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The Transience of Channel-Spanning Logjams in Mountain Streams

Ellen Wohl¹  and Emily P. Iskin¹ 

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

Key Points:

- Logjam persistence (the median timespan over which a jam is present during the 11-year study) is 1–2.5 years
- Site persistence (the median timespan over which at least one jam is present in retentive sites) is 6–10 years
- Despite the transience of most logjams, the jams create persistent effects in channel planform and backwater storage

Supporting Information:

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

Correspondence to:

E. Wohl,
ellen.wohl@colostate.edu

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Author Contributions:

Conceptualization: Ellen Wohl

Formal analysis: Emily P. Iskin

Investigation: Ellen Wohl

Methodology: Ellen Wohl

Resources: Ellen Wohl

Writing – original draft: Ellen Wohl

Writing – review & editing: Emily P. Iskin

Abstract We use 11 years of annual surveys in streams of the Southern Rockies of Colorado, USA, to examine the persistence and geomorphic effects of logjams. Each year's survey includes ~300 logjams along more than 21 km of four mountain streams in primarily old-growth subalpine forest. Streams alternate longitudinally between laterally confined reaches with a single channel and wider reaches with multithread-channel planform. We distinguish logjam persistence and site persistence. Logjam persistence is the median timespan over which an individual jam is present. Site persistence describes the tendency for jams to disappear and then re-form at the same site. We hypothesize that (a) site persistence is greatest in multithread reaches, (b) logjam persistence is greatest in multithread reaches, and (c) average backwater storage at each jam is greater in multithread reaches. We find that spatial and temporal metrics of site persistence differ significantly between single and multithread reaches. Individual logjam persistence does not differ significantly. Backwater storage is significantly greater in multithread reaches. Varying combinations of riparian forest age and average logjams per channel length explain variation in jam and site persistence and backwater storage via multivariate linear regression analyses. Over the 11 years of survey, a total of 429 distinct logjams were observed. Only 2.1% of the population was present for all 11 annual surveys. Median jam persistence is 1–2.5 years; median site persistence is 6–10 years. Despite the transience of most channel-spanning logjams in the population, these jams create persistent effects in channel planform and backwater storage.

1. Introduction

Large wood (>10 cm diameter and 1 m long) creates numerous geomorphic and ecologic effects in stream corridors (active channel and floodplain). By creating obstructions and increasing hydraulic roughness, large wood affects the distribution of hydraulic force (Manners et al., 2007; Shields & Smith, 1992) and therefore hyporheic exchange flows and solute dynamics (Doughty et al., 2020; Sawyer et al., 2011), as well as the transport of sediment and particulate organic matter (Hinshaw et al., 2020; Wohl & Scott, 2017). The presence of large wood can influence the type and dimensions of channel bedforms (MacFarlane & Wohl, 2003); the presence and grain-size distribution of alluvium (Faustini & Jones, 2003; Massong & Montgomery, 2000; Ryan et al., 2014); and the characteristics of reach-scale gradient, cross-sectional geometry, and planform geometry (Collins et al., 2012; O'Connor et al., 2003). The flow obstructions and erosion-resistant points associated with wood accumulations can increase channel-floodplain hydrologic and sediment connectivity, as well as altering channel migration rate and floodplain turnover time (Collins et al., 2012; Sear et al., 2010). Finally, channel and floodplain large wood can enhance aquatic and riparian habitat and biological productivity (Herdreich et al., 2018; Richmond & Fausch, 1995; Venarsky et al., 2018).

After centuries of deforestation and active wood removal from stream corridors (Montgomery et al., 2003; Wohl, 2014), large wood is now recognized as a beneficial feature of stream corridors and the retention and reintroduction of large wood are increasingly incorporated in river management and restoration (Cashman et al., 2019; Grabowski et al., 2019; Roni et al., 2015). Although reintroduced large wood and logjams are commonly fixed in place (Kail et al., 2007), some restoration projects strive to achieve more natural conditions by allowing flows to mobilize introduced large wood (Gerhard & Reich, 2000). Other projects have a hybrid design in which a limited amount of fixed wood is designed to trap and accumulate mobile wood pieces to create larger wood accumulations with time (Abbe & Brooks, 2011). Reintroduced large wood is also more likely to be single logs or structurally simple engineered logjams, although structurally complex pieces and jams are likely to create greater habitat diversity (Harvey et al., 2018) and backwater storage (Livers & Wohl, 2021; Welling et al., 2021). The reach-scale geomorphic context and the natural wood regime (Wohl et al., 2019) are important considerations when restoring using either fixed or mobile introduced wood.

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Numerous studies of naturally occurring logjams indicate that logjams are nonrandomly distributed along the length of a stream, with more closely spaced and/or larger logjams in portions of the stream corridor that are typically wider, of lower gradient, and with channel planform complexity created by islands, bars, secondary channels, or bends (Gurnell et al., 2000; Ruiz-Villanueva et al., 2016; Scott & Wohl, 2018; Wohl & Cadol, 2011). Few studies, however, have examined how long individual logjams persist in stream reaches that are either retentive of wood or naturally depauperate in wood because of high transport capacity and limited trapping and storage potential. Studies monitoring the mobility of naturally occurring wood pieces and logjams indicate a wide range of mobility values, from relatively frequent (most pieces moving at least once during study periods of ~1–10 years; Berg et al., 1998; Dixon & Sear, 2014; K. J. Gregory et al., 1985; Wohl & Goode, 2008) to relatively infrequent (very few pieces move in most years, with most transport during large floods; Benke & Wallace, 1990; S. Gregory, 1991), to inferred residence times of decades to centuries based on the age of trees growing from fallen, decaying wood (e.g., Hyatt & Naiman, 2002; Murphy & Koski, 1989) or tree-ring dating of wood pieces (Galía et al., 2017). Studies of wood mobility indicate that factors such as the ratio of piece length to channel width, branching complexity, wood piece diameter, location in the channel, and incorporation within a jam strongly influence piece mobility, with piece mobility generally increasing in larger streams (e.g., Kramer & Wohl, 2017; Lienkaemper & Swanson, 1987). Studies including logjams also indicate that individual logjams can form and disappear and, even where a logjam persists, the component pieces can be removed and replaced (Dixon & Sear, 2014; K. J. Gregory et al., 1985; Wohl & Goode, 2008; Wohl & Scamardo, 2021). We are not aware of any published studies that have explicitly and directly measured the residence time of individual logjams over periods of greater than 1–2 years, rather than inferring residence time using dendrochronology (e.g., Hyatt & Naiman, 2002; Kaczka, 2009; Silhán et al., 2018).

Here, we use 11 years of annual surveys of a population that totaled ~300 logjams each year to evaluate logjam persistence. We focus on logjams that span the bankfull active channel because these logjams can have particularly strong influences on physical and ecological variables (Andreoli et al., 2007; Livers & Wohl, 2016, 2021; Welling et al., 2021), although the specific effects depend on factors such as logjam porosity, height relative to peak flow depth, and erodibility of the adjacent banks (e.g., Dixon, 2016). We examine three basic questions: how long individual logjams are present in the study area (jam persistence) and the cumulative residence time of logjams that disappear and then re-form at the same site (site persistence); what factors influence logjam and site persistence; and how the geomorphic effects of logjams relate to logjam persistence.

This paper is the second to examine the characteristics of the same set of channel-spanning logjams in subalpine mountain streams of the Southern Rockies in Rocky Mountain National Park, Colorado, USA. The first paper examined the influences on the longitudinal distribution of logjams and the resilience of patterns of longitudinal distribution to floods of varying magnitude (Wohl & Scamardo, 2021). That paper demonstrated that the number of logjams per unit length of channel, which we describe as logjam distribution density, correlates significantly with increasing ratio of floodplain width to channel width and wood piece length to channel width. Multithread-channel reaches also contain a higher average distribution density than single-thread reaches. Similar spatial trends have been demonstrated in other studies (Braudrick & Grant, 2001; Gurnell et al., 2000; Livers & Wohl, 2016; Scott & Wohl, 2018; Wyzga & Zawiejska, 2005). For the Southern Rockies data set, wide, low-gradient valley reaches with greater logjam distribution density exhibit greater interannual variation in distribution density but are also resilient to high peak flows in that logjam distribution density values return to preflood levels within a few years. Wohl and Scamardo (2021) thoroughly analyzed the Colorado data set with respect to hydrologic fluctuations through time and along the river network, so this paper focuses on other influences on logjam dynamics.

In this paper, our objective is to examine the persistence of logjams and the implications for their geomorphic effects. Persistence in this context refers to both the timespan over which an individual jam is present during the course of this 11-year study and the tendency for jams to disappear and then re-form at the same site along a stream: we describe these as jam persistence and site persistence, respectively. We examine geomorphic effects using a categorical rating for backwater storage of fine sediment and organic matter and using the presence of multithread-channel planform caused by the presence of one or more channel-spanning logjams.

