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Key Points:

- Logjam distribution density process domains in this region are best defined by drainage area, reach morphology, and wildfire history
- Reaches with relatively wide floodplains and reaches in catchments with no recent wildfire have greater logjam distribution density
- Smaller sample sizes across space (fewer than 300 reaches) and time (fewer than 10 years) adequately described these same process domains

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. Triantafyllou,
shayla.triantafyllou@colostate.edu

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Evaluating the Sensitivity of Process Domains for Logjams to Spatial and Temporal Sample Size in River Networks of the Southern Rockies, USA

Shayla Triantafyllou¹  and Ellen Wohl¹ 

¹Department of Geosciences, Colorado State University, Fort Collins, CO, USA

Abstract Modification of river corridors, particularly deforestation and the removal of large wood, has greatly altered the abundance and influence of large wood in most rivers in the temperate latitudes. The conceptual framework of large wood process domains can assist in both directing research and facilitating large wood-related management and restoration in rivers. Large wood process domains are spatially or temporally distinct portions of a river network or region with distinct processes of wood recruitment, transport, and storage. Previous research has shown wood to be unevenly distributed across space and time. We use a data set of logjam distribution density (# of channel-spanning logjams/100 m length of channel) in 304 spatially distinct reaches of mountain streams in the Colorado Front Range, and up to 11 years of repeat measurements at some reaches, to (a) statistically evaluate whether a priori designated process domains for logjam distribution density are distinctly different and (b) evaluate the sensitivity of process domain delineations to spatial and temporal sample size. Our results indicate that the major spatial controls on logjam process domains for logjam distribution density in the Southern Rockies are drainage area, reach morphology, and wildfire disturbance history. Greater logjam distribution densities were present in wide reaches and undisturbed catchments. Using subsets of the data set composed of under 100 reaches created similar results. The relationship between geomorphic and hydrologic characteristics and their ability to describe logjam distribution density was minimally affected when using fewer than 10 years of data.

Plain Language Summary Rivers in forested areas used to have abundant logjams or accumulations of wood. Historically, logjams have been removed from river channels, but we now understand that logjams in river channels have many benefits. Logjams can create habitat for fish, aquatic insects, and plants, slow floods, and store sediment. Because of these benefits, river restoration practitioners are reintroducing logjams to river channels. There is a wide range over both space and time in how many logjams are present. To effectively use logjams in restoration, it is important to understand where logjams occur in natural systems and what controls the number of logjams in these locations. We use a large data set from over 300 segments of river corridors across the Southern Rockies to understand where logjams occur in Mountain Rivers. There were more logjams in segments of the river corridor that had wide valleys relative to the channel and in catchments that did not recently burn in a wildfire. Additionally, when we used smaller subsets of our data over space and time, our conclusions were similar. The number of logjams in a river system can be accurately estimated by collecting data at fewer locations over a shorter period of time.

1. Introduction

Large wood (LW) serves many functions in river corridors. LW in river corridors is commonly defined as downed, dead wood pieces ≥ 10 cm in diameter and 1 m long (Wohl et al., 2010). Studies have documented the impacts of LW in attenuating flood flows, storing sediment, facilitating nutrient uptake via hyporheic exchange flows and floodplain inundation, creating dynamic channels and floodplains, and forming habitat for aquatic organisms (Gurnell & Bertoldi, 2022; Ruiz-Villanueva et al., 2016; Wohl, 2017). Despite these benefits, LW has been removed both directly from channels and floodplains and indirectly through deforestation for centuries (Montgomery et al., 2003). Once abundant across forested river corridors in temperate latitudes, relatively unmodified river corridors with abundant LW are now few. Although there are few river corridors that have unaltered wood regimes, studies in these river corridors (Wohl et al., 2017) and historical and geological records (Davies & Gibling, 2011; Guyette et al., 2002; Wohl, 2014) indicate the former abundance and importance of wood in rivers.

The magnitude, frequency, duration, timing, rate, and mode of wood recruitment, transport, and storage describe the large wood regime for a reach or entire river network (Wohl, Kramer, et al., 2019). Wood process domains (*sensu* Montgomery, 1999) are spatially distinct portions of a river network or a larger region in which defining wood regime characteristics results in a distinct regime over a specified timespan. For example, the low order segments of a mountainous river network might be dominated by mass wood recruitment during debris flows, with limited wood transport capacity (Benda et al., 2003; Hassan et al., 2005; Pfeiffer & Wohl, 2018). In contrast, higher-order river segments in the network might have a different process domain in which wood recruitment results mainly from bank erosion (e.g., Martin & Benda, 2001) and greater wood transport capacity allows logjams to form and persist in the river corridor (Bertoldi et al., 2013; Marcus et al., 2011; Wohl & Jaeger, 2009).

Using large wood regimes and process domains as conceptual frameworks can both direct research toward poorly understood aspects of wood in rivers and facilitate river management and restoration employing large wood. In the context of research, differentiating wood regimes across river networks or regions can highlight the relative importance of different mechanisms of recruitment or transport, and resulting differences in wood storage and its effects on river corridor process and form, as discussed conceptually in Benda et al. (2003), Benda and Sias (2003) and Wohl (2011, 2020). In a management setting, identification of distinct wood process domains can inform prioritization of sites for wood reintroduction and details of reintroduced wood such as abundance and placement (Benda & Bigelow, 2014; Hassan et al., 2005; May & Gresswell, 2003; Wohl, Scott, & Yochum, 2019).

Large wood process domains can be delineated based on a focus on wood recruitment, transport, or storage or the combined effects of these components of a wood budget. Direct or remote observations of processes, such as photographs of wood transport (Ghaffarian et al., 2020; Kramer & Wohl, 2014), could be used to infer process domains. Most commonly, wood process domains are inferred from indirect evidence of processes, such as mass movement scars and deposits (May & Gresswell, 2003) or bank erosion (Comiti et al., 2016; Ruiz-Villanueva et al., 2014) as indications of recruitment, or wood abundance and distribution in the channel or floodplain as indications of transport and storage (Scott & Wohl, 2018; Wohl & Jaeger, 2009; Wyżga & Zawiejska, 2005). Either approach may fail to represent the range of temporal variation in recruitment (Piégay et al., 2017; Wohl et al., 2012), transport (Kramer et al., 2017; Lucía et al., 2015), and storage (Tonon et al., 2017; Yazzie et al., 2024). Direct observations or inferences from a limited length of river corridor also may not adequately reflect spatial variation across an entire catchment or river network or along the length of a single river (Wohl & Cadol, 2011; Young et al., 2006).

The timespan of observations or inferences needed to accurately represent wood dynamics depends on the temporal variation in wood recruitment, transport, and storage. In regions where infrequent, high-magnitude events such as blowdowns or hillslope mass movements that recruit wood or floods that transport wood are particularly influential, characterizations of wood dynamics may need to be conducted over a sufficiently long timespan to include more than one such event, or the data set may require a space-for-time substitution using sites with differing time periods since analogous disturbances (e.g., Wohl et al., 2009; Zischg et al., 2018). Similarly, the appropriate spatial extent of observations or inferences depends on the spatial variation in wood dynamics along a length of river or throughout a river network. Regions or catchments with greater spatial variations in wood recruitment, transport, and storage may require characterizing wood dynamics across larger extents of river corridors. The details of a representative timespan and area of study remain poorly constrained for most rivers. Here, we use a multi-year and multi-river data set of wood distribution to examine these knowledge gaps.

