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RESEARCH ARTICLE

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Seasonal and diurnal fluctuations of coarse particulate organic matter transport in a snowmelt-dominated stream

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Abstract

We measured coarse particulate organic matter (CPOM) transport along a wood-rich, pool-riffle mountain stream in the Southern Rockies of Colorado, USA, to examine how spatial variations in storage features and temporal variations in discharge influence the transport of CPOM. Ecologists have found that the majority of annual CPOM export occurs during periods of high discharge. More recently, geomorphologists have begun to examine the transport of CPOM as bedload. There has been, however, little direct sampling of CPOM to evaluate how shorter (diurnal) and longer (seasonal peak flow) variations in discharge affect CPOM transport, and no examination of where CPOM is transported in the water column (primarily in suspension or as bedload). We collected CPOM moving as bedload, in suspension (at 0.6 of the flow depth) and at the surface to evaluate CPOM transport processes. Samples were collected at three sites: (1) in the backwater pool upstream from a channel-spanning logjam; (2) immediately downstream from the logjam; and (3) in a riffle about 10 bankfull-channel-widths downstream from any channel-spanning logjams. During sample sets, we collected samples over 15-min increments at approximately 4-hr intervals over a 24-hr period. Seven sample sets were distributed over a period of 2 months that spanned the rise, peak, and recession of the annual snowmelt flood. We found that the majority of CPOM is transported in suspension following a clockwise hysteresis loop in which CPOM peaks prior to discharge during the seasonal hydrograph.

KEYWORDS
carbon, hysteresis, organic matter, snowmelt, transport dynamics

1 | INTRODUCTION

Coarse particulate organic matter (CPOM) spanning a diameter of 1 mm–10 cm (Tank, Rosi-Marshall, Griffiths, Entrekin, & Stephen, 2010) is critical to the physical and ecological processes of stream ecosystems. Leaves, branches, wood fragments, and other allochthonous material composing CPOM enter the channel via fluvial transport from upstream, litter fall from riparian vegetation, wind, bank erosion, tree fall, and overland transport from the adjacent riparian and upland zones (Jochner, Turowski, Badoux, Stoffel, & Rickli, 2015; Wallace et al., 1995; Webster, Covich, & Crockett, 1994). Once in the channel, CPOM can be transported downstream or stored by channel features such as logjams or eddies (Beckman & Wohl, 2014) and decomposed by abrasion, leaching, microbial processing, and macroinvertebrate feeding (Tank et al., 2010).

In shaded forest streams with limited autochthonous primary production in the form of instream photosynthesis, CPOM forms the basis of stream food webs (Fisher & Likens, 1972; Tank et al., 2010), and ecologists regard CPOM inputs as a terrestrial subsidy to the stream ecosystem (Fisher & Likens, 1972). The fluvial transport of CPOM is one of the forms in which carbon is exported annually from a forested basin (Battin et al., 2008; Piégay, Thévenet, & Citterio, 1999; Worrall, Burt, & Howden, 2014). Accumulations of CPOM can influence the porosity and permeability of the stream bed and thus hyporheic exchange (Harvey & Gooseff, 2015), as well as the porosity and permeability of logjams within the channel and, therefore, the physical effects of such logjams on channel hydraulics and sediment transport (Livers, Lininger, Kramer, & Sendrowski, 2020).

The physical morphology of a stream determines whether CPOM is simply routed through a stream reach or retained by either the channel boundary or in-channel structure (Gorecki, Fryirs, & Brierley, 2006; Livers & Wohl, 2016; Pfeiffer & Wohl, 2018; Small, Doyle, Fuller, & Manners, 2008). Whether moving in contact with the stream bed or in suspension, CPOM is typically of lower density than mineral sediment and is therefore more readily transported. Physical complexity, such as large wood (LW, defined here as downed, instream wood ≥1 m in length, and ≥10 cm in diameter) or other boundary irregularities that create sites of lower velocity and shear stress, promotes storage and retention zones that can extend the residence time of CPOM during downstream transport (Beckman & Wohl, 2014; Bilby & Likens, 1980; Jochner et al., 2015; Lautz & Fanelli, 2008; Livers & Wohl, 2016; Livers, Wohl, Jackson, & Sutfin, 2018; Raikow, Grubbs, & Cummins, 1995). Streams with lower wood loads (volume of wood per area) are significantly less retentive of CPOM and less physically complex than streams with abundant wood loads (Beckman & Wohl, 2014; Livers et al., 2018; Livers & Wohl, 2016). Even transient CPOM storage on timescales of hours provides opportunities for microorganisms to develop as attached biofilms or suspended aggregates and to metabolize carbon and other nutrients for energy and growth (Battin et al., 2008). Headwater streams are particularly important in CPOM dynamics because of their proximity to upland sources of CPOM and their limited transport capacity for large wood (Battin et al., 2008; Beckman & Wohl, 2014; Pfeiffer & Wohl, 2018).

Ecological investigations of CPOM dynamics have focused on its contribution to stream energy budgets (e.g., Fisher & Likens, 1972) and on the specific characteristics of CPOM inputs (e.g., Molinero & Pozo, 2004); the mass balance between inputs and outputs (e.g., Cummins et al., 1983); rates and processes of CPOM decomposition (e.g., Whiles & Wallace, 1997); and retention mechanisms and residence time (e.g., Aumen, Bottomley, Ward, & Gregory, 1983). Although previous work has demonstrated that transport of CPOM strongly reflects discharge (e.g., Goebel, Pregitzer, & Palik, 2003; Wallace et al., 1995; Webster et al., 1994) and that the majority of annual CPOM export can occur during floods (e.g., Newbold, Bott, Kaplan, Sweeney, & Vannote, 1997), there has been little direct sampling of CPOM transport across a seasonal hydrograph, and no examination of whether CPOM is transported primarily in suspension or as bedload.

More recently, geomorphologists have started to examine CPOM transport, documenting rapid changes in CPOM bedload transport rates with increasing flow in small streams (e.g., Bunte, Swingle, Turowski, Abt, & Cenderelli, 2016; Iroume, Ruiz-Villanueva, & Salas-Coliboro, 2020; Turowski et al., 2013), and substantial transport during periods of intense precipitation and storms over large catchments (e.g., Hilton, Galy, & Hovius, 2008; Ramos Scharrón, Castellanos, & Restrepo, 2012). In snowmelt runoff regimes, nearly all of the annual CPOM export (97%) may be concentrated during the seasonal high flow (Bunte et al., 2016). Previous studies have employed bedload traps to sample CPOM (e.g., Bunte et al., 2016; Iroume et al., 2020), and the question of how to extrapolate from bedload samples to whole-stream transport of CPOM requires untested assumptions (Bunte et al., 2016) because the relative proportions of CPOM carried as bedload and suspended load remain unknown. Bunte et al. (2016) documented seasonal hysteresis in bedload CPOM transport in a snowmelt stream, with generally clockwise relations and higher CPOM transport on the rising limb of the snowmelt hydrograph, but little is known about how CPOM transport varies in relation to shorter (diurnal) as well as longer (seasonal peak flow) variations in discharge.