The population analyzed consists of, on average, 300 logjams that were surveyed once each year during late summer base flow on four streams. Each stream was divided into reaches of consistent channel gradient, bedform and planform morphology, and valley width. Stream corridor morphology varies among reaches, from steep,

laterally confined single channels to lower gradient, relatively wide floodplains with multithread-channel planform. We test three hypotheses. (H1) Site persistence is greatest in multithread reaches. Our rationale is that peak flows capable of mobilizing and transporting large wood are dispersed among multiple channels and across the floodplain in these relatively wide, low-gradient valley reaches. Any local factor that limits wood transport, such as a change in channel width or an obstruction such as a stable ramp or bridge piece of wood (Beckman & Wohl, 2014; Braudrick & Grant, 2001), is more likely to initiate formation of a logjam. Even if peak flows remove a logjam, another logjam is more likely to re-form at the same site in these portions of the river network where wood-transport capacity is limited. (H2) Logjam persistence is greatest in multithread reaches. The rationale is similar to H1: dispersal of peak flow into multiple channels limits the drag and buoyant forces exerted on a logjam (Merten et al., 2010) and may lead to longer persistence of individual jams. (H3) Average backwater storage at each jam is greater in multithread reaches. Our rationale is that greater logjam persistence and site persistence equate to larger and more stable logjams with greater levels of backwater storage at each logjam. We thus expect a greater proportion of logjams within multithread reaches to have large backwater storage. If logjam distribution density is also higher in multithread reaches, then the cumulative backwater storage within the reach is also greater.

We are interested in the persistence of logjams because understanding of logjam residence time on a stream remains constrained by limited field data. River restoration that incorporates potentially mobile large wood can benefit from greater understanding of the mobility of that wood and the duration of geomorphic and ecological effects associated with the presence of a logjam. Greater insight into the persistence of logjams can also enhance our understanding of basic fluvial process and form in forested river networks. For example, logjams commonly interrupt downstream bedload transport (e.g., Reid et al., 2019; Wohl & Scott, 2017) and logjam backwaters form critical aquatic habitat (House & Boehne, 1986; Richmond & Fausch, 1995) and sites for enhanced nutrient uptake (Battin et al., 2008), but are individual logjam effects most relevant on an annual timescale or over longer timespans? By evaluating logjam and site persistence in mountain streams of the Southern Rockies, we start to address these questions.

2. Study Areas

The four study areas are located in the North St. Vrain Creek watershed of Colorado, USA. This creek, which is part of the South Platte River network, heads at the continental divide and flows eastward from elevations of ~4,000 m down to 1,500 m at the base of the mountains. We focus on the subalpine (2,850–3,500 m elevation) portions of the stream network, between timberline and the eastern boundary of Rocky Mountain National Park. In addition to North St. Vrain Creek, study sites are on Ouzel, Cony, and Hunters Creeks, which are tributary to North St. Vrain Creek (Figure 1). Study reaches are within third to fifth order portions of the stream network (Strahler, 1957), with the uppermost reach close to timberline and the lowermost reaches near the boundary of the national park.

Precambrian-age Silver Plume Granite underlies the study area (Braddock & Cole, 1990). Wood recruitment to the stream corridor results primarily from blowdown, although bank erosion, mass mortality via wildfire and insect infestation, and fluvial transport from upstream reaches also contribute wood to the channels. The spatial density of standing trees in the floodplain forest limits fluvial transport of large wood into the floodplain and there are few floodplain logjams present (Wohl et al., 2018). Mass movements occur in the drainage basins (e.g., Patton et al., 2018) but are infrequent. Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*) dominate upland forests, whereas stream corridors also include Douglas-fir (*Pseudotsuga menziesii*), blue spruce (*Picea pungens*), aspen (*Populus tremuloides*), and willows (*Salix* spp.; Veblen & Donnegan, 2005). Stand-killing wildfires recur at intervals of 100–400 years (Veblen et al., 2000), and one portion of the Ouzel Creek study area burned in 1978. Blowdowns have less consistent return intervals, but at least small blowdowns covering a few tens of square meters typically occur each year. Blowdowns in patches ~1 ha in area occurred in the study area during the winter of 2011–2012. Insect infestations by the native mountain pine beetle (*Dendroctonus ponderosae*) occur at irregular intervals and at differing severity with regard to proportion of tree mortality within a stand. The study area has experienced widespread tree mortality from mountain pine beetles during the past decade but standing dead trees do not necessarily fall immediately into the stream corridor (Jackson & Wohl, 2015). Forest stand ages in the study area vary from old-growth (~1500 CE) in

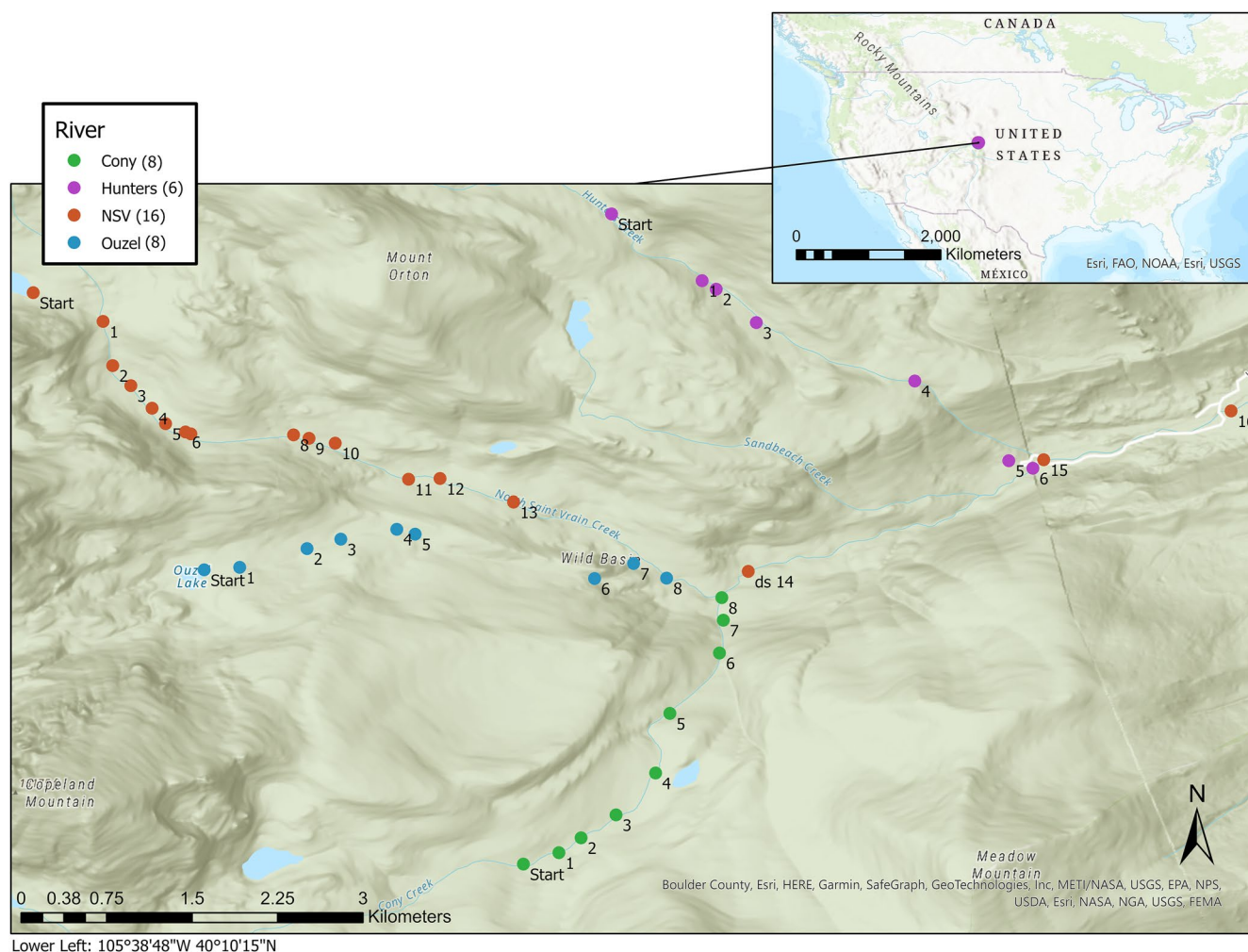


Figure 1. Location map showing the spatial distribution of reaches designated within the study area. Reaches are numbered sequentially downstream on each channel. Each numbered point is the downstream end of the reach.

the upper portion of each catchment to stands that date from 1880 CE in the lower portion of each catchment and 1978 CE in the burned portion of the Ouzel and Cony Creek watersheds (Sibold et al., 2006).

