Received: 25 April 2024 | Revised: 7 November 2024 | Accepted: 10 November 2024

DOI: 10.1002/esp.6041

RESEARCH ARTICLE

ESPL WILEY

Restoring streams with large wood: An analysis of geomorphic changes 7 years post-restoration in small coastal streams

Madelyn M. Maffia[1] | Catalina Segura[1] | Christopher M. Lorion[2] | Erik Suring[2] | Dana R. Warren[3]

[1]Department of Forest Engineering, Resources, and Management, Oregon State University, Corvallis, Oregon, USA

[2]Oregon Department of Fish and Wildlife, 4034 Fairview Industrial Dr SE, Salem, Oregon, USA

[3]Department of Forest Ecosystems and Society, Oregon State University, Corvallis, Oregon, USA

Correspondence
Madelyn M. Maffia, Forest Engineering Resources and Management Department, Oregon State University, Corvallis, OR, USA.
Email: maffiam@oregonstate.edu

Funding information
Fish and Wildlife Habitat in Managed Forests Research Program

Abstract

Introducing large wood (LW) into streams for restoration purposes is a common practice, as it creates habitat through processes like scouring, deposition and sediment sorting. However, while monitoring often focuses on short-term (<3 years) or long-term (>10 years) changes in habitat features, there is a lack of understanding regarding annual geomorphic changes over relatively long periods. In this study, we investigated annual geomorphic adjustments (channel geometry and substrate size) over 7 years in three tributaries of the Mill Creek watershed (Oregon, USA). The 7-year period included moderate to high flows, with peak annual flow exceeding bankfull flow (Q_{bf}) 2–5 times and flows being above half Q_{bf} on average 4–20 days per year. Data included topographic surveys and surface pebble counts collected from 2014 (1 year before LW) to 2021 (6 years after LW). We quantified scour and deposition and estimated sediment grain sizes and sorting from topographic surveys and pebble counts. Our analysis revealed that stream size influenced geomorphic adjustment, with smaller streams experiencing more scouring compared with larger streams over the 6 years. LW structures promoted increased scouring at the cross-section scale, with a strong relationship found between volumetric blockage ratio and scour. In our case, the most significant scouring changes were associated with volumetric blockage ratios between 35% and 50%; further research is needed to investigate scouring for higher blockage ratios. Instream changes in scour and deposition peaked around 3–4 years after LW introductions but persisted until the end of the monitoring period. Sediment size dynamics were influenced more by time since restoration than by proximity to LW jams. While LW introductions increased sediment sorting into patches, the degree of sorting declined 5–6 years post-restoration at all sites. Our findings offer insights into the long-term persistence and magnitude of instream changes associated with LW introductions.

KEYWORDS
geomorphic response, large wood restoration, long-term monitoring, small coastal streams

1 | INTRODUCTION

Restoration of forested riverine environments is an important strategy in addressing long-standing issues related to aquatic habitat degradation, overexploitation and flow modifications induced by human activities (Dudgeon et al., 2006; Palmer, Hondula, & Koch, 2014). These disturbances adversely impact freshwater ecosystems, resulting in the loss of critical stream features, including deep-water habitats, sorted substrate cover and structural complexity—all of which are essential for supporting robust populations of freshwater fish species (Crispin, House, & Roberts, 1993; Dolloff & Warren, 2003; Hallbert & Keeley, 2023; House & Boehne, 1986; Palmer, Hakenkamp, & Nelson-Baker, 1997). The introduction of unanchored large wood (LW) structures is not only an effective method for restoring many of these habitat features but also it is cost-effective, especially when compared with resource-intensive alternatives like deflectors, weirs and grade control structures (Foote, Biron, & Grant, 2020; Roni et al., 2002; Roni, Hanson, & Beechie, 2008; Whiteway et al., 2010).

When evaluating changes in habitat conditions after stream restoration projects, the interaction between sediment scouring and deposition plays a fundamental role in shaping the stream geometry. Instream LW promotes localized converging and diverging flow patterns that prompt heightened changes to the channel form. In regions where flow is confined by the presence of LW, water velocity is high, and increased scouring of the channel bed can occur. Changes in the streambed associated with scour are often observed in the vertical and longitudinal dimensions as increases in the channel depth and frequency or size of pool habitat (Abbe & Montgomery, 1996; Brooks et al., 2006; Buffington et al., 2002; Collins, Montgomery, & Haas, 2002; Gurnell & Sweet, 1998; Hilderbrand et al., 1997; Montgomery et al., 1995; Montgomery & Buffington, 1997; Richmond & Fauseh, 1995; Webb & Erskine, 2003). Further, lateral scouring of the stream banks near the LW can concurrently promote channel widening or lateral channel migration (Keller & Swanson, 1979; Nakamura & Swanson, 1993; Webb & Erskine, 2003) and increased floodplain connectivity from overbank flow events (Abbe & Brooks, 2011; Brummer et al., 2006; Keys et al., 2018). As scour often increases near the location of the LW pieces, sediment deposition is often observed upstream or downstream of them. Upstream of LW structures, the backwater phenomenon can promote sediment accumulation in wedges (Faustini & Jones, 2003; Lisle, 1986; Parker et al., 2017; Pfeiffer & Wohl, 2018; Wohl & Beckman, 2014; Wohl & Scott, 2017). Downstream of LW, energy dissipation around the flow obstruction can create sediment bars (Lisle, 1986). While scour and deposition create habitat features by altering channel geometry (Faustini & Jones, 2003; Gurnell et al., 2002), sediment sorting shapes the quality of habitat features by altering substrate sizes (Osei, Harvey, & Gurnell, 2015).

Ultimately, LW introductions result in channels having coarse and fine sediment patches due to sediment sorting processes (Powell, 1998). Many post-restoration monitoring studies have demonstrated substrate fining at the reach scale following LW introductions (Flannery et al., 2017; Osei, Harvey, & Gurnell, 2015; Pess et al., 2022). However, rather than the size of the substrate being the most important consideration, it is the sorting of sediment into patches that serves the greatest potential ecological function. For example, a juvenile salmonid fish may need patches of boulders and cobble for refugia purposes, whereas the adult form may need gravel and cobble for spawning purposes, depending on their body size (Kondolf & Wolman, 1993). And different species may require further sorting—such as anadromous lamprey, which require accumulations of fine sediment for juvenile rearing. This supports the need for a heterogeneous streambed with multiple sediment patches to support numerous life stages and potential species. While sediment sorting after the addition of structural elements is known, there are a limited number of empirical studies that quantify how LW introductions affect sediment patchiness or the sorting processes that control those patches following LW introductions.