Previous work on suspended and bedload sediment transport indicates that the peak of sediment transport is commonly temporally offset from the peak of discharge—a phenomenon described as hysteresis. Sediment moving in suspension typically follows three distinct forms of hysteresis; (1) a clockwise loop where the peak sediment concentration precedes the peak discharge because available sediment is depleted before runoff peaks, (2) a counter-clockwise loop in which peak sediment concentration lags peak discharge, and (3) a figure-of-eight loop in which peak sediment concentration precedes peak discharge, but the shape of sediment output is skewed relative to the flood peak (Williams, 1989). The details of hysteresis reflect sediment delivery processes (e.g., Smith & Dragovich, 2009) and influence scaling of transport with discharge and extrapolations and prediction of total suspended sediment transport (Aich, Zimmermann, & Elsenbeer, 2014). We assume that CPOM moving in suspension could display hysteresis, although the greater buoyancy of CPOM could create different patterns of hysteresis than those observed for sediment. As for suspended sediment, greater understanding of the temporal scales of hysteresis would improve estimates of total CPOM transport that are now being published and compared across sites (e.g., Bunte et al., 2016; Iroume et al., 2020).

Here, we address some of the gaps in understanding CPOM transport in relatively small channels. Working in a snowmelt-dominated stream in the Southern Rockies of Colorado, USA, we measured CPOM moving in suspension and in contact with the stream bed at 4-hr intervals during the rising and recessional limbs of the snowmelt hydrograph. We measured CPOM transport at three sites: (1) in the backwater pool upstream from a channel-spanning logjam; (2) immediately downstream from the logjam; and (3) in a riffle about 10 bankfull-channel-widths downstream from any channel-spanning logjams. Our sampling strategy was designed to test four hypotheses.

H1. *CPOM mass in suspension will be greater than CPOM mass moving as bedload.*

We expect this relationship because of the generally lower density of CPOM relative to mineral sediment. If CPOM is moving predominantly in suspension and CPOM retention is important for biological uptake of nutrients, then river management and restoration intended to facilitate CPOM retention can focus on strategies that affect the movement of suspended material.

H2. *Seasonal CPOM transport is greater during the rising limb of the annual snowmelt hydrograph than during equivalent discharge on the recessional limb.*

We expect CPOM stored in the channel and overbank areas to be mobilized as stage rises and snowmelt runoff enters the channel, and thus we expect the supply of CPOM to be depleted as stage declines after peak flow.

H3. *Daily CPOM transport will be greater during the daily rising limb of channel flows. During the snowmelt hydrograph, flow reaches a peak around midnight during each 24-hr cycle. We expect CPOM transport to precede or coincide with this daily discharge peak for similar reasons as seasonal transport (H2).*

H4. *CPOM transport will be lower in the backwater area of the channel-spanning logjam than at the sites downstream of the logjam.*

The greater flow depth and lower downstream velocities in the backwater pool will limit the quantity and size of CPOM that can enter suspension and be transported. These characteristics of deeper backwater flow also increase the likelihood of CPOM storage instead of transport. Previous studies have demonstrated greater storage of CPOM in logjam backwaters during baseflow but understanding the effect of a logjam on CPOM transport during peak flow could have management implications for anthropogenically altered streams with limited CPOM inputs.

We expect that the hypothesized patterns of CPOM transport in snowmelt systems have ecological and geomorphic implications. Ecologists have shown that abscission (leaf fall) is the time of greatest CPOM abundance in river systems draining deciduous forests (Weigelhofer & Waringer, 1994), and although conifers do not have the same seasonal behavior, our qualitative observations of streams in the study area suggest that CPOM is heavily exported in suspension during the spring snowmelt rising limb and peak. Suspended transport may equate to greater travel distances and therefore headwater subsidies of CPOM to downstream portions of the river network. Understanding the relative locations and timing of CPOM transport at the reach scale is critical to river management designed to enhance CPOM retention and processing (Lepori, Palm, & Malmqvist, 2005). If the majority of CPOM is moving in suspension, we can infer that river restoration designed to enhance CPOM retention should incorporate retention structures (i.e., logjams) that span the channel at high flows.

2 | FIELD AREA

Little Beaver Creek (LBC) is a third-order tributary of the South Fork of the Cache la Poudre River in the Colorado Front Range, USA. The catchment is underlain by Precambrian-age Silver Plume Granite (Cole et al., 2010), with a narrow valley flood and a floodplain that does not exceed 10 times the average bankfull channel width of 6 m. The area has a warm, semiarid climate with mean annual precipitation of 55 cm and mean annual temperature of 8.3°C (Barry, 1973). The creek drains 40 km^2 and flow is dominated by snowmelt, which produces an annual hydrograph with a sustained May–June peak. Channels in this elevation range of the study area have an annual snowmelt peak that seldom exceeds 1.1 $m^3/s/km^2$, as well as infrequent (recurrence interval 10^2 years) summer floods associated with convective storms, which can create peak flows up to 40 $m^3/s/km^2$ (Jarrett, 1990). Little Beaver Creek is ungauged, but the snowmelt peak averages 1.26 m^3/s at the study area based on long-term regional regression equations from US Geological Survey stream gages (streamstats.usgs.gov) and base flow is ~0.15 m^3/s (Ader, Wohl, McFadden, & Singha, 2021). The channel has a pool-riffle to low step-pool morphology, with steps forced by channel-spanning logjams. Channel gradient averages 0.02 m/m and D_{50} of channel substrate averages 45–60 mm, except in logjam backwaters where sand and fine gravel are present.

Riparian vegetation in the study area is old-growth montane forest dominated by ponderosa pine (*Pinus ponderosa*), Engelmann spruce (*Picea engelmannii*), Douglas-fir (*Pseudotsuga menziesii*), aspen (*Populus tremuloides*), and willows (*Salix* spp.). Stands of old-growth montane forest are small and patchy across the Front Range of Colorado but serve as valuable reference sites for understanding instream wood dynamics, given their lack of flow alterations (Jackson & Wohl, 2015). Old-growth riparian forests have greater basal areas (density of forest and size of trees), which correspond to greater instream wood loads (Richmond & Fausch, 1995; Warren, Bernhardt, Hall, & Likens, 2007) and more closely spaced channel-spanning logjams (Beckman & Wohl, 2014). Large wood is recruited to the creek primarily from bank erosion and individual tree fall and wood is abundant throughout the channel. The channel is densely shaded and both upland and riparian sources of CPOM are abundant. Coniferous vegetation produces litter fall throughout the year, whereas the riparian aspen and willows produce the greatest litter fall during leaf abscission in autumn.