Valley geometry exhibits substantial longitudinal variability as a result of valley glaciation (R. S. Anderson et al., 2006) and spatial differences in the density of bedrock jointing (Ehlen & Wohl, 2002). Relatively wide (10^1 – 10^2 m wide), lower gradient (<0.03 m/m) segments of stream corridor repeatedly alternate downstream over distances of 10^1 – 10^3 m with narrower, steeper valley segments. Wider, lower gradient segments can have multi-thread (anastomosing) channel planform (Livers & Wohl, 2016; Livers et al., 2018; Wohl, 2011), abundant large wood in the active channel and floodplain (Livers et al., 2018; Wohl & Cadol, 2011), and plane-bed to step-pool channel morphology. Narrower, steeper segments in the study area typically have relatively straight, single channels, less large wood (Wohl & Cadol, 2011), and step-pool to cascade channel morphology. Streambed substrate is commonly cobble- to boulder-size except for logjam backwaters and other areas of flow separation.

The study area has a continental climate, with greater precipitation and colder temperatures at higher elevations. In the lower portions of the study area, mean annual precipitation is just over 500 mm and average temperature is 0°C in winter and 22.5°C in summer. Stream flow is dominated by the annual snowmelt flood, which does not typically exceed a peak unit discharge of ~ 1.1 $\text{m}^3/\text{s}/\text{km}^2$ (Jarrett, 1990). The magnitude and duration of the snowmelt hydrograph vary substantially between years, however: estimated maximum daily peak flow for each year varied from 19.8 to 4.9 m^3/s during the study period (Wohl & Scamardo, 2021). A seasonally uncharacteristic autumn rainfall flood in September 2013 produced the highest discharge during the 2010–2020 study period.

The study streams are ungaged, but daily discharge on the neighboring Big Thompson River at a slightly lower elevation was nearly twice the snowmelt peak for 2013. Rainfall exceedance probabilities for the September 2013 storm ranged from 1/10 years at the highest elevations (our study area) to 1/500 years at elevations below our study area (Gochis et al., 2015; Wohl & Scamardo, 2021).

3. Methods

3.1. Study Design

We chose control variables that might influence the recruitment, transport, and storage potential of large wood, and thus the location and characteristics of channel-spanning logjams. Potential control variables include drainage area, estimated peak flow magnitude, channel gradient, the ratio of average wood piece length to bankfull channel width, riparian stand age, lateral confinement (the ratio of floodplain width to bankfull channel width), and channel planform (single or multithread). Each of these variables was characterized at the reach scale.

Riparian stand age provides a proxy of volume of wood available for local recruitment to the stream. Within the subalpine conifer forest of the study area, tree height and diameter increase with age, so that older riparian forests can contribute larger and potentially more stable wood pieces to the channel. Channel gradient is an indirect indicator of wood recruitment potential in that steep reaches in the study area are more likely to have bedrock banks and limited wood recruitment through bank erosion.

In these ungaged channels, fluvial transport capacity of large wood is represented by drainage area and peak flow estimated from regional regression equations. Little to no wood movement occurs during base flow. The ratio of average wood piece length to bankfull channel width also provides a proxy of transport capacity: previous field studies and physical experiments indicate that the potential for fluvial transport of large wood increases substantially as average channel width exceeds average wood piece length (Braudrick & Grant, 2001; Gurnell et al., 2002).

Wood storage potential in the study streams is represented by metrics of channel and valley geometry: channel gradient, ratio of wood piece length to channel width, lateral confinement, and channel planform. Logjams forming in steep channel reaches with minimal floodplains experience greater hydraulic force during peak flows because of the lack of overbank flows (Wohl, 2011). With increasing ratio of piece length to active channel width, wood in transport is more likely to be trapped and stored by lodging against living bank vegetation, protruding boulders in the channel, or other irregularities along the channel margins (Braudrick & Grant, 2001; Gurnell et al., 2002). Wider floodplains and less lateral confinement facilitate energy dissipation during overbank flows and the development of a multithread-channel planform in which secondary channels can effectively trap and store large wood (Livers et al., 2018; Wyzga & Zawiejska, 2005).

3.2. Field Methods and Supporting Data

Each year during late summer base flow, we located channel-spanning logjams along each creek using a handheld GPS (Garmin eTrex). The maximum horizontal accuracy of the GPS is ± 3 m, but at times during each survey topographic shielding or other factors reduced horizontal accuracy to ± 7 m. Annual surveys were conducted from 2010 to 2020 (inclusive) on four streams (Table 1). To be included in the survey, each logjam must (a) include at least three pieces of wood that exceed 10 cm in diameter and 1 m in length and which physically contact each other, (b) completely span the bankfull channel width, and (c) alter the water-surface gradient across at least $\frac{3}{4}$ of the wetted channel width at low flow. (A logjam with high porosity and permeability can span the entire channel width but still have little effect on low-flow water surface over a small portion of the channel if the base of the logjam on one side of the channel is above low-flow stage.) In addition to GPS location, we described each logjam categorically in terms of key piece type, key piece decay category, and logjam backwater storage (Table 2). In multithread-channel reaches, only the logjams on the channel with the largest cross-sectional area and discharge were measured. Consequently, the logjam distribution density for multithread reaches, if considered per unit valley length (rather than per unit channel length) represents a minimum value.

We subdivided the total length of surveyed channel into reaches based on observed changes in primary bedforms within the active channel. Bedforms (cascade, step-pool, plane-bed, and pool-riffle; Montgomery & Buffington, 1997) in these channels correlate strongly with channel gradient, substrate grain size, and lateral valley

Table 1
Stream Characteristics

Creek	Dr A (km ²)	L (m)	Reaches	Stand ages	Avg no. jams	Q2 (m ³ /s)	S (m/m)	Fp w/ch w
North St. Vrain	88	10,480	16 (5)	1500, 1880	98	2.4–15.1	0.018–0.18	1.3–8.0
Ouzel	14	3565	8 (4)	1500, 1880, 1978	78	3.9–4.3	0.027–0.247	1.7–7.7
Cony	20	3200	8 (4)	1500, 1978	50	3.2–4.6	0.016–0.295	1.1–11.4
Hunters	12	4000	6 (4)	1500, 1880	58	3.8–4.0	0.111–0.479	1.5–6.8

Note. Dr A is drainage area at downstream end of study area. L is total surveyed length of channel. Reaches is the total number of reaches within each creek, with the number of detailed reaches in parentheses. Stand ages are average age of floodplain forest in calendar years CE. Number of jams surveyed in each creek averaged over the period of study. Q2 is range of values estimated for 2-year peak flow along the length of the creek based on regional regression equations from Capesius and Stephens (2009). S is the range of reach-scale gradient values along the creek. Fp w/ch w is the ratio of floodplain to active channel width and the values are the range among the reaches on each creek.

confinement (Livers & Wohl, 2015). Individual reaches are 10¹–10³ m long and exhibit consistent channel and valley geometry. Field-designated reach boundaries were subsequently confirmed against channel gradient obtained from topographic maps. Riparian stand age maps (Sibold et al., 2006) were used where appropriate to designate additional reaches within lengths of consistent channel bedforms and gradient because of the potential influence of riparian stand age on volume and piece size of wood recruited to the channel.

We derived values for drainage area, peak flow magnitude (as represented by the estimated 2-year peak flow; Capesius & Stephens, 2009), and channel gradient from the US Geological Survey website StreamStats

Table 2
Variables and Categories Within Each Variable Included in Analyses

Potential control variables
Watershed-scale variables
<i>Drainage area (Dr A)</i>
<i>Estimated 2-year peak discharge (Q2)</i>
Reach-scale variables
<i>Riparian stand age</i>
<i>Channel gradient (S)</i>
<i>Ratio average wood piece length/bankfull channel width</i>
<i>Ratio of floodplain width/bankfull channel width (fp w/ch w)</i>
<i>Channel planform (single or multithread)</i>
Response variables for individual logjams
Logjam key piece type (ramp, bridge, buried, pinned, or unattached)
Logjam key piece decay
1 = fine branches, bark and needles present
2 = moderate branches and some bark present
3 = smooth cylinder, firm to touch
4 = decayed cylinder, wood surface can be fragmented by hand
Backwater storage
high = elevated backwater surface across entire channel, minimal velocity in the backwater and substantial trapping of finest sediment and particulate organic matter
medium = elevated backwater surface across much of the channel and associated trapping of finer sediment
low = backwater effects on flow and sediment across much of the channel, but bed aggradation to the top of the jam or high jam porosity and permeability limit backwater storage of fine sediment and organic matter

Note. Potential control variables are italicized. Variables including channel width use values from the largest channel in multithread reaches. Key piece refers to the log(s) visually assessed to be supporting much of a jam.

(<https://streamstats.usgs.gov/ss/>) based on the GPS coordinates for each reach. We measured reach length on 2019 Google Earth imagery using GPS coordinates. Average bankfull channel width within each reach was derived from field measurements of bankfull width at 100-m increments and floodplain width was derived from floodplain transverse measurements using a handheld laser rangefinder (TruPulse 360B, accuracy ± 0.1 m). In multithread reaches, only the channel with the largest cross-sectional area and discharge was measured. (Some of the secondary channels can be only 1 m wide.) Wood piece length within each reach was an average of all wood pieces within each reach, as measured at the start of the study in 2010. Average piece length varies by ± 1 m among the study reaches and there is no indication that this value changed during the course of the study.