The dimension and orientation of LW pieces play a role in mediating patterns of scour and deposition. For example, as much as 80% of the deposited sediment in mixed bedrock-alluvial streams occurs around channel-spanning LW structures (Welling, Wilcox, & Dixon, 2021). The height of LW jams has a positive correlation to LW-forced pool volume (Mao et al., 2008). Whereas, a blockage ratio, defined as the cross-sectional area blocked by LW (Gippel et al., 1996), is strongly related to pool volumes created by recruited trees (Kail, 2003). In fact, it has been found that blockage ratios greater than 10% significantly increase the water surface elevation, backwater effect and occurrence of overbank flow (Gippel, 1995; Gippel et al., 1996). These hydraulic conditions largely control transport capacity and thus the geomorphic features such as pools, riffles and channel bars. The importance of these flow conditions has been long recognized; however, few studies have quantified changes in scour and deposition as they relate to the LW additions. Furthermore, detailed studies about the retention and transport of LW pieces added as part of restoration efforts are rare, limiting the understanding of the longevity of geomorphic changes triggered by LW additions.

Channel size is a fundamental driver of LW mobility and stability. Generally, in headwater systems today, wood loadings in a watershed tend to decrease downstream as streams increase in size, reflecting an increase in stream power with increasing drainage area (Marcus et al., 2002; Martin & Benda, 2001; Pfeiffer & Wohl, 2018; Piégay, Thévenet, & Citterio, 1999; Wohl & Jaeger, 2009). The relationship between channel size and LW mobility has also been shown as a positive correlation between annual transport percentage and channel width, specific discharge and annual transport rate, and exported wood volume and catchment size (Ruiz-Villanueva et al., 2016). While LW mobility can be measured in a variety of ways, for example, by tagging and monitoring individual pieces (Máčka et al., 2010), these same techniques can be used to quantify LW stability. LW stability has been shown to have a positive relationship with LW length in smaller streams (Gurnell et al., 2002; Warren & Kraft, 2008). More so, Dixon & Sear (2014) found LW pieces greater than 2.5 channel widths more stable. While these factors may hold true in smaller systems, in larger systems where stream width is greater than tree height, the embedment of the LW becomes an increasingly important factor for its stability (Abbe & Brooks, 2011). Despite these insights into LW mobility, studies that monitor wood mobility at the reach scale for multiple years are rare (Ruiz-Villanueva et al., 2016). Furthermore, studies in natural systems that directly investigate wood stability and its effects on scour and deposition remain mainly unstudied.

Following LW restoration, reach-scale monitoring efforts have traditionally focused on the immediate effects of the restoration on pool habitat and channel features (Hallbert & Keeley, 2023; House & Boehne, 1986). Yet, a gap exists in our understanding regarding the duration required to attain the 'maximum' geomorphic changes associated with LW restoration or how long they persist over moderate (5–10 years) time scales. While some studies suggest that LW-induced effects may diminish after 3 years (Krall et al., 2019), other studies indicate that habitat created by LW structures can persist for many decades (Pess et al., 2022). Shorter-term (1–3 years) studies tend to provide more detailed insights into annual changes in habitat features, but their limited duration constrains their scope (Flannery et al., 2017; Hilderbrand et al., 1997; Parker et al., 2017). For example, a study in the Pacific Northwest found that 1 year after a LW restoration project there was increased scour pool habitat, D_{50} fining, greater pool depth, more sediment sorting and greater channel widths (Flannery et al., 2017). Longer-term studies more often provide before-after comparisons of geomorphic features, but these types of studies lack interannual dynamics of change (Jones et al., 2014). For example, a study conducted 23 years after the introduction of LW to small mountainous streams revealed substantial geomorphic changes, including deeper and more frequent pools, reduced particle size, increased sediment storage and a narrower stream width (Pess et al., 2022). However, it is not clear if those changes occurred early after the LW was added and persisted or if the changes developed slowly over time. Arguably a primary mediator of the geomorphic response to LW restoration is the frequency of high flow events (Wohl et al., 2019; Yazzie et al., 2023). As such, streamflow greater than 30%–50% of bankfull discharge are of particular interest because these correspond to the threshold for bedload transport in many gravel bed rivers (Parker, Klingeman, & McLean, 1982; Torizzo & Pitlick, 2004). In summary, many studies have explored the impact of LW on stream morphology through both short-term detailed analyses and long-term comparative investigations. However, few studies have specifically examined annual changes over 5–10 years post-restoration over variable flow regimes in terms of scour and deposition, which are crucial factors controlling geomorphic changes.

In the Oregon Coast Range, the introduction of LW is a prominent strategy for stream restoration, particularly for the enhancement of salmonid habitat. In 2015–2016, a large-scale restoration effort was undertaken in the Mill Creek basin (a tributary of the Siletz River) to support a wild population of coho salmon (*Oncorhynchus kisutch*). The restoration project involved extensive LW structure placements across 12 km of stream with a monitoring plan spanning 1 year before to 6 years after the LW introductions (ODFW, 2014). While these structures had the intended effects on stream hydraulics by reducing reach velocities and enhancing streambed stability within the first year following their introduction (Bair, Segura, & Lorion, 2019), a comprehensive understanding of reach-scale sediment dynamics, including sediment scour, deposition and sorting over time, remains relatively unexplored. This study presents findings from seven consecutive years of detailed cross-section sampling conducted in association with LW additions in three tributaries within the Mill Creek network. Our research investigates the evolving stream adjustment (channel form and grain size) and seeks to address the following question: How do LW additions impact sediment scouring, deposition and sediment sorting of small headwater streams over 7 years that included moderate and high flow conditions?

2 | METHODS

2.1 | Study area

Mill Creek Basin is situated on the western side of the Oregon Coast Range, and nearly the entire watershed is managed as commercial timberland in private or tribal ownership. The watershed drains 32.1 km^2 with an elevational relief of 678 m before entering the Siletz River (Figure 1). The basin geology is primarily underlain with sedimentary sandstone from the Tyee formations, with a Mafic intrusion of basaltic rock in the upper-northern section of the watershed (Walker & MacLeod, 1991) (Figure S1). The climate in the region is marine-temperate, with approximately 2300 mm of rainfall during the fall and winter months (November–March) and a range of annual temperatures from about 4 to 17°C (PRISM Climate Group, 2014). Mill Creek's hydrological regime is rainfall-dominated, as the basin receives less than 26 mm of snowfall each year. Given its ownership, the area is dominated by intensively managed Douglas fir (*Pseudotsuga menziesii*) forest, with unmanaged riparian areas dominated by red alder (*Alnus rubra*), bigleaf maple (*Acer macrophyllum*) and vine maple (*Acer circinatum*).