3 | METHODS

3.1 | Sample collection and processing

Three sampling locations were selected along the creek: a depositional reach in the backwater area of a channel-spanning logjam (D1), a transport reach below the logjam (T1), and a transport reach without a depositional feature downstream of the other two sites (T2; Figure 1). CPOM was collected in the thalweg at each location at three levels in the water column: surface, midpoint (60% below the water surface and approximate location of average flow velocity), and on the channel bed. Midpoint measurements were not taken at base flow due to a lack of sufficient flow depth to allow three distinct sampling points. CPOM at the surface and midpoint was sampled using seines constructed of polyester 0.25 mm mesh fabric with an expanded entrance (orifice diameter 13 cm, total area 120.4 cm^2). The

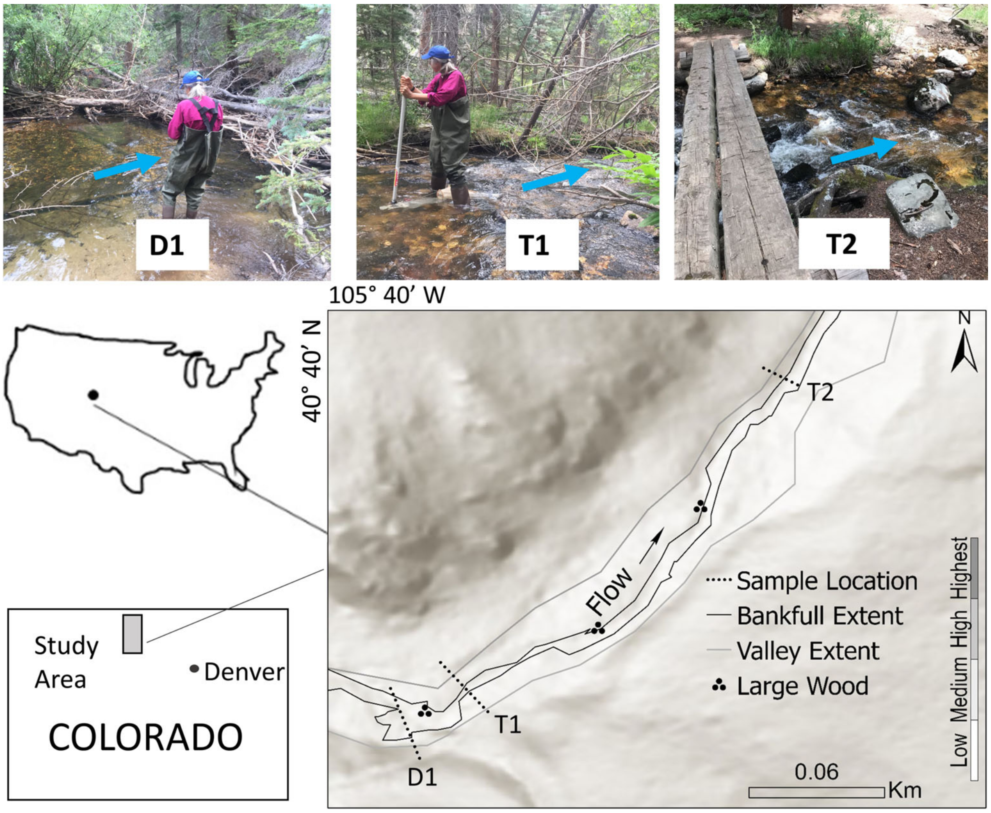

FIGURE 1 Little Beaver Creek sample locations: (D1) backwater pool upstream from a channel-spanning logjam; (T1) transport reach immediately downstream from the logjam; (T2) transport reach in a riffle about 10 bankfull-channel-widths downstream from any channel-spanning logjams. Sample locations are depicted by a black dotted line. Channel-spanning logjams are mapped as large wood in the figure and represented by the three-dot symbology. Inset maps show the location of the study area within the contiguous United States and the State of Colorado [Color figure can be viewed at wileyonlinelibrary.com]

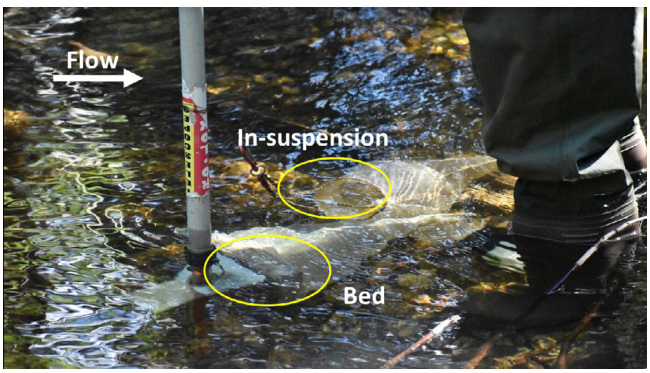

FIGURE 2 Helley-Smith bedload sampler and surface seine with expanded orifice used for CPOM sampling at surface, midpoint, and bed depths. Three nets were used at high flows at surface, midpoint, and bed depths and only surface and bed nets were used at low flows. This photo, taken at base flow, shows surface and bed nets [Color figure can be viewed at wileyonlinelibrary.com]

expanded orifice was effective in increasing hydraulic efficiency of the sampler, thereby preventing backflow that could otherwise result in the loss of suspended CPOM. CPOM was sampled from the bed of the stream with a Helley-Smith bedload sampler (Figure 2; orifice dimensions 8 cm × 8 cm, total area 58 cm^2, mesh size 0.25 mm) (Edwards & Glysson, 1988; Merritt & Wohl, 2006). At each site, all samples were collected simultaneously by affixing the surface and midpoint samplers to the rigid handle of the bedload sampler and allowing water to flow through the traps for 15 min.

Thalweg flow depth varied from ~40 cm at base flow to 110 cm at the highest stage measured during the snowmelt hydrograph. This suggests that during base flow, the bedload and surface samplers together accounted for ~50% of the total flow depth, whereas at the highest stage, the three samplers together accounted for ~30% of the total flow depth. However, the surface sampler was not always completely submerged at base flow (it had a tendency to float with the upper portion above the water surface). Consequently, we likely sampled 30–40% of the total flow depth during all flows.

Sampling events occurred in sequence with the snowmelt hydrograph from May through August 2020. Four samples were taken on the snowmelt hydrograph rising limb (5/22–23, 5/28–29, 6/1–2, 6/9–10), one during the receding limb (6/16–17) and two at base flow (7/22–23, 7/23–24). Because we do not know exactly when the seasonal peak flow occurred, the 6/9–10 samples may have coincided with peak flow. Samples were collected at roughly 4-hr intervals for a duration of 24 hr. Samples in the 12 a.m.–4 a.m. range were not collected during peak runoff due to hazardous conditions and were not collected at the second base flow sampling event due to a lack of change in stage. Vertical velocity measurements were taken at the bed, 0.6 depth, and surface for each sampling location once per sampling event. Stage below the logjam was also recorded once per sampling event and was used as a proxy for discharge in this ungauged stream.

All surface, midpoint, and bedload samples were air-dried for a minimum of 96 hr at 21°C and then weighed. A qualitative assessment of sample compositions was recorded, with attention to the primary material in each sample (i.e., sand and gravel, leaf matter, pine needles). Samples that included sand and gravel were processed using an ash-free dry mass method (AFDM), which indicated the loss on ignition (LOI) or percent of weighted carbon that was burned out of the greater sediment sample. Samples undergoing AFDM were placed in crucibles and heated for 1 hr prior to testing in order to remove any moisture before being weighed empty. The crucible was then filled with a sample of sediment and weighed. The sediment-filled evaporating dishes were placed in a muffling furnace at 450°C for 8 hr. The dried samples were weighed to determine LOI. A 10% subset of surface and midpoint samples were randomly selected for quality control to compare pre-and post-LOI weights. This control process confirmed that running LOI was only necessary for samples that had a significant amount of mineral sediment in them (visual estimate). All samples, regardless of LOI analysis or not, were weighed on a research balance with precision to the 0.001 g.

