streams. *Geomorphology*, 51(1-3):207–223, 2003. doi: 10.1016/S0169-555X(02)00337-9.

Keller, E. A. and Swanson, F. J. Effects of Large Organic Material on Channel Form and Fluvial Processes. *Earth Surface Processes*, 4 (4):361–380, 1979. doi: 10.1002/esp.3290040406.

Kramer, N. and Wohl, E. Rules of the road: A qualitative and quantitative synthesis of large wood transport through drainage networks. *Geomorphology*, 279:74–97, 2017. doi: 10.1016/j.geomorph.2016.08.026.

Latterell, J. J., Scott Bechtold, J., O'Keefe, T. C., Pelt, R., and Naiman, R. J. Dynamic patch mosaics and channel movement in an unconfined river valley of the Olympic Mountains. *Freshwater Biology*, 51(3):523–544, 2006. doi: 10.1111/j.1365-2427.2006.01513.x.

Leung, V. *Large woody debris and river morphology in scour pool formation, dam removal, and delta formation*. PhD thesis, University of Washington, 2019, http://hdl.handle.net/1773/45030.

Livers, B. and Wohl, E. All Logjams Are Not Created Equal. *Journal of Geophysical Research: Earth Surface*, 126(8), 2021. doi: 10.1029/2021JF006076.

Manners, R. B., Doyle, M. W., and Small, M. J. Structure and hydraulics of natural woody debris jams. *Water Resources Research*, 43(6), 2007. doi: 10.1029/2006WR004910.

Martens, K. D. and Devine, W. D. Pool formation and the role of instream wood in small streams in predominantly second-growth forests. *Environmental Management*, 71(5):1011–1023, 2023. doi: 10.1007/s00267-022-01771-z.

Martens, K. D., Devine, W. D., Minkova, T. V., and Foster, A. D. Stream Conditions after 18 Years of Passive Riparian Restoration in Small Fish-bearing Watersheds. *Environmental Management*, 63(5):673–690, 2019. doi: 10.1007/s00267-019-01146-x.

Matheson, A., Thoms, M., and Reid, M. Does reintroducing large wood influence the hydraulic landscape of a lowland river system? *Geomorphology*, 292:128–141, 2017. doi: 10.1016/j.geomorph.2017.03.035.

Merten, E., Vaz, P. G., Decker-Fritz, J. A., Finlay, J. C., and Stefan, H. G. Relative importance of breakage and decay as processes depleting large wood from streams. *Geomorphology*, 190:40–47, 2013. doi: 10.1016/j.geomorph.2013.02.006.

Mikuś, P., Wyżga, B., Kaczka, R. J., Walusiak, E., and Zawiejska, J. Islands in a European mountain river: Linkages with large wood deposition, flood flows and plant diversity. *Geomorphology*, 202:115–127, 2013. doi: 10.1016/j.geomorph.2012.09.016.

Montgomery, D. R., Buffington, J. M., Smith, R. D., Schmidt, K. M., and Pess, G. Pool Spacing in Forest Channels. *Water Resources Research*, 31(4):1097–1105, 1995. doi: 10.1029/94WR03285.

Müller, S., Follett, E. M., Ouro, P., and Wilson, C. A. M. E. Influence of ChannelSpanning Engineered Logjam Structures on Channel Hydrodynamics. *Water Resources Research*, 58(12), 2022. doi: 10.1029/2022WR032111.

Ockelford, A., Wohl, E., RuizVillanueva, V., Comiti, F., Piégay, H., Darby, S., Parsons, D., Yochum, S. E., Wolstenholme, J., White, D., Uno, H., Triantafillou, S., Stroth, T., Smrdel, T., Scott, D. N., Scamardo, J. E., Rees, J., Rathburn, S., Morrison, R. R., Milan, D., Marshall, A., Lininger, K. B., Kemper, J. T., Karpack, M., Johaneman, T., Iskin, E., Gibaja Del Hoyo, J., Hortobágyi, B., Hinshaw, S., Heath, J., Emmanuel, T., Dunn, S., Christensen, N., Beeby, J., Ash, J., Ader, E., and Aarnink, J. Working with wood in rivers in the Western United States. *River Research and Applications*, 40 (8):1626–1641, 2024. doi: 10.1002/rra.4331.

Pagliara, S. and Kurdistani, S. M. Flume experiments on scour downstream of wood stream restoration structures. *Geomorphology*, 279:141–149, 2017. doi: 10.1016/j.geomorph.2016.10.013.

Pfeiffer, A. and Wohl, E. Where Does Wood Most Effectively Enhance Storage? Network-Scale Distribution of Sediment and Organic Matter Stored by Instream Wood. *Geophysical Research Letters*, 45(1):194–200, 2018. doi: 10.1002/2017GL076057.

R Core Team. R: A language and environment for statistical computing, 2023.

Ravazzolo, D., Mao, L., Picco, L., Sitzia, T., and Lenzi, M. Geomorphic effects of wood quantity and characteristics in three Italian gravel-bed rivers. *Geomorphology*, 246:79–89, 2015. doi: 10.1016/j.geomorph.2015.06.012.

Ravazzolo, D., Spreitzer, G., Tunnicliffe, J., and Friedrich, H. The effect of large wood accumulations with rootwads on local geomorphic changes. *Water Resources Research*, 58(5), 2022. doi: 10.1029/2021WR031403.

Roni, P., Beechie, T. J., Pess, G., and Hanson, K. Wood placement in river restoration: fact, fiction, and future direction. *Canadian Journal of Fisheries and Aquatic Sciences*, 72(3):466–478, 2015. doi: 10.1139/cjfas-2014-0344.