2.2 | Large wood addition sites

In August 2015, LW was added to three sites as the first stage of a project that placed over 700 unanchored LW pieces in 63 LW jams throughout the Mill Creek Basin in August 2015 through August 2016. Three alluvial, fish-bearing reaches draining 5–16 km^2 in different tributaries were selected for intensive pre- and post-restoration monitoring (2014–2021) of instream geomorphic changes triggered by the LW introductions. Site 1 is in a section of the 3rd order Mill Creek main stem; Site 2 is in a section of the 2nd order Cerine Creek; and Site 3 is in a section of the 2nd order South Fork Mill Creek (Figure 1). The lithology of the drainage area of Site 2 is 100% sandstone, while the lithology of the drainage area of Sites 1 and 3 is 90%–95% sandstone and 5%–10% basalt (Table 1). Site 1 is fully confined by a road that lies parallel to the stream on the right bank and the presence of a steep hillslope on the left bank (Figure 1). Sites 2 and 3 are partially confined by the presence of steep hillslopes on the left bank and unconfined floodplains on the right bank (Figure 1). In addition to the dominant deciduous trees in the riparian zone, vegetative grasses lie in all the riparian areas, with Sites 2 and 3 having an increased amount of grass intrusion encroaching the flow field. Around one-third of the channel banks in Sites 1 and 3 are relatively stable given the presence of a basalt outcropping. Conversely, Site 2 lacks bedrock outcrops. The shrubby and herbaceous vegetation in portions of the channel banks of Sites 2 and 3 provide additional bank stability. Sinuosity is variable among the sites, with Site 1 showing a fairly straight pattern, Site 2 having some minor curvature and an upstream 90-degree bend and Site 3 revealing moderate curvature throughout (Figure 1).

We established 20–28 cross-sections (cross-section hereafter referred to as XS), per site spaced at approximately 0.5 bankfull widths apart and marked with left and right bank wooden stakes (Figure 1). Two LW jams were placed in each site, consisting of at least 8–13 LW pieces per reach. Site 3 additionally had a singular log placed in the downstream portion of the reach, totaling to three separate wood installations in this site. The wood was placed with the assistance of an excavator, which created some local ground disturbance evident for ~1 year. All wood pieces lacked rootwads, were sourced regionally from mills, were longer than 6 m and had diameters between 0.5 and 1.6 m. The volume of wood placed in the sites varied between 73 and 198 m^3 (Table 1). In most cases, LW jams were configured in parallel orientations to the flow of water to maximize the amount of wood below the bankfull flow and ensure geomorphic changes from contact with various flow regimes. When feasible, LW jams were placed in natural river bends, and in most cases, additional LW pieces were stacked on top, perpendicular to the flow, to increase stability and limit downstream movement. No artificial anchoring of the LW was used to ensure natural responses in the channel form following the LW introductions.

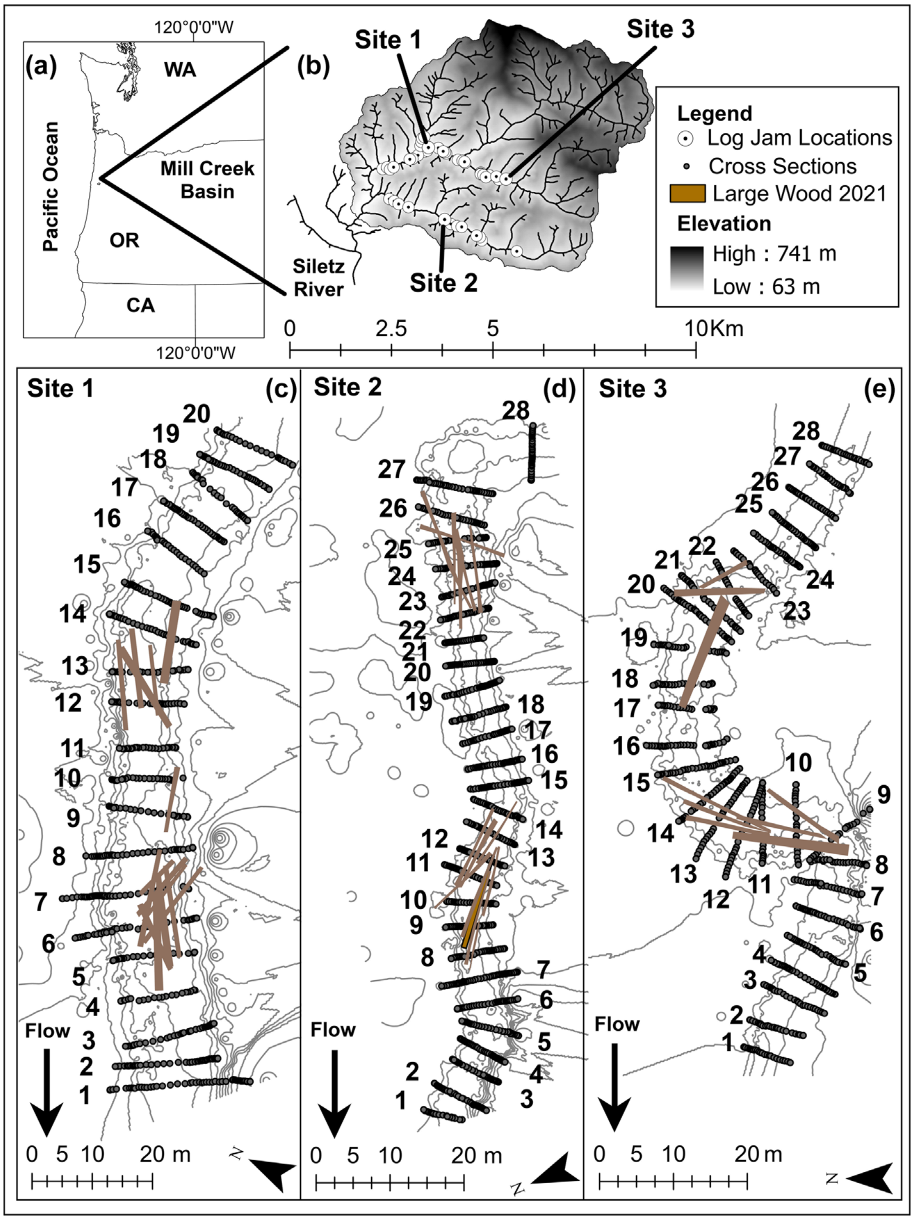

FIGURE 1 (a) Location of the Mill Creek watershed in Oregon, USA. (b) LiDAR-derived watershed elevation, location of the 63 large wood (LW) jam introductions implemented across the watershed in 2015–2016 and location of the three sites. (c–e) Site maps with 0.2 m contour lines with labelled cross-sections and individual LW locations as of 2021; the flow direction is indicated.

2.3 | Field methods

Each reach was instrumented with a pressure transducer located at a uniform XS to estimate streamflow between 2014 and 2021 (Bair, Segura, & Lorion, 2019). Field measurements of stage height and discharge were estimated using the velocity-area method (Dingman & Dingman, 2015) with a Hack FH950 portable velocity metre. We collected >20 stage-discharge pairs for the establishment of reach-specific rating curves (Figures S2–S4).

Annual topographic surveys were conducted during the summer with a Nikon XF HP Total Station (prism precision is ±(2 mm + 2 ppm) along each XS from 2014 (1 year before the LW introductions) to 2021 (6 years after LW introductions). Survey points were spaced at ~0.25 m in the channel, with points surveyed at higher densities near the banks to capture abrupt changes in the elevation. No data was collected in 2019 nor at XS 1 or 7 in Site 1 in 2016.

