JGR Earth Surface

RESEARCH ARTICLE
10.1029/2021JF006076

Key Points:

- Logjams that span the bankfull channel create significantly greater storage of water and organic matter than non-spanning logjams
- Channel-spanning logjams also have significantly more wood, larger pieces of wood, and more ramp and bridge wood pieces
- Stream rehabilitation projects employing engineered logjams should consider channel-spanning logjams to achieve greater retention

Supporting Information:

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

Correspondence to:

B. Livers,
blivers@iastate.edu

Citation:

Livers, B., & Wohl, E. (2021). All logjams are not created equal. *Journal of Geophysical Research: Earth Surface*, *126*, e2021JF006076. https://doi.org/10.1029/2021JF006076

Received 28 JAN 2021
Accepted 28 JUL 2021

All Logjams Are Not Created Equal

Bridget Livers[1] and Ellen Wohl[2]

[1]Natural Resource Ecology and Management, Iowa State University, Ames, IA, USA, [2]Department of Geosciences, Colorado State University, Fort Collins, CO, USA

Abstract Logjams create diverse physical and ecological effects in stream channels, including at least temporary storage of water, sediment, and particulate organic matter. We hypothesize that logjams that span the entire bankfull channel width in channels ≤25 m wide are more effective in storing these materials than non-channel spanning logjams. We test this hypothesis by systematically comparing characteristics of 183 logjams from 17 stream reaches in the Southern Rocky Mountains. Our data set is novel in that it evaluates naturally occurring logjams in unaltered streams in a single study area specifically based on whether they span the stream channel. We find that channel-spanning logjams have a significantly larger number of wood pieces, longer & wider pieces, more ramp and bridge pieces, and greater logjam height and volume, both as raw data and when standardized by average channel width. Channel-spanning logjams also have significantly greater backwater pool volume and volume of particulate organic matter stored in backwater pools and in logjams. Restoration employing engineered logjams in relatively small channels currently focuses on non-spanning logjams, but could be expanded to include spanning logjams.

Plain Language Summary Logjams are accumulations of three or more large wood pieces in streams and stream environments. Logjams can obstruct flow and create frictional resistance in small stream channels, creating many physical and beneficial ecological effects in stream environments. This includes, but is not limited to, temporary storage of water, sediment, and organic matter, which translates to habitat and nutrient availability for aquatic organisms. Despite these benefits, deforestation and active wood removal from stream environments have significantly reduced the size and abundance of logjams throughout the temperate latitudes, contributing to the loss of ecological integrity and the simplification of stream channels. Stream restoration projects are increasingly using engineered logjams (ELJs), which are less likely to span a stream channel than naturally occurring logjams. Limited understanding of how logjam characteristics relate to specific effects constrains our ability to evaluate whether ELJs have comparable effects to natural logjams. We systematically evaluate characteristics and effects of 183 logjams in unaltered headwater Southern Rocky Mountain streams. We find that channel-spanning logjams have significantly greater effects, such as pool and organic matter volume storage, than non-channel-spanning logjams, and recommend considering channel-spanning ELJs in restoration projects in small streams to maximize retention.

1. Introduction

By creating flow obstructions and increasing hydraulic roughness, logjams create diverse physical and ecological effects in stream channels. Logjams alter the distribution and magnitude of hydraulic forces (Curran & Wohl, 2003; Manners et al., 2007; Wilcox et al., 2011), as well as the transport of sediment and particulate organic matter (POM) (Beckman & Wohl, 2014a; Brummer et al., 2006). Where riparian forests shade a substantial portion of the channel and limit photosynthesis, POM introduced from the floodplain forms the foundation of the aquatic ecosystem's trophic cascade (Tank et al., 2010) and retention of POM for even a few hours can substantially increase the availability of nutrients to microbial and macroinvertebrate communities (Battin et al., 2008). Backwater and scour pools, overhead cover, and organic substrate associated with logjams provide important habitat for aquatic organisms (Herdrich et al., 2018; Richmond & Fausch, 1995; Stewart et al., 2012) and logjams in abandoned channels that have accreted to the floodplain provide habitat for terrestrial organisms (Harmon et al., 1986; Pettit et al., 2005). Logjams increase pressure gradients within the channel that enhance hyporheic exchange flows (Doughty et al., 2020; Hester & Doyle, 2008; Sawyer et al., 2011) and logjams obstruct flow and enhance overbank flow and lateral channel migration, thus enhancing channel-floodplain connectivity (Collins et al., 2012; Jeffries et al., 2003; Wohl, 2011). The diverse and critical functions of logjams in streams suggest that systematically differentiating the geomorphic and ecological effectiveness of different types of logjams can be useful in understanding and managing rivers.

Logjams can form via diverse mechanisms at different points along a stream. Where transport of large wood is limited by flow width and depth relative to wood piece size in relatively small streams, *in situ* logjams coalesce around a relatively immobile obstacle such as a ramp or bridge wood piece that has one or both ends resting above bankfull flow, respectively (Abbe & Montgomery, 2003; Beckman & Wohl, 2014b), or around living vegetation in relatively wide, shallow channels (e.g., Gurnell & Grabowski, 2016). Such logjams are more likely to completely span the width of the channel. As transport capacity increases, logjams are more likely to be composed of pieces transported to a site with persistent, locally reduced transport capacity, such as the head of a bar or vegetated island or the mouth of a secondary channel (Abbe & Montgomery, 2003; Bertoldi et al., 2013; Gurnell et al., 2000; Schenk et al., 2014; Wohl et al., 2018). Logjams are less likely to span the entire bankfull channel as channel width increases relative to wood piece size, although naturally occurring wood rafts composed of thousands of individual wood pieces occur in a few places today (Boivin et al., 2015; Kramer & Wohl, 2015) and were more widespread historically (Triska, 1984; Wohl, 2014). Consequently, the size of wood accumulations that are commonly the focus of management and that are capable of creating channel-spanning logjams and backwater pool storage typically occur in channels ≤25 m wide (e.g., Abbe & Montgomery, 2003; Bilby & Ward, 1989; Wohl & Scott, 2017).

Despite the many beneficial effects associated with logjams, deforestation and active wood removal from channels and floodplains have significantly reduced wood loads in river corridors and the size and abundance of logjams in channels throughout the temperate latitudes (Montgomery et al., 2003; Wohl, 2014). Reduced wood loads and thus reduced logjam formation have contributed to the widespread simplification and homogenization of rivers (Collins et al., 2012; Peipoch et al., 2015) and to the loss of retentive capacity and biogeochemical processing of nutrients (Krause et al., 2014; Livers et al., 2018; Stanley & Doyle, 2002). This has fostered increased attention to restoring habitat heterogeneity (Polvi et al., 2014), including actively reintroducing large wood and logjams as part of river restoration (Grabowski et al., 2019; Roni et al., 2015). Emplacement of engineered logjams, in particular, is used to create fish habitat (Pess et al., 2012), stabilize channel boundaries (Gallisdorfer et al., 2014), and reduce downstream flood hazards by increasing hydrologic connectivity between the channel and floodplain (Grabowski et al., 2019). However, as with other types of river restoration, the effectiveness of wood reintroduction projects remains poorly known in many cases because of lack of monitoring. Dimensionless geomorphic metrics can be used to differentiate logjams into classes of differing channel blockage and logjam porosity, and each class creates distinct primary geomorphic functions (Dixon, 2016). However, limited understanding of how characteristics of naturally occurring logjams relate to specific functions such as sediment storage, backwater pool volume and organic matter storage (Beckman & Wohl, 2014a; Brummer et al., 2006; Dixon, 2016; Mao et al., 2008; Wohl & Scott, 2017) still constrains our ability to evaluate the extent to which engineered logjams create geomorphic and ecological effects similar to those of natural logjams.

