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The resilience of logjams to floods

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Abstract

Logjams that span the bankfull channel strongly influence hydraulics and downstream fluxes of diverse materials. Several studies quantify the longitudinal distribution of channel-spanning logjams, but fewer studies examine changes in longitudinal distribution in response to disturbances such as floods. We use 10 years of annual surveys of a population of channel-spanning logjams along mountain streams in the Southern Rocky Mountains. Surveys from 2010 to 2019 bracket substantial interannual variability in the snowmelt peak flow as well as a rainfall flood in 2013. We characterised the number of logjams per unit length of valley (logjam distribution density) within and between reaches designated based on longitudinally consistent channel and valley geometry. Our primary objectives are to evaluate the influences on logjam distribution density of (i) spatial variations in valley and channel geometry and (ii) temporal variations in peak annual flow. We hypothesized that logjam distribution densities are resilient to disturbance at both spatial scales. At the creek scale, logjam distribution density correlates significantly with increasing ratio of floodplain width to channel width and wood piece length to channel width. Wide, low gradient reaches with greater distribution density exhibit greater interannual variation in distribution density. These reaches lost jams during the 2013 flood but returned to pre-flood distribution density values by the end of the study. The pattern of greater logjam distribution density in unconfined reaches relative to confined and partially confined reaches is also consistent over the period of the study. We interpret these results as indicating the resilience of logjam distributions to disturbance. The persistence of greater numbers of logjams in wide, low gradient reaches suggests that river restoration employing engineered logjams and wood reintroduction can focus most effectively on these reaches.

KEYWORDS
disturbance, Logjam, flood, large wood, mountain streams, Southern Rocky Mountains

1 | INTRODUCTION

Logjams are defined here as accumulations of three or more pieces of downed, dead wood (≥10 cm diameter and 1 m length) in contact with one another as a result of river transport and deposition. Like individual pieces of large wood, logjams increase the roughness of the channel boundaries and obstruct the flow. Consequently, logjams influence hydraulics (Dudley et al., 1998; Gippel, 1995; Manners et al., 2007) and transport or retention of mineral sediment and particulate organic matter (Beckman & Wohl, 2014a; Bilby, 1981; Livers & Wohl, 2016; Wohl & Scott, 2017). By obstructing flow and creating pressure gradients, logjams enhance hyporheic exchange flows (Doughty et al., 2020; Hester & Doyle, 2008; Lautz et al., 2006). Logjams also influence channel cross-sectional and planform geometry (Collins et al., 2012; Curran & Wohl, 2003; Wohl, 2011) and aquatic habitat and biomass (Herdrich et al., 2018; Richmond & Fausch, 1995;

Venarsky et al., 2018). Logjams are an essential component of the physical structure and function of channels in forested river corridors.

An extensive body of literature now describes the spatial distribution of logjams within channels at the reach- to network-scales and in relation to potential control variables (Abbe & Montgomery, 2003; Kraft & Warren, 2003; Morris et al., 2007; Warren et al., 2007; Wohl & Cadol, 2011; Wohl & Beckman, 2014; Pfeiffer & Wohl, 2018). These studies indicate that logjams tend to be non-randomly distributed.

Logjams preferentially form in portions of streams with lower transport capacity and greater trapping potential. Transport capacity for wood pieces reflects the ratio of piece length to flow width and piece diameter to flow depth (Braudrick & Grant, 2001) and the spatial density of pieces in transport: during semi-congested or congested transport, wood pieces moving together interfere with each other's transport (Braudrick et al., 1997).

Trapping potential reflects characteristics such as the presence of protruding boulders, bars, and islands (Gurnell et al., 2000), a multi-channel planform (Livers & Wohl, 2016; Wohl, Scott, et al., 2018; Wyzga & Zawiejska, 2005), channel bends (Braudrick & Grant, 2001; Nakamura & Swanson, 1994), and ramp and bridge wood pieces that have one or both ends resting above the bankfull channel (Beckman & Wohl, 2014b). Each of these features increases spatial heterogeneity and the contact between wood pieces in transport and the channel boundaries and thus enhances the potential for trapping and storage of wood (Scott & Wohl, 2018).

Logjam-related physical and ecological effects, such as storage of sediment and particulate organic matter and provision of aquatic habitat, are also non-randomly distributed (Beckman & Wohl, 2014a; Bellmore & Baxter, 2014; Venarsky et al., 2018). This implies that differing segments of a river network have different levels of retention, connectivity, and biological productivity and may therefore warrant different management (Wohl et al., 2019; Wohl, Lininger, et al., 2018).

Less attention has been given to how the spatial distribution of logjams varies through time in response to fluctuations in potential control variables that influence wood recruitment, transport, and retention. Here, we use repeat surveys of a population of channel-spanning logjams within a mountainous drainage basin in the Southern Rockies of Colorado, USA to examine the effects on logjam distribution of variations in peak annual snowmelt flow and a rainfall flood that affected the drainage basin in September 2013.

We define channel-spanning logjams as those that include at least one wood piece touching each bank of the active channel and that create at least some perturbation in the water surface as a result of partial flow obstruction. We focus on channel-spanning logjams, whether they were formed in situ around an immobile key piece or as transport jams at a site of reduced conveyance for large wood (Abbe & Montgomery, 2003). Channel-spanning jams are most likely to create emergent effects with respect to hydraulics, sediment dynamics, and channel geometry (Abbe & Montgomery, 1996; Collins et al., 2012; Mao et al., 2008; Wohl, 2011; Wohl & Scott, 2017).

We use the field data to examine the degree to which the occurrence of annual peak flows of varying magnitude alter the longitudinal distribution of logjams. The greater transport capacity of a large flood might be expected to destroy channel-spanning logjams. On the other hand, if higher flows mobilise individual wood pieces stored along the channel margins and carry these pieces into a channel reach in which high trapping capacity persists during the flood, then the large flood might be expected to create additional channel-spanning logjams. We know from previous work in the study area (Wohl & Cadol, 2011) and elsewhere that logjams are not randomly distributed along the length of a channel but rather form preferentially in wide, low gradient valley reaches. Using repeat surveys that bracket peak flows of varying magnitude, we investigate whether logjams in these reaches are more or less resilient to the effects of floods than logjams in narrow, steep valley reaches.

We define a reach as a length of channel with consistent geometry, based on channel gradient, bedform type (Montgomery & Buffington, 1997), and ratio of active channel width to floodplain width. Each creek in the study area includes multiples reaches. We characterise the number of logjams per 100 m length of valley, which we refer to as logjam distribution density and then analyse logjam distribution density within each reach through time (intra-reach variations), as well as differences between reaches through time (inter-reach variations).

In describing changes in intra- and inter-reach logjam distribution density through time, we distinguish resistance, sensitivity, and resilience. These terms come from ecology and have been defined in different ways. We use the following definitions: Resistance describes the ability of a system to remain essentially unchanged when subject to disturbance (e.g., Simon, 2009); sensitivity is the inverse. Resilience is the persistence of relationships within a system and a measure of the ability of the system to absorb changes of state and driving variables and still persist (Holling, 1973). In the context of this study, logjam populations are resistant when the intra- and inter-reach longitudinal distributions of logjams exhibit little change in response to a flood. In other words, the average numbers of logjams per unit length of valley does not change significantly through time within a reach (intra-reach) and the differences in logjams per valley length between reaches do not change significantly (inter-reach). Resistance could reflect high transport capacity and lack of trapping potential, such that few logjams form in a reach under any conditions. Resistance could also occur where existing logjams are highly stable and are not removed by high flows. Logjam populations are sensitive when they change significantly in response to a flood, whether that change involves net gain (many new logjams form) or net loss (many existing logjams disappear). Logjam populations are resilient when the intra- and inter-reach longitudinal distributions of channel-spanning logjams return to pre-flood characteristics within a few years. We hypothesize that both intra- and inter-reach patterns of logjam distribution density logjams are resilient, rather than resistant or sensitive, to large floods. As judged over a 10-year study, this implies that logjam distributions may change significantly following a large flood, but then return to pre-flood values within the timespan of the study.