1.1. Objectives

We use over two decades of direct field observations of logjams in mountain rivers of the Colorado Front Range to (a) make and then test *a priori* assumptions about large wood process domains in the context of wood trapping and implied transport as reflected in the presence of logjams and (b) evaluate the sensitivity of process domain delineations to sample size in the context of space and time. We use the metric of logjam distribution density (Wohl & Scamardo, 2021), that is, the number of channel-spanning logjams per 100 m length of channel. We focus on logjams rather than the total wood load for three reasons. First, compared to individual pieces of large wood, logjams are disproportionately important in creating flow obstructions that enhance channel-floodplain connectivity (e.g., Sear et al., 2010) and hyporheic exchange (e.g., Marshall et al., 2023; Sawyer et al., 2011), facilitating backwater formation, storing sediment and organic matter (Comiti et al., 2008; Livers & Wohl, 2021; Welling et al., 2021; Wohl & Scott, 2017), and creating habitat for diverse aquatic species (Richmond &

Fausch, 1995; Schenk et al., 2015; Vera et al., 2014). Second, engineered logjams are likely the most common form of wood reintroduction (Abbe & Brooks, 2011; Norbury et al., 2021). Third, the data sets we use in the Colorado Front Range have a greater spatial extent and longer duration for logjams than those for total wood load and thus facilitate analysis of the data set representativeness over space and time.

The location of individual logjams, the relative abundance of logjams along different reaches of the river corridor, and the potential controls on the recruitment of wood and formation of logjams have been documented in numerous studies (e.g., Abbe & Montgomery, 2003; Cienciala et al., 2024; Wohl & Cadol, 2011). These studies indicate that logjams tend to be preferentially located in river corridors with lower transport capacity and greater trapping potential (e.g., Kraft & Warren, 2003; Wohl & Cadol, 2011). Transport capacity reflects characteristics such as wood piece length relative to flow width and piece diameter relative to flow depth (Braudrick & Grant, 2001; Dixon & Sear, 2014; Morris et al., 2007), especially as these change during floods (e.g., Comiti et al., 2016; Martin et al., 2023; Tonon et al., 2018), as well as the spatial density of pieces in transport (Braudrick et al., 1997). Trapping potential reflects the presence of obstacles (Beckman & Wohl, 2014; Gurnell et al., 2000; Marshall & Wohl, 2024; Piegay et al., 1999), a multichannel planform and less lateral confinement (Hassan et al., 2024; Marshall et al., 2024; Scott & Wohl, 2018; Wohl & Beckman, 2014; Wyżga & Zawiejska, 2005), and channel bends (Braudrick & Grant, 2001; Nakamura & Swanson, 1994). The size and abundance of wood pieces reflect riparian forest stand age (Beckman & Wohl, 2014; Livers et al., 2018; Warren et al., 2007); and wood recruitment sources from bank erosion, hillslope inputs, and transport from upstream (Cathcart et al., 2025). Multiple studies have also shown a trend from headwaters with few logjams due to insufficient transport capacity to sufficient transport to form jams downstream (e.g., Cienciala et al., 2024; Marcus et al., 2002; Wohl & Jaeger, 2009).

We made and then tested a priori assumptions about potential process domains for logjam distribution density based on (a) forest characteristics, including disturbance regime, (b) river corridor morphology, and (c) recent disturbance history. We compare logjam distribution density in subalpine versus montane elevation zones of the study area, reaches with differing lateral confinement, and reaches in catchments that burned 2–3 years prior to data collection versus sites in catchments not subject to recent wildfires. The distinction between subalpine and montane elevation zones incorporates differences in forest species composition, return interval of stand-killing wildfires, and magnitude of peak stream flow. We designate reaches with differing lateral confinement as beads and strings. Beads are relatively laterally unconstrained reaches and strings are laterally confined reaches of the river corridor (Stanford & Ward, 1993). We expect beads and strings to have differences in river corridor morphology (Montgomery & Buffington, 1997), peak flow attenuation at the reach scale (Wohl, Lininger, et al., 2018; Wohl, Cadol, et al., 2018), and differences in wood transport capacity (Wohl et al., 2024). The time since the last stand-killing wildfire represents differences in recent disturbance history. Therefore, we test the hypotheses that logjam distribution density will differ between reaches with varying: (a) elevation (subalpine and montane), (b) morphology (bead and string), and (c) disturbance history (burned and not burned).

2. Study Area

River reaches from 38 mountain catchments (each drainage area $<240 \text{ km}^2$) in the Colorado Front Range with minimal human disturbance (flow regulation; timber harvest; roads and other infrastructure) were included in this study (Figure 1, Table S1 in Supporting Information S1). Mountain streams in the Colorado Front Range portion of the Southern Rocky Mountains of Colorado, USA are underlain by Precambrian-age crystalline rocks (Cole et al., 2010). River corridors characteristically alternate downstream between relatively wide portions known as beads (Wohl, Lininger, et al., 2018; Wohl, Cadol, et al., 2018) and more laterally constrained portions known as strings. Bead and string spacing reflect glacial history and spatial variations in bedrock fracture density (Ehlen & Wohl, 2002). Beads typically have wider floodplains relative to channel width and lower reach-scale gradients compared to strings.

River corridors included in this data set lie within the subalpine zone (3,450–2,840 m elevation) or the montane zone (2,740–1,830 m) (Figure 1). The two zones differ with respect to forest composition and disturbance regime. Subalpine forests are dominated by lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*), with Douglas fir (*Pseudotsuga menziesii*), blue spruce (*Picea pungens*), aspen (*Populus tremuloides*), and willows (*Salix* spp.) present in riparian zones (Veblen & Donnegan, 2005). Stand-killing wildfires recur at intervals of 100–400 years (Veblen et al., 2000). Stream flow is dominated by the annual snowmelt flood and does not typically exceed a peak unit discharge of $\sim 1.1 \text{ m}^3/\text{s}/\text{km}^2$ (Jarrett, 1990).