We assess the geomorphic effectiveness of naturally occurring logjams in relation to whether they span the active channel using field data from mountain streams in the Southern Rockies, USA. We test the inference that channel-spanning logjams create significantly different geomorphic effects than otherwise similar logjams that do not span the channel (Figure 1). We use backwater pool volume and POM volume associated with a logjam to assess geomorphic effectiveness, and other measured channel and logjam characteristics to evaluate differences between channel-spanning versus non-spanning logjams. Specifically, we hypothesize that, when comparing logjams of similar size (obstruction ratio, wood volume, and logjam height) in similarly sized channels, channel-spanning logjams have the potential to create significantly greater backwater storage. While it is intuitively assumed that channel-spanning logjams more effectively store water and organic matter, this study is novel in evaluating a robust data set of naturally occurring logjams in a single study area specifically based on whether they span the channel. If channel-spanning logjams create significantly greater geomorphic effects than other logjams, this suggests that restoration in small streams should put more emphasis on creating and maintaining channel-spanning logjams in lieu of logjams that only occupy a portion of the active channel.

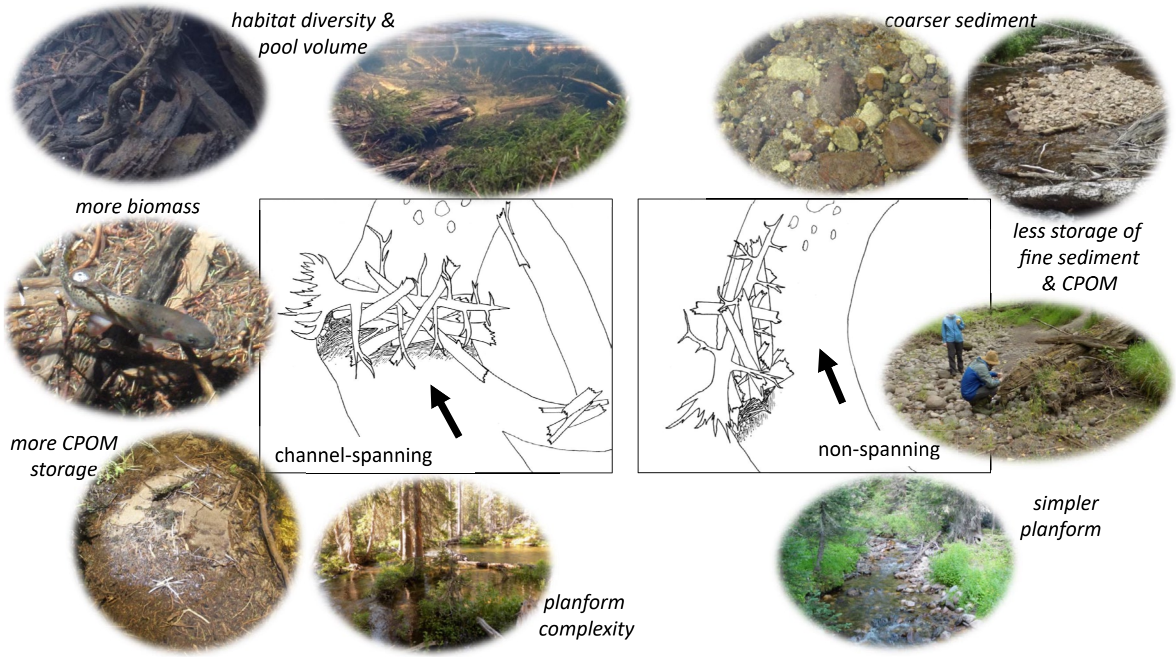


Figure 1. Conceptual diagram showing hypothesized differences in planform, habitat, and storage of water, sediment, and coarse particulate organic matter (CPOM) between channel-spanning and non-spanning logjams. Channel-spanning logjams can lead to greater trapping of organic material and backwater pool volumes, leading to the settling and storage of fine sediment and particulate organic matter, as well as instream habitat diversity, biomass, and, in some cases, channel avulsions and multithread stream planform.

2. Study Area and Methods

2.1. Colorado Front Range Study Sites

All study sites are within the subalpine vegetation zone of the Colorado Front Range, USA. Mean annual precipitation is in the range of 70–90 cm and stream flow is dominated by snowmelt, which produces an annual hydrograph with sustained peak flow in June. Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), and limber pine (*Pinus flexilis*) dominate upland subalpine forests, with Engelmann spruce, Douglas-fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*) present in riparian subalpine forests (Veblen & Donnegan, 2005). Tree diameters at breast height are commonly 20–40 cm, but can reach 1 m in old-growth (>200 years age) stands. Wood decay is slow, with turnover times for large downed logs on the forest floor of 600–900 years (Kueppers et al., 2004). Wood is recruited to channels primarily through bank erosion, wildfire, insect infestation, and blowdowns, rather than hillslope mass movements. Although wood in streams likely decays more rapidly (Harmon et al., 1986), individual wood pieces in logjams require decades to centuries to decay. Step-pool, plane-bed, and pool-riffle channel morphologies are most common, and streambed substrate is typically cobble to boulder size. Wood loads and number of logjams exhibit significant longitudinal variation in these mountain streams (e.g., Wohl & Cadol, 2011) as a result of spatial and temporal differences in wood recruitment and wood-trapping capacity along the channel. Wood is trapped in channels on the upstream side of boulders, vegetated islands, and bridge and ramp pieces, as well as along channel margins. Logjams can be formed *in situ* or composed entirely of transported pieces. Stream reaches in the data set include single- and multi-thread channel planforms and old-growth and younger riparian forests. Drainage area for individual sites ranges from 6.4 to 34 km^2.

2.2. Field Data Collection and Analyses

We chose 17 stream reaches in second to third order channels with no history of timber harvest or other human alteration. All sites are within the Big Thompson River and North St. Vrain Creek watersheds in

Rocky Mountain National Park, which contain some of the largest old-growth forest stands in the region (Sibold et al., 2006) (Figure 2).

We delineated reaches, which ranged from 200 to 700 m in valley length, to include consistent channel and valley geometry. For each reach, we took 4–5 measurements of bankfull width, floodplain width, lateral valley confinement (ratio of channel width to floodplain width), water-surface gradient, and basal area of the riparian forest to calculate reach-averaged values. Drainage area for the downstream end of each reach was determined using U.S. Geological Survey StreamStats. We designated wood accumulations with three or more pieces in contact as logjams and every logjam within each reach was evaluated. For each logjam, we measured dimensions and orientation of every large wood (>10 cm in diameter and 1 m in length) piece in the logjam, although some pieces may have been buried, submerged, or unmeasurable within the logjam matrix, and thus total wood volume estimates are minimum. We also recorded GPS coordinates, measured logjam dimensions (best-fit box), and visually estimated porosity and POM volume, both as the proportion of the best-fit box volume (Livers et al., 2020). Although these visual estimates are relatively subjective and porosity is likely underestimated (Livers et al., 2020), consistent methodology was used by the same researcher, making comparisons within the data set possible. For logjams with backwater pools, we measured backwater residual pool volume and POM volume in the backwater pool, both calculated as the product of measured length, width, and average of several depth measurements; and a binary descriptor of channel-spanning or other (Figure 3). (Hereafter, we refer to backwater pools simply as pools.) Channel-spanning logjams completely span the bankfull channel, either transverse or oblique to flow. We used these basic field measurements to derive variables such as logjam wood volume (sum of all wood pieces in each logjam, using measured dimensions and assuming cylindrical shape) and standardized ratios such as obstruction index (logjam width/average channel width) (Table 1). We standardized variables as ratios whenever possible (e.g., pool volume/channel width) in order to facilitate comparison to data from other sites in future. We refer to all variables that are standardized by reach-average bankfull channel width as unit values (e.g., unit pool volume).

