Received: 22 August 2020 | Revised: 2 December 2020 | Accepted: 18 December 2020

DOI: 10.1002/esp.5057

RESEARCH ARTICLE

ESPL WILEY

Logjams as a driver of transient storage in a mountain stream

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Funding information
National Science Foundation Hydrologic Sciences, Grant/Award Number: 1819068

Abstract

We use four stream segments along a wood-rich, pool–riffle mountain stream in the Southern Rockies of Colorado, USA to examine how spatial variations in wood load and variations in discharge during and after the snowmelt peak flow influence the magnitude of surface and subsurface transient storage. Segments range in complexity from a single channel with no large wood to an anabranching channel with closely spaced, channel-spanning logjams. Discharges at which transient storage was assessed range from base flow to snowmelt peak flow. To explore these relations, we used 10 geomorphic variables representing channel morphology and bed substrate, four wood-related variables representing wood load and associated backwater storage, and two measures of skewness from instream and bulk electrical conductivity breakthrough curves during tracer tests. Instream curves reflect surface and subsurface transient storage, whereas bulk curves primarily represent subsurface transient storage. Higher values of skewness indicate greater retention, and we used the values here as a metric of increased transient storage. Although limited sample size restricts the power of our results, our findings suggest that stream segments with greater instream large wood loads have more and larger pools, greater storage of fine sediment and particulate organic matter, and higher values of skew from instream conductivity. The results also suggest that the presence of instream wood, rather than changes in channel morphology associated with wood, is the most important driver of transient storage. This implies that river management designed to foster transient storage should focus on retaining instream large wood. We did not find significant correlations between geomorphic or wood-related variables and the skew estimated from bulk conductivity, which may reflect the relatively thin alluvium present in the field area and the prevalence of surface transient storage in this system.

KEYWORDS
hyporheic exchange, large wood, logjam, mountain stream, transient storage

1 | INTRODUCTION

An extensive literature documents the numerous beneficial geomorphic and ecological effects of large wood (>10 cm diameter and 1 m long) in river corridors (e.g. Gurnell, 2013; Wohl, 2017). Among these effects are the potential for direct and indirect enhancement of surface and subsurface transient storage. Transient storage influences stream biogeochemical cycling by increasing the residence time of stream solutes and the opportunity for microbial uptake, and provides microbial and macroinvertebrate habitat (Battin et al., 2008; Fischer et al., 2005; Gooseff et al., 2007; Harvey & Gooseff, 2015; Tonina & Buffington, 2009).

By creating an obstruction to flow and increasing hydraulic resistance within the channel, large wood can influence surface transient storage by creating low-velocity zones within the channel (e.g. Gippel, 1995), enhancing the formation of backwater pools (Beckman & Wohl, 2014; Kaufmann & Faustini, 2012; Livers & Wohl, 2016; Richmond & Fausch, 1995). Large wood can also increase surface transient storage by deflecting flow towards the channel bed, creating scour pools that enhance residual pool volume (Ensign & Doyle, 2005; Fausch & Northcote, 1992; Mao et al., 2008) and deflecting flow towards the channel banks, creating marginal eddies (Zhang et al., 2020). Although previous studies strongly suggest that large wood can increase surface transient storage (e.g. D'Angelo et al., 1993; Stofleth et al., 2008), the effects of varying wood load on surface transient storage have not been explicitly quantified, with the exception of Kaufmann and Faustini (2012), who found a linear increase in surface transient storage with increasing wood load.

Large wood can also enhance subsurface transient storage in the form of hyporheic exchange flows. Advective pumping, induced by streamflow over an irregular permeable bed, leads to a distribution of pore-water flow paths in the streambed (Wörman et al., 2002). By creating an obstacle to flow and an associated head gradient, large wood facilitates Darcy flux into the bed of a permeable stream and directly enhances the magnitude of hyporheic exchange (Fanelli & Lautz, 2008; Hester & Doyle, 2008; Lautz et al., 2006; Sawyer & Cardenas, 2012; Sawyer et al., 2011).

Factors influencing the magnitude and spatial dimensions of hyporheic exchange flows around large wood include ambient groundwater discharge rate, sediment hydraulic conductivity and heterogeneity of bed permeability, channel gradient, depth to bedrock, proportion of the channel blocked by the wood and permeability of a logjam (Fox et al., 2016; Hester & Doyle, 2008; Lautz & Fanelli, 2008; Lautz et al., 2006; Sawyer & Cardenas, 2009, 2012; Sawyer et al., 2011). Exchange rates are greatest in proximity to the wood and decay exponentially with distance up- and downstream (Sawyer et al., 2011).

Wood indirectly influences hyporheic exchange by altering the magnitude and type of bedforms present in a channel and the associated bed heterogeneity (Buffington & Montgomery, 1999; Buffington et al., 2002; Curran & Wohl, 2003; Hassan & Woodsmith, 2004; Keller et al., 1995; MacFarlane & Wohl, 2003; Wohl & Scott, 2017). Bedform-induced advection is the major mechanism of hyporheic exchange in channels with alternating pools and riffles (e.g. Gomez-Velez & Harvey, 2015), and the mean depth and residence time of hyporheic exchange flows are greatest where bedform amplitude is greatest (Tonina & Buffington, 2007, 2011). Spatial heterogeneity of bed substrate grain size and thickness also influence hyporheic exchange flows (e.g. Cardenas & Wilson, 2004; Marion et al., 2008; Salehin et al., 2004; Sawyer & Cardenas, 2009). Wood can also influence channel planform and migration rate (Collins et al., 2012; Wohl, 2011), as well as channel–floodplain connectivity (Collins et al., 2012; Sawyer et al., 2015; Wohl, 2011), all of which can influence hyporheic exchange.