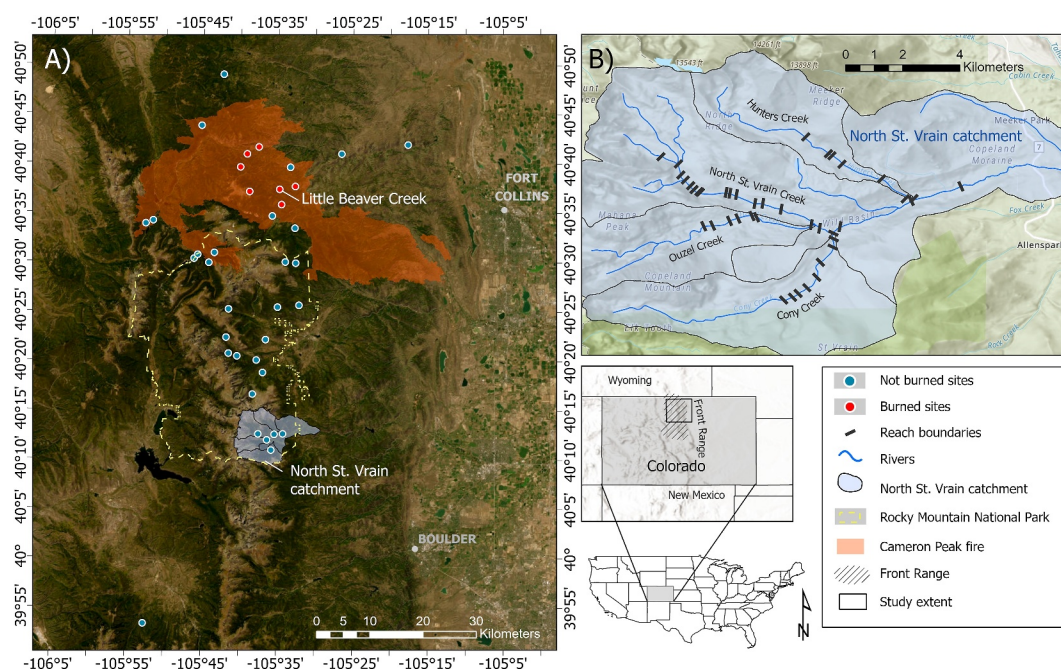


Figure 1. (a) Regional map of study sites (38 catchments) throughout the Colorado Front Range of the Southern Rocky Mountains used in spatially extensive analysis. (b) Catchment map of North St. Vrain Creek and tributaries in Rocky Mountain National Park were used in a temporally extensive analysis.

In contrast, forests of the montane zone are dominated by ponderosa pine (*Pinus ponderosa*), lodgepole pine, and Douglas fir, with willows, river birch (*Betula fontinalis*), aspen, and cottonwood (*Populus* spp.) along river corridors. The montane zone has a variable fire-severity regime, with low severity ground fires that recur at ~5–30 years intervals at the 100-ha scale and stand-killing fires at ~40–100 years intervals (Veblen & Donnell, 2005). Stream flow includes the annual snowmelt flood, but intense convective storms can cause flash floods that reach peak unit discharge values of $40 \text{ m}^3/\text{s}/\text{km}^2$ (Jarrett, 1990).

The study area has a continental climate with greater precipitation and colder temperatures at higher elevations. Mean annual precipitation varies from just over 500 mm at lower elevations, where the mean annual temperature is just over 8°C , to 770 mm of precipitation and 1°C at higher elevations. Mass movements are rare in the subalpine zone but occur in the montane zone at recurrence intervals of a few decades following intense rains or rainfall after wildfire (Coe et al., 2014; Patton et al., 2018). Patch blowdowns occur in both elevation zones but are more common in the subalpine where small blowdowns covering 10^2 – 10^3 square meters typically occur each year (Wohl, 2013). Insect infestations occur across elevational zones at irregular intervals and at differing severity in terms of proportion of tree mortality within a stand. Widespread tree mortality from native mountain pine beetles (*Dendroctonus ponderosae*) has occurred in the study area during the past decade, but standing dead trees do not immediately fall into the river corridor (Jackson & Wohl, 2015). Forest stand ages across the study area vary from old growth (~1500 CE) to 1978 CE (Sibold et al., 2006). Data from seven of the study catchments were collected after they burned in the 2020 Cameron peak fire (Figure 1).

Burned reaches included those in which the riparian area burned at high severity and those immediately downstream from burned areas that were subject to post-wildfire flooding and wood transport. Depletion of large wood and logjams in these reaches has been interpreted as reflecting post-wildfire flooding and greater wood transport than occurred during pre-fire conditions (Triantafyllou & Wohl, 2024; Wohl et al., 2022, 2024).

3. Methods

3.1. Field Data

The field data used in these analyses were collected for previous projects and, as such, were analyzed and reported in earlier publications (Table 1). Logjams were surveyed using a handheld Garmin eTrex (horizontal

Table 1

Data Sources Compiled for This Study Including the Associated Publication, the Number of Reaches Included, Reach Lengths or Range of Reach Lengths, and the Definitions of Logjams (Channel-Spanning or All In-Channel) From Each Data Source

Publication	Number of reaches	Reach length range (m)	Logjam definition
Beckman (2013)	16	1,000	Channel spanning; 3 or more pieces (≥ 10 cm diameter and ≥ 1 m length) in contact with each other, completely span the active channel and create longitudinal discontinuities of the water surface and stream bed across at least 2/3 of the channel width
Wohl and Beckman (2014)	66	3,130–28,989	
Wohl and Scamardo (2021), Wohl and Iskin (2022)	38	40–2,445	
Wohl unpublished data	5	30–425	All jams; as 3 or more pieces (≥ 10 cm diameter and ≥ 1 m length) in contact with each other
Jackson and Wohl (2015)	14	30–73	
Livers (2016)	9	150–1,000	
Triantafillou and Wohl (2024)	152	10–940	
Wohl and Jaeger (2009)	4	1,250	

accuracy ± 3 m) to record jam locations, with jams defined where 3 or more pieces of large wood are in contact with one another and at least partly within the bankfull active channel. Logjam volumes were measured for jams in the North St. Vrain Creek catchment (Figure S1 in Supporting Information S1). Jam distribution density reflects the number of jams per 100 m length of channel. Where a multichannel planform was present (anastomosing planform with secondary channels that branch from and rejoin the main channel), only jams on the mainstem were included in the estimation of jam distribution density; inclusion of secondary channels would undoubtedly increase the values of jam distribution density in these reaches because secondary channels have even more limited wood transport and tend to have closely spaced jams. Additional variables (contributing drainage area, reach-scale channel gradient) were derived from the digital elevation data and StreamStats from the US Geological Survey.

Individual data sets were collected from 2008 to 2023 (Table 1). We analyze two data sets: spatially extensive data collected in 2008–2023 from streams with and without the recent wildfire disturbance; and long duration data from the North St. Vrain Creek catchment collected during 2010–2020. For the spatially extensive data analysis, reach morphology was classified as bead (floodplain/channel width > 2) or string (floodplain/channel width ≤ 2). For the long-duration data set, we classified reach morphology as confined (floodplain/channel width < 2), partially confined ($2 < \text{floodplain/channel width} < 6$), or unconfined (floodplain/channel width > 6) to recreate the models associated with the data set (Wohl & Scamardo, 2021). Some catchments were sampled before and after a fire and flood. Between the first and second data collection, the geomorphic characteristics of the river channel changed significantly and, as a result, so did the number and location of logjams. The long duration data set from the North St. Vrain Creek catchment was included in the analyses performed in the spatially extensive analyses using the mean across all years of data collected for a given reach (Wohl & Iskin, 2022; Wohl & Scamardo, 2021).