3.2 | Data analysis

As with many studies that produce natural data, this dataset is non-normally distributed. The statistical data analysis thus requires alternative approaches that do not assume data normality. The median value, as opposed to the mean, is a better measure of center and is used in this analysis for comparisons. We used RStudio to perform the statistical analyses (R Core Team, 2020). To investigate H1 and H4, we used the Kruskal–Wallis Rank Sum test and Dunn's test (with no multiple testing adjustment) (Dunn test package; Dinno, 2017) to compare median CPOM mass values. An alpha of 0.05 was used in all statistical analyses. No statistical tests were required to address H2 and H3.

4 | RESULTS

Seven sample sets, each 24 hr in duration, were collected from May 22 to July 24, 2020. With the missed mid-point samples at very shallow flows, a total of 298 samples were collected from the water column at the three channel locations along LBC (184 samples at the surface and midpoint, 114 at the bed). Table S1 in the Appendix S1 contains the raw data used for analyses and explains the distribution of samples through time.

Visual characterization of CPOM sample compositions during the seasonal hydrograph indicates that CPOM samples were primarily composed of leaf fragments and some conifer needles during the rising limb. At peak stage, more conifer needles were present as well as larger leaves in addition to leaf fragments. There was an overall increase in CPOM material size as well as the presence of aquatic macroinvertebrates moving downstream at peak stage. During the receding limb, some larger material remained, but CPOM was primarily leaf fragments, conifer needles, and wood fragments, all of which were smaller and of a darker brown color compared to CPOM collected during peak stage. At base flow, CPOM samples primarily consisted of algal and leaf fragments.

Individual samples, each representing one 15-min sampling interval for a specific date, time, and sampling depth, were retained for analyses. Samples were grouped differently for specific analyses, as described in individual figure captions below.

4.1 | CPOM transport (H1)

Boxplots of CPOM mass at the three depths of flow were used to compare where in the water column CPOM is transported (Figure 3). Comparison of the CPOM masses by depth via Kruskal–Wallis (p-value <.0001) and Dunn's tests (p-value for all three pairwise comparisons ≤0.0001) show that the masses at each depth of flow are significantly different from each other (indicated by the letters), with:

$$\text{Mass}_{\text{Bed}} < \text{Mass}_{\text{Surface}} < \text{Mass}_{60\% \text{ from Surface}}$$

Specifically, CPOM mass transported in suspension is significantly greater than mass transported as bedload. The results thus support the first hypothesis.

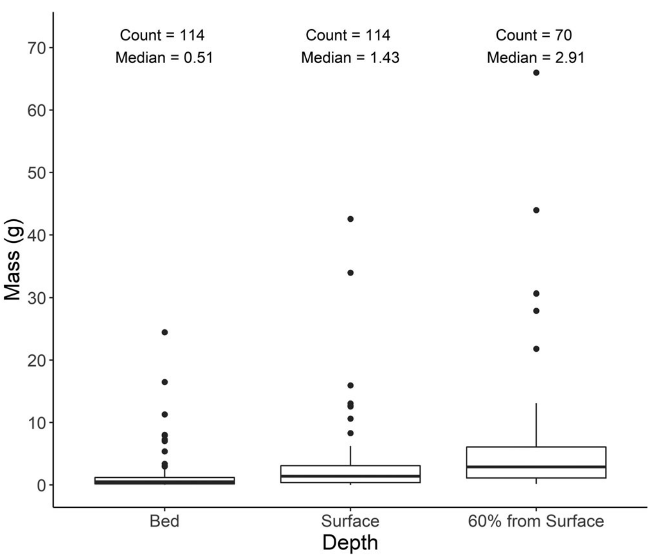

FIGURE 3 Boxplot of CPOM mass by sample depth showing a significant difference in the relationship between CPOM mass at each depth. Each population represents all samples taken at a particular depth for all sampling dates and times. Letters indicate statistically significant differences between median values of populations. The bold line represents the median. The box top and bottom represent 75th and 25th percentiles, respectively. The ends of the vertical lines represent 1.5 times the interquartile range. The circles represent outliers

4.2 | Seasonal hydrograph (H2)

Figure 4 illustrates seasonal CPOM trends. There is a more pronounced seasonal curve in the largest values of CPOM transport than in the average stage. Figure 5 depicts a clockwise hysteresis loop of CPOM mass over the seasonal hydrograph, where the peak CPOM precedes the peak stage (Williams, 1989). The most pronounced hysteresis curve occurs at T2, the transport reach without a depositional feature immediately upstream. The results thus support H2, indicating substantially greater CPOM transport during the final portion of the rising limb than at nearly equivalent stage on the falling limb of snowmelt hydrograph.

4.3 | H3: Diurnal cycle

There is no substantial change in CPOM mass in transport during the 24-hr hydrograph except during the highest stage each day. The difference is greatest at the transport reaches (Figure 6) but is also present at the depositional reach (Figure 7). The highest CPOM mass occurs before the highest stage during the diurnal cycle: CPOM mass peaks in the 5 p.m.–11 p.m. time window, while the peak stage was observed during the 11 p.m.–3 a.m. time window, when CPOM masses were lower.

The diurnal stage changes were unexpectedly small during each 24-hr sample period. The downstream sample site has the most confined cross-section, with a steep bedrock bank along channel right. The greatest stage change during a 24-hr period here was 3 cm during the 6/1–2 and 6/9–10 sample periods. Over the course of the snowmelt hydrograph, stage changed by 18 cm at this site.

The 6/1–2 time is the only sampling event with a pronounced diurnal hysteresis pattern (Figures 6 and 7). Diurnal trends during this sampling date match a clockwise hysteresis loop (Williams, 1989) where the peak CPOM precedes the peak stage. These results partly support the third hypothesis, indicating a diurnal hysteresis in CPOM transport only during the portion of the seasonal hydrograph with the greatest CPOM transport.

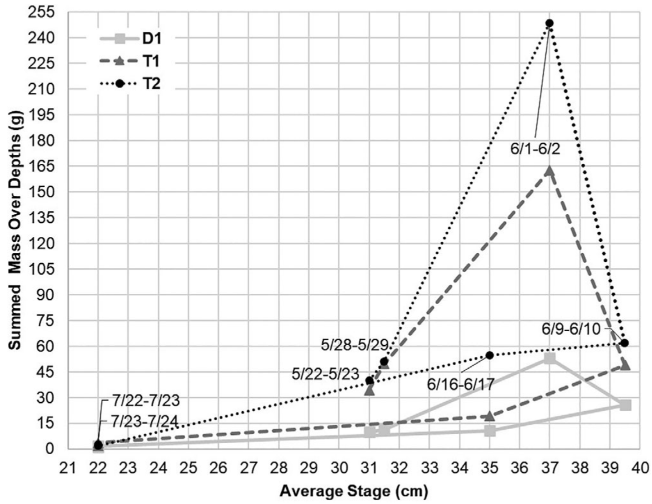

FIGURE 5 Hysteresis plot of mass corresponding with stage. Each data point represents the sum of all samples at a particular location during the 24-hr sampling period. The curves for each reach suggest clockwise hysteresis loops