We are interested in the resilience of the longitudinal distribution of channel-spanning logjams for two reasons. First, river restoration increasingly includes active restoration of engineered logjams, most of which are fixed in place (Roni et al., 2015), yet our understanding of appropriate spacing and likely persistence of naturally formed logjams remains constrained by limited field data. Second, given the diverse geomorphic and ecological effects of logjams, greater insight into the spatial distribution and persistence of these features will enhance our understanding of fluvial process and form in forested river networks. If individual logjams are present for many years, for example, associated storage of fine sediment and organic matter is relatively persistent, whereas logjams that form and disappear within 2–3 years create transient storage of material in transport at interannual timescales. Consequently, the primary objectives of this paper are to evaluate the influences on logjam distribution density of (i) spatial variations in valley and channel geometry and (ii) temporal variations in peak annual flow. Addressing these objectives allows us to test the hypothesis that both intra- and inter-reach logjam longitudinal distributions are resilient, rather than resistant or sensitive, to large floods.

2 | STUDY AREA

The North St. Vrain (NSV) Creek drainage heads at the continental divide and flows eastward from elevations of 4100 m down to 1500 m at the base of the Rocky Mountains, where NSV joins the South Platte River. The logjams analysed here lie within the upper part of the drainage in Rocky Mountain National Park. Channels in the upper basin flow from 3040 m in elevation to 2550 m at the eastern park boundary. Three large creeks are tributary to NSV in the upper basin: Ouzel, Cony and Hunters Creeks (Table 1; Figure 1).

The study area is underlain by Precambrian-age Silver Plume Granite (Braddock & Cole, 1990). Although debris flows occur in the drainage basin (Patton et al., 2018), they are relatively infrequent and wood recruitment to the river corridor (channel and floodplain) occurs mainly via bank erosion; individual tree mortality; mass mortality via wildfire, insect infestation, or blowdown; and fluvial transport from upstream. The upland forest includes Engelmann spruce (*Picea engelmannii*), lodgepole pine (*Pinus contorta*), and subalpine fir (*Abies lasiocarpa*) and the river corridor is dominated by Douglas-fir (*Pseudotsuga menziesii*), blue spruce (*Picea pungens*), and Engelmann spruce (Veblen & Donnegan, 2005). Stand-killing fires recur at intervals of 100 to 400 years (Veblen et al., 2000). Blowdowns have less consistent return intervals, but at least small blowdowns of 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 2011–12 (Wohl, 2013). Insect infestations by the native mountain pine beetle (*Dendroctonus ponderosae*) occur at irregular intervals and at differing severity in terms of proportion of tree mortality within a stand. The study area has been experiencing widespread tree mortality during the past decade from mountain pine beetles, but few of these trees have fallen directly into channels. Forest stand ages in the study area vary from old-growth (~1500 AD) at the headwaters to stands that date from 1880 AD in the lower catchment and 1978 AD in a burned portion of the Ouzel Creek and lower Cony Creek watersheds (Sibold et al., 2006).

Valley and channel geometry exhibit substantial longitudinal variation as a result of valley glaciation (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 (<0.02 m/m) segments of river corridor repeatedly alternate downstream over distances of 10^1–10^3 m with narrower, steeper valley segments. Wider, lower gradient segments can have anastomosing channel planform (Livers et al., 2018; Livers & Wohl, 2016; Wohl, 2011), abundant large wood in the active channel and floodplain, and plane-bed to step-pool channel morphology. Narrower, steeper segments are likely to have relatively straight, single channels, less large wood, and step-pool to cascade channels. The spatial density of standing trees in the riparian zone of the study area limits fluvial transport of wood into the floodplain and there are few floodplain jams present (Wohl, Cadol, et al., 2018).

The study area has a continental climate, with greater precipitation and colder temperatures at higher elevations. At the downstream end of the study area, mean annual precipitation is just over 500 mm and average temperature is 0°C in the winter and 22.5°C in summer. The annual snowmelt flood dominates stream flow, which does not exceed a peak unit discharge of ~1.1 m^3/s/km^2 (Jarrett, 1990).

During 9–16 September 2013, a seasonally uncharacteristic weather pattern brought significant amounts of rainfall to the Front Range of northern Colorado (Gochis et al., 2015). The resulting catastrophic flooding was mostly confined to lower elevations downstream of the study area within the North St. Vrain Creek catchment. No stream gages are present in the upper NSV watershed, but daily discharge on the neighbouring Big Thompson River, at an elevation slightly below the study area, was nearly twice the snowmelt peak

TABLE 1 Descriptive characteristics of the study area; see Table S1 for individual reach data along each creek

Drainage	A (km^2)	Stand ages	Reaches	L (m)	Jams/100 m	Q_2 (m^3/s)
North St. Vrain	88	1500, 1880	16	10 480	0.94	15.1
Ouzel	14	1500, 1880, 1978	8	3565	2.20	4.3
Hunters	12	1500, 1880	6	4000	1.46	4.0
Cony	20	1500, 1978	8	3200	1.57	4.6

Note: A is drainage area at the downstream end of the surveyed portion of the channel. Stand ages are in calendar years AD. Reaches lists the number of morphologically distinct channel reaches designated within each creek. L is total length surveyed for logjams within each channel. Jams/100 m is average number of jams per 100 m length of channel. Q_2 is the estimated 2-year peak flow at the downstream end of the surveyed portion of the channel.

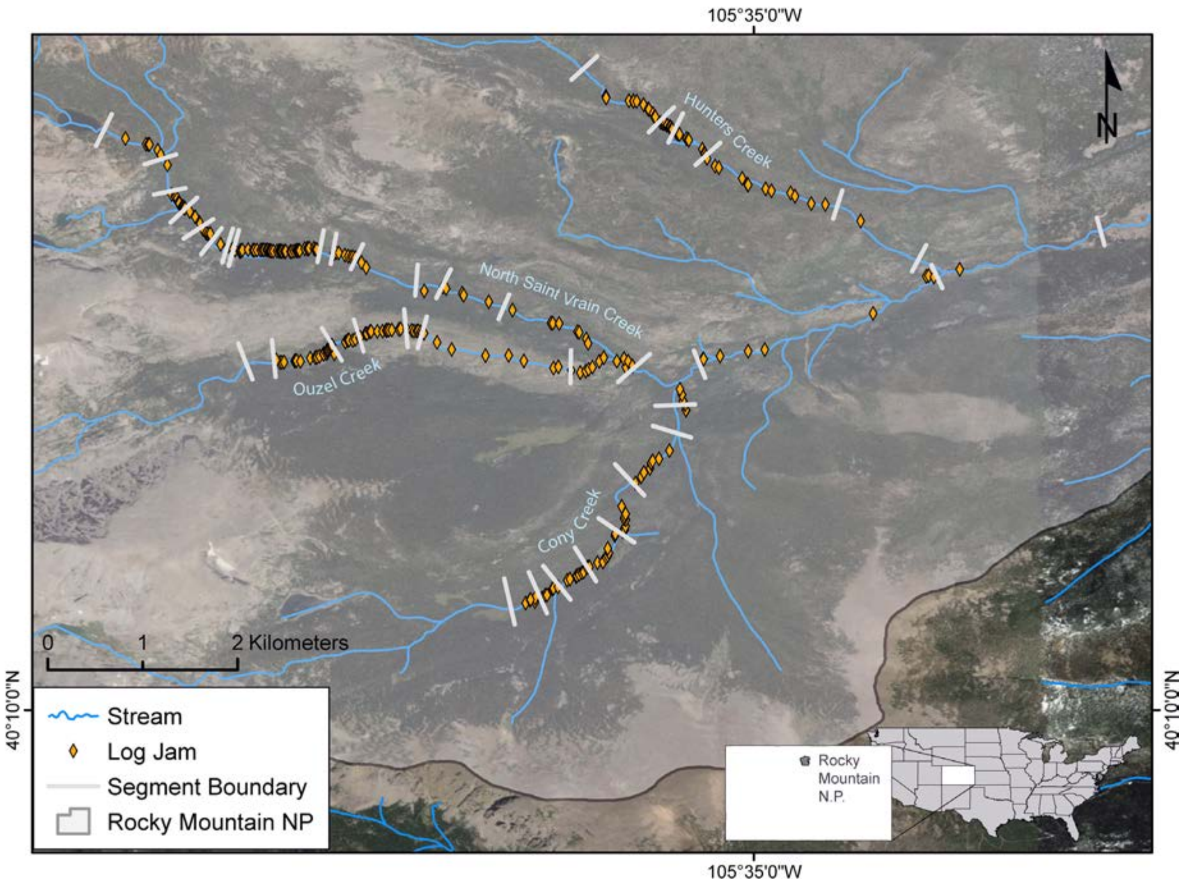

FIGURE 1 Location map of the study area, showing mapped channel-spanning logjams in 2018. Inset map indicates location of Rocky Mountain National Park within the continental United States