During each summer sampling campaign, the size of the channel bed material was characterized based on 100 particle pebble counts (Wolman, 1954) using a gravelometer along each XS in all sites and all years except 2015 and 2019.

Topographic survey points were collected on the upstream and downstream ends of each individual LW piece in 2015, 2018, 2020 and 2021 to capture potential piece movement (Figure 2). Topographic surveys were overlain to the prior years to quantify movements and rearrangement of the wood pieces. We documented in detail all movement of wood pieces of at least 1 m.

2.4 | Data analysis

Discharge data, estimated from the reach-specific rating curves, was used to quantify annual daily peak streamflow during the study period (channel XS did not change more than 5% over the survey period in the XS with the pressure transducers). This data was compared with reach-scale geomorphic changes at each site to investigate the relative influence of streamflow events on the instream changes.

Geomorphic changes of scour and deposition were quantified by calculating differences between XS profiles delineated by annual topographic surveys. XS topographic surveys interpolated to a 0.01-m resolution were analysed in two ways: overlaying each XS to the prior

TABLE 1 Study site characteristics: Site 1 (Mill Creek), Site 2 (Cerine Creek) and Site 3 (South Fork Mill Creek). Mean and standard error (in parenthesis), bankfull dimensions (width, depth, XS area), surface grain size percentiles (D_{16}, D_{50} and D_{84}) and gradation coefficient between 2014 and 2021.

Characteristics	Units	Site 1	Site 2	Site 3
Drainage area[a]	km^2	16	5	5
Length	m	119	123	115
Bankfull discharge	$m^3 s^{-1}$	8.7	2.4	2.5
Bankfull width	m	11.3 (1.7)	6.3 (1.0)	7.7 (1.6)
Bankfull depth	m	0.7 (0.2)	0.7 (0.1)	0.6 (0.1)
Bankfull XS area	m^2	8.2 (2.0)	4.4 (0.9)	4.7 (1.4)
Slope	$m\ m^{-1}$	0.0032	0.004	0.008
D_{16}	mm	12.4 (0.4)	9.1 (0.2)	13.8 (0.3)
D_{50}	mm	27.8 (0.9)	18.3 (0.4)	27.7 (0.6)
D_{84}	mm	63.4 (2.5)	34.2 (0.6)	51.2 (1.0)
Gradation coefficient		2.6 (1.2)	2.2 (0.6)	2.3 (0.8)
Sandstone	%	90	100	95
Basalt	%	10	0	5
Wood volume	m^3	198.2	72.9	108.6
No. of wood pieces	#	18	18	9

[a]LiDAR derived from DOGAMI (2011).

year's survey to compute annual variations in scouring and deposition at that location and overlaying each XS to the 2014 survey to estimate instream changes relative to the pre-restoration condition. Given that no substantial differences were observed between the two methods, only the results from the year-to-year comparisons were included. Positive (+) elevational changes implied sediment deposition, and negative (−) elevational changes implied sediment scour. Total change was estimated as the sum of the absolute values of scour and deposition for each XS, and net change was estimated as the sum of scour and deposition for each XS (Faustini & Jones, 2003; Goodman et al., 2023). Geomorphic metrics of scour, deposition, total change and net change were normalized with annual XS area for scaled comparisons across the three study reaches. These changes were assessed by analysing the cumulative and average amounts of change at the reach and XS scale to better understand the spatial influence of the LW structures.

Annual XS profiles delineated by the topographic surveys were also used to estimate changes in the bankfull dimensions (width, depth and area) for all reach XS. Average changes in the width and depth across the entire reach were assessed to understand general changes in the lateral and vertical dimensions.

To explore the influence that the size of the wood relative to the size of the channel may have on the geomorphic response, we calculated the LW jam volume relative to the channel volume. Blockage ratios, the area of wood intersecting the channel area, have been previously used to investigate how wood dimensions relative to the stream dimensions inflict instream changes (Gippel et al., 1996; Kail, 2003). However, the method outlined in Gippel et al. (1996) for calculating the blockage ratio assesses the wood-to-stream area at a single XS rather than considering the entire LW jam. This approach may overlook variations in blockage ratio that could occur between the upstream and downstream sections of the log jam, given the natural shapes LW jams often exhibit. To address this, in the current study, we expanded upon the 2-D blockage ratio approach and quantified the entire space the LW jam occupies within the stream length of the channel in which the jam occurs. To do this, we calculated the LW jam volume to channel volume (i.e., volumetric blockage ratio [VBR]) and used this to investigate how LW occupancy influences geomorphic changes. The volume of each LW piece (Log_{volume}) was determined by assuming the volume of a cylinder based on the measured length and diameter of each log. The total LW jam volume was obtained by summing the volumes of all individual logs within that particular LW jam. The channel volume where the LW structures interact was estimated by averaging the areas of the XS ($\overline{XS}_{area}$) that were within 3 m of the LW and multiplying it by the annually averaged longitudinal length of the LW jam (LJ_{length}). The VBR was calculated with the following equation:

$$\mathrm{VBR} = \frac{\sum Log_{volume}}{\overline{XS}_{area}\ x\ LJ_{length}} \tag{1}$$

Area normalized scouring ($Scour_{norm}$) at these locations was calculated as a dimensionless value by dividing the average scouring across these XS ($\bar{S}_{XS}$) by the average area of the respective XS ($\bar{A}_{XS}$):

$$Scour_{norm} = \frac{\bar{S}_{XS}}{\bar{A}_{XS}} \tag{2}$$

As the LW structures were mobile during various years, the XS considered in this analysis changed annually to reflect the changing location of the LW. Annual models between the VBR and area normalized scour were also created to examine the total and interannual changes of scour near the LW structures.

The cumulative frequency plots for each reach were averaged across XS grain sizes to understand overall trends in sediment size distributions. The D_{16} (sediment sizes of the 16th percentile), D_{50} (median particle size) and D_{84} (sediment sizes of the 84th percentile) were additionally estimated for each XS to evaluate the spatial