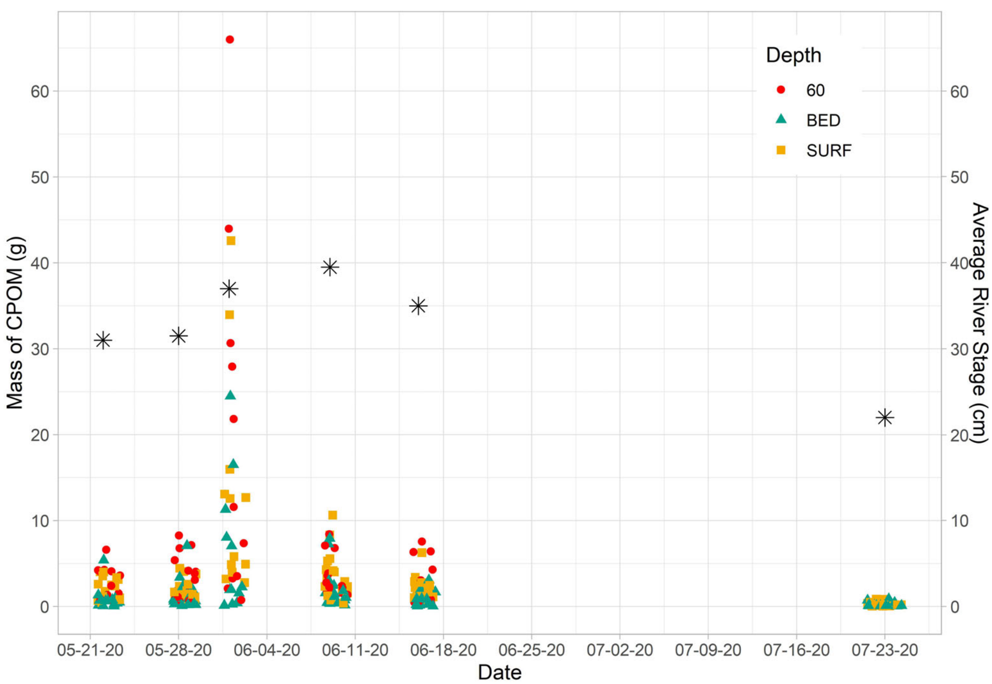

FIGURE 4 Mass of CPOM and corresponding average stage during sampling event. Black stars indicate average stage for each sampling period. Each data point in this plot represents an individual sample with respect to sampling depth, time interval, and date [Color figure can be viewed at wileyonlinelibrary.com]

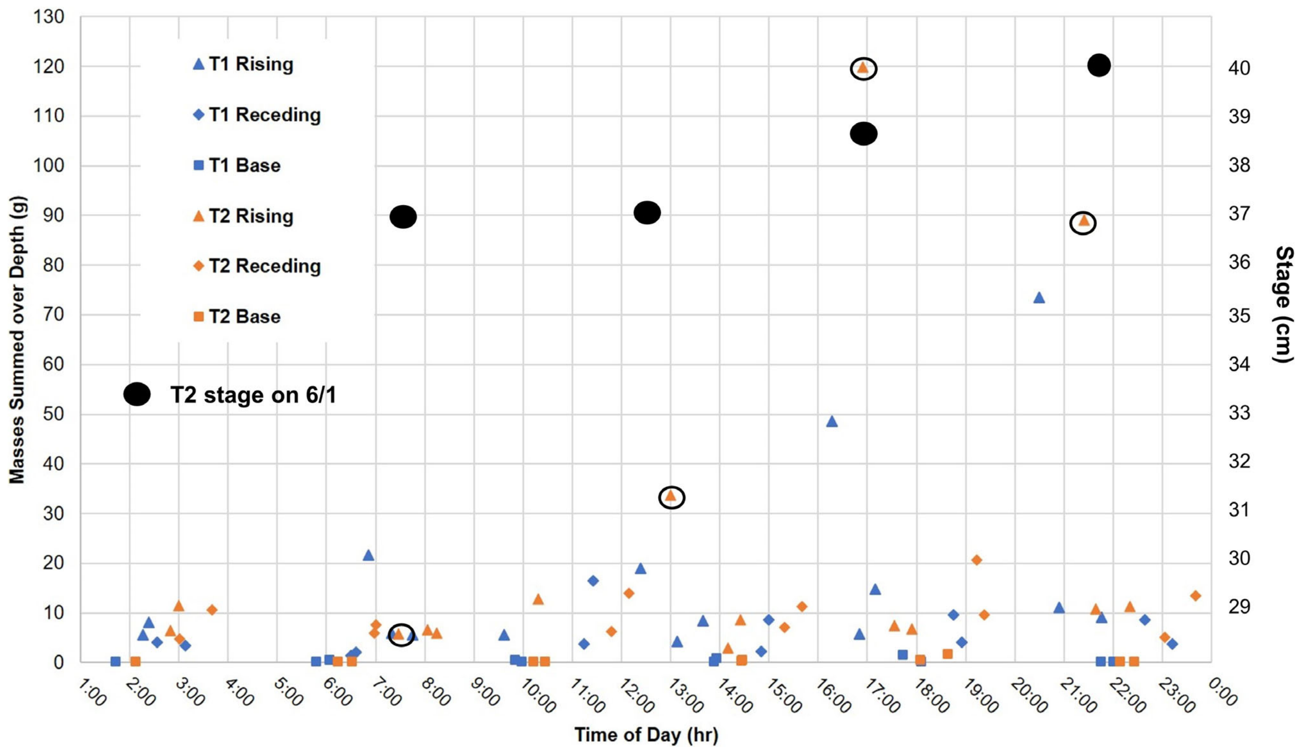

FIGURE 6 Sums of CPOM in transport reaches (T1 and T2) along the diurnal cycle. Each data point represents the sum of all sample depths taken at a particular sampling location, date, and time. Black ovals represent stage during the June 1–2 sampling period; circled CPOM masses collected during the June 1–2 sampling period [Color figure can be viewed at wileyonlinelibrary.com]