All of the studies thus far examining the effects of large wood on hyporheic exchange focus on a single log or logjam (Lautz et al., 2006; Sawyer & Cardenas, 2012; Sawyer et al., 2011). However, natural channels in forested regions with minimal human alteration commonly contain abundant dispersed large wood pieces and multiple logjams spaced irregularly along the channel (Wohl & Beckman, 2014; Wohl amp; Cadol, 2011). In particularly wood-rich river corridors, numerous jams spaced relatively closely can result in an anabranching channel planform in which several subparallel channels branch and rejoin downstream at lengths of 10^1–10^3 m, with multiple logjams in each subparallel channel (Collins et al., 2012; Wohl, 2011). In mountain streams, multiple logjams can convert bedrock reaches to alluvial reaches (Massong & Montgomery, 2000) and logjams can force pool–riffle morphology in what might otherwise be a plane-bed stream (Montgomery et al., 1995). In cobble- to boulder-bed mountain streams, multiple jams can increase the volume of backwater pools, the storage of sand in these pools (Buffington & Montgomery, 1999; Wohl & Scott, 2017), the formation of scour pools, and thus the vertical and horizontal heterogeneity of the streambed. These changes affect transient storage—both surface and subsurface—which suggests the need to better quantify the effects of abundant large wood and multiple jams on transient storage in natural channels.

Our objectives in this study are to examine (i) potential correlations between wood load and channel morphologic variables that might be influenced by wood load and might also affect transient storage; (ii) the effects of multiple jams on transient storage; and (iii) potential correlations between bulk electrical conductivity, from geophysics, as a measure of hyporheic exchange and wood and geomorphic variables related to transient storage. Although previous studies have examined surface transient storage in relation to wood load (Kaufmann & Faustini, 2012), the effects of an individual jam or piece of wood on subsurface transient storage (e.g. Sawyer & Cardenas, 2012; Sawyer et al., 2011) and the ability of bulk electrical conductivity to reflect subsurface transient storage (e.g. Ward et al., 2010), the work presented here is unique in examining the potential effects of multiple logjams on transient storage as well as the potential correlations between geomorphic variables and bulk conductivity.

We hypothesize that, of the geomorphic variables that might influence transient storage, including wood and channel morphologic parameters, wood load (m^3 wood/ha of channel area) will correlate most strongly with transient storage (*H1*). The presence of wood directly affects surface transient storage by creating flow separation, and directly affects subsurface transient storage in that dispersed pieces and individual logjams create pressure gradients in the flow. Geomorphic variables such as backwater pool volume and longitudinal variations in bed elevation enhance transient storage and create indirect effects on hyporheic exchange, in that they are influenced by the presence of wood and also create pressure gradients and spatial variation in alluvial thickness and bed permeability.

Our alternative hypothesis is that the proportion of total wood load within logjams will correlate more strongly than total wood load with transient storage (*H2*). Although dispersed wood pieces can obstruct flow and create scour, backwater, bank erosion and pressure gradients, aggregations of pieces in jams are likely to create a disproportionately larger effect. Existing research demonstrates that logjams create nonlinear effects on stream metabolism (Day, 2015; Day & Hall, 2017); spatial heterogeneity of physical channel characteristics (Livers & Wohl, 2016; Livers et al., 2018), including channel and floodplain planform (Buffington & Montgomery, 1999; Wohl, 2011); retention of particulate organic matter (Beckman & Wohl, 2014); and animal biomass and biodiversity (Herdrich et al., 2018; Venarsky et al., 2018). Streams with significantly lower wood loads are significantly less retentive and physically complex than streams with abundant large wood and logjams (Beckman & Wohl, 2014; Livers & Wohl, 2016; Livers et al., 2018). Our second hypothesis represents a test of the potential for logjams to create nonlinear effects in transient storage.

2 | STUDY AREA

Field measurements were conducted along four segments of Little Beaver Creek, a tributary of the Poudre River in north-central Colorado, USA (Figure 1). The creek drains 37 km^2 and the annual hydrograph is dominated by a late spring–early summer snowmelt peak that averages 1.26 m^3/s (Capesius & Stephens, 2009). Mean annual precipitation is 55 cm (Barry, 1973). The catchment is underlain by Precambrian-age gneiss and schist (Nesse & Braddock, 1989) and bedrock outcrops discontinuously along the valley sides and bottom in the study area. The average alluvial depth is ~2–3 m at the downstream segment (segment 1) and ~1 m at the upstream segment (segment 4) based on two transects of ground-penetrating radar data (Dan McGrath, Colorado State University, personal communication, October 2018). The valley bottom is laterally confined and along most of the study area is <10× bankfull channel width (Table 1). We define the valley bottom as the area covered by alluvium deposited by the contemporary channel and potentially forming part of the hyporheic zone. Within this, we distinguish the active floodplain that is inundated every year based on wetland vegetation, recent high-water marks (e.g. fine organic debris) and subtle topographic breaks in the valley bottom. The active floodplain equates to the valley bottom at segments 3 and 4 but is only about half the width of the valley bottom at segments 1 and 2. Riparian forest in the study area is old-growth (>200 years) montane forest dominated by ponderosa pine (Pinus ponderosa), Engelmann spruce (Picea engelmannii), Douglas fir (Pseudotsuga menziesii), aspen (Populus tremuloides) and willow (*Salix* spp.).

The creek in the study area is predominantly a straight, single channel with pool–riffle bedforms and an average gradient of 0.025 m/m. Median grain size (D_{50}) of bed material in the study area averages 45–60 mm. Large wood is recruited primarily from bank erosion and individual tree fall, and both dispersed individual wood pieces and channel-spanning logjams are common along the channel. Where channel-spanning jams are longitudinally spaced at less than or equal to a few bankfull channel widths, the channel can split into secondary channels that contain flow primarily during the snowmelt peak discharge. Evidence of past beaver activity is abundant along the creek, although there was no active beaver modification of the valley bottom in the study area at the time of measurements.