that year (on 10 June) and rainfall exceedance probabilities over the study area ranged from 1/10 years at the highest elevations (our study area) to 1/500 years at the lower elevations below our study area (Gochis et al., 2015). Figure S1 in the supplemental material shows that this flood peak is the largest over the period of record (1997–2019) at the Big Thompson River gage. Observations of 2013 high-water marks during data collection in 2014 indicated that channels throughout the study area experienced peak flows exceeding the annual snowmelt flood. Although the 2013 flood was exceptional in terms of timing and had the largest peak flow during the study period of 2010–2019, this study period includes substantial variability in the annual snowmelt hydrograph and peak flows of magnitude comparable to 2013 during the 2010, 2011 and 2014 snowmelt seasons (Figure 2).

3 | METHODS

3.1 | Study design

Potential control variables in this study at the reach-scale include drainage area, channel gradient, floodplain width, bankfull channel width, average wood piece length, the ratio of wood piece length to bankfull channel width, the magnitude of flood with a two-year recurrence interval (Q_2), estimated annual peak flow at each reach (Q_{ap}), the estimated peak flow of the 2013 flood (Q_{2013}), riparian stand age, and lateral confinement (the ratio of floodplain width to bankfull channel width). Potential control variables were chosen to represent recruitment, transport, and storage potential for large wood.

Riparian stand age is an indicator of volume of wood available for recruitment at the reach-scale via processes such as bank erosion and blowdowns on the floodplain. The study reaches are all within subalpine conifer forest and tree height and diameter increase with age. Consequently, older riparian forest stands can contribute larger and potentially more stable wood pieces to the channel. Channel gradient is a secondary indicator of wood recruitment potential: Steep reaches in the study area are more likely to have bedrock exposed along the channel banks, limiting wood recruitment through bank erosion.

In these ungauged channels, fluvial transport capacity is represented by drainage area, Q_2, Q_{ap} and Q_{2013}. Little to no wood movement occurs in the study area during base flow, so we use estimated two-year peak flow (Q_2), each year's snowmelt peak flow (Q_{ap}), and a rainfall flood peak flow (Q_{2013}) to represent high flow transport capacity in these ungauged channels. Drainage area is used as a proxy for peak flow.

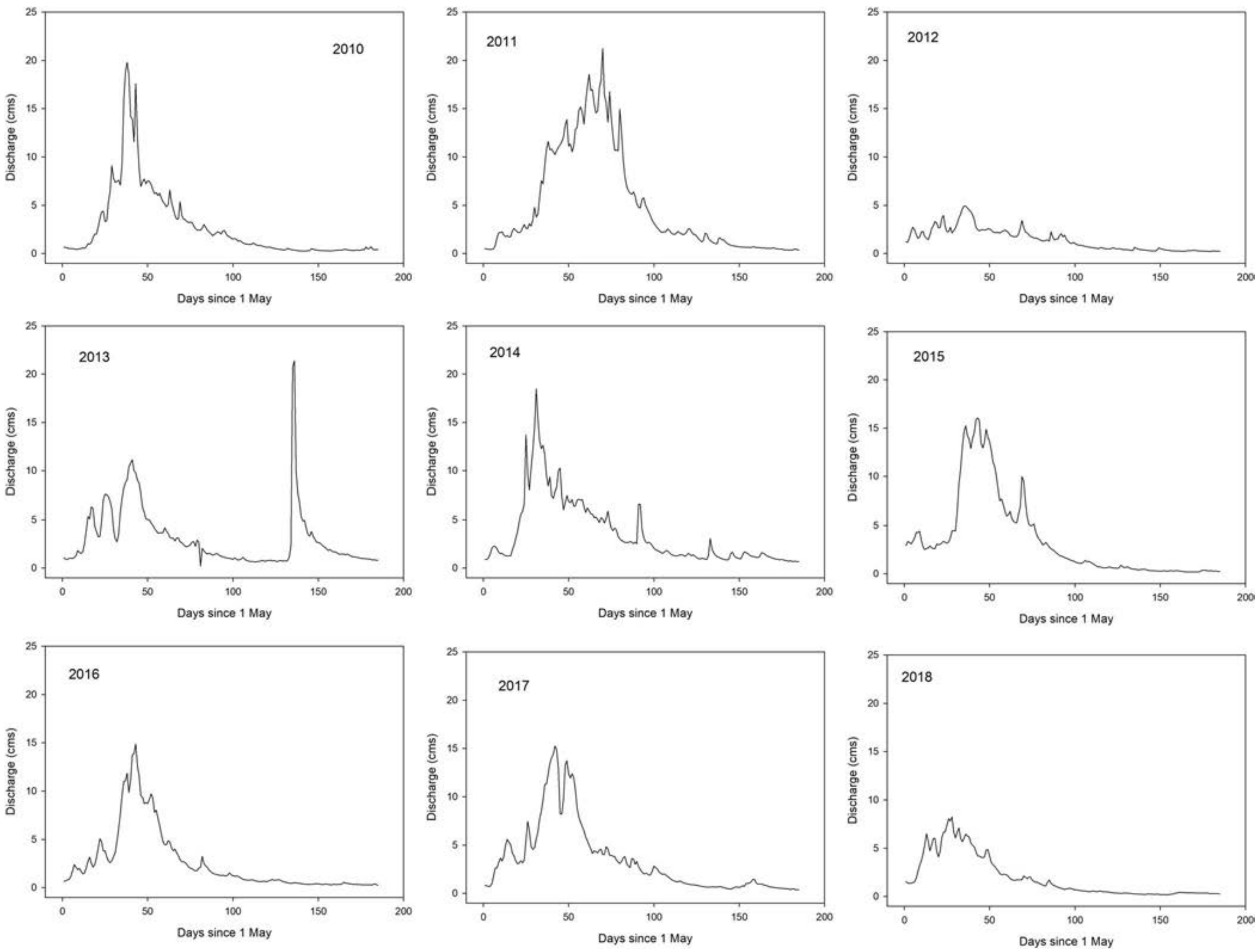

FIGURE 2 Annual snowmelt hydrograph at the big Thompson River gauge, 2010–2019

Storage potential for large wood is reflected in channel and valley geometry, as indicated by channel gradient, the ratio of average wood piece length to bankfull channel width, lateral confinement, and floodplain width. Steeper gradient reaches in the study area typically have cascade or step-pool morphology, large boulder substrate, and minimal floodplain development. Logjams forming in these reaches are subject to greater hydraulic force during peak flows because of the lack of overbank flows (Wohl, 2011). Lower gradient reaches are plane-bed or pool-riffle channels with small boulder to cobble substrate and floodplain widths that can exceed several times the active channel width (Livers & Wohl, 2015). As the ratio of piece length to channel width increases, pieces in transport are more likely to be trapped and stored by lodging against living vegetation on the channel banks, protruding boulders in the channel, islands and bars, or other irregularities along the channel margins (Braudrick & Grant, 2001; Gurnell et al., 2002). Wider floodplains and lower lateral confinement facilitate energy-dissipating overbank flows and the development of an anastomosing channel planform in which smaller, secondary channels can be very effective at trapping and storing large wood (Livers et al., 2018).