We have 38 reaches distributed among the four primary streams. We refer to this as the complete data set. We chose 17 of the 38 reaches, distributed across the four streams and the range of drainage areas, for more detailed analyses. In these reaches, we used annual GPS coordinates for each jam and Google Earth imagery to trace the history of individual jams during the 11 years of the study. We refer to this as the “detailed” data set. Within each of the 17 reaches, we designate a logjam site as the particular location at which a logjam(s) was present during each annual survey. Based on the horizontal resolution of the handheld GPS unit, we assume that any jam within 3–7 m of a particular location in successive annual surveys is the same jam, even if the individual wood pieces within the logjam have undergone extensive substitution (i.e., some pieces have left the logjam while other, new pieces have joined it). (In many cases, photographs taken during each annual survey confirm this assessment and all field data were collected by the first author.) If there is a gap between years (e.g., a jam was present at a location during the 2010 survey, was not present during the 2011 survey, and was again present during the 2012 survey), we assume that the original jam disappeared but then a new jam re-formed at the same location. If at least one jam (the same jam continuously or jams that re-formed at the same location) was present for six or more annual surveys (i.e., more than half of the annual surveys) at a site, we refer to this as a “sticky site” that tends to trap and retain wood in logjams. The choice of 6 as a minimum value is arbitrary. If we assume a range of 2 years to the 11 years of the study, 6.5 years is a median value. The designation of sticky sites is, therefore, dependent on timespan of the study. In some cases, field surveys noted two distinct logjams that were separated by <7 m along a channel. In these cases, both jams were tallied as being part of the same sticky site. We compared individual jam persistence for sticky versus nonsticky sites. We also analyzed site persistence at sticky sites. Our spatial metric of site persistence within a reach is the number of sticky sites per 100 m length of channel. Our temporal metrics are number of years that a sticky site is occupied by at least one logjam and median number of jams in a sticky site per year.

3.3. Statistical Analyses

Our statistical analyses focused on the timespan of logjam persistence and site persistence and on potential predictors of logjam and site persistence. Because the individual channel reaches are of differing length, we standardized along-stream tallies (number of logjams, number of sticky sites) as per 100 m of channel length. Similarly, because the number of logjams varied substantially between individual reaches and between years, we standardized reach-scale logjam-population descriptors (number of jams with ramp or bridge key pieces, number of jams with moderate to high backwater storage) as proportions across the entire period of the study.

All data analysis was completed in R (R Core Team, 2021), and the data were formatted and summarized using the *tidyverse* package (Wickham et al., 2019) and Microsoft Excel. To compare various sample medians and variances, nonparametric Kruskal–Wallace Rank Sum tests (base R), Dunn’s tests (*dunn.test* package; Dinno, 2017), and Brown–Forsythe tests (*car* package; Fox & Weisberg, 2019) were performed. Multivariate linear models were built using base R and all subsets model selections via Akaike information criterion (AIC) were performed using the *MuMIn* package (Barton, 2020).

For all multivariate analyses, Q2 was removed as a predictor variable because of high correlation with drainage area and because the calculated value of Q2 is partly based on drainage area. Response and predictor variables were natural log-transformed or square root-transformed as needed when they exhibited high skew (square root transformation is useful when 0 values are present that make logarithmic transformation invalid). Two observations were removed from the multivariate analysis predicting the average jam persistence due to high Cook’s distances (Hess, 2019). Significance level for all tests is $\alpha = 0.05$.

Finally, we performed binary logistic regression modeling (*DescTools* package; Signorell, 2021) on a subset of the data (all of the annual data for individual logjams on North St. Vrain Creek) to assess potential predictors of backwater storage category (high/moderate vs. low) and jam key piece category (ramp/bridge vs. pinned/buried). We did not use ordinal logistic regression for the backwater storage category analysis to simplify the logistic regression. We calculated Efron pseudo- R^2 (*DescTools* package; Signorell, 2021) for the backwater storage analysis in order to present an analogous measure of variability in the response explained by the predictors for logistic regression (UCLA: Statistical Consulting Group, 2011).

4. Results

Summary data for the complete and detailed data sets are reported in Tables 3 and 4. We start with a summary of network-scale patterns of logjam distribution, with a focus on confluence effects and the importance of relative drainage area of the confluent channels. We then present the results of statistical analyses of logjam and site persistence and potential controls on persistence. These results strongly support the first hypothesis, that site persistence is greatest in multithread-channel reaches. The results do not, however, support the second hypothesis, that logjam persistence is greatest in multithread-channel reaches. Finally, we present the analyses of the geomorphic characteristics of logjams. These results support the third hypothesis, that average backwater storage at each logjam is greater in multithread reaches.

4.1. Network-Scale Patterns of Logjam Distribution

We used the complete data set to assess potential influences of network structure on reach-scale logjam longitudinal distribution. We find higher logjam distribution density values on the two smallest channels upstream from their confluence with the mainstem.

Average logjam distribution density within each reach over the 11 years of study plotted against cumulative distance downstream reveals the longitudinal spacing of multithread reaches with higher average jam distribution density (Figure 2) and confluence effects. Ouzel Creek (drainage area 14 km²) joins North St. Vrain Creek where the latter has a drainage area of 22 km² and neither reach immediately above the confluence shows a pronounced increase in average jam density relative to the next reach upstream. In contrast, Cony (drainage area 20 km²) joins North St. Vrain where the latter has a drainage area of 39 km² and Hunters Creeks (12 km²) joins North St. Vrain where the latter drains 69 km². Both Cony and Hunters show a pronounced increase in logjam distribution density in the downstream-most reach, which includes the junction with the mainstem. The reach on North St. Vrain Creek above the Hunters junction does not show a pronounced increase in logjam distribution density.

4.2. Logjam and Site Persistence and Potential Controls

All analyses of logjam and site persistence use the 17 reaches of the detailed data set. A total of 429 distinct logjams were present for at least 1 year of the survey. Nine of these were present for all of the 11 annual surveys (2.1% of the total population). Another 19 were present for 10 years (4.4% of the total population) although only 4 (0.9% of the total population) of these were present for 10 consecutive years. The other 15 disappeared but then a new logjam formed in the same location.

Using the detailed data set, we compared jam persistence between rivers, between reaches on a river, and for all sticky sites in the data set. We found no difference between rivers, but we did find differences between reaches and differences between sticky sites in single and multithread reaches.

Median jam persistence is 1–2.5 years across the data set (range variance 0.3–13.0) and there are no statistically significant differences among the rivers (p -value > 0.05) or reaches (p -values > 0.05), except for Hunters reach 5. Median jam persistence at sticky and nonsticky sites is significantly different (p -value < 0.05) and the variance also differs significantly. Median jam persistence is 2 years for sticky sites and 1 year for nonsticky sites. Figure 1 in Supporting Information S1 illustrates the distribution of the number of years a logjam was present at sites in the detailed data set.

Table 3
Summary Data for All Reaches; Bolded Reach Names Indicate Detailed Reaches

Reach ID	Dr A (km ²)	Q2 (m ³ /s)	S (m/m)	Stand age (year CE)	Reach L (m)	Fp w/ ch w	Avg jam density	Planform	Avg R & B	Avg BW
NSV 1	5.5	2.4	0.085	1500	605	1.5	0.7	Single	0.74	0.22
NSV 2	10.0	3.8	0.180	1500	415	2.5	0.2	Single	0.63	0.19
NSV 3	15.0	5.2	0.100	1500	230	5.9	2.9	Multi	0.75	0.33
NSV 4	15.3	5.3	0.044	1500	260	3.7	1.8	Single	0.80	0.55
NSV 5	15.5	5.3	0.018	1500	170	5.4	2.5	Multi	0.66	0.64
NSV 6	15.6	5.3	0.033	1500	155	4.7	1.2	Single	0.53	0.74
NSV 7	15.7	5.3	0.121	1500	40	4.0	1.8	Single	0.93	0.50
NSV 8	16.4	5.4	0.066	1500	750	8.0	5.2	Multi	0.67	0.79
NSV 9	16.5	5.5	0.042	1500	115	5.7	1.6	Single	0.76	0.59
NSV 10	18.8	5.8	0.062	1500	190	7.7	3.5	Multi	0.71	0.71
NSV 11	19.5	5.9	0.090	1500	660	1.5	0.5	Single	0.75	0.65
NSV 12	20.0	5.9	0.019	1500	255	7.1	0.8	Multi	0.74	0.65
NSV 13	20.8	6.0	0.041	1500	560	2.4	0.4	Single	0.48	0.46
NSV 14	59.4	12.0	0.081	1880	2,140	1.3	0.7	Single	0.49	0.49
NSV 15	82.2	14.8	0.054	1880	2,445	1.4	0.2	Single	0.34	0.40
NSV 16	87.8	15.1	0.026	1880	1,490	1.8	0.04	Single	0.50	0.25
OUZ 1	10.9	3.9	0.027	1500	255	3.0	1.0	Single	0.20	0.91
OUZ 2	11.6	4.0	0.062	1500	490	6.8	4.0	Multi	0.68	0.65
OUZ 3	11.9	4.0	0.030	1500	275	4.0	2.7	Single	0.61	0.61
OUZ 4	12.1	4.1	0.038	1978	400	7.7	3.6	Multi	0.71	0.79
OUZ 5	12.1	4.1	0.044	1978	130	6.6	4.6	Multi	0.59	0.75
OUZ 6	14.0	4.3	0.064	1978	1,410	3.5	1.3	Single	0.37	0.70
OUZ 7	14.1	4.3	0.247	1880	330	2.3	1.8	Single	0.32	0.52
OUZ 8	14.2	4.3	0.094	1880	275	1.7	1.2	Single	0.69	0.56
CON 1	10.3	3.2	0.056	1500	210	2.5	1.7	Single	0.91	0.34
CON 2	13.1	3.6	0.040	1500	230	4.3	3.0	Multi	0.72	0.67
CON 3	13.4	3.7	0.076	1500	330	4.1	2.3	Single	0.61	0.57
CON 4	14.4	3.8	0.016	1500	570	11.4	1.5	Single	0.63	0.51
CON 5	14.9	3.9	0.093	1500	660	2.4	1.2	Single	0.57	0.52
CON 6	19.7	4.6	0.132	1500	690	1.2	1.4	Single	0.54	0.61
CON 7	19.8	4.6	0.295	1500	310	1.1	0.3	Single	0.67	0.70
CON 8	19.9	4.6	0.141	1978	200	4.7	3.1	Multi	0.53	0.73
HUN 1	10.4	3.8	0.120	1500	960	3.6	1.6	Single	0.65	0.44
HUN 2	10.7	3.8	0.111	1500	140	6.8	6.0	Multi	0.60	0.75
HUN 3	11.5	3.9	0.062	1500	405	3.4	2.7	Single	0.65	0.63
HUN 4	12.2	4.0	0.061	1500	1,290	3.3	0.9	Single	0.42	0.50
HUN 5	12.4	4.0	0.006	1880	1,015	1.5	0.8	Single	0.44	0.45
HUN 6	12.5	4.0	0.123	1880	190	4.4	1.7	Single	0.59	0.68