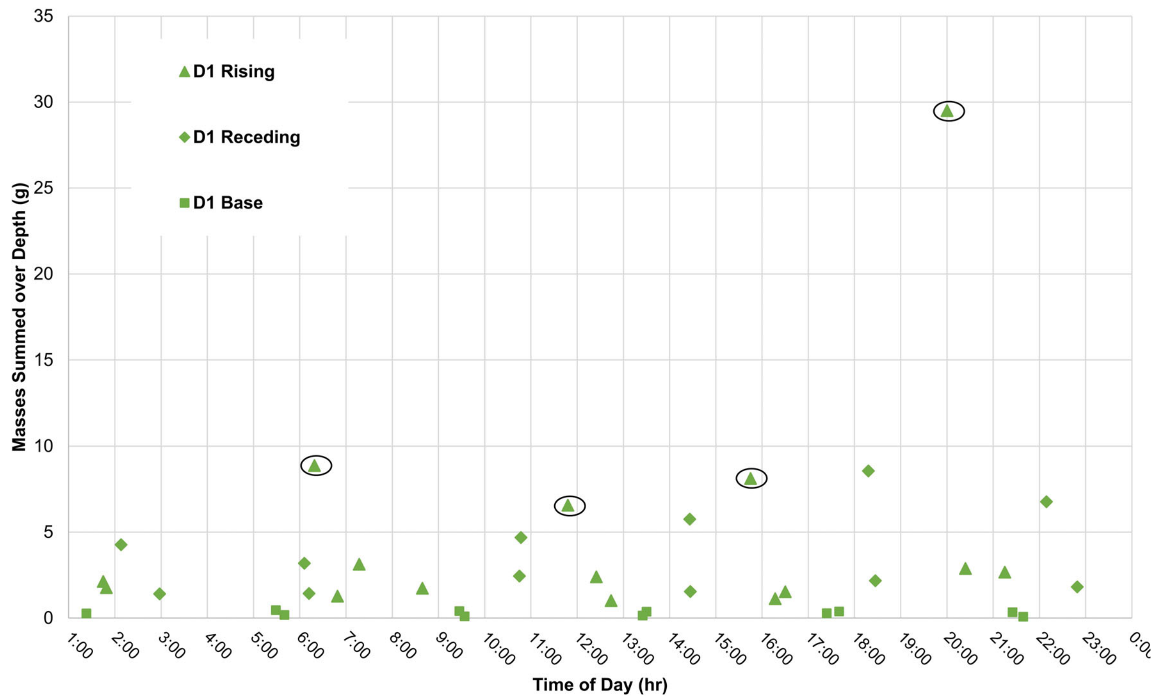

FIGURE 7 Sums of CPOM in the depositional reach along the diurnal cycle. Each data point represents the sum of all sample depths taken at a particular sampling location, date, and time Circled data points are from the June 1–2 sampling interval [Color figure can be viewed at wileyonlinelibrary.com]

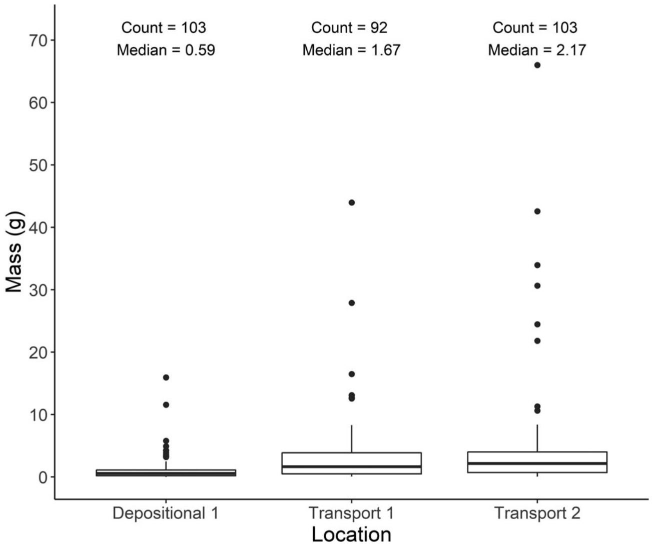

FIGURE 8 Boxplot of CPOM mass by location. Each population represents all samples taken at a site for all sampling dates and times. Letters A and B indicate statistical differences and similarities between the three sample sites. The bold line represents the median. The box top and bottom represent 75th and 25th percentiles, respectively. The ends of the vertical lines represent 1.5 times the interquartile range. The circles represent outliers

4.4 | H4: Local storage features

To address H4, we compared CPOM mass at the three distinct sampling locations (Figure 8). Kruskal–Wallis (p-value $<1 \times 10^{-8}$) and Dunn's tests (p-value$_{(T2\text{-}D1)} = p$-value$_{(T1\text{-}D1)} = 0$, p-value$_{(T2\text{-}T1)} = .2908$) show that there is a statistically significant difference in CPOM masses between deposition and transport reaches but not a statistically significant difference between the transport reach with and without a local storage feature (as indicated by the letters). The results thus support the fourth hypothesis in showing significantly different rates of CPOM transport in the logjam backwater than in the transport sites.

5 | DISCUSSION

Because we sampled only at the channel thalweg, we did not attempt to calculate total CPOM flux in the creek. Suspended and bedload transport of mineral sediment commonly vary across a channel cross section. Sampling of CPOM using bedload traps also indicates cross-channel variations in transport, although these may be smaller than those commonly present for mineral sediment transport, with the majority of CPOM bedload transport (64–67%) occurring in and near the thalweg (K. Bunte, 18 Febraury 2021, pers. comm.). We chose to sample in the thalweg as likely having the highest concentrations of suspended and bedload CPOM transport.

The mass of CPOM in suspension (at depths of 0.6 and at the surface) is greater than the mass of CPOM moving as bedload. This relationship makes sense as CPOM generally has a low density and is therefore easily entrained by flow at a wide range of velocities. The greater mass of CPOM at 0.6 depth compared to the surface may reflect a decrease in CPOM concentration with distance from the bed, analogous to that commonly observed in suspended sediment (Kuhnle, 2013). The difference in suspended CPOM mass with depth may also reflect experimental design. The seines used to collect CPOM in suspension oscillated in the swift, turbulent flow of the transport reaches, sometimes even changing their relative vertical positions during a 15-min sampling interval. Additionally, the flow in D1 was often too slow to maintain lift of the seins, causing them to drift lower in the water column than expected in the experimental design. These movements of the sample bags create uncertainty in the relative masses of CPOM moving at 0.6 depths versus the surface. Therefore, our results support H1 that more CPOM is moving in suspension, but more data may need to be collected using a different sampler design to determine exactly where in the water column most suspended CPOM is being transported. Given the lack of diurnal fluctuations in CPOM transport during most sampling events, future studies might more effectively focus on additional sampling dates and/or sites rather than repeated sampling during 24-hr periods.

The observed seasonal hysteresis patterns suggest that CPOM stored in the channel and overbank areas is more likely to be mobilized as stage rises and snowmelt runoff enters the channel, whereas the supply of CPOM is depleted as the snowmelt hydrograph continues. A similar hysteresis in CPOM transport does not occur during diurnal fluctuations in discharge except during the sampling date of greatest CPOM movement. The extent to which these patterns might represent those in rainfall-dominated streams and watersheds with more strongly seasonal abscission remains to be determined.

Our results show that the channel-spanning logjam has a significant effect on the mass of CPOM in transport above and below the jam. The statistical difference in masses indicates that the reach above the logjam is storing CPOM while the reaches below are transporting it. The lack of statistical significance between the two downstream transport reaches suggests that there is no local effect, or CPOM "shadow," from the channel-spanning logjam. We infer that logjams act as storage features for CPOM, and despite the greater presence of stored CPOM in pool backwaters demonstrated in other studies (e.g., Beckman & Wohl, 2014; Livers et al., 2018), the lower velocities in the backwater limit CPOM suspension and transport.

6 | CONCLUSIONS

Sampling CPOM at two to three depths of the water column during regular intervals throughout 24 hr at three locations and different portions of the annual snowmelt hydrograph reveals significant variations in transport of coarse particulate organic matter in relation to channel location (depositional vs. transport reaches), depth within the water column, and portion of the seasonal hydrograph. The greatest mass of CPOM moves in suspension in transport-dominated locations of the channel and during the final portion of the rising limb of the snowmelt hydrograph. Diurnal fluctuations in CPOM transport are negligible except during the period of greatest CPOM transport.

Because a substantial portion of CPOM is transported in suspension, flow obstructions that have a vertical dimension similar to peak flow depth are likely to be more effective in trapping and retaining CPOM than are obstructions with a smaller protrusion height. Similarly, areas of flow separation with substantially reduced flow velocity are more likely to retain CPOM in suspension. Current installations of large wood and engineered logjams, for example, typically do not include channel-spanning logjams (Grabowski et al., 2019; Roni, Beechie, Pess, & Hanson, 2015), which greatly increase retention of CPOM if the logjam has limited porosity and permeability (Livers et al., 2018). Even relatively brief retention of CPOM over periods of hours to days can increase microbial processing of CPOM and render nutrients within the CPOM more available to organisms in the stream (Battin et al., 2008).