We used *t*-tests, or nonparametric Wilcoxon rank sum tests, to analyze differences in means of logjam variables between channel-spanning logjams and non-channel spanning logjams. We examined significant differences between channel-spanning versus non-spanning logjams in two ways: using all logjams and a reduced set using only logjams with pools. Within our data set, channel-spanning and non-spanning logjams exist both with and without pools. Some channel-spanning logjams may still be porous under more densely organized pieces that span the channel, allowing leakage underneath a logjam and preventing backwater pool formation. We examined the reduced set of only logjams with pools to determine if comparable retention could be attained in non-spanning jams once the threshold of a backwater pool formation occurs.

We used linear regression models and binomial logistic regression models to evaluate potential predictors for logjam geomorphic effects and channel-spanning logjams, respectively, using stepwise selection and choosing the models with the lowest AIC values.

3. Results

The data set includes 183 logjams from 17 stream reaches in Rocky Mountain National Park, Colorado in the Southern Rockies (Data Sets S1 and S2). Comparison of channel-spanning and non-spanning logjams indicates significant differences in all variables analyzed except porosity. Channel-spanning logjams have a larger number of wood pieces and total wood volume, larger wood pieces (length and diameter) and a wider range of piece sizes, more ramp and bridge pieces, and greater logjam height (Table 1). These differences hold for unit variables, including obstruction ratio, maximum piece length, logjam height, and logjam volume. With respect to geomorphic effects, channel-spanning logjams have significantly greater pool volume, pool organic matter (OM) volume, and logjam OM volume, both as raw data and when standardized by average channel width (Table 1).

Within the data set, channel-spanning logjams were twice as likely as non-spanning logjams to have backwater pools (84.5% vs. 42.5%). When only logjams with pools are retained, channel-spanning logjams still have significantly greater geomorphic effects and similar porosity values (Table 1, selected variables). Porosity was only found to be significantly different (lower) when comparing all logjams with pools versus those

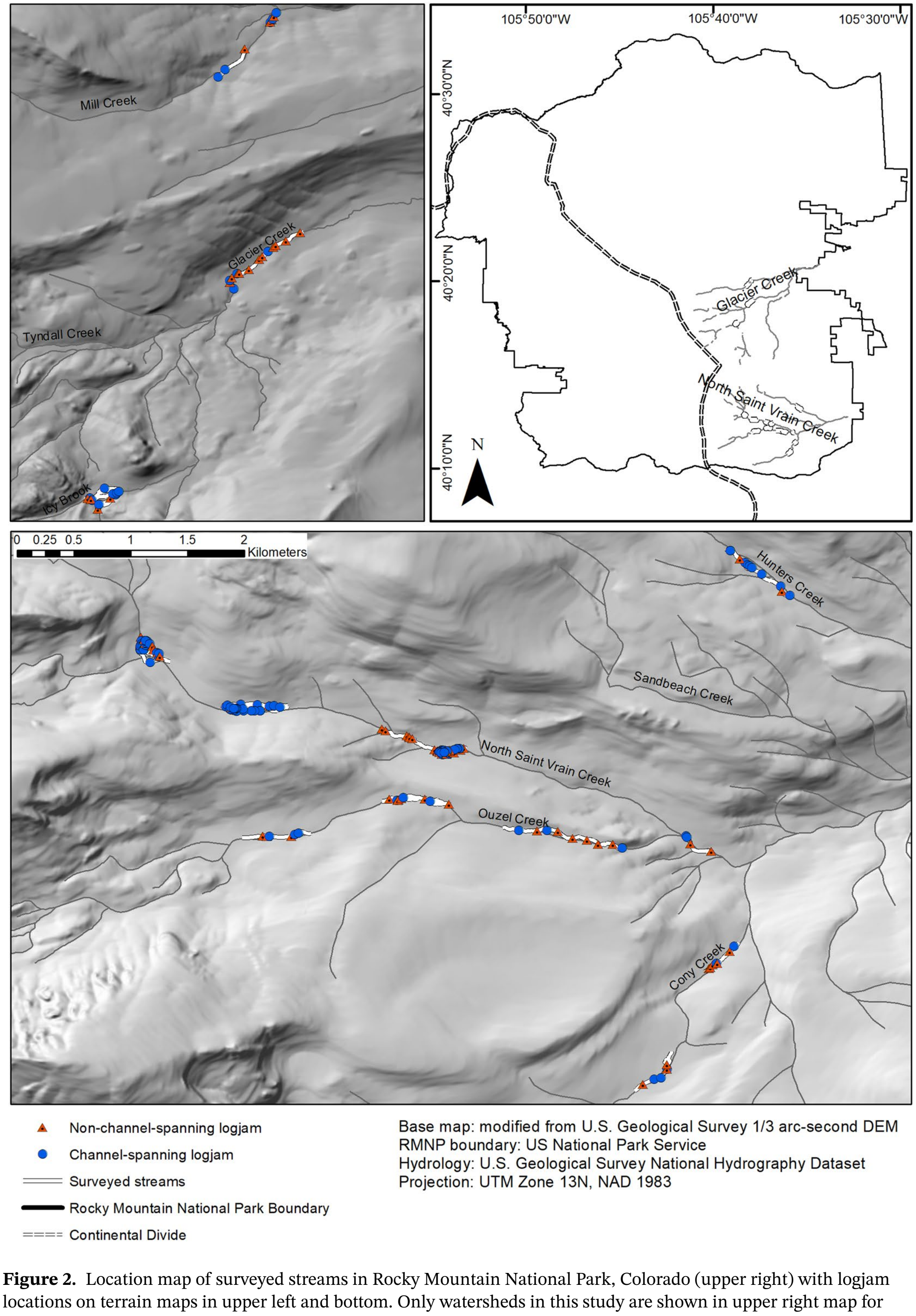


Figure 2. Location map of surveyed streams in Rocky Mountain National Park, Colorado (upper right) with logjam locations on terrain maps in upper left and bottom. Only watersheds in this study are shown in upper right map for ease of locating study streams.

Figure 3. Non-channel spanning logjams (left column, a–d) and channel-spanning logjams (right column, e–h), with red and white arrows pointing downstream. Note differences in forest cover and valley confinement. Channel-spanning logjam in e has noticeable pool with organic matter storage, both of which are highly localized. These logjams are identified as 3 (a–h) in Data Set S2.