Note. Reach ID: NSV is North St. Vrain, OUZ is Ouzel, CON is Cony, and HUN is Hunters; reaches numbered consecutively from upstream to downstream; Dr A is drainage area at downstream end of reach; Q2 is average 2-year return interval flow; S is average reach gradient; Age is average stand age of floodplain forest in calendar years CE; Reach L is reach length; Fp w/ch w is ratio of floodplain width to bankfull channel width; Avg jam density is number of jams per 100 m length of channel averaged over the 11 years of study; Avg R & B is proportion of jams with ramp or bridge key pieces averaged over the 11 years of study; and Avg BW is proportion of jams with moderate or high backwater storage averaged over the 11 years of study.

We evaluated potential predictors of number of years of average jam persistence for sticky and nonsticky sites using all subsets selection, where the full model is detailed in the Supporting Information. Riparian age, $\ln(\text{reach-scale average logjam distribution density})$, and $\ln(\text{channel gradient})$ appear in the best subsets (Model 1), and the intercept, riparian age, and average logjam distribution density are significant. The adjusted R^2 value is 0.57 and the entire model is also significant.

For the spatial metric of site persistence ($\sqrt{\text{number of sticky sites}/100 \text{ m}}$), we evaluated the full model with predictors of drainage area, $\ln(\text{channel gradient})$, riparian age, $\ln(\text{floodplain width/channel width})$, piece length/channel width, $\ln(\text{average logjam distribution density})$, planform, and number of nonsticky sites per 100 m. The model with the lowest AIC using all subsets selection includes $\ln(\text{average logjam distribution density})$; Model 2). The adjusted R^2 value of the model is 0.88 and the entire model is significant.

The first temporal metric of site persistence is number of years that a sticky site is occupied by at least one logjam. The median number of years that sticky sites had 1+ logjams varied from 6 to 10 across the sites, with an overall data set median of 8 years. For nonsticky sites, the overall data set median is 2 years. The median values and variances for sticky and nonsticky sites differ significantly ($p < 0.05$). This finding is expected, given our original definition of a sticky site as one in which a jam is present for six or more annual surveys.

The second temporal metric is median number of logjams in a sticky site. The median value is 9 logjams for sticky sites and 2 logjams for nonsticky sites across the period of study for all detailed sites. Both the median values and the variances are significantly different ($p < 0.05$).

We hypothesized that site persistence is greatest in multithread-channel reaches (H1). Comparing the untransformed spatial metric, we found that the median values of number of sticky sites per 100 m differ significantly ($p < 0.05$) between single and multithread reaches, but the variances are not significantly different (Figure 3). Comparing the temporal metric of number of years that a sticky site is occupied by at least one logjam, there are significant differences between single and multithread reaches. The median value is 9 years for sites in multithread reaches, whereas the median value is 7 years for sites in single-thread reaches. The variances do not differ significantly. Using the temporal metric of median number of logjams in a sticky site per year, both median values and the variances differ significantly between single-thread and multithread reaches ($p < 0.05$). Sticky sites in multithread reaches have a median value of 8 logjams, whereas sticky sites in single-thread reaches have a median value of 3 logjams. In other words, all three metrics of site persistence differ significantly between multithread and single-thread channel reaches, so the results strongly support H1.

We hypothesized that logjam persistence is greatest in multithread-channel reaches (H2), but neither median nor variance values for the temporal variables of years differ significantly between single and multithread reaches. Our results do not support H2.

4.3. Geomorphic Characteristics of Logjams

Our indicators of geomorphic characteristics of logjams are backwater storage and presence of multithread-channel planform. Using the entire data set, we found significant differences between single and multithread-channel reaches.

The median values of average logjam distribution density differ significantly between single (median 1.2) and multithread (median 3.5) reaches, but the variances are not significantly different (Figure 3). The median values of floodplain width/channel width differ significantly between single (median 2.5) and multithread (median 6.8) reaches, but the variances are not significantly different (Figure 3). The median values for proportion of jams with moderate or high backwater storage differ significantly between single (median 0.52) and multithread (median 0.71), reaches, but the variances are not significantly different (Figure 3). The median values for the proportion of key pieces that are ramps or bridges do not differ significantly between single and multithread reaches, although the variances do. In other words, multithread-channel reaches occur on valley floors with less lateral confinement and have significantly more logjams per unit length of channel and a significantly greater proportion of logjams with moderate or high backwater storage. Again, the logjam distribution density was tallied only for the largest channel in the multithread reaches, so these reaches likely have even greater cumulative backwater storage than comparisons of only the single channel and multithread main channel suggest.

Table 4
Summary Data for Detailed Reaches

Reach ID	Sticky sites/100 m	All sites/100 m	Proportion sticky	Avg jam density	Planform	Fp w/ch w
NSV 1	0.7	2.1	0.3	0.7	Single	1.5
NSV 2	0	0.7	0	0.2	Single	2.5
NSV 8	4	6.4	0.6	5.2	Multi	8.0
NSV 11	0	0.6	0	0.5	Single	1.5
NSV 13	0.7	1.1	0.7	0.4	Single	2.4
OUZ 2	3.5	5.5	0.6	4.0	Multi	6.8
OUZ 3	1.8	5.5	0.3	2.7	Single	4.0
OUZ 7	1.8	2.7	0.7	1.8	Single	2.3
OUZ 8	1.1	2.5	0.4	1.2	Single	1.7
CON 1	1.4	3.8	0.4	1.7	Single	2.5
CON 4	0.9	3.7	0.2	1.5	Single	11.4
CON 6	1.2	3.9	0.3	1.4	Single	1.2
CON 8	2.5	4.5	0.6	3.1	Multi	4.7
HUN 1	1.5	3.4	0.4	1.6	Single	3.6
HUN 2	3.6	6.3	0.6	6.0	Multi	6.8
HUN 5	0.6	3.0	0.2	0.8	Single	1.5
HUN 6	1.6	5.3	0.3	1.7	Single	4.4

We examined potential predictors of logjam characteristics of backwater storage and type of key piece. Although we found statistically significant models for storage and for key piece, the models do not explain much of the variability in the response variables.

Using the full data set and the response variable of reach-scale proportion of logjams with moderate and high backwater storage, we evaluated the full model with predictors of $\ln(\text{drainage area})$, $\ln(\text{channel gradient})$, riparian age, $\ln(\text{floodplain width/channel width})$, piece length/channel width, $\sqrt{\text{average logjam distribution density}}$, and planform. The model with the lowest AIC using all subsets selection includes $\sqrt{\text{average logjam distribution density}}$; Model 3). The adjusted R^2 for the model is 0.28 and the model is significant. Using the response variable of reach-scale proportion of logjams with ramp or bridge key pieces, we evaluated the full model with the same predictors as Model 3. The model with the lowest AIC using all subsets selection includes riparian stand age and channel planform (Model 4). The adjusted R^2 for the model is 0.18 and the model is significant. The low R^2 values for Models 3 and 4 indicate that the models do not describe very much of the variability in the response variables.