3.2. Statistical Analyses

We analyzed data using R software and packages (R Core Team, 2022). Statistical differences between population distributions were assessed with *t*-tests or the Wilcoxon Rank Sum test when data did not meet the assumptions of normality or equal variance. We used a linear mixed effects model to describe the relationships between spatial river corridor characteristics and logjam distribution density (Douglas, 2015). We used a mixed model to reflect the nested nature of the data and to address the problems caused by dependence in data. We calculated the R^2 for the linear mixed effects model using the Nakagawa and Schielzeth method (Nakagawa & Schielzeth, 2013). Statistical tests were assessed at the $\alpha = 0.05$ level for significance.

To address the influence of the number of reaches on the conclusions, we created subsets of the spatially extensive data set by randomly resampling the complete spatial data set ($n = 304$) with replacement to create subsets of data of different sample sizes. In a process similar to bootstrapping, one hundred random subsamples of the complete spatial data set were taken at every even sample size from $n = 10$ to $n = 304$ for repeated pairwise comparisons and from $n = 20$ to $n = 304$ for repeated construction of linear mixed models to account for the number of terms in

Table 2
Summary Statistics for All Data and Hypothesized Logjam Process Domains

Category	n (# of reaches)	Median (interquartile range) jam distribution density (#/100 m)	Median drainage area (km ²)	Median channel gradient
All data	304	0.99 (1.92)	11.2	0.069
Montane	150	0.72 (1.98)	13.6	0.055
Subalpine	154	1.23 (2.06)	10.0	0.088
String	111	0.75 (1.04)	11.4	0.080
Bead	193	1.48 (2.68)	10.9	0.062
Unburned	152	1.35 (1.74)	12.4	0.068
Burned	152	0.50 (1.91)	6.4	0.069

the model and the resulting degrees of freedom. Using these subsets, we repeated pairwise tests and linear model construction. Additionally, we performed pairwise tests on a subset of catchments to illustrate the results of decreasing sample size with regard to the number of catchments.

To address the influence of temporal extent on the results, we reconstructed linear models using the temporally extensive data set as described in Wohl and Scamardo (2021). To remain consistent with the analyses in Wohl and Scamardo (2021), we used a square root transformation to address the non-normal distribution of logjam distribution density. We built three linear models for confined, partially confined, and unconfined settings using peak flow in 2013, floodplain to channel width ratio, and reach slope, respectively, to describe the square root of the average jam density over the period of record in three simple linear models. To assess the influence of the length of the period of record, we iteratively removed years from the average jam distribution density to understand how the relationships between predictors and response changed with shorter periods of record.

4. Results

4.1. Spatial Patterns

The data set includes 304 spatially explicit reaches from 38 different mountain catchments across an area of ~4,860 km². The median jam distribution density among all reaches is 1 and the interquartile range is 1.92 jams/100 m (Table 2). Individual jam characteristics measured at sites in the North St. Vrain catchment included a range of 3–100+ pieces within a jam and jam volumes ranging from <0.1 to >10 m³ (Figure S1 in Supporting Information S1). The median values of drainage area and channel gradient are similar between the subalpine and montane reaches in the context of logjam dynamics (Table 2). Logjam distribution density is significantly higher in subalpine sites relative to montane sites (52% greater median value, Figure 2a, $p < 0.001$). Logjam distribution density is significantly higher in beads than in strings (65% greater median value, Figures 2a, Table 2 and Table S3 in Supporting Information S1, $p = 0.001$). Across the data set, logjam distribution density is significantly greater in unburned reaches than in burned reaches (92% greater median value, Figures 2a and Table 2, Table S3 in Supporting Information S1, $p < 0.001$). Comparing only reaches from catchments that did not recently burn, there is no difference in logjam distribution density between montane and subalpine reaches (Figure 3a, Table S3 in Supporting Information S1). There is a difference in the logjam distribution density between beads and strings amongst unburned catchments (Figure 3b, Table S3 in Supporting Information S1, $p < 0.001$).

4.2. Linear Mixed Effects Model

The multivariate model uses drainage area, morphology, and burn history to describe the log-transformed logjam distribution density and had an R^2 of 0.23 (Table 3). In the interpretation of log-transformed data, the exponentiated mean is the geometric mean of the original data scale. The fitted slope coefficient is interpreted such that for each one unit change of the explanatory variable, the response variable changes by $100(\exp(b-1))$ % of the geometric mean. In other words, a difference in 1 km² drainage area is associated with an estimated 1% lower (95% CI: –3%, 0.4%) geometric mean logjam distribution density. The drainage area estimate has a bimodal distribution associated with subsets of data with different distributions (Figure S2 in Supporting Information S1). There is an estimated 79% greater (95% CI: –4%, 232%) geometric mean logjam distribution density in subalpine compared to montane reaches. There is an estimated 79% greater (95% CI: –4%, 235%) geometric mean logjam