Table 1
Means, Standard Deviations, and Significant Differences Between Channel-Spanning and Non-Spanning Logjams

		Mean	SD	Mean	SD	
		Non-spanning jams (n = 80)		Channel-spanning jams (n = 103)		p-value
Logjam variables	Wood volume (m^3)[a]	1.91	2.37	***4.75***	7.69	**<<0.01**
	Number pieces (#)[a]	11.3	9.76	***15.6***	17.87	**0.05**
	Logjam height (m)	0.72	0.47	***0.93***	0.44	**<<0.01**
	Porosity (proportion)	0.38	0.16	0.36	0.19	0.30
	Logjam POM volume (m^3)	0.46	0.74	***1.93***	3.52	**<<0.01**
	Pool volume (m^3)	1.27	2.95	***11.60***	21.69	**<<0.01**
	Pool POM volume (m^3)	0.09	0.34	***0.763***	1.56	**<<0.01**
Wood piece variables	No. bridge & ramp pieces (#)	1.5	1.5	***2.9***	2.4	**<<0.01**
	Mean diameter (m)	0.21	0.07	***0.23***	0.06	**0.01**
	Mean length (m)	3.78	2.79	***3.79***	1.18	**0.04**
	Maximum diameter (m)[a]	0.33	0.11	***0.40***	0.15	**<0.01**
	Maximum length (m)[a]	8.50	5.36	***10.26***	5.40	**0.01**
	SD of piece length (m)[a]	2.71	2.52	***2.94***	1.71	**0.04**
	SD of piece diameter (m)	0.07	0.04	***0.09***	0.05	**0.02**
	SD of piece volume (m^3)[a]	0.28	0.44	***0.38***	0.51	**<0.01**
Unit variables	Obstruction ratio (m/m)[a]	0.66	0.35	***0.97***	0.51	**<<0.01**
	Jam height (m/m)	0.12	0.07	***0.18***	0.09	**<<0.01**
	Maximum piece length (m/m)	1.46	1.23	***2.07***	1.39	**<<0.01**
	Mean piece length (m/m)	0.62	0.52	***0.76***	0.56	**<0.01**
	Wood volume (m^3/m)[a]	0.30	0.37	***0.77***	1.03	**<<0.01**
	Pool volume (m^3/m)	0.19	0.39	***1.96***	3.51	**<<0.01**
	Pool POM volume (m^3/m)	0.02	0.08	***0.14***	0.24	**<<0.01**
	Logjam POM volume (m^3/m)	0.08	0.13	***0.32***	0.56	**<<0.01**
Only logjams with pools		Non-spanning jams (n = 34)		Channel-spanning jams (n = 87)		
Logjam and wood piece variables	Porosity (proportion)	0.353	0.17	0.351	0.2	0.75
	Pool volume (m^3)	3.05	3.96	***13.74***	22.98	**<<0.01**
	Logjam POM volume (m^3)	0.47	0.48	***2.22***	3.74	**<0.01**
	Pool POM volume (m^3)	0.21	0.5	***0.9***	1.66	**<0.01**
	No. bridge & ramp pieces (#)	1.6	1.4	***2.8***	2.5	**0.02**
Unit variables	Wood volume (m^3/m)[a]	0.25	0.22	***0.81***	1.07	**<<0.01**
	Pool volume (m^3/m)	0.45	0.5	***2.32***	3.71	**<<0.01**
	Pool POM volume (m^3/m)	0.05	0.13	***0.17***	0.26	**<0.01**
	Logjam POM volume (m^3/m)	0.07	0.07	***0.37***	0.6	**<<0.01**

Note. n = # indicates sample size; Bold, italic font = significantly higher at alpha = 0.05; Unit variable indicates standardized by average channel width; << indicates p-values lower than 0.001.
Abbreviation: POM, Particulate organic matter.
[a]Variables that have normal distributions when log-transformed.

without pools ($p = 0.045$), suggesting that reduced porosity from infilling of finer material could represent a threshold for production of backwater pools.

These results support the hypothesis and suggest that channel-spanning logjams can create significantly different geomorphic effects than otherwise similar logjams that do not span the channel. However, all variables have large ranges and many are skewed, and thus standard deviation values are high (Figure 4). None of the variables analyzed had normal distributions, and only nine variables included in Table 1 were able to be transformed into normal distributions, all through logarithmic transformations. Thus, nonparametric tests were required for comparisons between spanning and non-spanning logjams; for variables with a normal distribution when transformed, the larger *p*-value between the *t*-test versus Wilcoxon rank sum test was retained.

Differences in the geomorphic effects of channel-spanning and non-spanning logjams are more easily visualized in bivariate comparisons of potential control variables (obstruction ratio, unit wood volume, and unit logjam height) and response variables (unit pool volume, pool OM volume, and logjam OM volume) (Figure 5). Each of these comparisons indicates that, although not all channel-spanning logjams create greater geomorphic effects than non-spanning logjams, the upper values of backwater storage are only created by channel-spanning logjams. In other words, for the same obstruction ratio, unit wood volume, or unit logjam height, channel-spanning logjams can create much greater backwater storage. Of the three response variables, unit pool volume has the greatest range between channel-spanning and non-spanning logjams.

We used stepwise linear regression models to evaluate the strongest predictors for the unit response variables of pool volume, pool OM volume, and logjam OM volume (Tables 2 and S1). For each response variable, we evaluated models for the entire data set and then separately for channel-spanning and non-spanning logjams. Although this analysis produced a statistically significant model in every case ($p<<0.05$), the predictive value (adjusted R^2) is generally low. The only models that were able to predict about half of the variation in the response variables are those for the organic matter contained within a logjam. Of the 21 predictor variables included in these models, 18 were significant in at least one model. Of these 18, logjam height, porosity, unit wood volume, and unit wood pieces are the most common. Using all logjams, lower mean reach gradient was the most significant predictor variable for unit pool volume and unit pool OM volume using all logjams; spanning the channel was significant in predicting unit pool volume. Unit logjam OM volume is dependent only on logjam variables, and wood piece variables are only significant in models that include only channel-spanning or only non-spanning logjams, particularly variation in wood piece diameter. In general, variables that predict retention variables are similar between models that use all logjams or only channel-spanning logjams, while models that predict retention variables in non-channel spanning jams require a different combination of variables to achieve higher retention values. We used binomial logistic regression models to evaluate the strongest predictors for channel-spanning logjams. Significant predictors included channel width (negative coefficient), basal area of riparian forest, logjam height, and number of bridge and ramp pieces; logjam height appears to be the most significant predictor of channel-spanning logjams. McFadden's pseudo R^2 (0.216) also indicates low predictive power of this model. Because porosity and logjam POM were estimated visually as the proportion of the best-fit box, their values may not be comparable to those from other studies, and they may be a source of low predictive power. In addition, the skewness of data and low backwater retention in some channel-spanning logjams complicate prediction. Although these results are too statistically weak to be used for prediction, they indicate the importance of the amount of wood in a logjam, the height to which wood accumulates, and the infill of the logjam matrix (low porosity) as significant influences on backwater and within-logjam storage of water and organic matter.