3.2 | Field methods and supporting data

Annual field surveys were conducted in August following recession of snowmelt peak flows. These field surveys began in 2010 and are ongoing. Each survey consists of walking the length of channel in the study area and using a handheld GPS unit (Garmin eTrex, horizontal accuracy ±3 m) to map the locations of channel-spanning logjams. In order to be included in the logjam tally, each jam must (i) include at least 3 pieces of wood that exceed 10 cm in diameter and 1 m in length and which physically contact each other and (ii) alter the water-surface gradient across at least ¾ of the active channel width at low flow (Figure 3). Although other logjams are present in these channels, only those logjams meeting these criteria were included in the survey.

Reaches were designated in the field based on observed changes in primary bedforms within the active channel. Past work indicates that primary bedform (cascade, step-pool, plane-bed, pool-riffle; Montgomery & Buffington, 1997) correlates strongly with channel gradient, streambed grain size, and valley-bottom width (Livers & Wohl, 2015). Individual study reaches are 10^1–10^2 m long with drainage areas from 5 to 90 km^2. Field-designated reach boundaries were

FIGURE 3 Examples of channel-spanning logjams in the study area. The degree to which each logjam alters flow and sediment transport varies. White arrows indicate flow direction. All channels shown here are about 15 m wide

subsequently checked against channel gradient obtained from topographic maps. Riparian stand age maps (Sibold et al., 2006), which reflect wood recruitment potential, were used where appropriate to designate additional reaches within lengths of consistent channel bedform and gradient.

We derived values for drainage area, Q_2, and channel gradient from the USGS website StreamStats (https://streamstats.usgs.gov/ss/) based on the GPS coordinates for each jam. Q_2 refers to the 2-year peak flow and is derived from regional regressions based on drainage area and elevation (Capesius & Stephens, 2009; Kohn et al., 2016).

We estimated the 2013 peak flow for each study reach based on the 2013 peak flow at the Big Thompson River USGS stream gage (402114105350101) This gage, which is 16 km north of the North St. Vrain Creek drainage, is the only gage without flow regulation in the study area. We divided the 2013 peak discharge at the gage by the upstream drainage area to determine a unit peak discharge (0.308 $m^3/s/km^2$) and then multiplied this value by the drainage area for each study reach to estimate the 2013 peak discharge. We used the same approach to estimate peak discharge for each year of the study, based on that year's peak discharge at the Big Thompson River gage. This approximation does not account for elevational differences that influence actual peak discharge but should reasonably estimate interannual differences in peak flow.

Reach length was measured on Google Earth imagery using GPS coordinates for each jam. We recorded GPS coordinates for the upstream and downstream boundary of each river segment in the field based on visual assessment of downstream changes in channel and valley geometry. Channel width within each reach was averaged from measurements of bankfull width at 100-m increments along the study reach. Floodplain width within each reach was averaged from several floodplain transverse measurements using a handheld laser rangefinder (TruPulse 360B, accuracy ±0.1 m). 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. There is no indication that average piece length, which varies by ±1 m among the study reaches, changed during the course of the study.

3.3 | Statistical analyses

All statistical analyses were performed using R statistical software (R Core Team, 2019). The significance of all correlations, models, and comparisons was assessed at the 95th percentile (α = 0.95) for all statistical analyses performed.

3.3.1 | Patterns and changes to logjam randomness

We first evaluated the degree to which logjams are randomly distributed at the scale of an entire creek and within each reach. As noted in the introduction, previous work indicates non-random logjam distribution at the creek scale, but logjams might be randomly distributed within a study reach designated based on consistent channel and valley geometry. We statistically evaluated the randomness of logjam longitudinal distribution as a means of objectively testing our perception that logjams are not randomly distributed. We chose the three time intervals of 2010, 2014 and 2018 to bracket the potential effects of higher peak snowmelt flows in 2010 and 2011, as well as the September 2013 rainfall flood, when evaluating randomness of longitudinal logjam distribution. We used network pair correlation to analyse potential deviations from randomness of the longitudinal distribution of logjams based on the distance between points (logjams). Pair correlation is the ratio of the probability of the measured point pattern compared to the probability of a random, Poisson point pattern at distinct distances or spacings (Glass & Tobler, 1971; Illian et al., 2008). Because the logjam data are linear, equations for pair correlation for a network (points along a linear feature) were calculated using functions in the *spatstat* R package (Baddeley et al., 2015) with networks arbitrarily created as straight lines to simplify the analysis. We analysed pair correlations for each reach and for each of the four creeks as a whole. Pair correlation output can be illustrated as a curve that shows whether point distributions are more separated or clustered than random. The Maximum Absolute Deviation test was used to determine whether an output distribution deviates significantly from random at any given distance (Ripley, 1981). Additionally, confidence intervals surrounding the definition of random were calculated by running 199 Monte Carlo simulations to create random logjam patterns using the same number of logjams over the same distance for each reach and creek.

3.3.2 | Correlations to logjam distribution

To further investigate changes in logjam distribution over time, we used the metric of logjam distribution density, a simple indicator of the average longitudinal spacing of logjams, as the response variable. Spearman correlations were used to determine significant correlations between logjam distribution density and reach and flow characteristics.

First, we calculated the average logjam distribution density and the maximum change in distribution density for each reach across all years (2010–2019). To investigate whether physical or hydrological factors have a greater influence on patterns and changes in logjam distribution density, we developed multiple linear regressions to evaluate the relative importance of potential control variables on logjam distribution density. Because of the apparent differences in logjam distribution density in relation to lateral confinement, we developed three separate models to investigate controls on distribution density in confined, partially confined, and unconfined reaches. Confinement is defined by the ratio of floodplain width to active channel width. Reaches with ratios less than 2 are confined, those with ratios between 2 and 6 are partially confined, and reaches with ratios greater than 6 are unconfined. Regression models were built using average annual discharge, the 2013 flood discharge, channel gradient, riparian stand age, the ratio of average wood piece length to channel width, and the ratio of floodplain width to channel width as predictor variables to describe the response of reach logjam distribution densities from 2010 to 2019 as well as maximum annual change between that period. Drainage area was excluded from the model due to strong collinearity with other variables, particularly discharge. Because logjam distribution density is not normally distributed, the response was square root transformed to meet model assumptions. To determine the most important and significant variables explaining logjam distribution density for various types of confinement, final models were chosen by all subsets model selection using the *MuMIn* R package (Barton, 2018). Additionally, we used a Mann–Whitney U test to determine whether average logjam distribution densities were higher in multi-thread channels compared to single-thread channels. With the exception of one multi-thread channel reach in a partially confined valley, multi-thread channels occur in unconfined reaches whereas single-thread channels are present in reaches with all three levels of lateral confinement.

3.3.3 | Flood-induced changes to logjam distribution

After investigating correlations to the decadal average and maximum change in logjam distribution density, yearly fluctuations in logjam distribution density for a given reach were compared to the maximum discharge in the year prior to each survey. A mixed model was built using logjam distribution density for a given year and reach as the response variable and maximum annual discharge as the sole fixed predictor. Because we calculated logjam distribution density over the same reaches across multiple years, reach is included as a random effect to account for reach-specific processes and characteristics that could affect logjam distribution density. Maximum annual discharge is included as the only fixed predictor because it is the only measured variable that fluctuates from year to year, whereas physical reach characteristics such as bankfull channel width and floodplain width remain constant.

To further investigate flood-induced changes compared to normal fluctuations in logjam distribution density, we calculated the annual change in logjam distribution density between successive surveys. The period 2013–2014 includes the largest flood during the study. A mixed model was created to determine whether changes to logjam distribution density in the year with a flood differed significantly from years without a flood. Confinement and whether a flood existed (flood or no flood) as well as the interaction between confinement and flood were included as fixed effects. Because change was calculated over the same reaches across multiple years, reach was included as a random effect to account for reach-specific processes and characteristics that could affect changes in logjam distribution density. Tukey adjusted pairwise comparisons from the mixed model were considered to test whether changes in logjam distribution densities in 2013–2014 are significantly different than other years using the *emmeans* R package (Lenth, 2020). Pairwise comparisons were considered for confined, partially confined, and unconfined reaches to further investigate whether the largest flood disproportionately influenced logjams in wide, unconfined reaches.