3 | METHODS

The entire study area includes 850 m of active channel length. We chose four stream segments within the study area for detailed measurements of channel and valley morphology and estimates of transient storage (Table 1). Selection was designed to facilitate testing our

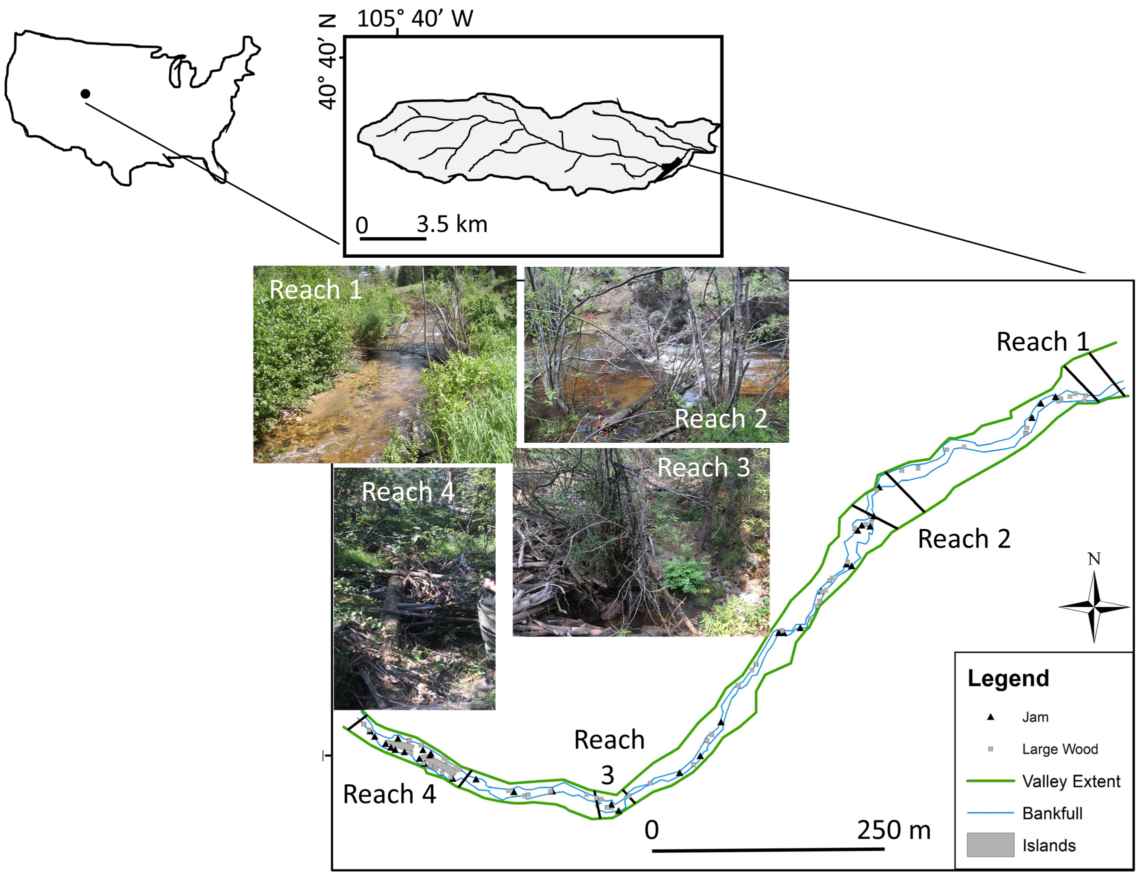

FIGURE 1 Map of the study area, showing the location within the continental USA and within the watershed of Little Beaver Creek, and the placement of the four river segments in relation to one another. The black lines across the channel indicate the upstream and downstream end of each segment in which subsurface transient storage was measured using electrical resistivity [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Characteristics of the measurement reaches

Stream segment	1	2	3	4
Segment length (m)	250	50	360	80
Channel gradient (m/m)	0.022	0.022	0.029	0.034
Bankfull channel average width (m)	4.7	5.6	7.5	8.9
Bankfull channel average depth (m)	0.50	0.57	0.53	0.60
Average valley-bottom width (m)	55	49	27	23
D_{16} (mm)	16	22.5	22.5	22.5
D_{50} (mm)	45	60	45	60
D_{84} (mm)	90	128	90	128
Bed gradation coefficient	2.4	2.4	2.0	2.4
σ_z (m)	0.12	0.08	0.19	0.16
Description	Single channel, no jam	Single channel, 1 jam	Multichannel, 3 jams	Multichannel, 14 jams
Wood load (m^3/ha)	0	122.8	360.3	112.7
Proportion of wood load in jams (by volume)	NA	0.99	0.94	0.88
Average [standard deviation] of jam volume (m^3); volume (porosity) of instrumented jam	NA	1.6 [1.4]; 2.6 (60%)	4.9 [6.8]; 9.7 (40%)	0.8 [1.6]; 4.3 (60%)
Unit pool volume (m^3/ha)	0	92	1120	332
Unit fines (m^3/ha)	0	23.5	332	22.7
Tracer test Q (m^3/s)	0.76, 0.17, 0.18	0.76, 0.17, 0.18	1.08, 0.60, 0.15	1.08, 0.50, 0.15

Note: σ_z is the standard deviation of the residuals of a regressed longitudinal profile; tracer test Q is the discharge at which tracer tests were conducted in that reach.

hypotheses by comparing a single channel with no channel-spanning jam (segment 1), a single channel with a single channel-spanning jam (segment 2), a channel-spanning logjam at the upstream end of a short split channel (segment 3), and multiple channel-spanning logjams along a length of valley with a longer length of subparallel channels (segment 4).