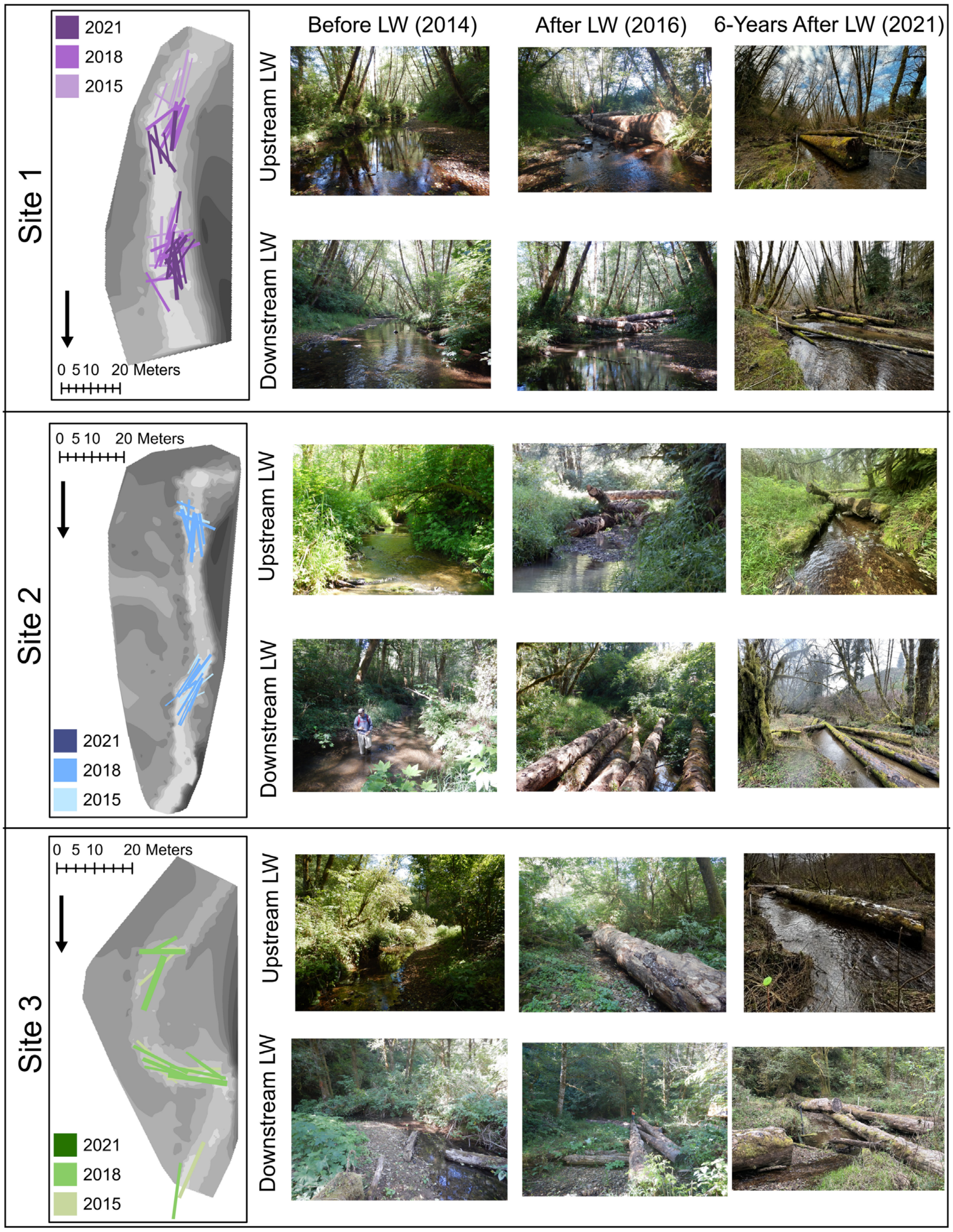

FIGURE 2 The movement of large wood (LW) was documented with LW surveys conducted in 2015, 2018 and 2021 at each of the sites. Darker colours of the LW indicate the most recent surveyed location (2021). Reach observations of each of the jams (upstream and downstream) before the LW introductions, after the LW introductions and 6 years following are additionally shown.

and temporal changes of sorted sediment patches. To do this, we calculated the gradation coefficient (σ_g) using the Julien (2018) equation:

$$\sigma_g = \sqrt{\frac{D_{84}}{D_{16}}} \tag{3}$$

where σ_g decreases for a well-graded sediment mixture (uniformity or equally distributed sediment sizes) and increases for poorly-graded (non-uniformity or unequally distributed sediment sizes) sediment mixtures. Throughout this paper, the term fining indicates a reduction in sediment sizes, and coarsening indicates an increase in sediment size.

2.5 | Statistical analysis

Multiple linear regression was used to investigate geomorphic changes associated with the presence of LW. In particular, we developed two models to explain how changes in scouring and deposition relate to XS with LW. To do this, we assigned each XS one of two categories: LW-present or LW-absent. LW-present was assigned to XS located within a 3 m radius from any LW piece. We used a 3 m threshold to clearly separate areas affected by LW, like around the jam or both upstream and downstream, from areas with less LW influence. The models included this category (LW-present or LW-absent) as a covariate, alongside bankfull dimensions (width and depth), grain size (D_{50}) and the site, which can also influence patterns of scour and deposition. Both of the linear mixed models can be described by Equation (4):

$$y_i = x_i^T \beta + \gamma_{s,i} + \gamma_{r,i} + \varepsilon_i \tag{4}$$

where y_i is the dependent variable (scouring or deposition), $x_i^T \beta$ the linear model for the fixed effects (LW-present, bankfull width, bankfull depth, D_{50} and site), $\gamma_{s,i}$ is the deviation from the mean (effect) of the XS associated with observation i, $\gamma_{r,i}$ is the deviation of the mean effect of the year associated with observation i, and ε_i is the random error term. To account for the repeated measures in space and time, factors for year and XS were incorporated as random effects. Model package lme4 (lmer function) in R was used to create and analyse the models (Bates et al., 2010).

To interpret the relative importance of the covariates in explaining scour or deposition, we centred and scaled each covariate by subtracting the mean and dividing by the standard deviation (scale function in R). Model robustness was ensured for each model by assessing assumptions (normality and equal variance) using normal quantile–quantile (QQ) and fitted-versus-residual plots. Linear patterns identified in the model residuals prompted log transforming of the response variables for both models. Log transforming the models significantly improved the distribution of residuals and equal variance assumptions. While the linearity assumptions (due to heavy tails) (Figures S5 and S6) and unequal variance (Figures S7 and S8) assumptions were not perfectly met in either of the models after log transforming the data, this was addressed by bootstrapping the residuals. Semi-parametric bootstrapping was conducted using the bootMer() function from the lme4 package in R.

Multicollinearity between covariates within both models was investigated by computing the variance inflation factor (VIF) for each parameter, with VIF values >10 indicating multicollinearity. The vif() function in the car package in R was employed for this purpose.

Temporal correlation was explored using partial autocorrelation plots that examine the correlation between the time series and its previous time step (lag). Partial autocorrelation was calculated using the pacf() function in R, which utilizes Pearson's correlation coefficient. From these time series analyses, partial autocorrelation did not appear to be problematic in any of the created models.

The relative strengths of the relationships between scour or deposition and the covariates were assessed through exponentiation of the standardized covariate estimates and confidence intervals (Popovic et al., 2024; Wasserstein, Schirm, & Lazar, 2019). Exponentiation returns the values to their original scale for interpretation. Estimates less than one indicate a negative effect, while estimates greater than one indicate a positive effect. Moreover, a larger exponentiated median estimate suggests a more significant influence on the geomorphic change (scour or deposition), whereas a smaller exponentiated median estimate indicates less impact. Exponentiated confidence intervals were also considered to assess the plausible range of values for the true relationship between the covariates and the geomorphic change of interest.