4. Discussion

Our study of logjams in unaltered headwater streams in Rocky Mountain National Park revealed significant differences between logjams that span the entire stream channel and those that do not. Both types of logjams were often present within the same stream reach, but channel-spanning logjams consistently had greater wood volumes, backwater pool volumes, and retention of particulate organic matter both within the logjam matrix and in pools. These results correspond to patterns of much greater sediment storage in channel-spanning logjams documented for Lost Horse Creek in Montana, USA (Welling et al., 2021). Channel-spanning logjams in Colorado also had significantly greater variation in wood piece sizes, which presumably assists in the infilling of the logjam matrix, lowering porosity and assisting with pool formation. Flume experiments indicate a strong correlation between backwater rise or pool volume and lower logjam porosity (Follett et al., 2020; Schalko et al., 2018). Not all channel-spanning logjams have high retention values, however, and this is reflected in high standard deviation values and outliers for many variables (Table 1

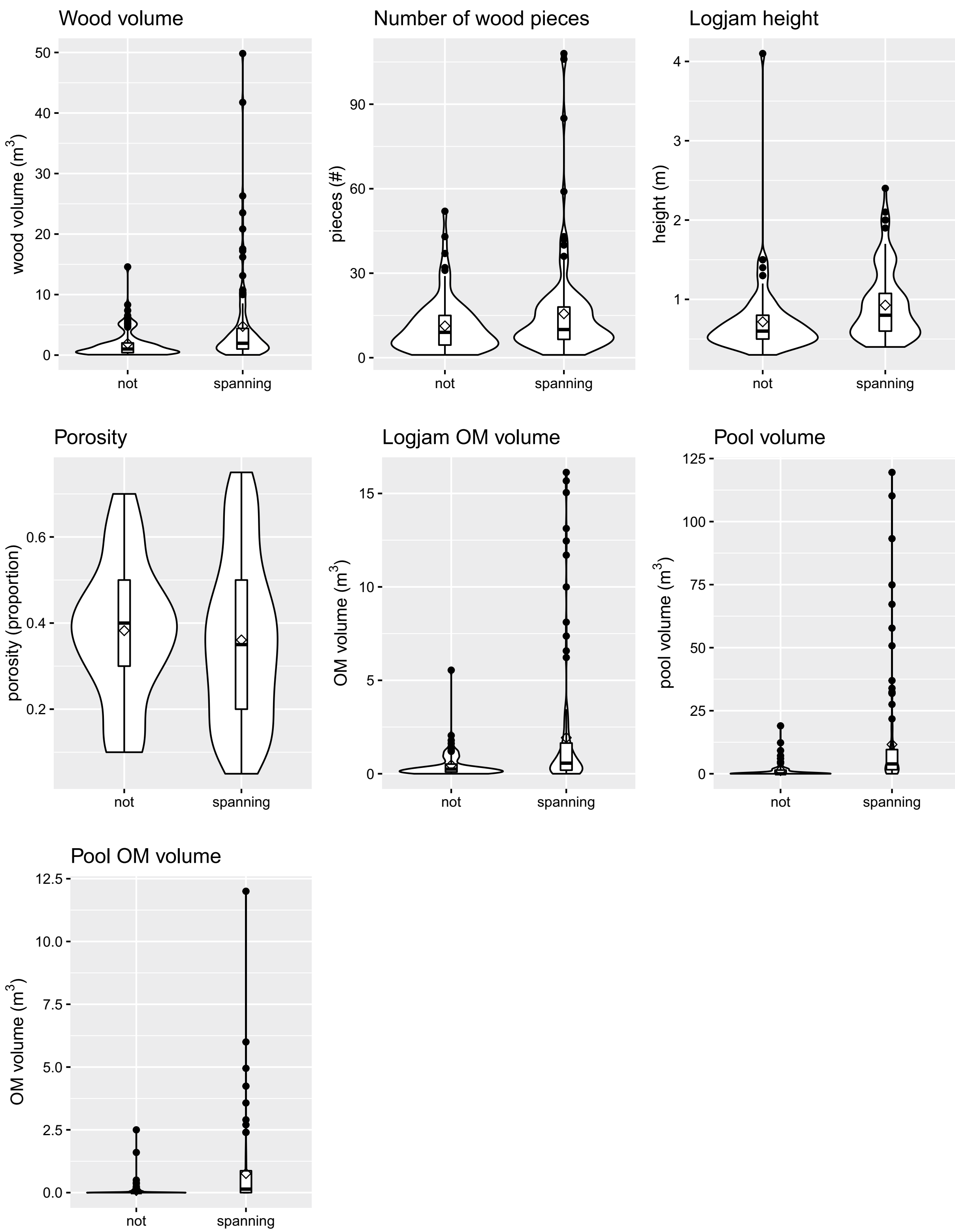
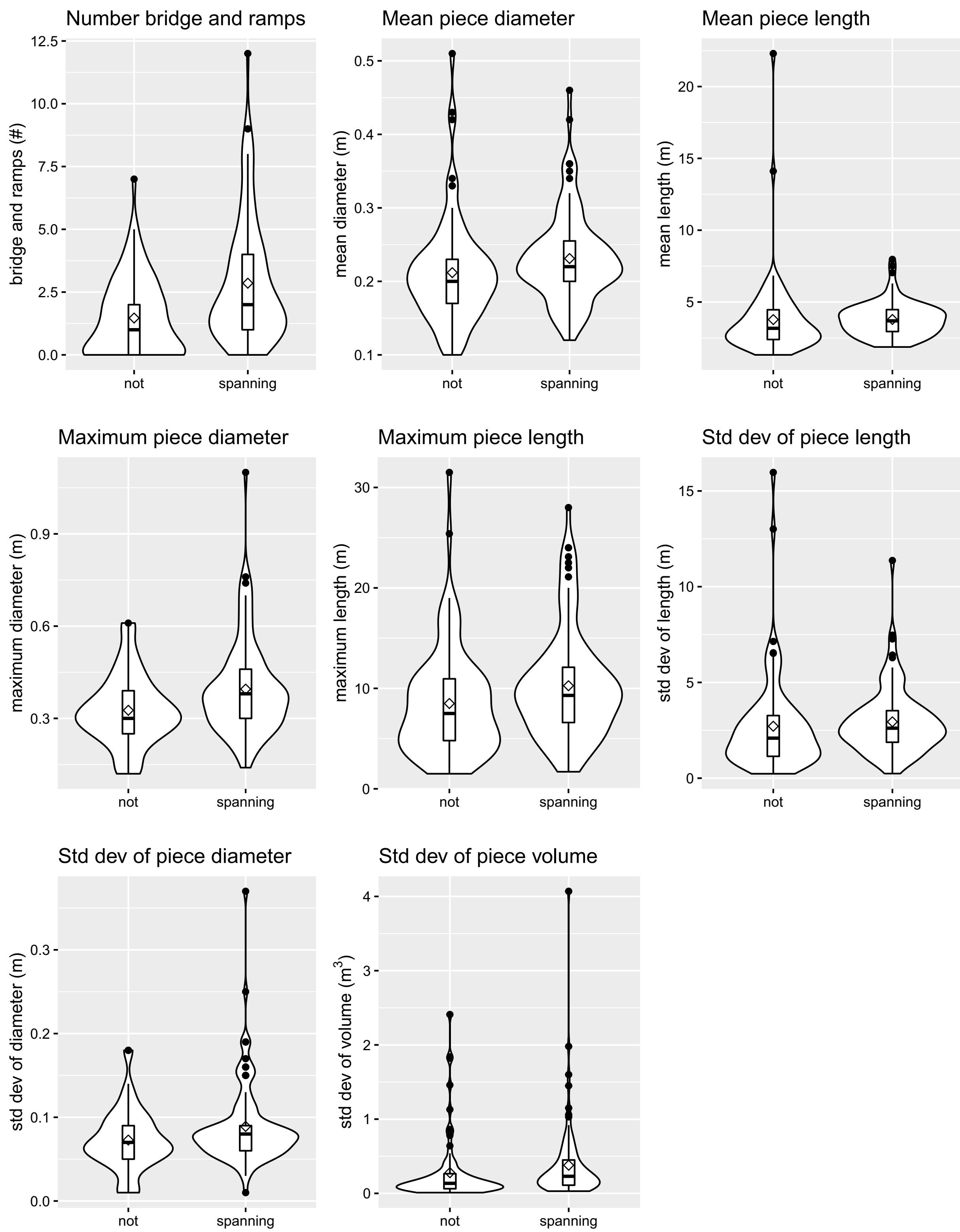


Figure 4. Violin plots of variables listed in Table 1, showing density and skewness of data. (a) Logjam variables, (b) wood piece variables, (c) unit variables, (d) selected variables using only logjams with pools. Vertical rectangle represents interquartile range with bold horizontal line as median; open diamonds represent means, listed in Table 1. Width of violin represents density of data points and solid black dots are statistical outliers. OM, organic matter; Std dev, standard deviation.