4 | RESULTS

The basic data used in statistical analyses are included in Tables S1 and S2 in the supplemental information. The study reaches fall into the medium channel category of Gurnell et al. (2002) because channel width is greater than the size of most, but not all, wood pieces. Within the study area, 47–91% of the logjams are formed by ramp pieces (one end resting above the bankfull channel) within individual creeks during each year, indicating the importance of riparian stand age (Dixon et al., 2019) in providing sufficiently large trees to create ramped pieces and individual tree fall in creating obstacles at which logjams can form (Beckman & Wohl, 2014b).

Field observations indicate changes in individual logjams from year to year. When tree fall creates a ramped piece, a channel-spanning logjam can form within a year if the tree is alive at the time it falls and retains abundant branches with needles for at least a few months after it falls. If the ramped piece is a snag (standing dead tree) with minimal branches or extends across a smaller portion of the bankfull channel, a channel-spanning logjam may require more than a year to form or may not form at all. An existing logjam can remain channel-spanning but have varying porosity and backwater effects through time or can be sufficiently reduced that it no longer spans the channel. Either form of change can be gradual or abrupt at the time-scale of an annual survey. During a gradual decline, the logjam partly breaches and concentrated flow around the breach progressively erodes the jam over a period of more than a year, although the logjam still spans the channel. In an abrupt decline, a logjam present the previous year has disappeared, although marginal deposits commonly remain for a few years, indicating the prior location of a logjam. At least one logjam, nicknamed the Mother Ship, went through a gradual decline and nearly disappeared before once more becoming a large logjam with a substantial backwater pool; these alterations occurred over a period of nearly a decade.

Our observations also indicate that secondary channels can form within one high-flow season when a channel-spanning logjam forces flow onto the floodplain. If the logjam then breaks up or breaches, the secondary channels persist for years, although typically with lower surface hydrologic connectivity than when the logjam is present.

Using the methods described previously for estimating peak annual flow for each reach in the study area, estimated peak discharge during the 2013 rainfall flood exceeded the estimated Q_{ap} value for all other years of the study in all reaches (Table S3). The most noticeable change in logjams after the 2013 rainfall flood occurred in the 1978 burn zone along Ouzel Creek. In this 2-km-long reach, a few large logjams that had been present since the first set of annual surveys in 2010 were gone, but two logjams at the downstream end of this reach caught the wood pieces mobilised upstream and became exceptionally large jams. Flood-induced changes in the number of channel-spanning logjams were not obvious during 2014 field surveys in the other reaches.

4.1 | Longitudinal distribution of logjams

4.1.1 | Patterns and changes to logjam randomness

To evaluate creek- and reach-scale randomness of logjam longitudinal distribution, we used the years of 2010, 2014 and 2018 to bracket the 2013 flood. The Maximum Absolute Deviation Test indicates that, except for Ouzel Creek in 2010, the distribution of logjams along each creek in all years deviates significantly from random (Figure 4). At the reach scale, however, very few of the reaches have a longitudinal distribution that deviates significantly from random. Of 114 reaches (38 reaches on the four creeks over 3 years), only 5 deviate from random at the reach scale (Table 2). Both of these results are as expected based on the designation of relatively homogeneous reaches, which is more likely to create a random longitudinal distribution within a reach, and likely substantial variations in large wood recruitment, transport, and trapping between reaches, which is likely to create non-random longitudinal distributions at the scale of entire creeks.

4.1.2 | Correlations to logjam distribution

Average logjam distribution density significantly increases as the ratio of floodplain width to channel width increases ($\rho = 0.75$, $p < 0.001$) and as the ratio of average log length to channel width increases ($\rho = 0.48$, $p = 0.002$) (Figure 5). Confined, partially confined, and unconfined channel reaches contain increasingly greater average logjam distribution densities (Figure 6), with a significant difference ($p < 0.05$ for all comparisons) between each category. When considering all reaches regardless of confinement, logjam distribution densities do not significantly increase with increasing drainage area ($p = 0.09$), indicating there is not a longitudinal downstream trend of logjam distribution density (Table 3). However, the maximum annual change in logjam distribution density between 2010 and 2019 did significantly decrease with increasing drainage area ($p = 0.03$), suggesting that downstream reaches were more resistant or resilient to change in logjam distribution density. Multi-thread reaches contain a higher average distribution density of logjams compared to single-thread

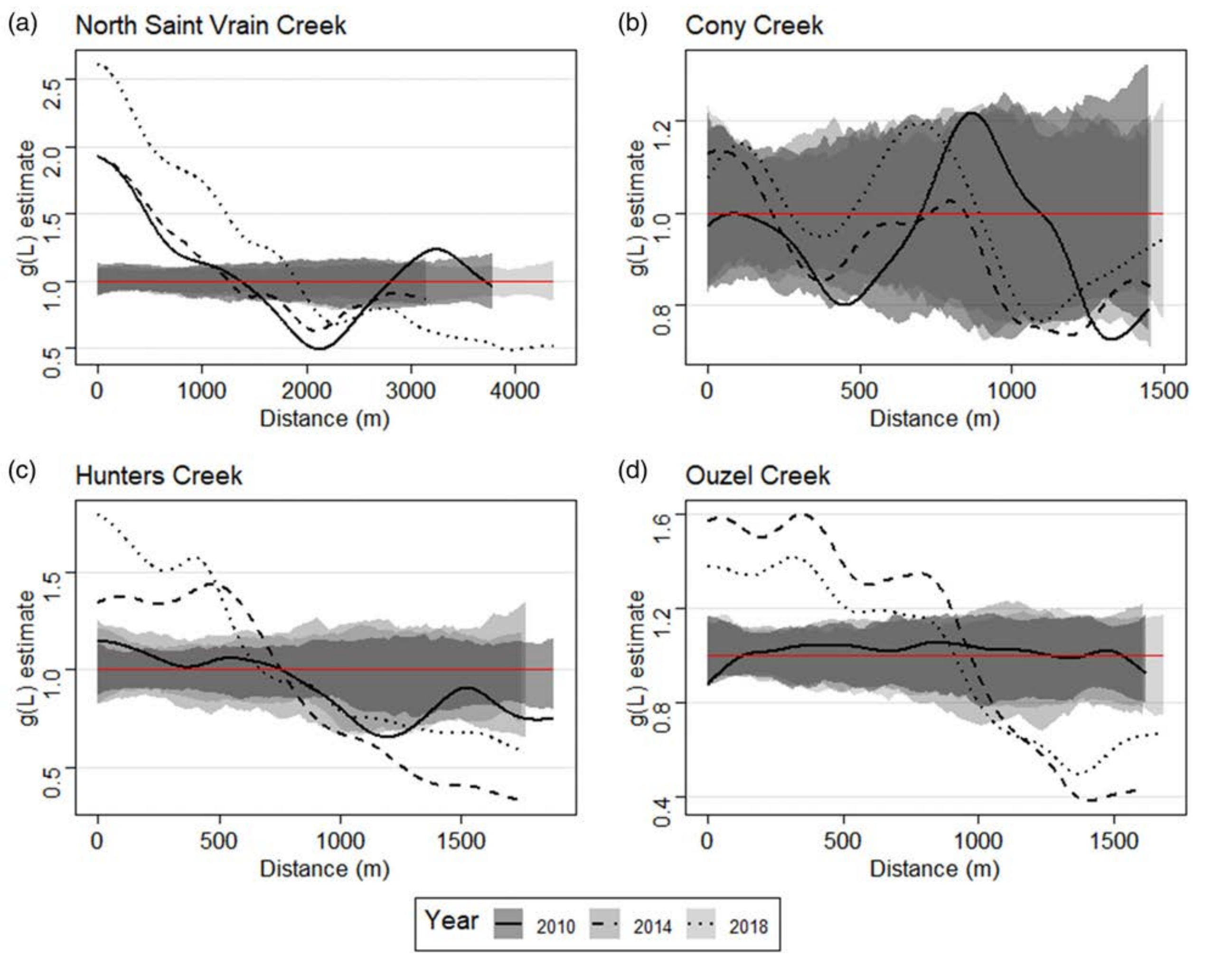

FIGURE 4 Linear pair correlation analysis for logjams on (a) North Saint Vrain, (b) Cony, (c) Hunters, and (d) Ouzel Creek in Rocky Mountain National Park in 2010, 2014 and 2018. The pair correlation function, g(l), is the probability of observing a pair of logjams separated by a certain distance due to natural processes, divided by the corresponding probability for a random (Poisson) process. A value of g(L) = 1 represents no correlation, essentially stating that logjams are randomly distributed (indicated by a red line). Values of g(L) > 1 indicate that the actual distribution of logjams is more clustered than a random distribution, and values of g(L) < 1 indicate the distribution of logjams is more separated than random. Confidence intervals surrounding g(l) = 1 represent the 95% confidence interval of true randomness, calculated using 199 Monte Carlo simulations