3 | RESULTS

3.1 | Hydrologic context

Streamflow hydrographs between 2014 and 2021 for all sites are typical of rain-dominated systems in the Costal Range of Oregon with wet winters and dry summers. Mean annual streamflow between 2015 and 2021 was 1.22 $m^3\ s^{-1}$ in Site 1, 0.28 $m^3\ s^{-1}$ in Site 2 and 0.23 $m^3\ s^{-1}$ in Site 3. Mean annal streamflow was highest in 2017 in Sites 1 and 3 and in 2016 in Site 2 (Figure 3). Maximum annual daily streamflow varied between 0.35 and 1.6 of bankfull flow (Q_{bf}) across all sites, varying between 0.7 and 1.6 of Q_{bf} on Site 1, 0.35 and 1.4 of Q_{bf} in Site 2 and 0.5 and 1.3 of Q_{bf} in Site 3. Peak annual streamflow was above Q_{bf} 5 out of 7 years in Site 1 and 3 out of 7 years in Sites 2 and 3.

3.2 | Large wood movement

Across all years, Site 1 had the greatest percentage of LW mean transport, and Site 3 had a greater percentage of LW mean transport than Site 2 in 2018 and 2021 (Figure 4). Analysis of all wood movements >1 m indicated that in Site 1, one log from the upstream jam was dislodged and moved downstream, and two of the logs in the downstream jam moved in 2018 (Figure 2). At the end of this study's survey period in 2021, Site 1 retained 9 of the original 12 logs in the reach (Figure 2). In Site 2, two of the logs in the upstream jam moved downstream in 2018 but did not leave the reach (Figure 2), and as of 2021, all of the 18 original pieces remained in the reach (Figure 2). In Site 3, between 2015 and 2018, a log piece was recruited in the upstream jam. Additionally, in 2020, a log originally placed in the downstream end moved out of the reach, and a new small piece was recruited in the lower end of the reach in 2021 (Figure 2). Site 3 had 1 new additional LW piece by the end of 2021 (Figure 2). Overall, in Site 1, 78% of wood was mobile (>1 m movement) between 2015 and 2018, 27% of wood was mobile between 2018 and 2020, and 73% of wood was mobile between 2020 and 2021. In Site 2, 6% of wood was mobile from 2015 to 2018, 11% of wood was mobile between 2018 and 2020, and 6% of wood was mobile between 2020 and 2021. LW movement in Site 3 was 40% between 2015 and 2018, 10% between 2018 and 2020 and 45% between 2020 and 2021 (Figure 4).

3.3 | Reach-scale channel adjustment over time

The magnitude of the annual peak streamflow (Q_{Peak}) to the magnitude of bankfull flow (Q_{bf}) explained 31% of the total geomorphic change variance ($R^2 = 0.305$, p-value $= 0.017$) considering all sites (Figure 5a). These relationships were weak considering sites independently. The duration of high flow events was also related to total geomorphic change, but the relation does not appear linear. As such, the number of days per year with $Q > 0.5Q_{bf}$ explained 27% of the total

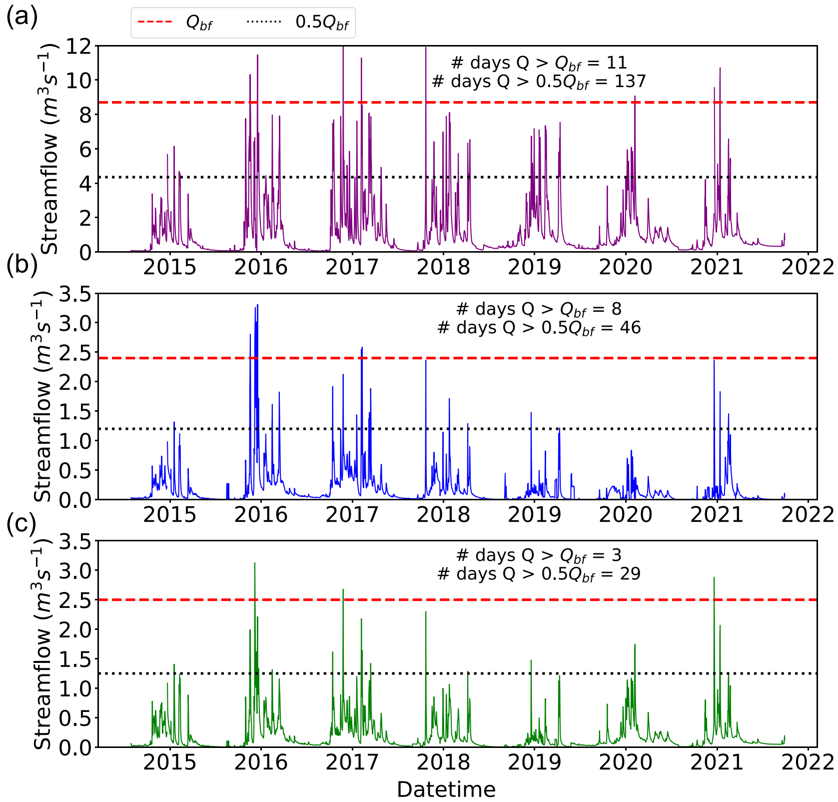

FIGURE 3 Hydrographs for the study reach between 2015 and 2021. The red dashed lines indicate bankfull flow (Q_{bf}), and the black dotted lines indicate half bankfull flow (Q_{bf}) in Site 1 (a), Site 2 (b) and Site 3 (c). The number of days the streamflow (Q) exceeds Q_{bf} and $0.5Q_{bf}$ is indicated on the figures for each site.

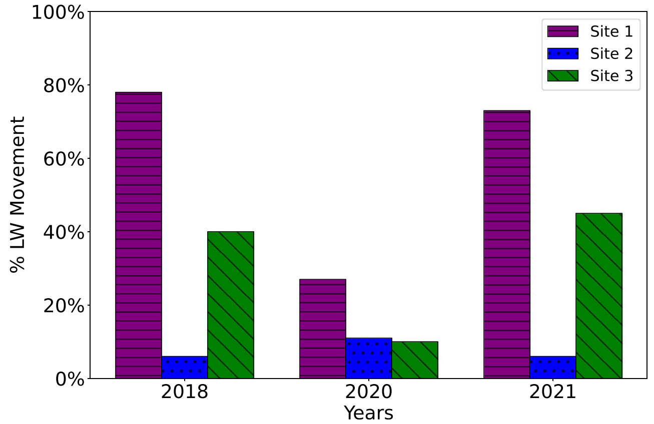

FIGURE 4 Percentage of large wood (LW) pieces that moved out of the total number of LW pieces in each reach from 2015 to 2018, 2018 to 2020 and 2020 to 2021. Here we consider wood movement for any piece that moves more than 1 m in any direction.

geomorphic change variance ($R^2 = 0.269$, p-value $= 0.027$). Total channel change does not increase above ∼15 days per year with Q > $0.5Q_{bf}$ (Figure 5b).