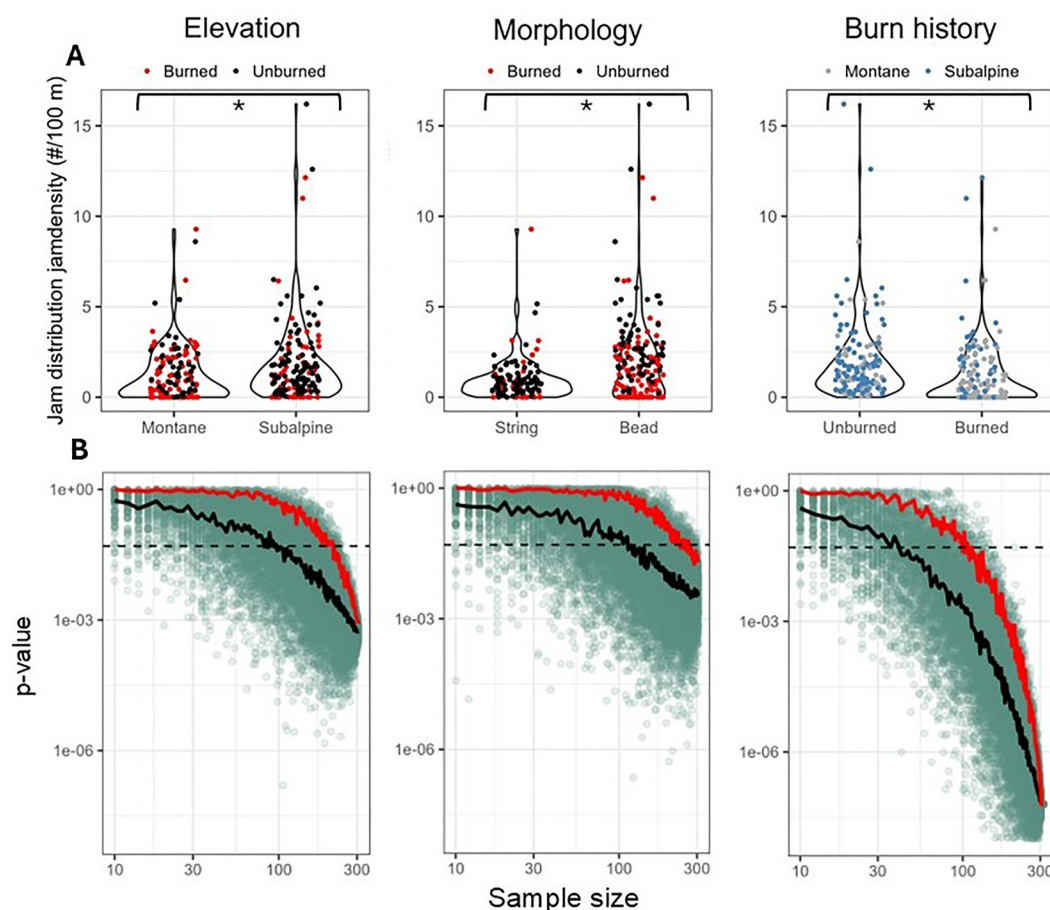


Figure 2. (a) Pairwise comparisons of logjam distribution density (# of jams/100 m of channel) plotted against spatial characteristics associated with each reach. Brackets indicate comparisons with significant differences. There is a significant difference in the distribution of jam distribution density between reaches in the montane and subalpine zones ($p < 0.001$), reaches that are beads and strings ($p = 0.002$), and reaches that were recently burned and not burned ($p < 0.001$). (b) The results of pairwise comparisons performed on randomized subsamples of the full spatial data set at different sample sizes. The significance threshold of $\alpha = 0.05$ is a dashed black line, the median p-value across sample sizes is a solid black line, and the 95th percentile p-value across sample sizes is a solid red line.

distribution density in beads compared to strings. There is an estimated 91% lower (95% CI: -96% , -80%) geometric mean logjam distribution density in burned compared to unburned reaches. We chose not to interpret the results of the model regarding channel gradient because of the large standard error and associated 95% confidence interval (Table 3).

4.3. Sample Size

After iterating pairwise tests 100 times over each even sample size between 10 and 304, the median p-value falls below 0.05 using sample sizes ≤ 100 across all spatial characteristics (Figure 2b). The median p-value falls below the significance threshold when comparing: elevation zones at sample sizes between 100 and 120, burn history at sample sizes between 50 and 60, and morphology at sample sizes between 35 and 50.

The 95th percentile p-value falls below the threshold for significance at larger sample sizes closer to that of the entire data set. The 95th percentile p-value falls below the significance threshold for elevation at 200 samples, for morphology at 250 samples, and for burn history at 100 samples. After iterating multivariate mixed effects models 100 times over each even sample size between 20 and 304, the median estimate for each term in the model is consistently descriptive of the direction (negative or positive) across all sample sizes (Figure 4). The spread of the data, however, decreases substantially as the sample size increases. The 95th percentile of the slope estimate falls below zero between 250 and 300 reaches. The 95th percentile of the drainage area estimate falls below zero

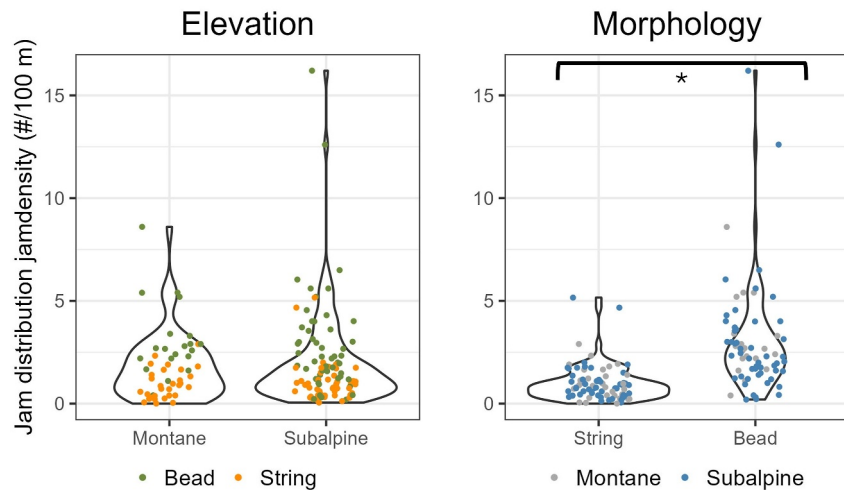


Figure 3. Pairwise comparisons of logjam distribution density (# of jams/100 m of channel) plotted against spatial characteristics associated with each reach among catchments that did not recently burn. Brackets indicate comparisons with significant differences. There is no difference in the distribution of jam distribution density between reaches in the montane and subalpine zones. There is a significant difference in the distribution of jam distribution density between reaches that are beads and strings ($p < 0.001$).

between 50 and 100 reaches. Iteration produced a bimodal distribution of the drainage area coefficient, explained by the distribution of the contributing data subset (Figure S2 in Supporting Information S1). The 5th percentile of the elevation estimate comparing subalpine to montane reaches is above zero between 150 and 200 reaches. The 5th percentile of the morphology estimate comparing beads to strings is above zero using fewer than 50 reaches. The 95th percentile of the disturbance coefficient comparing reaches in burned catchments to unburned catchments is below zero at all sample sizes above 15.

In summary, subsets of data composed of fewer than 300 reaches produce results statistically similar to those obtained from the full data set. The size of the data set necessary to produce statistically similar results varies depending on the statistical method applied to the data (pairwise comparison or multivariate model) and the term, or reach characteristics, examined.

We selected five catchments with many reaches in each catchment to assess the importance of the number of catchments in the results of our analysis. Among the reaches from Little Beaver Creek and the North St. Vrain Creek catchment, there were significant differences in logjam distribution density in reaches that differed by elevation zone, morphology, and burn status (Figure 5). In other words, the specific catchments used for analyses do not appear to significantly affect the results.

Table 3

Mixed Effects Model Describing the Logarithmically Transformed Jam Distribution Density Using Five Fixed Effects and Site as a Random Effect

Final model	R^2		
$\log(\text{Jam distribution density}) \sim \text{Channel gradient} + \text{Drainage area} + \text{Elevation} + \text{Morphology} + \text{Burn history} + (1 \text{Site})$	0.23		
Coefficient	Estimate	Standard error	95% confidence interval
Channel gradient	−0.94	2.16	−5.19, 3.31
Drainage area	−0.01	0.008	−0.027, 0.0037
Elevation, subalpine coefficient	0.58	0.32	−0.040, 1.20
Morphology, bead coefficient	0.58	0.32	−0.043, 1.21
Burn history, burned coefficient	−2.49	0.43	−3.34, −1.63
Site	0.74	—	—

Note. The R^2 value was calculated using the Nakagawa and Schielzeth approach.