We used field measurements to derive 10 geomorphic variables and 4 wood-related variables (Table 2). Within each segment, valley and active-channel cross-sections were measured using a TruPulse laser rangefinder (±0.1 m accuracy). Longitudinal profiles for the main and secondary channels were measured with an autolevel, metric tape and stadia rod. Within at least two riffles and two pools in each stream segment, we measured grain-size distribution for 100 clasts using a gravelometer. We measured the length and diameter of all wood pieces greater than 10 cm in diameter and 1 m in length. We designated jams as including three or more pieces in contact (Livers & Wohl, 2016). Channel-spanning jams are those that completely span the bankfull channel. For jams that included a substantial amount of finer organic material in the interstices between large wood pieces, we measured the hypothetical 3D rectangle that encompassed the jam and visually estimated the porosity of the jam (Livers et al., 2020). At each channel-spanning jam, we also measured the residual volume of the backwater pool and the volume of fines (sediment finer than the average bed substrate and particulate organic matter) within the backwater pool by dividing the pool surface area into a grid and probing the depth of fines (Lisle & Hilton, 1992). Because the segments were of differing length, we standardized wood volume, pool volume and volume of fines by surface area of the bankfull channel(s) to create wood load, unit pool volume and unit fines volume (Table 2).

TABLE 2 Geomorphic, wood-related and skewness variables used in analyses

Geomorphic variables	Wood-related variables[a]	Skewness variables
Bed substrate D_{50}	Wood load	Skewness of instream electrical conductivity
Bed substrate gradation coefficient	Unit pool volume	Skewness of bulk electrical conductivity
Average bankfull depth Average bankfull width	Unit fines volume (fine sediment + particulate organic matter)	
Average bankfull width/depth ratio	Proportion of total wood load within logjams	
Average cross-sectional area		
Average channel gradient		
Average valley-bottom width		
σ_z (standard deviation of the residuals of a regressed longitudinal profile)		
Total sinuosity		

[a]All wood-related variables were standardized by channel surface area.

At each stream segment, we conducted three constant-rate tracer tests at the discharges listed in Table 1 using sodium chloride tracers and collected fluid and bulk electrical conductivity data to estimate transient storage. These discharges represent nearly bankfull flow, approximately half bankfull and base flow. Three tracer tests were conducted on the same days at segments 1 and 2 during summer 2018 (Doughty et al., 2020), and three on the same days at segments 3 and 4 during summer 2019. Tracer was injected into the centre of the creek, tens of metres upstream to allow complete mixing above the stream segments and for 4 h during each test. Measurements continued for at least 24 h after tracer injection stopped. Channel and instream large-wood characteristics did not change during the study period.

Instream fluid electrical conductivity was collected every 10–60 s using Onset U24–001 HOBO freshwater conductivity data loggers, which were placed near the centre of the stream channel. Changes in instream conductivity with time following tracer injection represent the combined effects of surface transient storage in the channel (e.g. backwaters, eddies) and subsurface transient storage via hyporheic exchange.

Changes in values of bulk electrical conductivity with time were obtained within 1–2 m of the instream conductivity via an IRIS Syscal Pro Resistivity Meter during the tracer tests, using 24 electrodes at the narrower river segments (1 and 2) and 34 electrodes at segments 3 and 4. Electrodes were spaced 0.5 to 1 m apart to span the bankfull channel and the adjacent floodplain (Figure S1). These data are primarily sensitive to changes in the subsurface and are thus used to explore hyporheic exchange (e.g. Ward et al., 2010). We used one line of electrodes across the channel and floodplain in the control segment (segment 1) and two lines in each of the other stream segments; the two lines were spaced 4, 10 and 14 m apart (downstream distance) in segments 2, 3 and 4, respectively. Spacing between the two lines at each segment reflected the position of one line upstream from a channel-spanning logjam and the second line downstream from the logjam. Electrodes were spaced 0.5 m apart within the bankfull channel and 1 m apart from each channel bank to the far edge of the floodplain. Measurements were collected across the stream segments every 7 min for reaches 1 and 2 and every 10–17 min for segments 3 and 4 before, during and for a minimum of 24 h post-injection. Two hundred and seven (207) measurements were collected per 7-min timestep for segments 1 and 2; 277 measurements per 10-min timestep were collected at segment 3; and 519 measurements per 17-min timestep were collected at segment 4. Differences in the number of measurements collected reflect differences in stream width, as more electrodes were needed to span wider portions of the stream while maintaining consistent spacing between electrodes among stream segments.

The statistical moment of skewness represents the asymmetry of a distribution and is used here as a proxy for the amount of retention (e.g. Nordin & Troutman, 1980): higher values of skewness indicate greater amounts of transient storage. Skew calculated from instream measurements is commonly used to describe transient storage within the channel and in underlying aquifer materials (e.g. Lees et al., 2000). Skew calculated from bulk electrical conductivity is much less frequently reported but reflects the transport of solutes everywhere that the geophysics instrumentation is sensitive to, which makes bulk skew a better indicator of hyporheic exchange (and solute pathways that do not return to the channel) across the entire alluvial valley bottom than instream measurements (e.g. Ward et al., 2010). Doughty et al. (2020) provides additional details for the hyporheic exchange flow calculations at Little Beaver Creek. To create the bulk electrical conductivity measurements used to estimate skew, the many hundreds of apparent (i.e. not inverted) bulk conductivity measurements described in the previous paragraph were averaged at each time step for each segment and each tracer test to create a time series for each segment (Figure S2; Doughty et al., 2020). We estimate skewness from both our instream and bulk conductivity data—we call these instream and bulk skew moving forward.