Using the detailed data set, we compared backwater storage and key pieces in sticky and nonsticky sites. Nonparametric pairwise comparisons indicate significant differences in the medians but not the variances between sticky and nonsticky sites with respect to both proportion of logjams with moderate to high backwater storage and proportion of logjams with ramp and bridge key pieces ($p < 0.05$).

Finally, with the subset of North St. Vrain Creek individual logjams, we examined potential predictors of backwater storage category and key piece category. We used binary logistic regression with high/moderate backwater and ramp/bridge key piece as the “events.” The full models for both analyses included the predictor variables of annual logjam distribution density, key piece decay category, drainage area, riparian age, piece length/channel width, planform, and channel gradient. Floodplain width/channel width was excluded due to high correlation with annual jam distribution density. For the backwater category analysis, the model with the lowest AIC includes annual jam distribution density, key piece decay category, and channel gradient (Model 5). The Efron pseudo- R^2 is 0.11 (UCLA: Statistical Consulting Group, 2011). This model shows that a one-unit increase in annual logjam distribution density increases the odds that backwater storage will be high/moderate by a multiplication factor

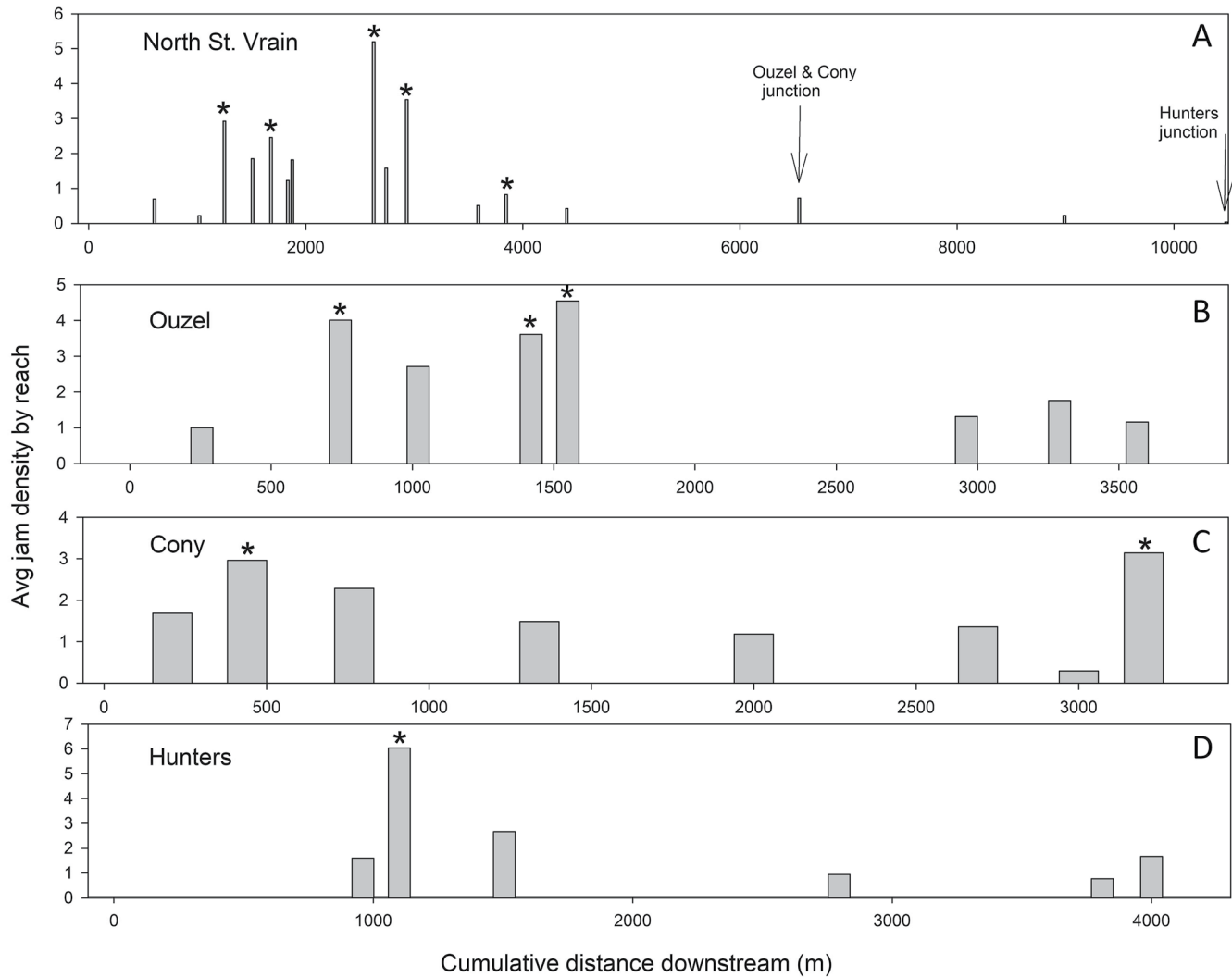


Figure 2. Bar graph of logjam distribution density by reach along each stream: (a) North St. Vrain Creek mainstem, (b) Ouzel Creek, (c) Cony Creek, and (d) Hunters Creek. Reaches are numbered consecutively downstream. The Ouzel, Cony, and Hunters study areas each end at the junction with North St. Vrain Creek. Bars are plotted at the midpoint of each reach. Asterisk above a bar indicates a multithread reach.

of $e^{0.2738}$ ($p < 0.05$), and key piece decay category is positively associated with increased odds of high/moderate backwater storage. Additionally, a one-unit increase in channel gradient decreases the odds of high/moderate backwater storage by $e^{-12.7066}$ ($p < 0.05$). For the key piece category analysis, the model with the lowest AIC includes key piece decay category, piece length/channel width, channel planform, and channel gradient. This model shows that decay category and channel planform are negatively associated with increased odds of a ramp/bridge key piece. Additionally, a one-unit increase in (a) channel gradient or (b) piece length/channel width increases the odds of a ramp/bridge key piece by (a) $e^{6.2717}$ ($p > 0.05$) or (b) $e^{5.0872}$ ($p < 0.05$).

We hypothesized that average backwater storage at each logjam is greater in multithread reaches (H3). At the reach scale, the proportion of logjams with moderate or high backwater storage is greater in multithread reaches (Figure 3). The average logjam distribution density is also greater in multithread reaches (Figure 3). In other words, using reach-averaged values, there are more logjams in multithread reaches and a greater proportion of those logjams have substantial backwater storage, which equates to greater cumulative backwater storage per length of valley in multithread reaches. The results thus support H3.