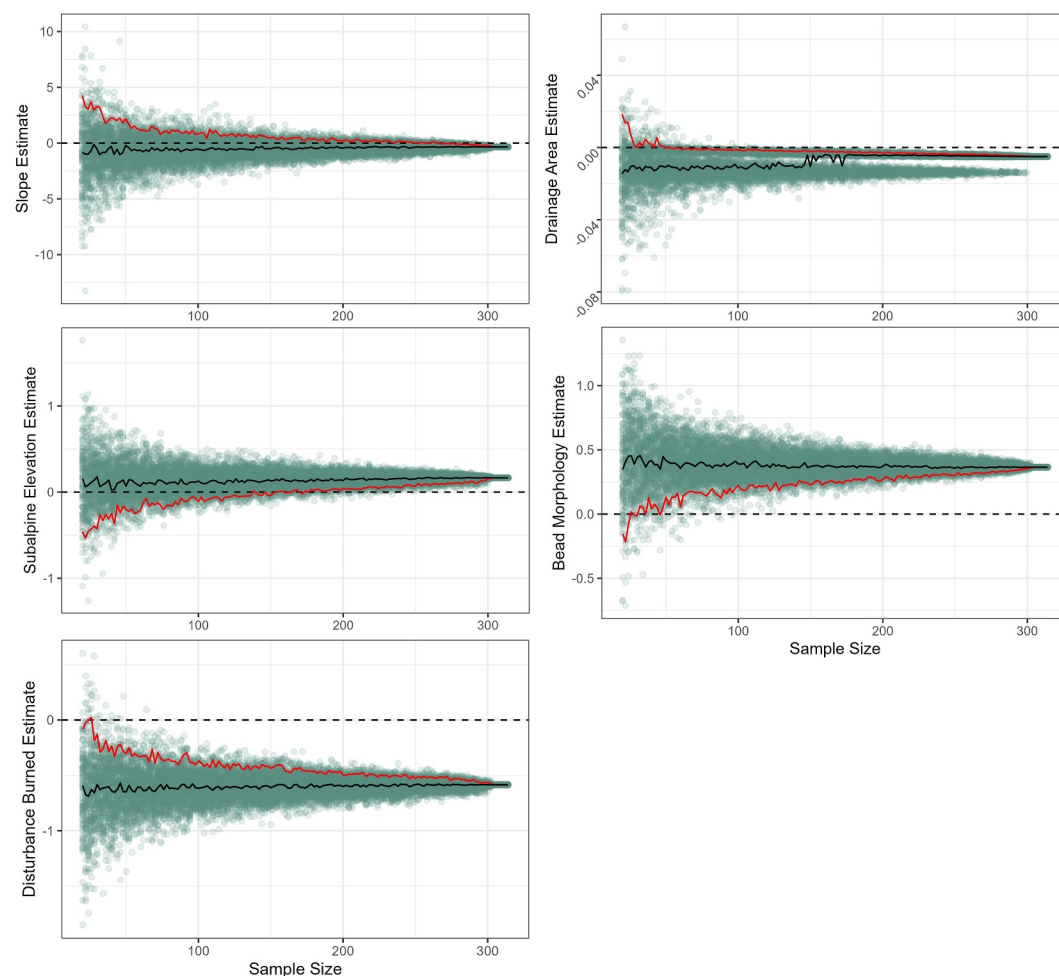


Figure 4. Mixed effects model estimates from models constructed using randomized subsamples of the full spatial data set at different sample sizes or number of reaches. The estimate at zero is labeled with a dashed black line. The median coefficients across sample sizes are solid black lines. The 5th or 95th percentiles across sample sizes are solid red lines.

4.4. Temporal Patterns

Analyzing the temporal data set enabled us to investigate how the duration of a data set influences the conclusions drawn about the logjam distribution density of a river corridor. With an additional year of data, the regression model results describing logjam distribution density in North St. Vrain Creek catchments are similar to those presented in Wohl and Scamardo (2021) (Table 4). With the removal of multiple years of observations from the reach-averaged jam distribution density, the R^2 of each model does not substantially change (Figure 6). The direction of the relationships described between predictor variables and the square root of jam distribution density do not change with the removal of multiple years of observations (Figure 7). The intercept changes but the direction and magnitude of the relationship between flow and the square root of jam distribution density change minimally when described using subsets of the 10-year data set in confined settings. In unconfined settings, the slope or magnitude of the relationship between the predictor of channel gradient and the square root of jam distribution density changes while the intercept of the models remains similar across all subsets of data. In the partially confined settings, both the slope and intercept vary, although minimally, in describing the relationship between floodplain/channel width and the square root of jam distribution density. The differences between different model iterations are significantly less than the range of average logjam distribution densities between reaches, suggesting that observations from a single year may be sufficient to distinguish process domains for logjam distribution density.

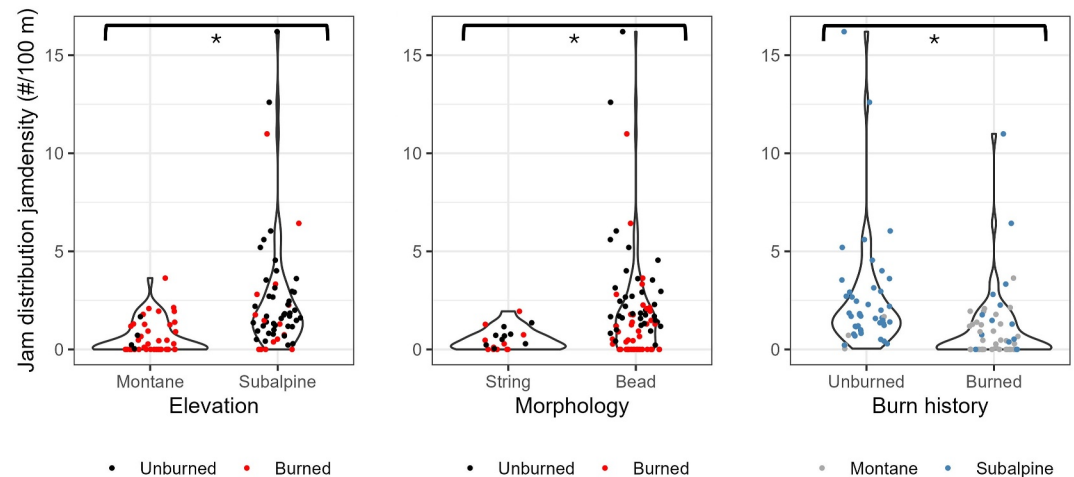


Figure 5. Jam distribution density values from a subset of 5 catchments, Little Beaver Creek and the North St. Vrain catchment (N. St. Vrain, Hunters, Ouzel, and Cony). Jam distribution density (# jams/100 m of channel) plotted against spatial characteristics. Brackets indicate significant differences in distributions. There is a significant difference in the distribution of jam distribution density between reaches in the montane and subalpine zones ($p < 0.001$), beads and strings ($p = 0.002$) and reaches that were recently burned and not burned ($p < 0.001$).

5. Discussion

Previous studies that have examined regional (Fox & Bolton, 2007) or catchment-wide (Wohl & Cadot, 2011) spatial patterns of large wood load in relation to potential controls are distinct from the data set analyzed here because we included only logjams rather than all large wood within the active channel. Studies that compare wood load or logjam distribution density through time (e.g., Lininger & Hilton, 2022; Wohl & Iskin, 2022; Wohl & Scamardo, 2021) have not used these data to examine whether a shorter duration study would produce similar inferences about representative wood loads. Consequently, the analyses presented here are unique.