There was no significant relationship between the magnitude of annual Q_{Peak}/Q_{bf} and average scouring across all sites (Figure S9A). Likewise, the number of days when streamflow exceeded $0.5Q_{bf}$ did not account for variations in average annual scour values (Figure S9B). Notably, the annual average scour during the 2015 water year was significantly lower compared with other years (Figure S9A,B).

The magnitude of annual Q_{Peak} relative to Q_{bf} explained 24% of the variance in average annual deposition ($R^2 = 0.236$, $p = 0.041$, Figure S9C). Relationships at individual sites were generally weak, with Site 1 showing the strongest, though still a modest correlation ($R^2 = 0.263$, $p = 0.298$; Figure S9C). No significant relationship was found between the number of days with streamflow exceeding $0.5Q_{bf}$ and average annual deposition (Figure S9D).

Channel scour increased from 2015 to 2021 in all three sites (Figure 6a); however, annual fluctuations in channel scour varied. In Site 1, scour between 2015 and 2021 had a smaller range (between -2.12 m^2/m^2 and -0.94 m^2/m^2) compared with the ranges of scour at the other sites, reflecting the lower variability in annual peak flows in Site 1 (Figure 3). Sites 2 and 3 had a larger variability of annual scouring values, ranging between -7.44 m^2/m^2 (2017) and -4.20 m^2/m^2 (2015) in Site 2 and -6.08 m^2/m^2 (2021) and -2.96 m^2/m^2 (2015) in Site 3 (Figure 6a). All sites experienced the lowest scour in 2015, when annual peak flows were relatively low (Figure 3). The largest scour years in Sites 1 and 2 were in 2017 and 2021 (Figure 6a), during which bankfull flow was either met or exceeded (Figure 3a,b). The greatest year of channel scouring in Site 3 occurred in 2021 (Figure 6a). Increased scouring additionally occurred in 2020 at this site (Figure 6a); however, this was a more moderate flow year (Figure 3c). Sites 2 and 3 experienced 2–3 times larger magnitudes of scour than Site 1 during all years (Figure 6a). The maximum amount of scour relative to pre-treatment conditions in Site 1 was reached in 2021 (2.12 m^2/m^2), Site 2 in 2017 (7.44 m^2/m^2) and Site 3 in 2021 (6.09 m^2/m^2).

Total channel deposition was comparable in magnitude in all three sites, but Site 2 had large amounts of deposition in 2015, while Sites 1 and 3 had their greatest amount of deposition in 2020 and 2021, respectively. Therefore, although the mean total deposition was similar among the sites, annual deposition in Sites 1 and 3 progressively increased while annual deposition in Site 2 progressively decreased (Figure 6a). Annual deposition gradually increased in Site 1 (ranging between 0.56 m^2/m^2 and 2.11 m^2/m^2) and Site 3 (ranging between 1.35 m^2/m^2 and 3.19 m^2/m^2). Deposition at Site 2 showed gradual

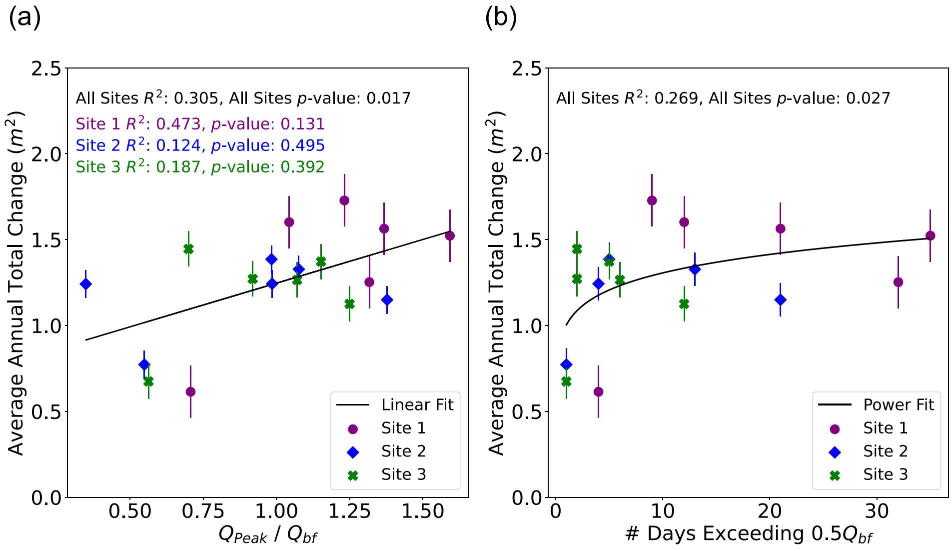

FIGURE 5 Reach-averaged reworked channel area (i.e., |scour| + |deposition|) versus (a) annual peak flows (Q_{Peak}) normalized by bankfull flow (Q_{bf}) and (b) the number of days per year Q > 0.5Q_{bf} and reach-averaged reworked channel. Bars represent the standard error.

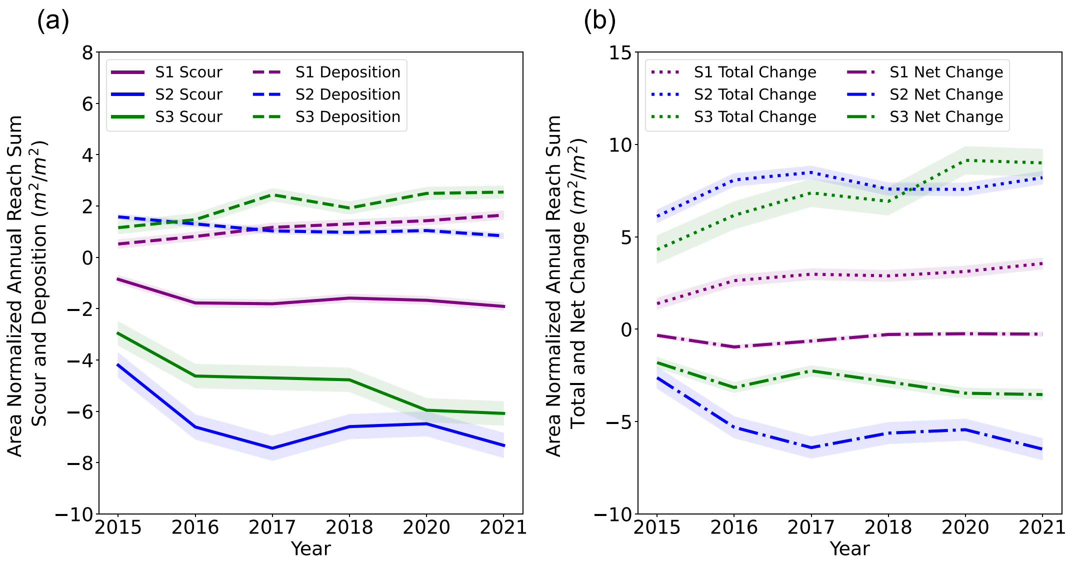

FIGURE 6 (a) Total annual reach sediment scour (m^2) and deposition (m^2) normalized by the reach XS area (m^2). (b) Total reach net change (m^2) and total change (m^2) normalized by the XS area (m^2). Error bands represent the annual standard error across the XS.