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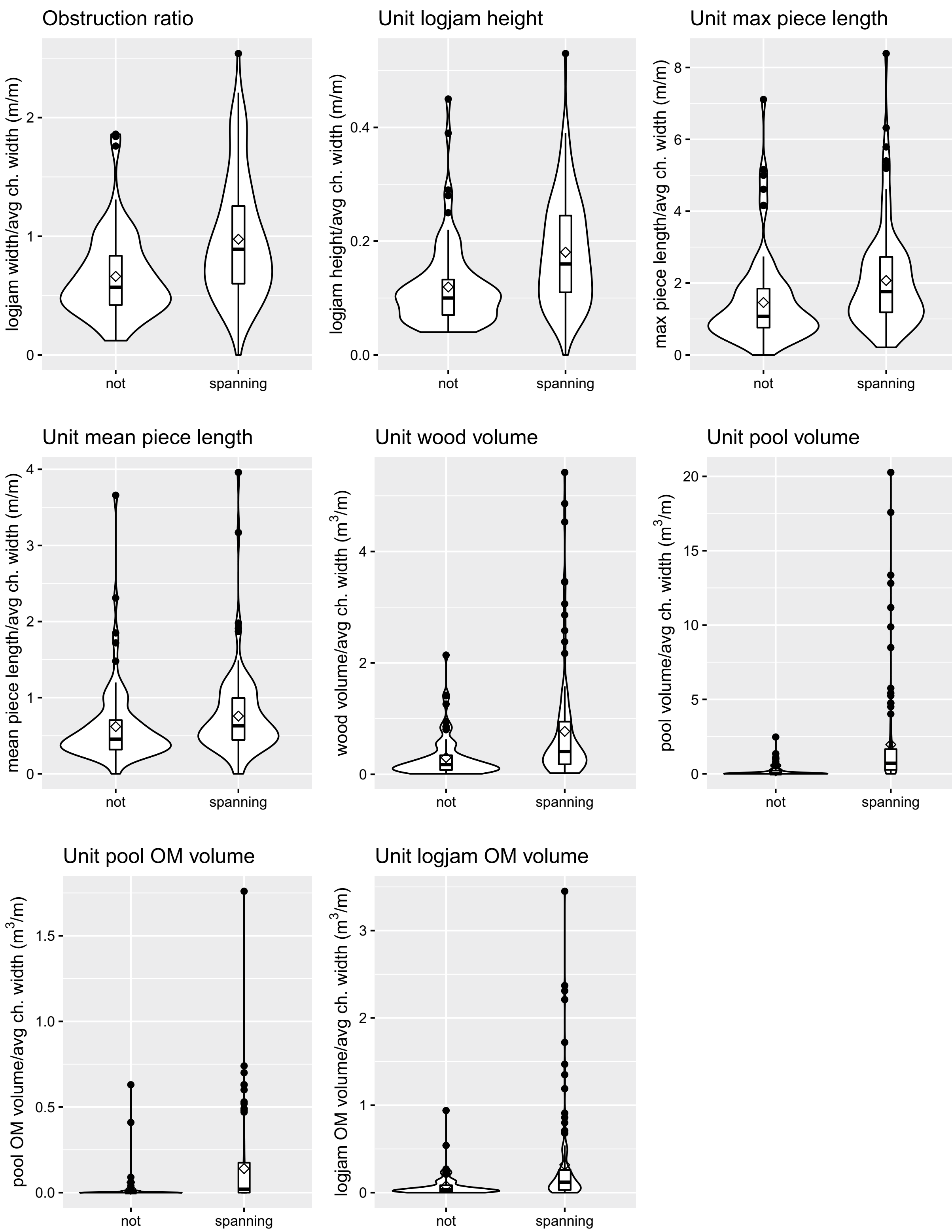

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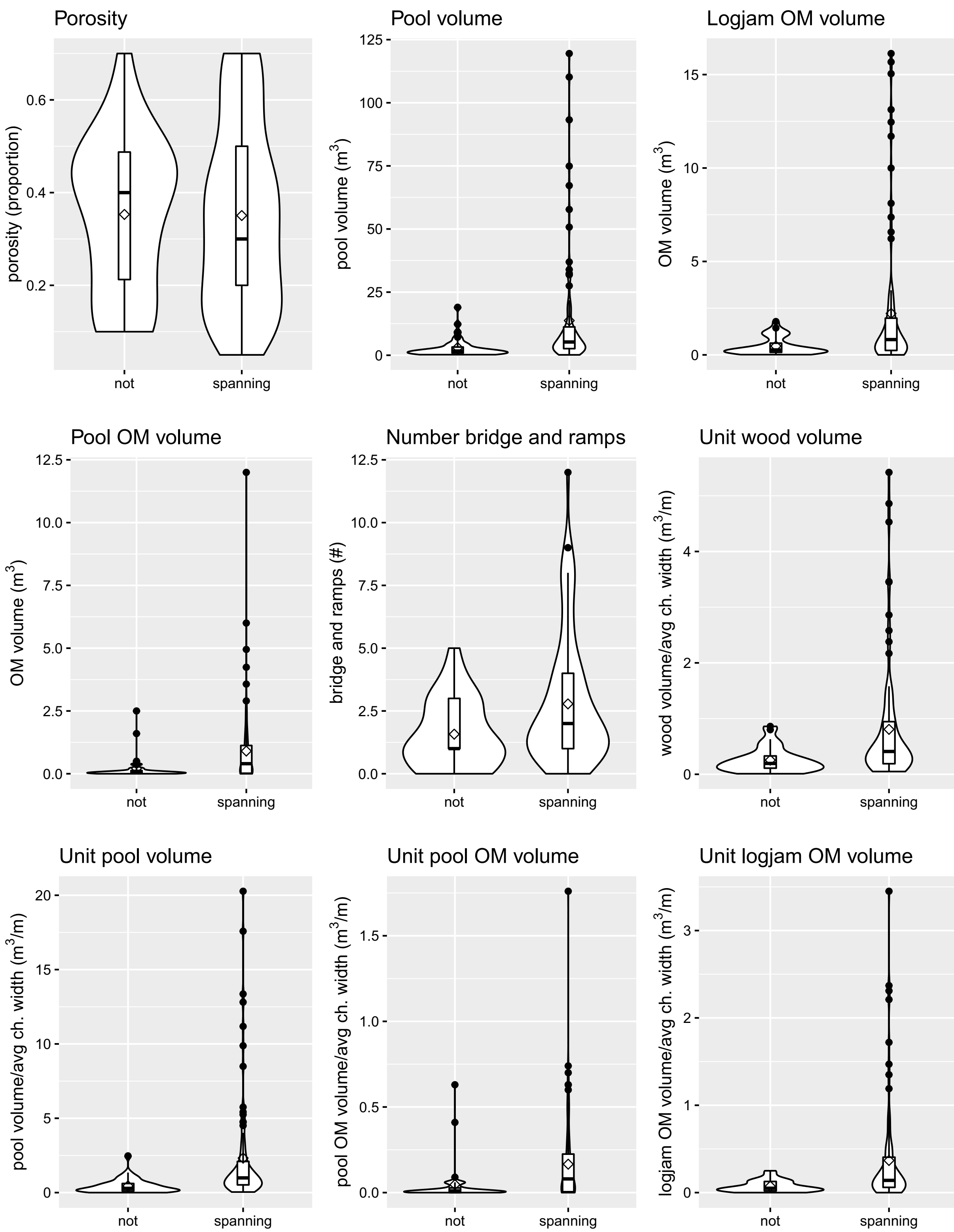