The specific biogeographic characteristics of the study area likely strongly influenced our results. All the sites investigated are relatively small, steep mountain streams (median drainage area = 11.2 km²) with predominantly coniferous forest and a semiarid climate. Although peak flows can vary substantially from year to year and between subalpine and montane elevation zones, these variations are likely lesser in magnitude than those associated with comparably sized tropical or desert streams. Analogously, although some of the sites experienced recent stand-killing wildfires that substantially increased water and sediment yields to the river corridor, these fires did not create substantial increases in wood recruitment within the period of this study, and other wood-recruitment disturbances such as blowdowns or hillslope mass movements affected only limited portions of the river corridor. This contrasts with river networks that may experience widespread, abrupt wood recruitment through multiple landslides (Wohl et al., 2009), widespread intense winds (Phillips & Park, 2009), ice storms (Kraft et al., 2002), or other disturbances. In these types of river networks, the delineation of logjam process domains might be more sensitive to the time at which logjams are characterized in the field relative to the history of disturbance.

Table 4

Simple Linear Regression Models Describing the Square Root Transformed Average Logjam Distribution Density (# Jams/100 m) in a Given Reach

Category	$\sqrt{\text{Jam distribution density}} \sim$	R ²	p-value
Confined	$-0.02(Q_{2013}) + 0.99$	0.48	0.06
Partially confined	$0.19(fp_w/ch_w) + 0.54$	0.37	0.003
Unconfined	$14.5(S) + 1.09$	0.7	0.01

Note. Regression models were built using the results of model selection presented in Wohl and Scamardo (2021). Q_{2013} is estimated flood peak discharge of the largest flood within the study period in 2013, fp_w/ch_w is the ratio of floodplain to channel widths, and S is channel gradient.

5.1. Spatial Logjam Distribution

Differences in the reach morphology, burn history, and reach position in the catchment created distinctly different values of logjam distribution density based on pairwise comparisons (Figure 2) and regression modeling (Figure 4). Discussion of process domains can be used as a proxy for multiple processes affecting logjams (Cienciala et al., 2024). Morphology, or the categorization as a bead or string based on the ratio of floodplain to channel width, represents multiple geomorphic characteristics affecting river processes in the context of logjams. The wide floodplains relative to channel

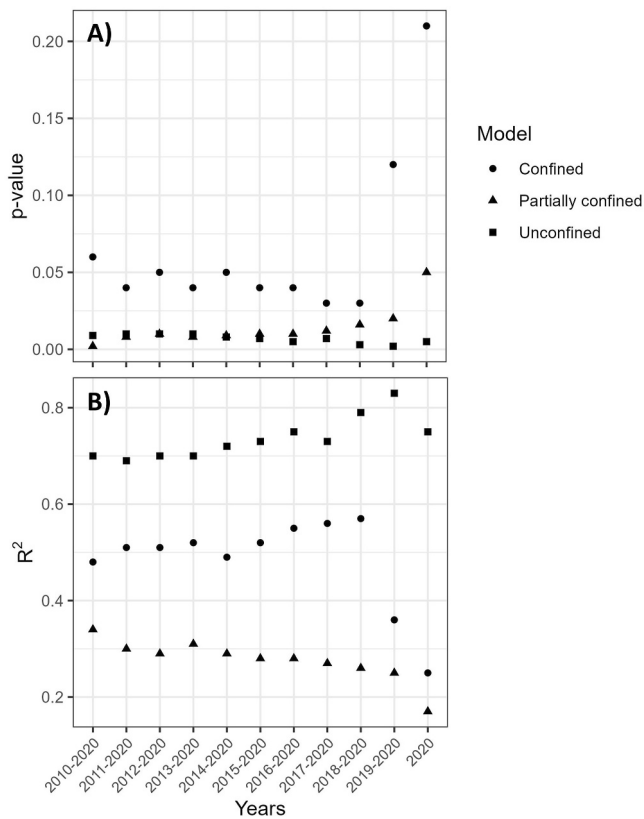


Figure 6. The p-values (a) and R^2 (b) from each of the models created with different subsets of temporal data to describe reach average logjam distribution density. Each set of models for different geomorphic settings (confined, partially confined, and unconfined) was built using the reach average logjam distribution density from different time periods ranging from 2010 to 2020.

width that define a bead allow wood-transporting flood flows to attenuate more than in strings. This decreases the transport capacity, facilitating wood deposition and the formation of logjams. Beads in mountain rivers tend to have more multithread channels. In these reaches, discharge is divided among multiple smaller channels, facilitating trapping of wood and formation of logjams (e.g., Hassan et al., 2024; Marshall et al., 2024; Scott & Wohl, 2018; Wyżga & Zawiejska, 2005; Wohl & Iskin, 2022).

Disturbance magnitude and frequency can control wood load (e.g., Comiti et al., 2016; Martin et al., 2023; Wohl, Lininger, et al., 2018; Wohl, Cadol, et al., 2018). Disturbance history is also a proxy for a suite of processes affecting the formation of logjams. The cascade of effects after a wildfire across the entire catchment results in disproportionately high flows relative to precipitation (Wohl et al., 2022). These higher flows post-fire, particularly during convective summer storms in the Southern Rockies, are much more effective at transporting LW and logjams, resulting in lower logjam distribution density (Wohl, Lininger, et al., 2018; Wohl, Cadol, et al., 2018; Wohl et al., 2024). Because the burned catchments in our data set burned in the same fire and subsequently had high-magnitude floods relative to their annual snowmelt peaks, much of the in-channel wood load was transported and stored on the floodplain (Wohl et al., 2024).

As the drainage area increases, there are increasing hydraulic forces acting on logjams (Benda et al., 2003; Braudrick & Grant, 2000) and potentially increased recruitment sources (Cienciala et al., 2024; Martin & Benda, 2001; May & Gresswell, 2003). Our study areas had an inverse relationship between drainage area and logjam distribution density. As the drainage area increases, it is likely that the capacity to transport logjams exceeds that of the potential to recruit LW and store it in logjams (Wohl & Jaeger, 2009). This is likely representative of the mountain catchments that we described rather than a trend across all rivers. Previous studies have found this inverse relationship between drainage area and large wood load or logjam distribution density (Cienciala et al., 2024; Marcus et al., 2002), but these studies have either not included large rivers or have been conducted in areas with historic deforestation and wood removal in the downstream-most regions. Consequently, the presence of naturally occurring wood rafts in large rivers (e.g., Boivin et al., 2015; Triska, 1984), which would alter catchment-scale longitudinal trends of wood retention in very large rivers, is not represented in these studies.