TABLE 2 Reaches and years in which the distribution of logjams deviates significantly from a random distribution as determined by 199 Monte Carlo simulations of the same number of logjams over the same distance

Reach	Year	p-value
NSV 5	2010	0.04
NSV 5	2014	0.03
NSV 14	2018	0.04
Hunters 1	2018	0.04
Hunters 4	2014	0.04

channels ($p < 0.001$). Average logjam distribution density in multi-thread reaches from 2010–2019 was 3.4 jams per 100 m compared to 1.2 jams per 100 m in single-thread reaches.

After investigating individual correlations between average logjam distribution density and maximum changes in distribution density, we used the multiple linear regressions developed for confined, partially confined, and unconfined channels to determine which factors are most important in explaining logjam distribution density. Channel and valley geometry are the most important significant factors influencing logjam distribution density, with maximum change in partially confined and unconfined reaches (Table 4). In unconfined reaches, channel gradient (m/m) is the only significant predictor included in the final regression models for average logjam distribution density ($R^2 = 0.69$, $p = 0.01$) and maximum change over the time period ($R^2 = 0.95$, $p < 0.001$). Both maximum change and average logjam distribution density increase with increasing channel gradient in unconfined channels. In partially confined reaches, the ratio of floodplain width to channel width is the only variable included in final models for average

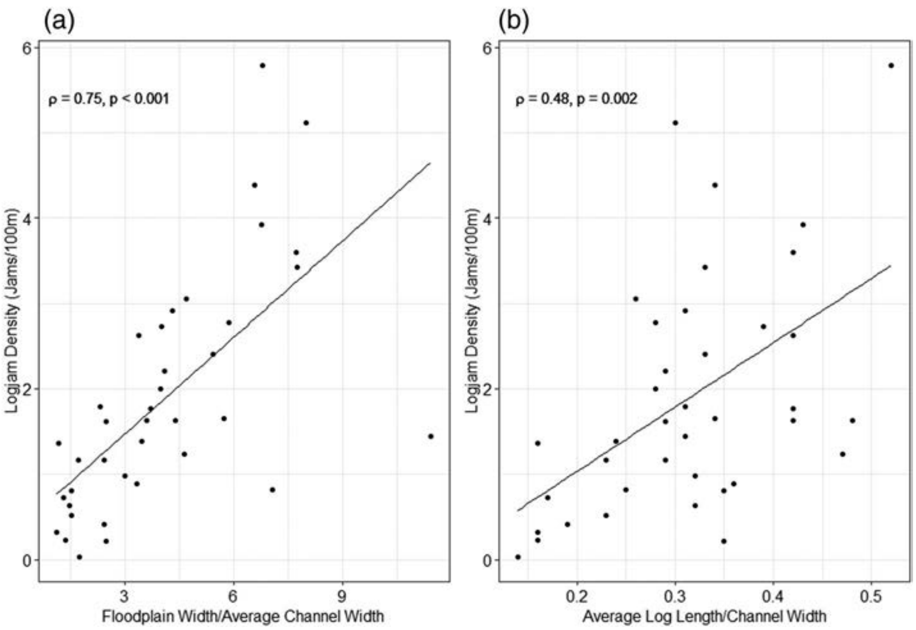

FIGURE 5 Scatterplots showing significant relationships between average logjam density and the ratios between floodplain width/average channel width and average log length/average channel width. Spearman correlation rho values and p-values are given

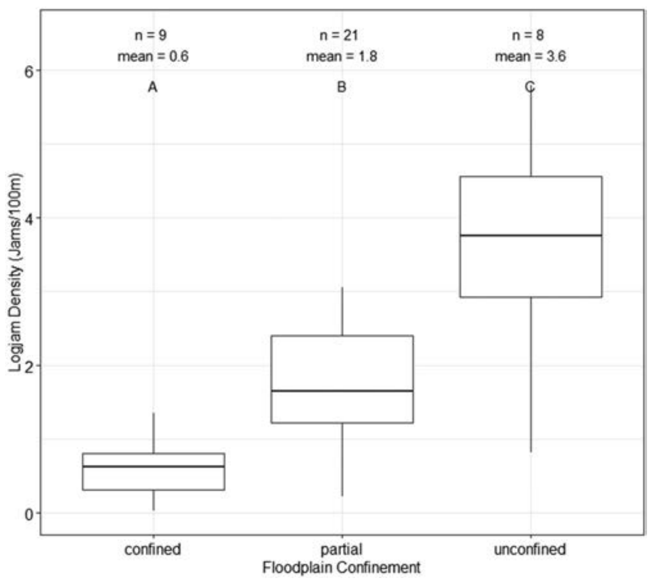

FIGURE 6 Distribution of average logjam density by floodplain confinement type

TABLE 3 Spearman correlations between average logjam density for each reach across all years, the maximum annual change that occurred in each reach between 2010 and 2019, and potential physical and hydrologic controls; significant correlations in bold

	Average logjam density (Jams/100 m)	Maximum annual change between 2010 and 2019
Slope (m/m)	−0.05	0.07
Riparian stand age	−0.02	−0.10
Q_2 (m^3/s)	−0.21	−0.23
Drainage area (km^2)	−0.28	**−0.36**
Floodplain width (m)	**0.56**	0.25
Channel width (m)	**−0.34**	**−0.38**
Average wood piece length (m)	0.30	0.03
Avg. wood piece length/Channel width ratio	**0.48**	**0.39**
Q_{2013} (m^3/s)	−0.28	**−0.36**
Floodplain width/Channel width ratio	**0.75**	**0.49**
Avg. logjam density	-	**0.77**
Maximum annual change	**0.77**	-

logjam distribution density (R^2 = 0.35, p = 0.005) and maximum change (R^2 = 0.24, p = 0.02). Logjam distribution density increases as the ratio of floodplain width to channel width increases. Logjam distribution densities and changes in confined reaches are significantly more influenced by peak streamflow. The predicted discharge of the 2013 flood within each reach is the only significant predictor included in a final model for average logjam distribution density in confined reaches (R^2 = 0.34, p = 0.005), while the 2013 flood discharge and average riparian forest stand age are both included as significant predictors of the maximum logjam distribution density change over the time period in confined reaches (R^2 = 0.79, p = 0.009). The 2013 flood discharge scales with drainage area, and downstream reaches with a higher discharge correlate to lower logjam distribution densities and smaller maximum change in confined reaches, while increasing age of riparian forest stand resulted in a greater maximum change.

4.2 | Flood-Induced changes in logjam distribution

Two lines of evidence can be used to assess flood-induced changes in randomness: the number of reaches in which logjam spacing deviates

TABLE 4 Final regression models for explaining average logjam density (Jams/100 m) and maximum change to logjam density (Jams/100 m) from 2010–2019

	Average logjam density			Maximum change to logjam density 2010–2019		
	Final model	R^2	p	Final model coefficients	R^2	p
Confined	$-0.02*(Q_{2013}) + 0.99$	0.5	0.03	$-0.1*(Q_{2013}) + 0.003*(\text{Stand age}) - 2.85$	0.79	0.009
Partially Confined	$0.18*(fp_w/ch_w) + 0.58$	0.35	0.005	$0.7*(fp_w/ch_w) - 0.15$	0.24	0.02
Unconfined	$14.08*(S) + 1.09$	0.69	0.01	$64.5*(S) - 0.37$	0.94	<0.001

Note: Q_{2013} is estimated 2013 flood peak discharge; fp_w/ch_w is ratio of floodplain to channel widths; S is channel gradient.