The field data were used for two sets of analyses: (1) comparisons of large wood to channel geomorphic characteristics and (2) comparisons of large wood to transient storage as estimated by instream and bulk conductivity skewness. The first set of analyses evaluates potential correlations between large wood and geomorphic characteristics that can influence transient storage. The second set of analyses directly tests the hypotheses that wood load or wood load within logjams will correlate most strongly with transient storage. Because of the small sample size (4), we use only simple linear correlations and qualitative assessments.

4 | RESULTS

Examining wood load as a predictor of the geomorphic and wood-related variables, Pearson correlations indicate marginally significant relationships at $\alpha = 0.05$ between wood load and three variables: bed substrate gradation coefficient (R^2 = 0.89, p = 0.045), unit pool volume (R^2 = 0.91, p = 0.044) and unit volume of fines (R^2 = 0.91, p = 0.047), respectively (Figure 2). Although the bed gradation coefficient is strongly correlated with wood load, the values for gradation coefficient have an extremely small range (Table 1), so we do not believe this correlation is physically meaningful.

Because of the small sample size, we implemented a bootstrap when calculating correlation coefficients, to make sure no single data point controlled the overall correlation. Using bootstrapping, we found that correlations between variables remained strongly positive. As might be expected, stream segments with greater wood loads have more and larger pools and greater storage of fine sediment and organic matter (Figure 2). Greater wood load also correlates with a wider range of grain sizes on the bed.

Examining all geomorphic and wood-related variables as predictors of instream skew, Pearson correlations indicate a significant relationship with wood load (R^2 = 0.96, p = 0.019), and marginally significant relationships with unit pool volume (R^2 = 0.91, p = 0.045) and unit volume of fines (R^2 = 0.91, p = 0.047) in relation to instream skew as a combined metric of surface and subsurface transient storage (Figure 3). Again, the small range of most geomorphic variables may prevent us from detecting additional potential significant correlations with instream skew, but bootstrapping indicates that correlations between variables are largely strongly positive, with the exception of the relation between reaches 2 and 4 only, which is negative. Greater wood load, greater pool volume and greater storage of sand-sized sediment and organic matter all correspond to greater surface transient storage.

As noted earlier, we had two electrical resistivity lines placed up- and downstream from a logjam in segments 2, 3 and 4. The instream and bulk skew data indicate that subsurface transient storage is basically the same up- and downstream from the logjam in segment 2 (Figure 4). In contrast, the bulk skew values are slightly lower downstream from the logjam in segments 3 and 4 and the instream skew data are mixed (higher downstream from the logjam in segment 3, but not in segment 4). The greater spread of skew values in segments 3 and 4 suggests that the greater wood load and morphological

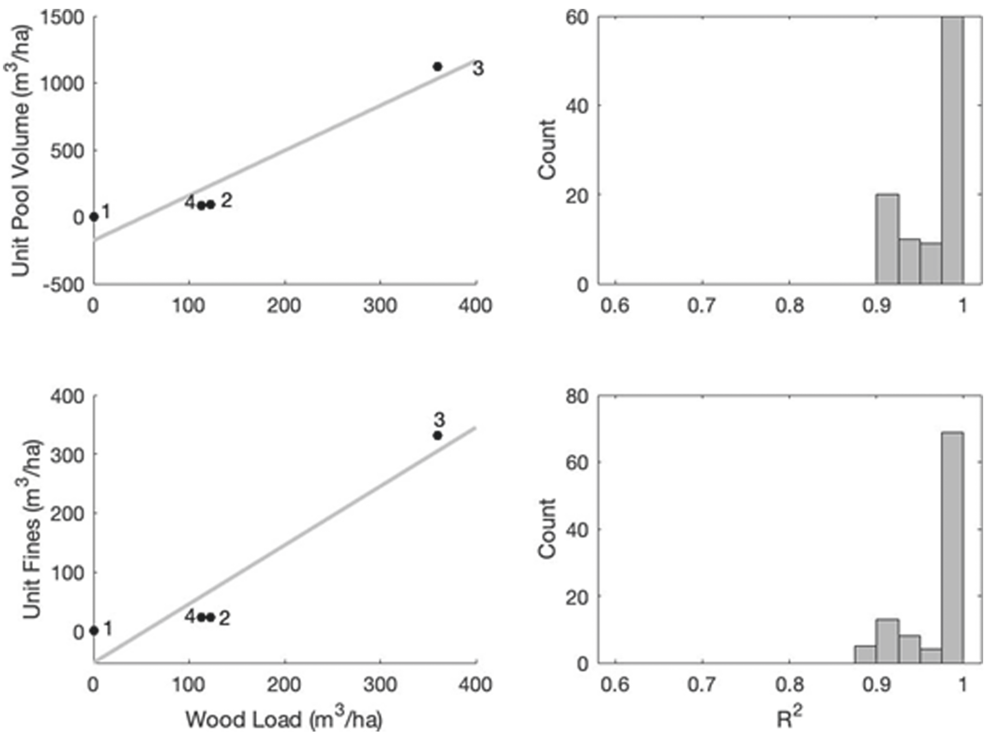

FIGURE 2 Bivariate plot (left) showing relationships between wood load and wood-related variables. Stream segment number is indicated next to each data point. Bootstrapped correlation coefficients for each plot (right). The 95% confidence interval in R^2 for wood load–unit pool volume is 0.906–0.930; the 95% confidence interval for wood load–unit fines is 0.899–0.99