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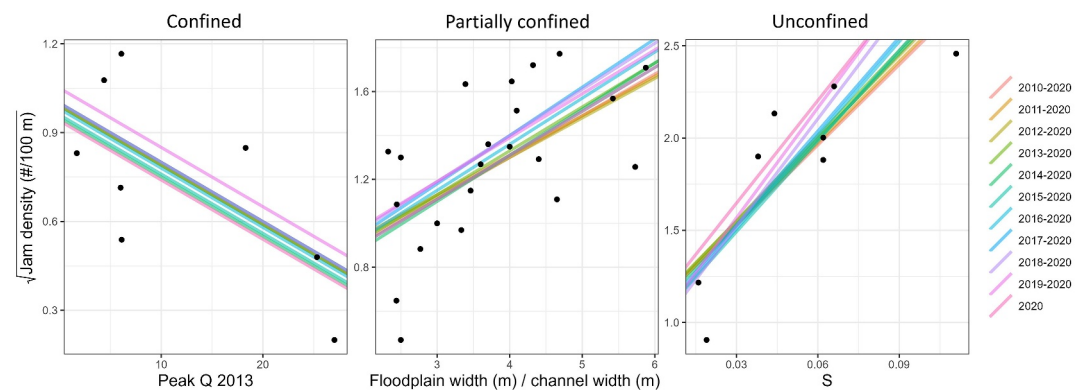


Figure 7. The square root of jam distribution density plotted against the predictor variables for confined, partially confined, and unconfined settings. The reach average values across all 10 years of data are plotted as points. The linear relationships described using subsets of temporal data included in the reach average values are plotted for every model iteration.

Although we found significant differences in logjam distribution density between different elevation zones, this relationship was influenced by burn history. Because the burned catchments burned in the same fire and are therefore in close spatial proximity, we could not untangle the effects of elevation and burn history. By removing the influence of disturbance and examining the relationship between spatial characteristics in only unburned catchments, we found that elevation zones alone did not have different logjam distribution densities. This indicates that the processes causing differences in logjam distribution density detected using the full data set were conflated with burn history. The data presented here did not support the hypothesis that there is a difference in logjam distribution density with varying elevation zones. The distinction between the montane and subalpine zones, which is a physically gradual transition, was likely not well captured using the two categories. Additionally, the study sites, while including two elevation zones, did not expand beyond low-order mountain catchments because higher stream orders are altered by diverse human activities in this region. The limited range of elevation in our data set likely contributed to it being a weak descriptor of logjam distribution density.

There are many variables documented as affecting logjam distribution density that were not included in this region-wide analysis. Piece length/channel width ratio (Nakamura & Swanson, 1994), channel sinuosity, degree of braiding or anastomosing (Scott & Wohl, 2018; Wohl & Iskin, 2022; Wyżga & Zawiejska, 2005), and degree of channel incision may also control the spatial distribution of logjams. Inclusion of such variables can provide insight into the mechanics of logjam formation and retention, but the fact that our limited set of predictor variables were able to differentiate significant differences in logjam distribution density can inform future efforts to distinguish logjam process domains within a region.

5.2. Sample Size

The evidence we presented from iterative analyses on various subsets of data suggests that we could draw similar conclusions about logjam process domains in this region using fewer reaches and catchments than the entire data set. By selecting random subsets of the full data set, we illustrated the relationship between sample size and statistical results. Pairwise comparisons between elevation and river corridor morphology indicate that the median *p*-value was below 0.05 using only 100 reaches. That is, using only 100 reaches, over half of the pairwise tests discerned the difference in logjam distribution density between montane and subalpine reaches and beads and strings identified using the entire data set. We could discern the difference between logjam distribution density in burned and unburned reaches in over half of pairwise tests using only 40 to 50 reaches (Figure 4). To achieve greater accuracy, larger sample sizes were necessary to arrive at similar conclusions based on pairwise comparisons. To accurately distinguish logjam distribution density in at least 95% of iterated scenarios, 200 reaches were necessary when testing elevation, 250 reaches when testing morphology, and 100 reaches when testing burn history.

The results of multivariate models resulted in similar conclusions about the relationships between spatial characteristics and logjam distribution density as those drawn from pairwise testing. Iterating this process with varying sample sizes, we could accurately describe these relationships using smaller sample sizes. Examining the relationship between sample size and the drainage area from multivariate models, the results indicate that 95% of iterated models accurately described the direction of the relationship between drainage area and logjam distribution density using sample sizes between 50 and 100 reaches. The results indicate that 95% of iterated models accurately described the direction of the relationship between burn history and logjam distribution density using as few as 15 reaches. These sample size estimates, which could guide the collection of instream wood measurements, are within the same order of magnitude as those arrived at using different statistical methods (Young et al., 2006). Still, the spread of estimates across all parameters decreases as sample size increases, indicating that larger sample sizes improve accuracy.

By performing pairwise tests on reaches from a subset of catchments, we explored how the number of catchments affects the delineation of process domains. Having fewer catchments resulted in similar conclusions about elevation, morphology, and disturbance history as controls on logjam distribution density, indicating no meaningful differences between catchments that were not otherwise captured by the geomorphic predictor variables.

Removing years of observations from the temporal data set did not dramatically change the results of the linear models built to describe the relationships between geomorphic and hydrologic characteristics and logjam distribution density. Because the changes to the linear models are small compared to the magnitude of difference between logjam distribution densities in individual reaches, using fewer years of observations may be appropriate

in some settings. For projects that do not explicitly aim to examine the influence of time on logjam distribution density, logjam distribution density may be accurately represented using a single year of observation. These results also suggest that in the absence of wildfire as a spatially extensive disturbance, logjam distribution density in the study area may be controlled more by spatial characteristics than by temporal characteristics.

5.3. Management and Research Implications

As our results suggest, minimally altered rivers have widely variable logjam distribution density across a biogeographic region. Some of this variation can be explained by delineating spatial process domains, as illustrated here for the Southern Rockies. Understanding spatial and temporal controls on logjam distribution density can therefore inform effective management of wood in rivers, especially river restoration. For example, projects aiming to maximize wood storage may target reaches with wide valley geometry or aim to reestablish channel-floodplain connectivity to maximize effective valley width and therefore promote logjam formation. In projects using mobile wood, site selection may prioritize reaches upstream from wide reaches that can trap wood that has been mobilized from the project reach. In the context of management that does not actively introduce wood into river corridors, our results provide context for expected relative ranges of logjam distribution density based on the location in a catchment, valley morphology, and disturbance history.

Our findings regarding spatial and temporal sample size indicate that, in some contexts, sample sizes smaller than those presented in the full data set would be sufficient to accurately delineate logjam process domains. Depending on the purpose of data collection, these results suggest the potential for minimizing fieldwork to meet budget, labor, and time constraints while understanding the accuracy of the conclusions given the spatial and temporal scope of data collection. For the most effective sample size selections, we recommend that future research or data collection efforts use the data presented here to calculate statistical power to directly inform sample sizes.

6. Conclusions

We identified and quantified the relative logjam distribution density in different spatial domains delineated by drainage area, valley morphology, and disturbance history in the Southern Rocky Mountains. Additionally, we explored different sample size scenarios to provide guidance for delineating spatial and temporal logjam process domains in other regions. We arrived at similar conclusions about logjam process domains using the same statistical models with significantly reduced sample sizes over space at both the reach and catchment scales. Building on previous work, we found that the temporal extent of data did not significantly impact the previously described relationship between local controls and logjam distribution density, although this may be specific to the disturbance regimes of the study area. This regional, high-level approach to understanding the controls on logjam process domains describes the top-down controls on logjam distribution and informs the sample sizes that are necessary to capture regional variability.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data associated with this manuscript are available in the Dryad data repository: <https://doi.org/10.5061/dryad.5hqbzkh5>.

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