Considering that CPOM is a primary energy source in the food webs of shaded forest streams, the management designed to foster the sustainability of stream ecosystems can benefit from maintaining or creating features that enhance CPOM retention. Understanding patterns of diurnal and seasonal hysteresis of CPOM transport can improve estimates of total CPOM export from watersheds (e.g., Bunte et al., 2016; Iroume et al., 2020) that are based on extrapolations from measurements; improve associated estimates of carbon storage and exports from rivers (Battin et al., 2008; Turowski, Hilton, & Sparkes, 2016); and inform management designed to enhance CPOM retention in anthropogenically modified streams with limited CPOM inputs and simplified channel morphologies that limit CPOM retention (Livers et al., 2018; Peipoch, Brauns, Hauer, Weitere, & Valett, 2015). As river scientists increasingly integrate their research and understanding of rivers across disciplines (e.g., Polvi et al., 2011; Castro & Thorne, 2019; Johnson et al., 2020), enhanced mechanistic understanding of CPOM transport, paired with biogeochemical and ecological understanding of the role of CPOM in nutrient dynamics, trophic cascades, and carbon dynamics, can underpin management of rivers as ecosystems.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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REFERENCES

Ader, E., Wohl, E., McFadden, S., & Singha, K. (2021). Logjams as a driver of transient storage in a mountain stream. *Earth Surface Processes and Landforms*, *46*(3), 701–711. https://doi.org/10.1002/esp.5057

Aich, V., Zimmermann, A., & Elsenbeer, H. (2014). Quantification and interpretation of suspended-sediment discharge hysteresis patterns: How much data do we need? *Catena*, *122*, 120–129.

Aumen, N. G., Bottomley, P. J., Ward, G. M., & Gregory, S. V. (1983). Microbial decomposition of wood in streams: Distribution of microflora and factors affecting [^{14}C] lignocellulose mineralization. *Applied and Environmental Microbiology*, *46*(6), 1409–1416.

Barry, R. G. (1973). A climatological transect on the east slope of the front range, Colorado. *Arctic, Antarctic, and Alpine Research*, *5*, 89–110.

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. I., … Sabater, F. (2008). Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience*, *1*(2), 95–100. https://doi.org/10.1038/ngeo101

Beckman, N. D., & Wohl, E. (2014). Carbon storage in mountainous headwater streams: The role of old-growth forest and logjams. *Water Resources Research*, *50*(3), 2376–2393. https://doi.org/10.1002/2013WR014167

Bilby, R. E., & Likens, G. E. (1980). Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology*, *61*(5), 1107–1113. https://doi.org/10.2307/1936830

Bunte, K., Swingle, K. W., Turowski, J. M., Abt, S. R., & Cenderelli, D. A. (2016). Measurements of coarse particulate organic matter transport in steep mountain streams and estimates of decadal CPOM exports. *Journal of Hydrology*, *539*, 162–176. https://doi.org/10.1016/j.jhydrol.2016.05.022

Castro, J. M., & Thorne, C. R. (2019). The stream evolution triangle: Integrating geology, hydrology, and biology. *River Research and Applications*, *35*, 315–326.

Cole, J. C., Trexler, J. H., Cashman, P. H., Miller, I. M., Shroba, R. R., Cosca, M. A., & Workman, J. B. (2010). Beyond Colorado's front range – A new look at Laramide basin subsidence, sedimentation, and deformation in north-Central Colorado. *Geological Society of America Field Guide*, *18*, 55–76.

Cummins, K. W., Sedell, J. R., Swanson, F. J., Minshall, G. W., Fisher, S. G., Cushing, C. E., … Vannote, R. L. (1983). Organic matter budgets for stream ecosystems: Problems in their evaluation. In J. R. Barnes & G. W. Minshall (Eds.), *Stream ecology: Application and testing of general ecological theory* (pp. 299–353). Boston, MA: Springer.

Dinno, A. (2017). Dunn.Test: Dunn's test of multiple comparisons using rank sums. R package version 1.3.5. Retrieved from https://CRAN.R-project.org/package=dunn.test

Edwards, T. K., & Glysson, G. D. (1988). In T. K. Edwards & G. D. Glysson (Eds.), *Field methods for measurement of fluvial sediment*, Department of the Interior. Washington, DC: US Geological Survey, Publications.

Fisher, S. G., & Likens, G. E. (1972). Stream ecosystem: Organic energy budget. *Bioscience*, *22*, 33–35.

Goebel, P. C., Pregitzer, K. S., & Palik, B. J. (2003). Geomorphic influences on large wood dam loadings, particulate organic matter and dissolved organic carbon in an old-growth northern hardwood watershed. *Journal of Freshwater Ecology*, *18*(3), 479–490. https://doi.org/10.1080/02705060.2003.9663984

Gorecki, V. I., Fryirs, K. A., & Brierley, G. J. (2006). The relationship between geomorphic river structure and coarse particulate organic matter (CPOM) storage along the Kangaroo River, New South Wales, Australia. *Australian Geographer*, *37*(3), 285–311. https://doi.org/10.1080/00049180600954757

Grabowski, R. C., Gurnell, A. M., Burgess-Gamble, L., England, J., Holland, D., Klaar, M. D., … Wharton, G. (2019). The current state of the use of large wood in river restoration and management. *Water Environment Journal*, *33*, 366–377.

Harvey, J., & Gooseff, M. (2015). River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins. *Water Resources Research*, *51*, 6893–6922. https://doi.org/10.1002/2015WR017617

Hilton, R. G., Galy, A., & Hovius, N. (2008). Riverine particulate organic carbon from an active mountain belt: Importance of landslides. *Global Biogeochemical Cycles*, *22*(1). https://doi.org/10.1029/2006GB002905

Iroume, A., Ruiz-Villanueva, V., & Salas-Coliboro, S. (2020). Fluvial transport of coarse particulate organic matter in a coastal mountain stream of a rainy-temperate evergreen broadleaf forest in southern Chile. *Earth Surface Processes and Landforms*, *45*, 3216–3230.

Jackson, K. J., & Wohl, E. (2015). Instream wood loads in montane forest streams of the Colorado front range, USA. *Geomorphology*, *234*, 161–170. https://doi.org/10.1016/j.geomorph.2015.01.022

Jarrett, R. D. (1990). Paleohydrologic techniques used to define the spatial occurrence of floods. *Geomorphology*, *3*(2), 181–195. https://doi.org/10.1016/0169-555X(90)90044-Q

Jochner, M., Turowski, J. M., Badoux, A., Stoffel, M., & Rickli, C. (2015). The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter in a steep headwater stream. *Earth Surface Dynamics*, *3*(3), 311–320. https://doi.org/10.5194/esurf-3-311-2015

Johnson, M. F., Thorne, C. R., Castro, J. M., Kondolf, G. M., Mazzacano, C. S., Rood, S. B., & Westbrook, C. (2020). Biomic river restoration: A new focus for river management. *River Research and Applications*, *36*, 3–12.