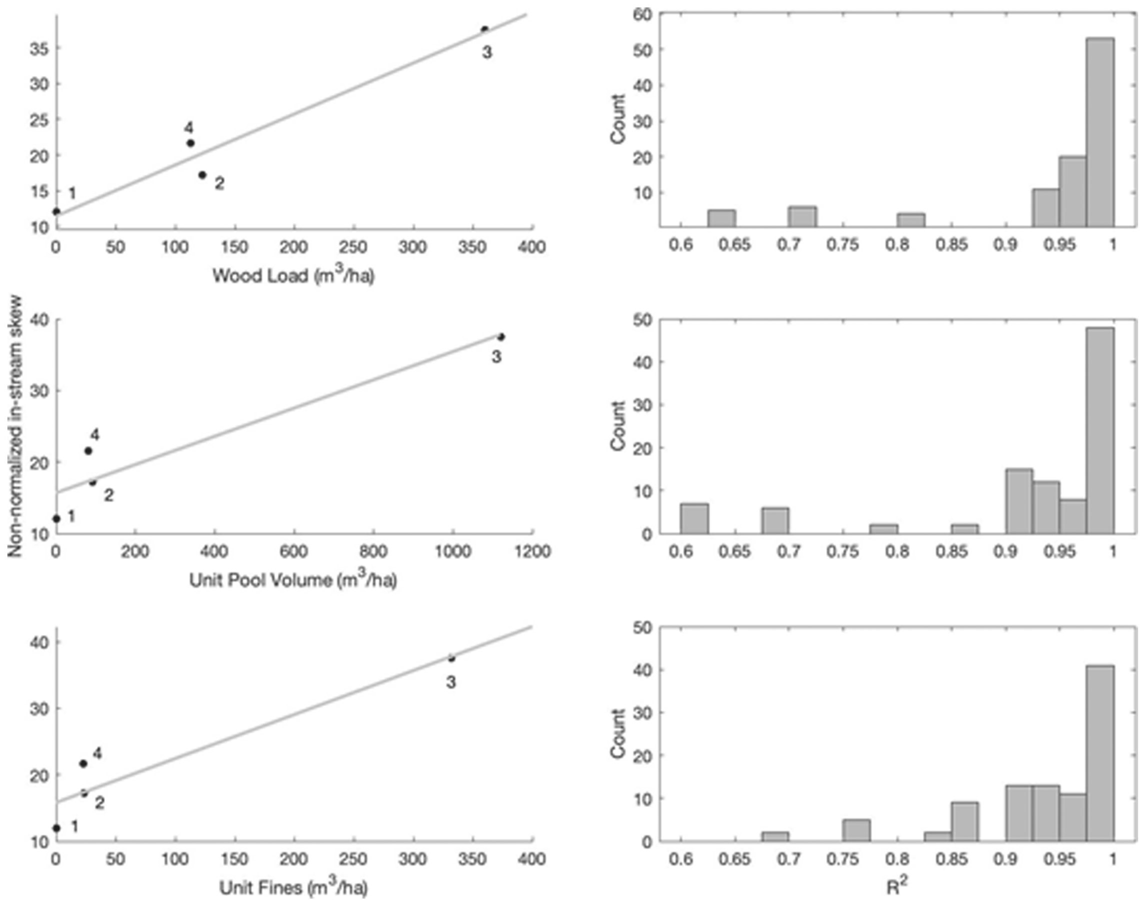

FIGURE 3 Bivariate plots (left) showing relationships between instream skew and wood-related variables. Stream segment number is indicated next to each data point. Bootstrapped correlation coefficients for each plot (right). The 95% confidence interval in R^2 between wood load and instream skew is 0.647–1; between unit pool volume and instream skew is 0.622–1; and between unit fines and instream skew is 0.691–1

complexity of these stream segments creates a wider range of skew across differing discharges.

None of the geomorphic or wood-related variables has a significant relationship with bulk skew (Figure 5), which may mean that our geomorphic variables more strongly controlled surface transient storage than subsurface transient storage. However, we note that the support volume of the geophysical measurements is hard to quantify and dependent on the properties of the subsurface, which may contribute to difficulty in analysis (e.g. Day-Lewis et al., 2005). We cannot quantify alluvial thickness accurately enough to calculate volume of alluvium, but a correlation analysis with average valley-bottom width indicates no significant relation with bulk skew.

The segment-averaged values of bulk conductivity skew show increasing values with increasing wood load for segments 1–3 but segment 4 is an outlier (Figure 5; R^2 = 0.24, p = 0.51). Bootstrapping indicates that correlations between variables vary markedly.

Our first hypothesis was that wood load would correlate with transient storage more strongly than other geomorphic variables, and the results support this hypothesis with respect to surface transient storage. Our second hypothesis was that the proportion of wood within jams would correlate more strongly with transient storage than total wood load, suggesting the potential for a nonlinear relation between instream wood and transient storage. The results do not support the hypothesis that the proportion of wood in jams is the most important influence on either surface or subsurface transient storage. Despite the substantial range of proportion of total wood load that occurs in the form of jams (0 to 0.99), the correlation between proportion of wood in jams and either measure of skew is not significant.

5 | DISCUSSION AND CONCLUSIONS

Greater wood load in Little Beaver Creek correlates with a wider range of grain sizes on the bed, which corresponds to results from previous studies (e.g. Buffington & Montgomery, 1999; Faustini & Jones, 2003). The lack of relations between wood load and other geomorphic variables such as bankfull width or standard deviation of bed elevation (Table S1) likely reflects the small range of values within most of the geomorphic variables (Table 1). Previous studies have demonstrated significant relations between wood load and these variables along other mountain streams. Fox and Bolton (2007), for example, found that bankfull channel width is the strongest predictor of wood load for mountain streams, with a range of width values from 1 to 200 m, and Faustini and Jones (2003) found that the longitudinal profile is more variable at the channel-unit scale when large wood is present.