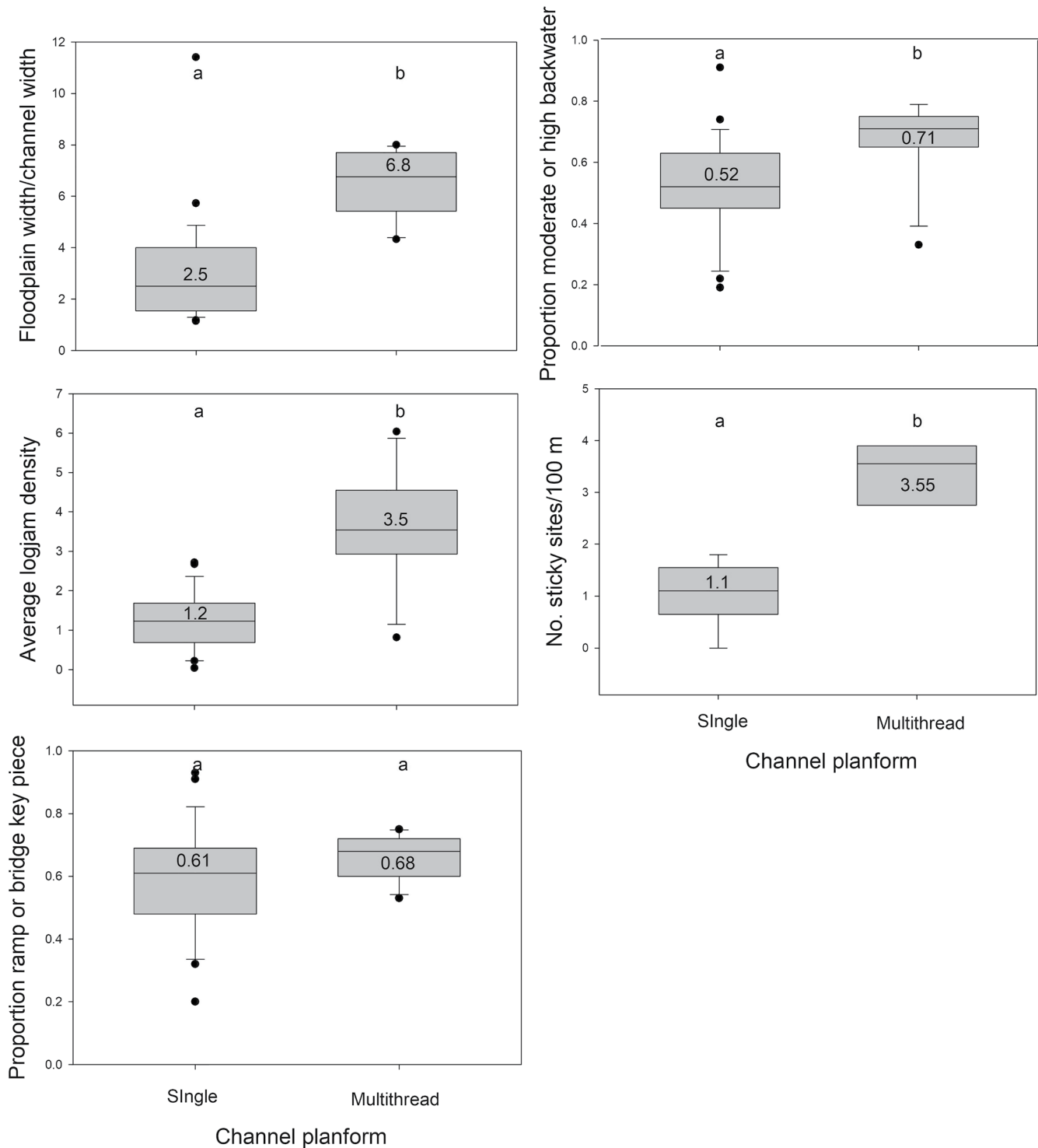


Figure 3. Box plots of valley and logjam characteristics for single versus multithread stream reaches. Median value for each population is within each box. Letter a or b indicates statistical similarity or difference, respectively.

5. Discussion

5.1. Network-Scale Patterns of Logjam Distribution

The spatial pattern of an increase in reach-averaged logjam distribution density where two channels of similar drainage area join, or along smaller channels that join a much larger channel, suggests that confluence effects analogous to those documented for bed-material grain-size distribution (Rice, 1998, 1999) may exist for instream accumulations of large wood. In the case of logjams, backwater effects during peak flows may enhance wood accumulation immediately upstream from the confluence with a much larger channel.

Figure 2 also illustrates that in the first ~4,000 m, North St. Vrain includes five multithread reaches, Ouzel includes three, Cony includes two, and Hunters has only one multithread reach. Multithread reaches correlate with wider valley floors, which correlate with greater spatial density of bedrock joints (Ehlen & Wohl, 2002). The drainage area and discharge of each creek are similar over the first 4 km of North St. Vrain and the length of each tributary, suggesting similar erosive potential. The greater number of multithread reaches on North St. Vrain might reflect underlying differences in bedrock jointing between this drainage and the upper reaches of its tributaries, or it might reflect glacial history. The primary Pleistocene valley glacier flowed down the North St. Vrain mainstem. A slightly smaller tributary valley glacier occupied Ouzel Creek, whereas much smaller tributary glaciers occupied Cony and Hunters Creeks (Braddock & Cole, 1990). These differences are reflected in each channel's longitudinal profile. Despite occasional steep reaches (reach-scale gradient up to 0.18 m/m), North St. Vrain has a relatively straight longitudinal profile. Ouzel Creek has a steep drop where it crosses into the main valley (reach-scale gradient up to 0.247 m/m), and both Cony and Hunters experience dramatic vertical drops (reach-scale gradients up to 0.295 and 0.479 m/m, respectively) where they join the main valley (Figure 2 in Supporting Information S1). The greater frequency of segments with wide valley floor along North St. Vrain might thus reflect more pronounced Pleistocene glacial erosion of the underlying bedrock.

5.2. Controls on Logjam Persistence and Characteristics

As summarized in Section 4, the predictor variables of riparian stand age and logjam distribution density explain a significant amount of the variation in logjam persistence and distribution density alone explains a significant amount of the variation in site persistence. Logjam distribution density also explains a significant amount of variation in reach-scale proportion of moderate to high backwater storage. Logjam distribution density, piece decay category, and channel gradient explain variation in backwater storage of individual logjams. Riparian stand age and channel planform explain variation in reach-scale proportions of logjams with ramp or bridge key pieces. Decay category, ratio of piece length/channel width, planform, and channel gradient explain variation in key piece category of individual jams.

The correlations observed in the data are physically reasonable. Older forest stands produce larger diameter and longer wood pieces that are more likely to form a ramp (one end resting above bankfull flow) or bridge (both ends resting above bankfull flow) pieces. A multithread-channel planform with multiple secondary channels has smaller average channel width than a single-thread channel passing the same discharge, so wood recruited from the riparian forest is more likely to be sufficiently long to span all or a large portion of the channel width. Because ramps and bridges remain partly unsubmerged and are commonly partly anchored in the bank by a partly buried rootwad, these are relatively stable wood pieces that can effectively trap and retain mobile wood pieces to create larger and more stable logjams with greater backwater storage. Where logjam distribution density is higher—that is, there are more logjams per unit length of channel—hydraulic roughness and flow separation are greatly increased and the number of sites along the channel potentially able to trap and retain mobile wood pieces is higher.

5.3. Persistence of Logjams and Geomorphic Implications

The precursor of this study involved choosing five logjams and tagging all of the wood pieces within each jam, with the intent of documenting changes in each jam through time. The original five logjams included three that were very large, with more than 100 individual pieces of large wood in each jam. These three large jams entirely disappeared within 3 years of being tagged (Figure 3 in Supporting Information S1). The dismantling of these

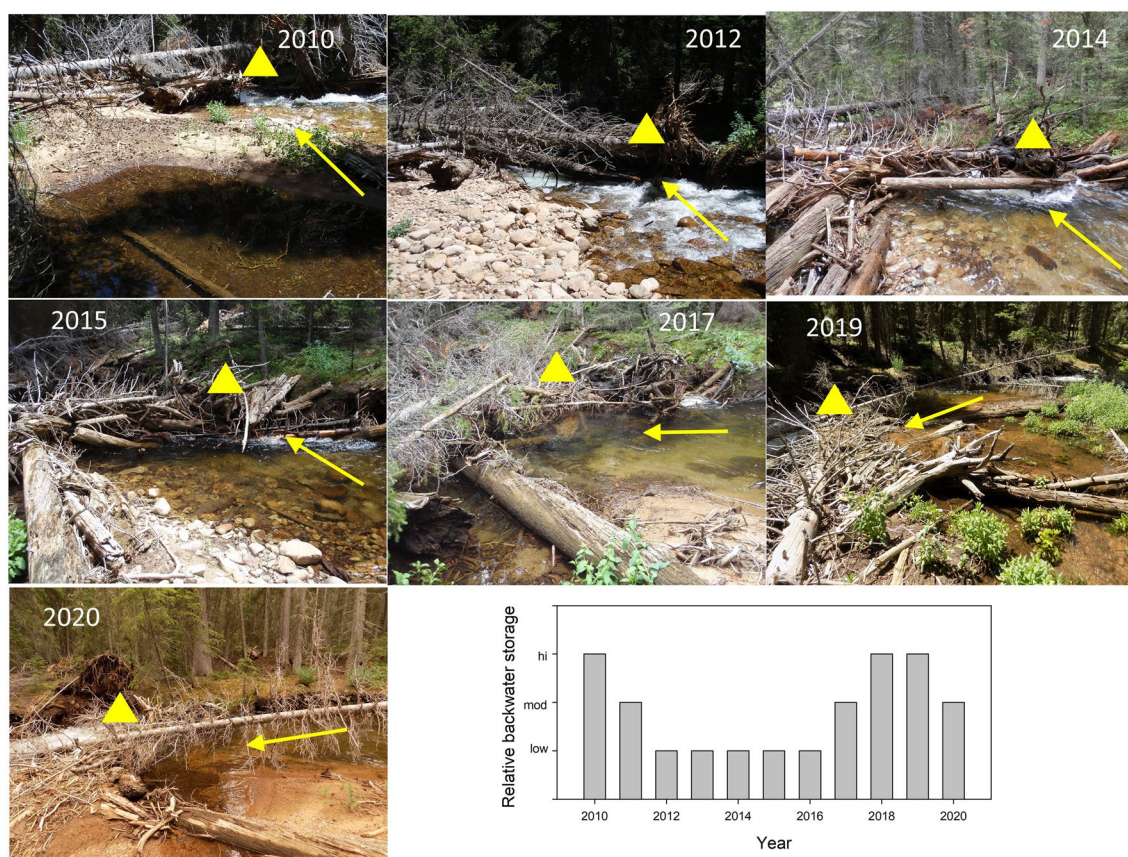


Figure 4. Sequential views of a logjam in a multithread reach of North St. Vrain Creek. Calendar year indicated in each photograph and category of backwater storage indicated by the bar graph at lower right. The yellow triangle in each photograph represents approximately the same location and the yellow arrow in each photograph indicates flow direction.

large jams during peak flows suggested that individual logjams, no matter how large, are relatively transient and this study has confirmed that observation.