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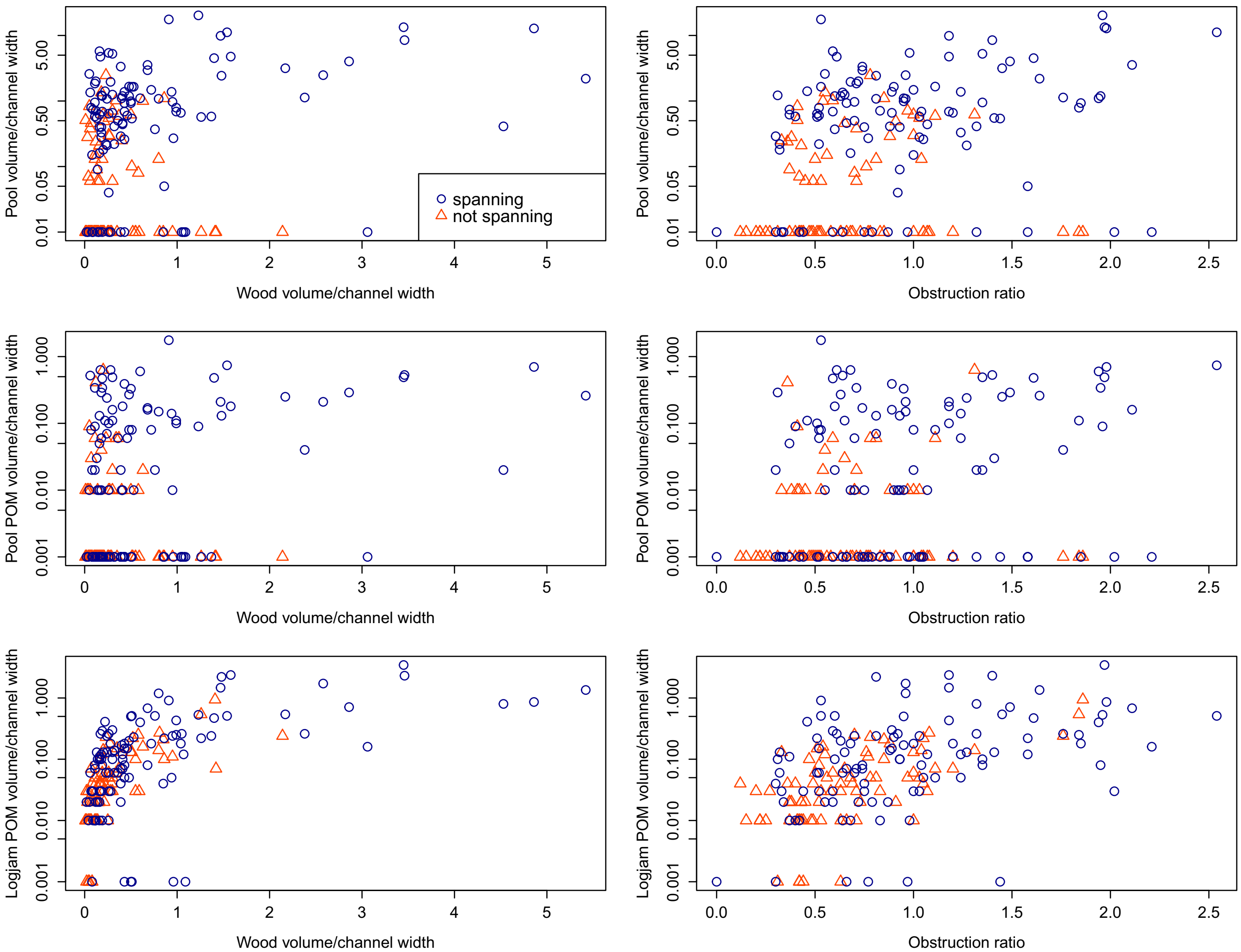

Figure 5. Sample bivariate plots for (a) unit pool volume, (b) unit pool organic matter (OM) volume, and (c) unit logjam OM volume in relation to unit wood volume (left column) and obstruction ratio (right column). Data are plotted with logarithmic *y* axes to better visualize spread of retention variables, although outliers are more difficult to distinguish; because many data points have values of zero, a small constant was added to values of zero (e.g., 0.01 in (a) plots, 0.001 in [b and c] plots) in order to retain data points.

and Figure 4), non-Gaussian distributions of data, and low predictive power of linear regression models (Table 2). Skewness in the data could be a consequence of some logjams forming pools while others do not, which may reflect lower logjam porosity, regardless of whether a logjam spans the entire stream channel. All channel-spanning logjams are not equal, perhaps due to: lack of pieces that block flow on the bottom of the logjam, making the logjam leaky on its underside; or from the flushing out of finer matrix material from the logjam during floods, overbank flow, or channel avulsions. Once the threshold of spanning the channel and backwater pool formation is reached, the logjam is able to capture any large wood, sediment, and organic matter that flows downstream toward it, allowing these logjams to grow much larger and develop greater retention than their non-spanning counterparts.

The results described here should be applicable to the lower gradient portions of other small to moderately sized channels in forested regions. We cannot precisely constrain the persistence of logjams and their associated effects, partly because logjam characteristics likely vary between regions (e.g., Curran, 2010; Dixon & Sear, 2014). A decadal study of channel-spanning logjams in the study area, however, indicates that the number of channel-spanning logjams within a reach remains relatively consistent, although individual logjams form and break apart over periods of a few years (Wohl & Scamardo, 2021). Disturbances such as blowdowns (Wohl, 2013) tend to create new logjams, whereas prolonged or high-magnitude snowmelt

Table 2
Retained and Significant Variables in Linear Regression Models for Three Retention Variables

	Potential control variable	Model response variable: Unit pool volume	Unit pool OM volume	Unit logjam OM volume	Channel-spanning jams
Reach variables	Drainage area (km²)				
	Mean bankfull width (m)		*		*x*(−)
	Basal area (m²/ha)				*x*
	Mean gradient (m/m)	*X*(−)	*X*(−)		
	Confinement ratio (m/m)	*x*(−)	*	*	
	Multithread planform (y)		*		
Logjam variables (including unit variables)	Porosity (proportion)	*x*(−)	*x*(−)		*
	Channel-spanning (y)	*x*			
	Height (m)	*x*		*x*	*X*
	Obstruction index (m/m)	*	*x*		
	Unit logjam POM volume (m³/m)	*x*			
	Unit wood volume (m³/m)	*		*X*	
	Unit wood pieces (#/m)	*x*		*x*(−)	
	Unit pool volume (m³/m)		*x*		
Wood piece variables	Maximum diameter (m)				
	Maximum length (m)				
	No. bridge & ramp pieces (#)				*x*
	Proportion bridge & ramp pieces		*		
	SD of piece length (m)				
	SD of piece diameter (m)				
	SD of piece volume (m³)	*	*		
	adjusted R^2	0.38	0.47	0.49	