As noted previously, the small sample size limits the inferences we can draw from statistical correlations, but the results support the idea that the amount of instream wood exerts a primary influence on surface transient storage. Although the ability of wood to increase

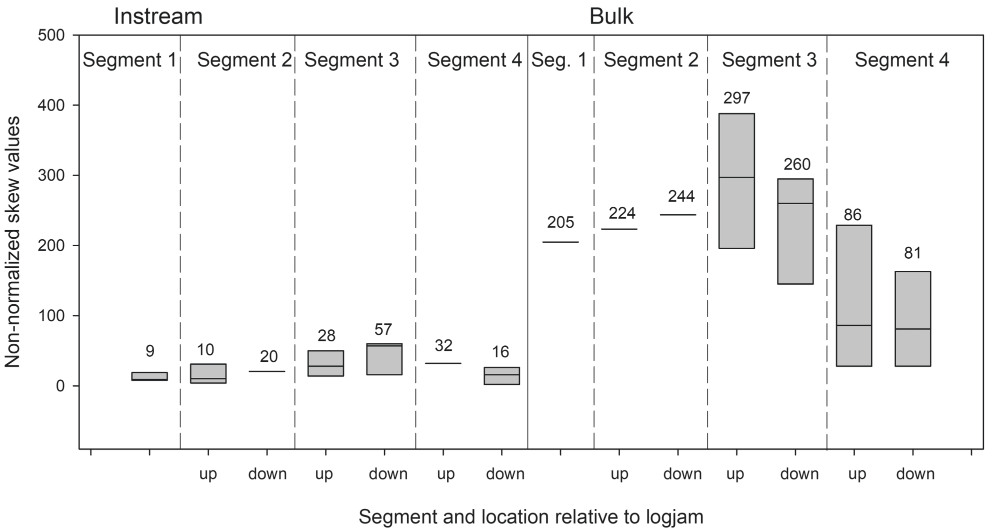

FIGURE 4 Distribution of non-normalized skew values for instream (left) and bulk (right) conductivity data in the four stream segments over all measurements. Segment 1 had a single electrical resistivity line. Segments 2–4 had two lines each, indicated here as 'up' for upstream from a logjam and 'down' for downstream from the same logjam. The line within each box indicates the median value and box ends are the upper and lower quantiles

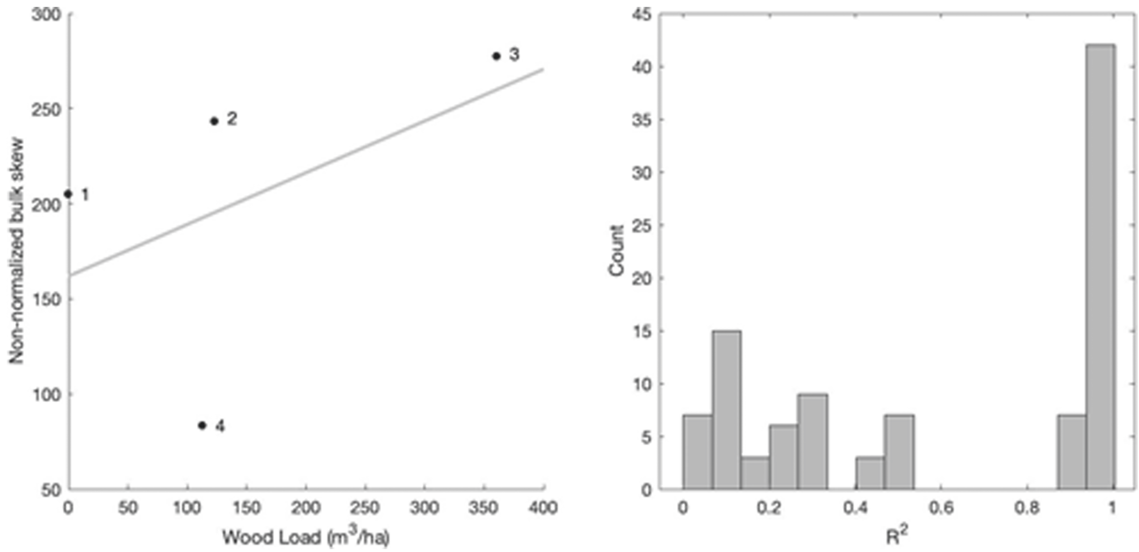

FIGURE 5 Segment-averaged non-normalized skew values for bulk conductivity data in the four study segments. Bivariate plots (left) showing relationships between bulk skew and wood load. Segment number is indicated next to each data point. Bootstrapped correlation coefficients for each plot at right. The 95% confidence interval in R^2 for this relationship is 3.4×10^{-4}–0.533

surface transient storage has been documented in previous studies (e.g. Kaufmann & Faustini, 2012; Livers & Wohl, 2016), it remains unclear whether surface transient storage increases linearly with total wood load or the proportion of wood load within logjams. The lack of significance and/or power for relations based on the proportion of wood in logjams, as well as the bivariate plots of instream skewness in relation to potential control variables (Figure 3), do not support our second hypothesis that logjams will be disproportionately important relative to individual wood pieces. Instead, the results suggest that the effect of instream wood on surface transient storage may be linear, as Kaufmann and Faustini (2012) documented, with progressively more wood creating progressively more storage. This interpretation should be tested further, however, with additional data from other field sites.