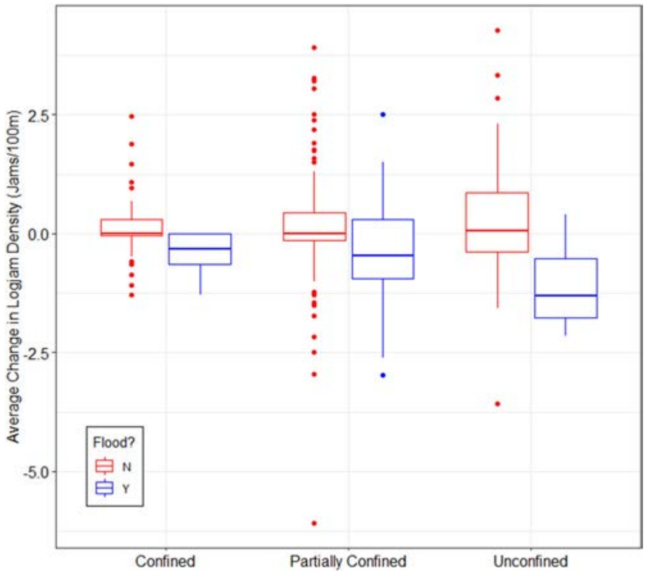

FIGURE 7 Average change in logjam density in years with (Y) and without (N) floods analysed within reaches of varying channel confinement

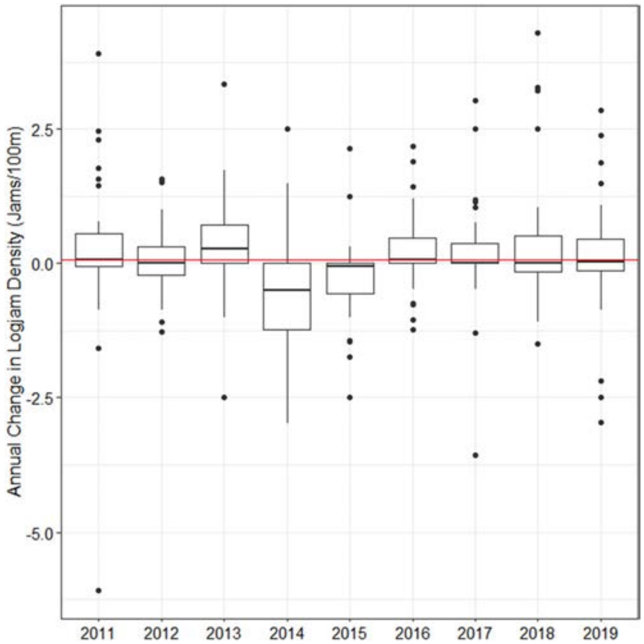

FIGURE 8 Annual change in logjam density from the previous year for all reaches from 2011–2019. Annual change was determined by subtracting previous year jam density from the labelled year jam density. The average change in jam density for all years and reaches is labelled as a red line

significantly from random (reach-scale randomness), and the shapes of the pair correlative curves (creek-scale randomness). Of the 5 reaches that deviate from a random distribution at the reach scale during the course of the study, only 1 deviates from random in 2010 and remains random after the flood (Table 2). In other words, the 2013 flood had minimal effects on the randomness of logjam longitudinal distribution within each reach.

The pair correlation curves in Figure 4 can be interpreted to indicate the degree to which logjam distributions over the entire length of a creek are more clustered ($g(L) > 1$) or separated ($g(L) < 1$) than random, and the downstream distance at which deviations from random occur. Values of $g(L) = 1$ represent a random distribution of logjams. A 95% confidence interval representing true randomness was calculated for each creek for each separation distance based on 199 Monte Carlo simulations of the same number of logjams over the same creek length; confidence intervals are shaded around g(L) in Figure 4. The differences between the 2010 and 2014 curves suggest that, after the 2013 flood, logjams became more separated on North St Vrain Creek at distances greater than ∼3000 m; logjams became more clustered up to distances <600 m on Hunters Creek; and logjams became more clustered at distances <900 m and more separated at distances >1100 m on Ouzel Creek. Comparing the 2014 and 2018 curves suggests that these changes largely persisted on each of the creeks. No significant changes in randomness occur on Cony Creek after the 2013 flood. These results suggest that the 2013 flood did increase deviations from randomness at the scale of entire creeks.

Additionally, the annual change in logjam distribution density between successive surveys was calculated and treated as time periods in which there was a flood (2013–2014) or there was not a flood (all other successive surveys). Changes to logjam distribution density that occurred in 2013–2014 were significantly different than other years for partially confined ($p = 0.05$) and unconfined reaches ($p = 0.003$). In general, there was a greater decline in logjam distribution density in partially confined and unconfined reaches in the year

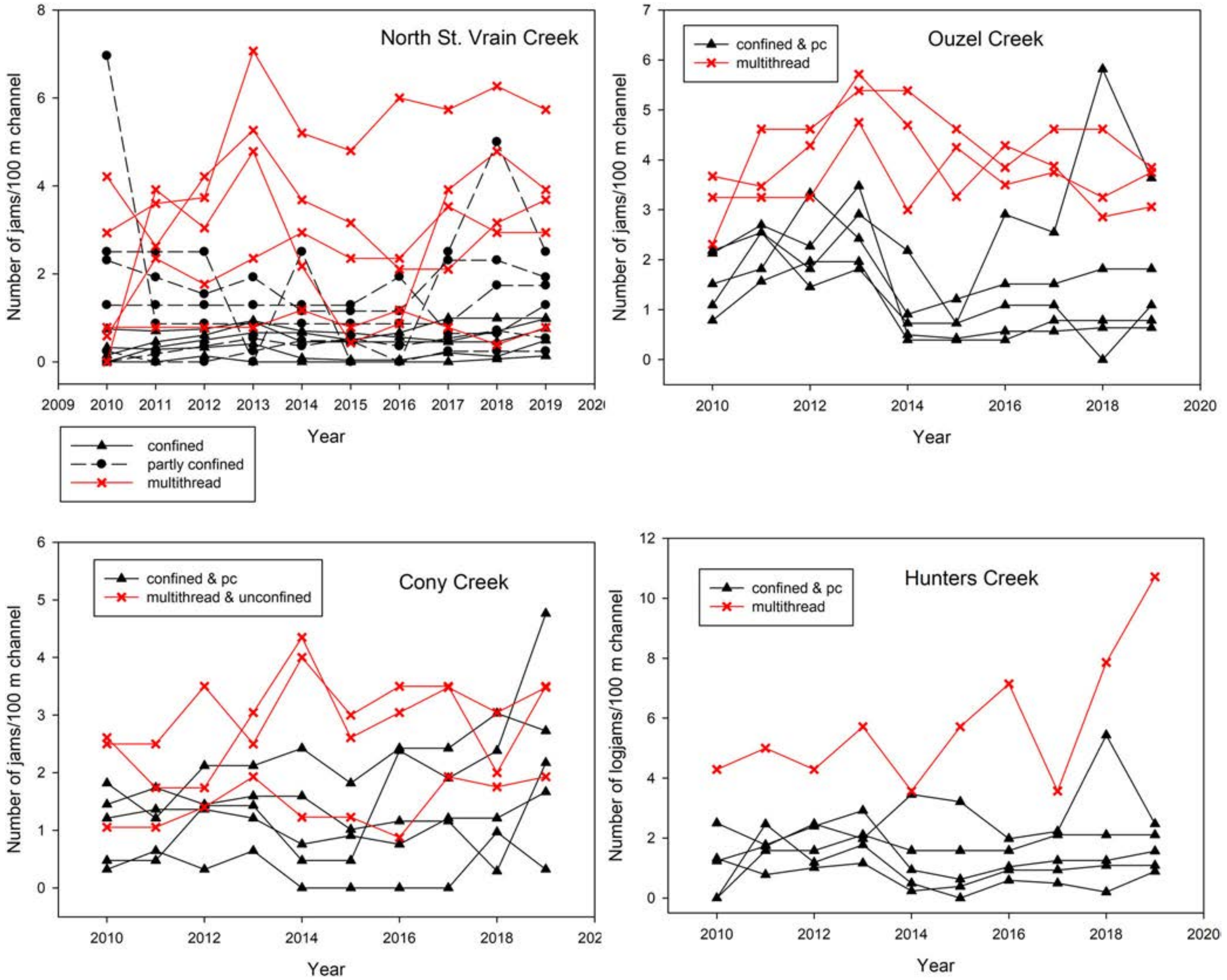

FIGURE 9 Changes through time in logjam density (number of logjams per 100 m of channel) plotted for multithread (unconfined) reaches, partially confined reaches (here abbreviated pc), and confined reaches