Note. ***x*** = variable significant in model; ***X*** = variable significant in model with largest coefficient estimate; (−) = coefficient estimate is negative; * = variable in model but not significant.
Abbreviations: OM, Organic matter; POM, Particulate organic matter.

flows tend to remove logjams. The locations within a river network at which channel-spanning logjams are likely to form reflects channel dimensions relative to the size of available wood pieces (Dixon & Sear, 2014; Gurnell et al., 2002). As channel width and flow depth increase relative to average wood piece length and diameter, wood mobility increases substantially and logjams typically obstruct only a portion of the bankfull channel. The specific channel and wood dimensions that support formation of channel-spanning logjams can thus be expected to vary among geographic regions with different climates and forest types, but the ratios of these dimensions should have a narrow range. Channel-spanning logjams have been documented from the tropics (Gomi, Sidle, et al., 2006), throughout the forested temperate latitudes (e.g., Costigan et al., 2015; Keller & Swanson, 1979), and in sub-Antarctic (Comiti et al., 2008; Mao et al., 2008), and boreal streams (Gomi, Johnson, et al., 2006; Robison & Beschta, 1990). Although these studies specifically mention the importance of channel-spanning logjams as sites of enhanced water, sediment, and organic matter storage and significant influences on bedform and planform characteristics, they do not provide the data that would allow the type of analysis we report here and queries to authors of some of these papers indicate that channel-spanning and non-spanning logjams were not distinguished during data collection because data collection was focused on a different question, such as the effect of forest stand age or disturbance on wood loads. In addition, little is known of the relative persistence of logjams and their geomorphic and ecological effects in diverse environments, although it is clear that there are regional differences (Curran, 2010; Dixon & Sear, 2014; Sear et al., 2010; Wohl & Goode, 2008; Wohl et al., 2012).

10.1029/2021JF006076

Formation of channel-spanning logjams in small to moderate channels is also greatly enhanced by the presence of relatively immobile obstacles that can trap small wood pieces in transport. Previous research in the study area suggests the importance of the presence and longitudinal spacing of ramp and bridge pieces (one or both ends resting above the bankfull channel, respectively) (Beckman & Wohl, 2014b). In the data set analyzed here, 92% of the channel-spanning logjams included one or more ramp or bridge pieces, whereas only 64% of the non-spanning logjams had such pieces. Although any size of tree that falls into a channel can create a ramp or bridge piece, the long, large diameter ramps and bridges associated with recruitment of old-growth trees are especially effective at trapping mobile wood pieces (Beckman & Wohl, 2014b). In the more retentive lower gradient, wider valley portions of mountain stream networks, ramp and bridge pieces are also more likely to trap smaller, mobile pieces and to form relatively stable channel-spanning logjams (Wohl & Cadol, 2011). The closer longitudinal spacing of channel-spanning logjams in wide portions of the valley relative to steep, narrow segments suggests that, although ramp and bridge pieces can form along any portion of a stream, their ability to create channel-spanning logjams is enhanced where transport capacity declines, commonly in association with the presence of multiple, sub-parallel channels in wider, lower gradient reaches (Livers & Wohl, 2016). The location of channel-spanning logjams thus reflects a particular wood regime with respect to potential wood recruitment, storage, and transport. These characteristics can be used to define a wood process domain (Wohl et al., 2019) based on channel and wood piece dimensions and the presence of sufficiently stable pieces to initiate logjam formation.

Restoration employing engineered logjams typically involves logjams that obstruct only a portion of the bankfull channel and have high porosity. Concerns that a channel-spanning logjam might become mobile and create hazards to downstream infrastructure, or that the logjam's presence might increase flood hazards or create hazards for recreational boating, can limit the emplacement of channel-spanning logjams (Grabowski et al., 2019; Roni et al., 2015; Wohl et al., 2016) and logjam design typically incorporates only large wood pieces. The significant differences in backwater storage between channel-spanning and non-spanning logjams described in this paper suggest that restoration aimed at enhancing aquatic habitat and retention of organic matter in channels can be most effective where logjams spanning the entire channel are emplaced or are allowed to form around relatively immobile obstacles such as naturally occurring or introduced ramp and bridge wood pieces. Aquatic habitat and backwater retention can also be enhanced if logjams are designed with the explicit intent of trapping finer organic material in transport, thus reducing logjam porosity with time. This might involve deliberately including smaller wood pieces in the engineered logjam or ensuring that spaces within the jam are sufficiently small to trap and retain mobile organic material. In managed stream corridors, engineering logjams or introduced ramp and bridge pieces can create geomorphic and ecological benefits while riparian forests become sufficiently mature to produce large, relatively stable instream wood. This may be particularly applicable in projects implementing stage 0 channels (Cluer & Thorne, 2014): anastomosing narrow channels with vegetated islands intended to restore degraded stream segments. Where channel-spanning logjams are sufficiently abundant and closely spaced, and the wood process domain supports persistent logjams and associated geomorphic effects, the river corridor can assume an alternative state that greatly enhances spatial heterogeneity, retention of materials in flux down the river, and habitat and biodiversity (Collins et al., 2012; Livers et al., 2018).

As disturbance regimes change with changing climate, channel-spanning logjams may also help to directly and indirectly enhance river corridor resilience to disturbances. Direct effects include at least temporary storage of sediment and thus attenuation of enhanced downstream sediment fluxes (e.g., Grabowski & Wohl, 2021; Hinshaw et al., 2020). Indirect effects associated with the presence of channel-spanning logjams include the formation of secondary channels (e.g., Wohl, 2011) that promote channel-floodplain hydrologic connectivity and thus attenuate downstream water and solute fluxes.

5. Conclusions

For relatively small, snowmelt-dominated mountain streams in the Southern Rockies, the logjam-induced geomorphic effects of backwater pool volume and particulate organic matter storage are significantly greater for logjams that span the bankfull channel than for logjams that only partially block the channel. Channel-spanning logjams include more and larger wood pieces and more stable pieces that partially rest on the stream banks above the bankfull flow stage. These logjams are taller and larger than non-spanning logjams relative to channel width. These differences in logjam characteristics have important implications for the geomorphic and ecological functions of logjams. Logjam dimensions relative to channel cross-sectional area, and logjam porosity as influenced by finer organic material, influence attenuation of downstream fluxes of water and particulate material, and can thus increase river corridor resilience to disturbances. Given the documented geomorphic and ecological importance of backwater pool storage, which is substantially enhanced by larger and less porous logjams, we suggest that stream management using engineered logjams in smaller streams could benefit from greater emphasis on channel-spanning logjams.

Data Availability Statement

The data supporting the conclusions in this study are currently located in Data Sets S1 and S2 and online at the Colorado State University Mountain Scholar Digital Repository, which can be accessed at http://dx.doi.org/10.25675/10217/232635.

Acknowledgments
The authors thank Gus Womeldorph and Reed Waldon for field assistance. Funding for this research was provided by NSF DEB-1145616. The manuscript benefited from comments by Simon Dixon, Nakul Deshpande, and anonymous reviewers.

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