The results also suggest that the presence of instream wood and changes in channel morphology that are likely to be present only while the wood remains in place (e.g. unit pool volume, unit fines volume) exert a stronger control on surface transient storage than wood-induced changes in channel morphology that can persist after an individual piece of wood or a logjam is transported downstream. Wood can induce channel morphologic features such as formation of backwater and scour pools and storage of fine sediment in backwater pools. These features are likely to disappear when the wood is removed from the site (e.g. Bilby & Likens, 1980; Mellina & Hinch, 2009). Wood can also induce more persistent morphologic features, such as formation of secondary channels that can persist after the wood is removed (Wohl & Scamardo, 2021). Comparing relations between instream skew and the geomorphic and wood-related variables for segments 3 and 4 at Little Beaver Creek, wood load has the strongest correlation with instream skew. Stream segments 3 and 4 both have split flow caused by the presence of channel-spanning logjams. The length of split flow and therefore total bankfull channel area per unit length of valley is greater in segment 4, which might be expected to enhance surface transient storage, yet segment 3, with higher wood loads, has the greater values of instream skew. In other words, the presence of large wood causes channel planform complexity (Livers & Wohl, 2016; Wohl, 2011), and this complexity can persist after the large wood is transported from the stream segment. The differences between segments 3 and 4 suggest that if channel complexity remains present but the wood driving that complexity has been transported downstream, then some of the associated increase in surface transient storage may be lost.

The lack of significant correlations between either geomorphic or wood-related variables and the bulk skew (Figure 5) indicates that we were unable to detect an influence on subsurface transient storage resulting from large wood. No other field studies have used bulk electrical conductivity to examine the geomorphic controls on hyporheic exchange. Field measurements of vertical seepage in the vicinity of logjams (Lautz et al., 2006) and channel-spanning logs (Sawyer & Cardenas, 2012), as well as flume experiments using salt and dye tracers (Sawyer et al., 2011), indicate enhanced hyporheic exchange around large wood. However, previous field studies measured hyporheic exchange within low-gradient meadow streams in which the channel is underlain by a greater thickness of alluvium than is present in Little Beaver Creek. The relatively thin alluvium present in our field area may limit the potential for large wood and logjams to enhance subsurface transient storage.

We were surprised to see a slight decrease in bulk skew downstream from the instrumented logjam in segments 3 and 4 (Figure 4), especially because the relatively small logjam in segment 2 was associated with a slightly higher value of bulk skew downstream from the jam. There are three factors that might be influencing these results. First, the electrical resistivity lines are placed only 4 m apart in the downstream direction at segment 2, whereas the lines are 10 and 14 m apart, respectively, at segments 3 and 4. If hyporheic exchange effects induced by logjams in this channel with limited alluvial depth are very local, the hyporheic exchange signal associated with a logjam might be weaker as a result of the longer downstream spacing of resistivity lines in segments 3 and 4. In other words, more widely spaced lines might miss the very local increase in skew caused by the logjam.

A second potential explanation for the decrease in bulk skew below the logjams in segments 3 and 4 is that the larger logjams at segments 3 and 4 each create a substantial backwater pool that collects a layer of sand, silt and clay. The backwater and associated finer sediment are minimal at the segment 2 logjam. The finer sediment in the backwater of larger logjams might be impeding hyporheic exchange. Previous field-based measurements of hyporheic exchange around wood involved single logs (Sawyer & Cardenas, 2012) or small jams (Lautz et al., 2006) that may not have created backwaters and fine sediment accumulation of the magnitude observed in Little Beaver Creek.

A third potential explanation is that segments 3 and 4 have minimal floodplain and the thinnest alluvium (based on GPR transects) and may simply lack the underlying volume of permeable material necessary to sustain substantial hyporheic exchange. We cannot distinguish which of these factors might be exerting the most important influence on hyporheic exchange in the study area, but the results suggest that the effects of large wood on subsurface transient storage may be difficult to predict because of multiple interacting factors that influence hyporheic exchange.

Analogously, the trend between wood load and bulk skew for segments 1–3 (Figure 5) suggests that more large wood in a channel can increase hyporheic exchange, but the low bulk skew for segment 4 (which has a wood load comparable to segment 2 but much lower bulk skew values) indicates that substantial wood, by itself, is not sufficient to guarantee increased hyporheic exchange. The low bulk skew in segment 4 may reflect minimal alluvial volume (narrowest floodplain, thin alluvium) in this segment.

In summary, our results suggest that large wood increases surface transient storage in a potentially linear manner. Large wood may also be able to increase subsurface transient storage, but the magnitude of potential increases in hyporheic exchange may also be strongly influenced by factors such as underlying alluvial volume and volume of fine sediment accumulating in the backwater pool of a logjam. From the observed differences in surface transient storage between geomorphically complex stream segments with greater and lesser amounts of large wood, we infer that river management designed to foster surface transient storage can effectively focus on retaining wood (either by continuing recruitment and transport or fixing engineered logjams in place). The effects of large wood on surface and subsurface transient storage may be very local, suggesting the need for multiple pieces and logjams to influence segment-scale transient storage.

ACKNOWLEDGEMENTS

This research was supported by National Science Foundation Hydrologic Sciences (award 1819068). We thank Jackie Randell for helping to conduct the tracer tests, Megan Doughty for participating in the first field season data collection and analysis, and Emily Iskin for assistance with the geomorphic field measurements. The labour of carrying 50-lb bags of salt and all of the equipment into the study area and running the tracer tests was shared by a large number of people. We thank Teodora Mitroi, Anna Marshall, James Proctor, Isabella Schalko, Amelia Nelson, Kenny Swift Bird, Zach Kornse, Danny White, Marissa Karpack, Juli Scamardo, Sarah Hinshaw, Ian Gambill and Garrett Wright for cheerful assistance with all aspects of the field work. The manuscript benefitted from comments by two anonymous reviewers and an associate editor.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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How to cite this article: Ader E, Wohl E, McFadden S, Singha K. Logjams as a driver of transient storage in a mountain stream. *Earth Surf. Process. Landforms*. 2021;46:701–711. https://doi.org/10.1002/esp.5057