RStudio Team. RStudio: Integrated Development Environment for R, 2020.

Sass, G. *Coarse Woody Debris in Lakes and Streams*, pages 60–69. Elsevier, 2009. doi: 10.1016/B978-012370626-3.00221-0.

Schalko, I. Wood retention at inclined racks: Effects on flow and local bedload processes. *Earth Surface Processes and Landforms*, 45(9):12, 2020. doi: 10.1002/esp.4864.

Schalko, I. and Nepf, H. M. Enhanced flow variability and morphological changes through individual wood placements on a gravel bed. *Geomorphology*, 453:109135, 2024. doi: 10.1016/j.geomorph.2024.109135.

Schalko, I., Wohl, E., and Nepf, H. M. Flow and wake characteristics associated with large wood to inform river restoration. *Scientific*

Reports, 11(1):8644, 2021. doi: 10.1038/s41598-021-87892-7.

Schalko, I., Ponce, M., Lassar, S., Schwindt, S., Haun, S., and Nepf, H. Flow and Turbulence Due To Wood Contribute to Declogging of Gravel Bed. *Geophysical Research Letters*, 51(2): e2023GL107507, 2024. doi: 10.1029/2023GL107507.

Scherer, R. Decomposition and Longevity of In-Stream Woody Debris: A Review of Literature From North America. In *Forest Land–Fish Conference II – Ecosystem Stewardship through Collaboration*, edited by Scrimgeour, G. J., Eisler, B., McCulloch, B., Silins, U., and Monita, M., Edmonton, Alberta, 2004.

Scott, D. N. Widespread wood placement and regrading drive lateral connectivity and reworking of the channel and floodplain in a valley bottom reset to Stage 0. *Geomorphology*, 446:108987, 2024. doi: 10.1016/j.geomorph.2023.108987.

Scott, D. N., Wohl, E., and Yochum, S. E. Wood Jam Dynamics Database and Assessment Model (WooDDAM): A framework to measure and understand wood jam characteristics and dynamics: Wood Jam Dynamics Database and Assessment Model (WooDDAM). *River Research and Applications*, 35(9), 2019. doi: 10.1002/rra.3481.

Seixas, G. B., Veldhuisen, C. N., and Olis, M. Wood controls on pool spacing, step characteristics and sediment storage in headwater streams of the northwestern Cascade Mountains. *Geomorphology*, 348:106898, 2020. doi: 10.1016/j.geomorph.2019.106898.

Spänhoff, B. and Meyer, E. I. Breakdown rates of wood in streams. *Journal of the North American Benthological Society*, 23(2):189–197, 2004. doi: 10.1899/0887-3593(2004)023<0189:BROWIS>2.0.CO;2.

Stout, J. C., Rutherfurd, I. D., Grove, J., Webb, A. J., Kitchingman, A., Tonkin, Z., and Lyon, J. Passive Recovery of Wood Loads in Rivers. *Water Resources Research*, 54(11):8828–8846, 2018. doi: 10.1029/2017WR021071.

Svoboda, C. D. and Russell, K. Flume Analysis of Engineered Large Wood Structures for Scour Development and Habitat. In *World Environmental and Water Resources Congress 2011*, pages 2572–2581, Palm Springs, California, United States, 2011. American Society of Civil Engineers. doi: 10.1061/41173(414)267.

Wallerstein, N. P., Alonso, C. V., Bennett, S. J., and Thorne, C. R. Distorted Froudescaled flume analysis of large woody debris. *Earth Surface Processes and Landforms*, 26(12):1265–1283, 2001. doi: 10.1002/esp.271.

Wheaton, J. M., Bennett, S. N., Bouwes, N., Maestas, J. D., and Shahverdian, S. Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Version 1.0. 2019. doi: 10.13140/RG.2.2.19590.63049/2. Publisher: Utah State University version: 2.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., and Yutani, H. Welcome to the Tidyverse. *Journal of Open Source Software*, 4(43):1686, 2019. doi: 10.21105/joss.01686.

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

Wohl, E. and Scott, D. N. Wood and sediment storage and dynamics in river corridors. *Earth Surface Processes and Landforms*, 42(1): 5–23, 2017. doi: 10.1002/esp.3909.

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D. N., Comiti, F., Gurnell, A. M., Piegay, H., Lininger, K. B., Jaeger, K. L., Walters, D. M., and Fausch, K. D. The Natural Wood Regime in Rivers. *BioScience*, 69(4):259–273, 2019. doi: 10.1093/biosci/biz013.

Wohl, E., Marshall, A. E., Scamardo, J., White, D., and Morrison, R. R. Biogeomorphic influences on river corridor resilience to wildfire disturbances in a mountain stream of the Southern Rockies, USA. *Science of The Total Environment*, 820:153321, 2022. doi: 10.1016/j.scitotenv.2022.153321.

Wohl, E., Uno, H., Dunn, S. B., Kemper, J. T., Marshall, A., Means-Brous, M., Scamardo, J. E., and Triantafillou, S. P. Why wood should move in rivers. *River Research and Applications*, 40(6): 976–987, 2023. doi: 10.1002/rra.4114.

Zhang, N. and Rutherfurd, I. D. The effect of instream logs on river bank erosion: field measurements of hydraulics and erosion rates. *Earth Surface Processes and Landforms*, 45(7):1677–1690, 2020. doi: 10.1002/esp.4838.

Zhang, N., Rutherfurd, I. D., and Ghisalberti, M. The effect of instream logs on bank erosion potential: a flume study with multiple logs. *Journal of Ecohydraulics*, 5(1):57–70, 2019. doi: 10.1080/24705357.2019.1669495.