Even when a logjam persists for multiple years, the geomorphic effects created by that jam can vary substantially with time in response to fluctuations in discharge, sediment supply, wood supply, channel stability, and the stability and characteristics of pieces within the jam. Figure 4 illustrates changes in backwater storage at a logjam on North St. Vrain Creek that was present throughout this study. Although the key pieces creating this jam never moved, the amount of material (other large wood pieces, smaller wood, and coarse particulate organic matter) trapped by the key pieces, and thus the porosity and permeability of the jam and its ability to create a backwater, started very high, then declined substantially, and finally increased again over the 11 years of this study. Other persistent jams underwent similar interannual fluctuations in morphology and backwater effects (Figure 4 in Supporting Information S1).

A transient channel-spanning logjam can, however, create more persistent geomorphic effects. One scenario that occurred in 14 locations throughout the study area during the 11 years of observations was formation of one or more secondary channels where a large logjam completely obstructed the bankfull channel. Overbank flow typically started as diffuse inundation of the adjacent floodplain, but within 1–2 years this overbank flow created one or more small headcuts, each of which eroded upstream and stabilized the location of a secondary channel (Figure 5 in Supporting Information S1). These newly formed secondary channels then persisted, even if the logjam disappeared or obstructed less of the main channel. Some of the secondary channels had surface flow only during peak snowmelt flow, but others became perennial throughout the snow-free period. Although we do not know how long these secondary channels can persist after a logjam disappears, we observed secondary channels associated with only the marginal remnants of a logjam on the mainstem that were present throughout the 11 years of the study. This indicates that, at least at some sites, the secondary channels can persist for more

than a decade after the logjam that initiated their formation has been removed by high flows. At timespans of a decade or more, transient logjams can thus create persistent geomorphic changes in local channel planform.

When a large channel-spanning logjam either disappears or becomes more permeable and creates less backwater, at least some of the finer (pebble to silt size) sediment and particulate organic matter stored in the backwater is transported downstream. Marginal deposits along the channel banks or close to portions of the jam still present can remain in storage, however. Organic matter and fine sediment that is present for even a few hours, let alone a year or more, can provide nutrients and habitat for microbial communities (Battin et al., 2008) and aquatic macroinvertebrates (Mbaka et al., 2015) and thus help to sustain stream biota. The diverse habitat provided by secondary channels associated with a logjam also benefits stream biota (Bellmore & Baxter, 2014; Venarsky et al., 2018).

Some of the channel-spanning logjams observed in the study area no longer created large backwater effects because the channel bed had aggraded to the top of the jam. These jams had a vertical step of 0.5–1.5 m and a plunge pool immediately downstream from the jam (Figure 6 in Supporting Information S1). Bedload movement in the study area is episodic: although some of the cobble- to boulder-size clasts forming the bed surface move each year, the entire bed surface is typically not mobilized (Mbaka et al., 2015). Similarly, the volume of finer bedload (sand to pebble size) moving during a typical year is not sufficient to completely fill the backwater created by a large channel-spanning logjam. Consequently, we interpret aggradation by cobble- to boulder-size material behind a now mostly buried logjam as indicating that the jam remained in place for at least several years. Over timespans of at least a decade, persistent logjams can thus create persistent changes in local channel gradient, bedform type and dimensions, and volume of stored alluvium.

Observations of persistent secondary channels, marginal storage of fine sediment and organic matter, and aggradation of coarse bed sediment upstream from logjams all suggest that even relatively transient channel-spanning logjams can create important and persistent geomorphic and ecological effects in the mountain streams that we examined for this study. Previous work demonstrates that, at any given moment in time, greater longitudinal density of channel-spanning logjams equates to greater cumulative backwater storage of fine sediment and organic matter (Livers et al., 2018); more spatially heterogeneous channels and floodplains (Livers & Wohl, 2016) that enhance habitat abundance and diversity, as well as biomass and biodiversity (Herdrich et al., 2018; Venarsky et al., 2018); greater lateral connectivity between channel(s) and floodplain (Sear et al., 2010); and greater vertical connectivity between the surface and the hyporheic zone (Ader et al., 2021; Doughty et al., 2020). The transience of individual logjams is not likely to reduce these effects as long as the recruitment of new large wood pieces from within a reach or from upstream portions of a river network is sufficient to allow formation of new logjams, and as long as the site configurations that trap and retain mobile wood pieces and create new jams remain present (“sticky sites”). Site configurations that trap wood in the study area include ramp and bridge wood pieces (Beckman & Wohl, 2014), the presence of secondary channels, and wider and lower gradient valley reaches (Wohl & Cadol, 2011). Maintaining or restoring a natural wood regime (Wohl et al., 2019) and the riverine spatial heterogeneity that enhances wood trapping and retention (Ruiz-Villanueva et al., 2016; Scott & Wohl, 2018), and that wood storage in turn creates (Collins et al., 2012), are integral to sustaining the geomorphic and ecological effects of channel-spanning logjams.

Although stream restoration is likely to continue to use wood fixed in place within engineered logjams where mobile wood pieces can create hazards for downstream infrastructure, the transience of naturally occurring logjams may create geomorphic and ecological benefits that have not yet been documented. Mobile wood pieces that mechanically damage bank vegetation can help to maintain the age and species diversity of riparian vegetation (Johnson et al., 2000), for example, and continuing exchange of wood pieces within a channel may create a more diverse population with respect to stage of wood decay and associated ecological effects (e.g., N. H. Anderson & Sedell, 1979; Gulis et al., 2004).

Where high wood loads and natural trapping mechanisms such as large ramp and bridge wood pieces are present, even mobile wood is unlikely to move large distances downstream. One of the important considerations for the study area described in this paper is that North St. Vrain Creek flows into a large beaver-meadow complex (Laurel & Wohl, 2019; Polvi & Wohl, 2012) immediately downstream from the logjam study reaches. This 2-km-long beaver meadow, which has a dense willow carr covering most of the floodplain, a multithread-chan-

nel planform, and multiple beaver dams and ponds, effectively traps almost all large wood transported from upstream reaches. This quantity of wood is not particularly large, however. Even after the anomalously large September 2013 flood, a field visit by the first author revealed only about 10 pieces of large wood that were newly deposited at the upstream end of the beaver meadow. Instead, most of the wood mobilized during the 2013 flood was trapped again before moving too far downstream, as observed during the 2014 logjam surveys. On Ouzel Creek, for example, the total number of logjams in 2013 prior to the flood was 129. The 2014 annual survey revealed only 61 logjams, but several of these were “megajams” that had substantially increased in size during the 2013 flood by trapping most of the wood mobilized from upstream logjams (Figure 7 in Supporting Information S1). Based on these considerations, we suggest that stream restoration involving wood reintroduction focus on using unanchored wood pieces that may be redistributed during peak flows and focus on sites that are geomorphically sticky. If wood transport to downstream reaches is a concern, then fostering or recreating the type of stream corridor spatial heterogeneity (multithread planform, bars, expansions and constrictions, ramp and bridge wood pieces) that naturally traps and retains wood may help to limit downstream transport distance of mobile wood pieces.

6. Conclusions

Surveys of logjam location and characteristics on four mountain streams over a period of 11 years indicate that individual logjams are transient and typically persist for only 1–2.5 years. Individual logjams in old-growth forest and in stream reaches with more abundant logjams tend to be more persistent. Old-growth forest produces larger wood pieces. Larger wood pieces are more likely to form the relatively stable ramp and bridge pieces that can initiate and stabilize channel-spanning logjams. Greater logjam distribution density equates to more obstacles to wood movement within the channel and to greater hydraulic roughness and potential for overbank flow that further dissipates energy during the peak flows most likely to mobilize instream wood.

Some channel sites facilitate repeated formation of logjams, however, even if the individual jams come and go through time. These sticky sites are more abundant in stream reaches with a multithread planform and with a greater logjam distribution density. In these reaches, the same factors that facilitate individual logjam persistence, as described above, also facilitate site persistence.

The presence of stream reaches with a multithread planform likely represents a self-enhancing feedback that greatly increases reach-scale backwater storage. We observed how formation or enlargement of a channel-spanning logjam initiated the formation of overbank flow. In wider valley reaches, overbank flow can create secondary channels which can persist for at least a decade, even if the associated logjam disappears. These secondary channels may also accumulate logjams, further increasing the logjam distribution density per unit length of valley. Individual logjams within multithread reaches are likely to have greater backwater storage than logjams in single-thread channel planform and the presence of more logjams per length of valley further increases cumulative backwater storage. The relative transience of channel-spanning logjams that we observed in these mountain streams thus does not appear to limit the geomorphic and ecological effects associated with the logjams and may be associated with as yet undocumented benefits. Consequently, we suggest that stream restoration involving wood reintroduction employ unanchored wood whenever possible.

Conflict of Interest

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

Data Availability Statement

The basic data analyzed for this paper are included in Excel workbooks in the Supporting Information accompanying this paper. Data can be accessed via Colorado State University’s Mountain Scholar, an open access data repository, at <http://dx.doi.org/10.25675/10217/234532>.

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