Kuhnle, R. A. (2013). Suspended load. In E. Wohl (Ed.), *Treatise on geomorphology, vol. 9, fluvial geomorphology* (pp. 124–136). San Diego, CA: Academic Press.

Lautz, L. K., & Fanelli, R. M. (2008). Seasonal biogeochemical hotspots in the streambed around restoration structures. *Biogeochemistry*, *91*(1), 85–104. https://doi.org/10.1007/s10533-008-9235-2

Lepori, F., Palm, D., & Malmqvist, B. (2005). Effects of stream restoration on ecosystem functioning: Detritus retentiveness and decomposition. *Journal of Applied Ecology*, *42*, 228–238.

Livers, B., Lininger, K. B., Kramer, N., & Sendrowski, A. (2020). Porosity problems: Comparing and reviewing methods for estimating porosity and volume of wood jams in the field. *Earth Surface Processes and Landforms*, *45*, 3336–3353. https://doi.org/10.1002/esp.4969

Livers, B., & Wohl, E. (2016). Sources and interpretation of channel complexity in forested subalpine streams of the southern Rocky Mountains. *Water Resources Research*, *52*(5), 3910–3929. https://doi.org/10.1002/2015WR018306

Livers, B., Wohl, E., Jackson, K. J., & Sutfin, N. A. (2018). Historical land use as a driver of alternative states for stream form and function in forested mountain watersheds of the southern Rocky Mountains. *Earth Surface Processes and Landforms*, *43*(3), 669–684. https://doi.org/10.1002/esp.4275

Merritt, D. M., & Wohl, E. E. (2006). Plant dispersal along rivers fragmented by dams. *River Research and Applications*, *22*(1), 1–26. https://doi.org/10.1002/rra.890

Molinero, J., & Pozo, J. (2004). Impact of a eucalyptus (*Eucalyptus globulus* Labill.) plantation on the nutrient content and dynamics of coarse particulate organic matter (CPOM) in a small stream. *Hydrobiologia*, *528*, 143–165.

Newbold, J. D., Bott, T. L., Kaplan, L. A., Sweeney, B. W., & Vannote, R. L. (1997). Organic matter dynamics in white Clay Creek, Pennsylvania, USA. *Journal of the North American Benthological Society*, *1*(16), 46–50.

Peipoch, M., Brauns, M., Hauer, F. R., Weitere, M., & Valett, H. M. (2015). Ecological simplification: Human influences on riverscape complexity. *Bioscience*, *65*, 1056–1065.

Pfeiffer, A., & Wohl, E. (2018). Where does wood most effectively enhance storage? Network-scale distribution of sediment and organic matter stored by instream wood. *Geophysical Research Letters*, *45*(1), 194–200. https://doi.org/10.1002/2017GL076057

Piégay, H., Thévenet, A., & Citterio, A. (1999). Input, storage and distribution of large woody debris along a mountain river continuum, the Drome River, France. *Catena*, *35*(1), 19–39. https://doi.org/10.1016/S0341-8162(98)00120-9

Polvi, L. E., Wohl, E. E., & Merritt, D. M. (2011). Geomorphic and process domain controls on riparian zones in the Colorado Front Range. *Geomorphology*, *125*(4), 504–516.

Raikow, D. F., Grubbs, S. A., & Cummins, K. W. (1995). Debris dam dynamics and coarse particulate organic matter retention in an Appalachian mountain stream. *Journal of the North American Benthological Society*, *14*(4), 535–546. https://doi.org/10.2307/1467539

Ramos Scharrón, C. E., Castellanos, E. J., & Restrepo, C. (2012). The transfer of modern organic carbon by landslide activity in tropical montane ecosystems. *Journal of Geophysical Research – Biogeosciences*, *117*(3). https://doi.org/10.1029/2011JG001838

Richmond, A. D., & Fausch, K. D. (1995). Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences*, *52*(8), 1789–1802. https://doi.org/10.1139/f95-771

Roni, P., Beechie, T., Pess, G., & Hanson, K. (2015). Wood placement in river restoration: Fact, fiction, and future direction. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*, 466–478.

R Core Team (2020). R: A language and environment for statistical computing. *R Foundation for Statistical Computing, Vienna, Austria*. https://www.R-project.org/.

Small, M. J., Doyle, M. W., Fuller, R. L., & Manners, R. B. (2008). Hydrologic versus geomorphic limitation on CPOM storage in stream ecosystems. *Freshwater Biology*, *53*(8), 1618–1631. https://doi.org/10.1111/j.1365-2427.2008.01999.x

Smith, H. G., & Dragovich, D. (2009). Interpreting sediment delivery processes using suspended sediment-discharge hysteresis patterns from nested upland catchments, South-Eastern Australia. *Hydrological Processes*, *23*, 2415–2426.

Tank, J. L., Rosi-Marshall, E. J., Griffiths, N. A., Entrekin, S. A., & Stephen, M. L. (2010). A review of allochthonous organic matter dynamics and metabolism in streams. *Journal of the North American Benthological Society*, *29*(1), 118–146. https://doi.org/10.1899/08-170.1

Turowski, J. M., Hilton, R. G., & Sparkes, R. (2016). Decadal carbon discharge by a mountain stream is dominated by coarse organic matter. *Geology*, *44*, 27–30.

Turowski, J. M., Jochner, M., Zurich, E., Turowski, J. M., Badoux, A., Bunte, K., … Jochner, M. (2013). The mass distribution of coarse particulate organic matter exported from an alpine headwater stream. *Earth Surface Dynamics Discussion*, *1*, 1–29. https://doi.org/10.5194/esurfd-1-1-2013

Wallace, J. B., Whiles, M. R., Eggert, S., Cuffney, T. F., Lugthart, G. J., & Chung, K. (1995). Long-term dynamics of coarse particulate organic matter in three Appalachian Mountain streams. *Journal of the North American Benthological Society*, *14*(2), 217–232.

Warren, D. R., Bernhardt, E. S., Hall, R. O., & Likens, G. E. (2007). Forest age, wood and nutrient dynamics in headwater streams of the Hubbard brook experimental Forest, NH. *Earth Surface Processes and Landforms*, *32*(8), 1154–1163. https://doi.org/10.1002/esp.1548

Webster, J. R., Covich, A. P., & Crockett, T. V. (1994). Retention of coarse organic particles in streams in the southern Appalachian Mountains. *Journal of the North American Benthological Society*, *13*(2), 140–150.

Weigelhofer, G., & Waringer, J. A. (1994). Allochthonous input of coarse particulate organic matter (CPOM) in a first to fourth order Austrian stream. *Internationale Revue der Gesamten Hydrobiologie Und Hydrographie*, *79*, 461–471.

Whiles, M. R., & Wallace, J. B. (1997). Leaf litter decomposition and macroinvertebrate communities in headwater streams draining pine and hardwood catchments. *Hydrobiologia*, *353*, 107–119.

Williams, G. P. (1989). Sediment concentration versus water discharge during single hydrologic events in rivers. *Journal of Hydrology*, *111*, 89–106.

Worrall, F., Burt, T. P., & Howden, N. J. K. (2014). The fluvial flux of particulate organic matter from the UK: Quantifying in-stream losses and carbon sinks. *Journal of Hydrology*, *519*, 611–625. https://doi.org/10.1016/j.jhydrol.2014.07.051

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