containing the 2013 flood compared to years not containing a flood (Figure 7). For confined reaches, changes that occurred between successive surveys in 2013–2014 were not significantly different than non-flood years ($p = 0.12$). However, long-term patterns in logjam distribution density changes are potentially averaged out over the course of multiple years so that deliberately selecting any given year would result in a significantly different annual change compared to the long-term average. To further investigate whether changes in 2013–2014 are an anomaly, we separated each year, built a mixed model, and tested significant differences from the long-term average for every annual period from 2010 to 2019. Between the 2014 and 2015 surveys, logjam distribution density significantly decreased in partially confined reaches ($p = 0.01$). However, beyond the 2013–2014 and 2014–2015 time periods, there were no other annual time periods (time between successive surveys) where changes to logjam distribution density were significantly above or below the natural annual variability (Figure 8).

5 | DISCUSSION

Our primary objectives were to evaluate the influences on logjam distribution density of (i) spatial variations in valley and channel geometry and (ii) temporal variations in peak annual flow. We hypothesized that both intra- and inter-reach logjam distribution densities are resilient to large floods.

5.1 | Spatial variations

A primary inference from field observations during these annual logjam surveys is that, although wood piece mobility exerts a substantial influence on the formation and persistence of channel-spanning logjams, the presence of obstacles in the form of ramped wood pieces resulting from individual tree fall is a critical prerequisite for the formation of logjams. Individual tree fall reflects both ongoing tree mortality and the episodic occurrence of localised blowdowns, primarily during the winter (Wohl, 2013). The inference of the importance of ramped wood pieces in creating channel-spanning logjams is supported by the finding that logjam distribution density increases as the ratio of average piece length to channel width increases.

The logjam clustering and separation at the scale of entire creeks and the lack of deviation from randomness at the reach scale for most reaches are intuitive. All of the factors that influence wood recruitment and retention – riparian forest stand age, flow depth, channel and floodplain width, average bed grain size and associated protrusion of grains – vary substantially between reaches and likely explain the non-random distribution of logjams at the creek scale. Analogously, because we delineated reaches to be relatively homogeneous with respect to channel and valley morphology, logjam distribution could be expected to be random within a reach.

Between reaches, channel and valley geometry strongly influence the longitudinal spacing of logjams and the observed changes in logjam distribution density through time. Unconfined reaches have significantly more closely spaced channel-spanning logjams than partially confined and confined reaches, as indicated by previous work in this study area and by studies in other regions.

5.2 | Temporal variations

The 2013 flood had minimal effects on the randomness of logjam longitudinal distribution within each reach but did increase deviations from randomness at the scale of entire creeks, primarily by causing a greater decrease in logjam distribution density in partially confined and unconfined reaches than occurred during years with lower peak flows. This indicates that reach-scale randomness of logjam distribution is resistant to disturbance, whereas creek-scale randomness is sensitive to disturbance. The creek-scale deviations from randomness resulting from the 2013 flood persisted until at least 2018, suggesting that this scale of randomness is not resilient to disturbance.

With respect to intra-reach variability in logjam distribution density through time, unconfined and partially confined reaches exhibited the greatest interannual changes in distribution density over the period of the study (Table 4). These results indicate that logjam distribution density is sensitive to disturbance in these reaches, as suggested by greater range of logjam distribution density through time (Figure 9). However, most of these reaches exhibited no significant net change in logjam distribution density over the period of the study (Figure 9), indicating that logjam distribution density is also resilient. In contrast, logjam distribution density in confined reaches is resistant, exhibiting lower interannual changes, as well as no significant net change over the period of study (Figure 9).

With respect to inter-reach variability in logjam distribution density through time, although unconfined reaches tended to lose logjams during the 2013 flood, the pattern of greater logjam distribution density in unconfined reaches relative to partially confined or confined reaches is consistent over the period of the study. This suggests resilience to disturbance at the scale of inter-reach variability in logjam distribution density.

In summary, we interpret the results of the annual logjam surveys as mostly supporting the hypothesis that both intra- and inter-reach logjam distribution densities are resilient to large floods. Intra-reach distribution densities are resistant in confined reaches and sensitive but resilient in partially confined and unconfined reaches. Inter-reach variation in distribution density is resilient to disturbance.

5.3 | Management implications

The deviations from random spacing of channel-spanning logjams when considered at the scale of entire creeks suggest that river restoration using engineered logjams or wood introduction intended to facilitate formation of logjams should focus on wood process domains that facilitate formation and retention of jams (Wohl et al., 2019). Spatially distinct wood process domains within a river network can be described in terms of wood recruitment, transport, and storage, as well as the associated geomorphic and ecological effects caused by the presence of stored wood. In mountainous stream networks such as that of North St. Vrain Creek, with strong longitudinal variation in valley geometry, logjams may be randomly distributed within a reach with consistent valley and channel geometry, but logjams are more closely spaced (i.e., form preferentially) within reaches of greater floodplain width and lower gradient.

6 | CONCLUSIONS

The temporal patterns of intra-reach and inter-reach logjam distribution densities over a decade that included substantial variations in snowmelt peak flow and a large rainfall flood indicate that the longitudinal distribution of channel-spanning logjam populations is resilient to disturbance. Wide, low gradient stream reaches tend to have the highest distribution density and to be the most sensitive to disturbance, whereas confined, steep reaches are resistant to disturbance. Within all reaches, individual logjams form and disappear, but continuing recruitment of large wood to the channel sustains persistent populations of logjams. The decline and subsequent recovery of logjam distribution density within unconfined reaches following a large flood suggests that these naturally retentive reaches of streams can be resilient to disturbance and can effectively be prioritised for logjam restoration. The short duration and high magnitude of the 2013 rainfall flood relative to annual snowmelt peak flows suggests that logjam longitudinal distribution at the inter-reach scale could also be resilient to floods in rainfall-dominated channels with greater hydrologic variability, but this remains to be demonstrated. Previous work indicates that unconfined, low gradient reaches, which have been referred to as "beads" along the string of a river's length (Stanford et al., 1996), are also disproportionately important with respect to denitrification (Wegener et al., 2017; Wohl, Lininger, et al., 2018), organic carbon storage (Sutfin & Wohl, 2019; Wohl et al., 2012), and biomass and biodiversity (Bellmore & Baxter, 2014; Herdrich et al., 2018; Venarsky et al., 2018). Because channel-spanning logjams can induce formation of secondary channels (Collins et al., 2012; Wohl, 2011), beads with logjams also exhibit more spatially heterogeneous river corridors and greater channel-floodplain and channel-hyporheic (Doughty et al., 2020; Sawyer et al., 2011) hydrologic connectivity. The resilience of the longitudinal distribution of logjams and associated changes in river corridor form and function suggest that introducing wood or engineered logjams to beads in small to moderate rivers can create persistent benefits in river corridors.

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DATA AVAILABILITY STATEMENT

The basic data used in the analyses are presented in the supplemental material (Table S1).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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