annual decreases (0.88 m^2/m^2 to 1.91 m^2/m^2) between 2014 and 2021 (Figure 6a). The highest deposition occurred in 2021 for Site 1 (2.101 m^2/m^2), in 2015 for Site 2 (1.91 m^2/m^2) and in 2020 for Site 3 (3.18 m^2/m^2). Both 2015 and 2020 were low-flow years, while 2021 was a higher-flow year, with all three sites reaching bankfull flow conditions (Figure 3). The annual trends of instream scour and deposition in Sites 1 and 3 exhibit mirrored scour and deposition patterns, indicating that the annual values of scour and deposition increased with comparable magnitudes each year but in opposing directions. Conversely, at Site 2, there was an inverse relationship between scour and deposition, meaning that the degree of scouring continually increased as deposition decreased (Figure 6a).

Overall, all sites had more scour than deposition within the study reach following wood additions. The net change (scour + deposition) was negative in all streams (Figure 6b). Net change in Site 1 was negative but near-zero (−0.919 m^2/m^2 to −0.011 m^2/m^2) between 2015 and 2021, indicating relatively balanced scour and deposition during the period. Scouring was 2.2–8.4 times higher than deposition at Site 2, with net change varying between −6.45 m^2/m^2 and −2.29 m^2/m^2. As such, net changes were the most negative at this site (Figure 6b). Net change values in Site 3 were between the values observed in Sites 1 and 2, varying between −3.08 m^2/m^2 and −1.62 m^2/m^2 across all years (Figure 6b). Similarly to scour, net change increased between 2015 and 2021 in Sites 2 and 3.

Total change (|scour| + deposition) at the reach scale increased over the study period in all sites. Site 1 underwent notably less total change than Sites 2 and 3 (Figure 6b), a result of the relatively smaller changes in deposition and scour in this site (Figure 6a). Despite the lower total change experienced in Site 1 compared with the other sites, continual increases occurred over the years in this site, with a maximum amount of total change relative to the initial conditions taking place in 2021 (4.223 m^2/m^2) (Figure 6b). Due to the continual change in Site 2 both in deposition and scouring between 2014 and 2021, the total change in Site 2 was the highest relative to the initial conditions in 2017 (8.48 m^2/m^2), with modest interannual fluctuations following thereafter (Figure 6b). Increased amounts of total change occurred in both Sites 1 and 2 during higher flow years (Figure 3). Increases in total change were staggered over the years in Site 3, with

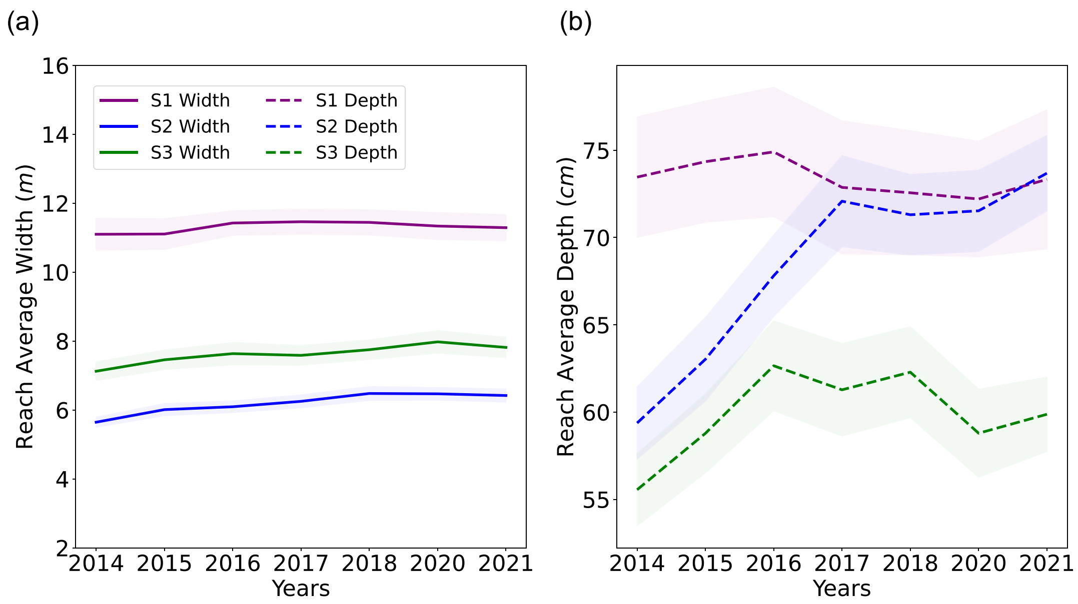

FIGURE 7 (a) Annual changes in the reach averaged width (m). (b) Annual changes in the reach averaged depth (cm) for all three sites. Bands represent the annual standard error of the mean of the XS.

maximum change in 2020 (9.14 m^2/m^2) (Figure 6b), despite this being a low flow year.

Reach-averaged width remained relatively constant between 2014 and 2021, with very slight increases over the years (Figure 7a). Changes in channel geometry predominantly took place vertically as a change in depth. In both Sites 1 and 3, the maximum reach-averaged depth was reached 2 years after the LW introductions in 2016, whereas in Site 2, reach-averaged depth increased consistently over time, and the change in depth at this site was 2.0–5.3 times larger than the change in depth experienced in the other two sites (Figure 7b).

3.4 | Cross-sectional-scale channel adjustments over space

Patterns of deposition generally occurred upstream and downstream of the LW jams (Figure 8). Increased deposition was rarely observed in the XS with LW-present in Site 1 (Figure 8a); however, XS 4 and 5 of the downstream logjam did undergo increased deposition from 2016 to 2020 (Figure 8a). The XS at Site 1 that experienced the greatest deposition (XS 1) had continuously high values of deposition from 2017 to 2021 (Figure 8a). However, XS 19 in this same site developed deposition over time, with no notable deposition in 2016, limited deposition in 2017, 2018 and 2020, but high deposition in 2021, indicating continued channel development over time. Deposition varied at Site 2, with elevated deposition observed between 2015 and 2021 across all XS (Figure 8c). Relative to the entire reach, increased deposition levels were observed in XS 8 and XS 28 in Site 2 between 2015 and 2021 (Figure 8c). High deposition adjacent to the LW jams occurred after 2017 in Site 3; however, slightly higher deposition was also observed in this site in 2015 near XS 11–13 (Figure 8e). In all three sites, increased deposition at the XS scale primarily occurred after 2017, with few exceptions in Sites 2 and 3 that occurred in 2015.

Patterns of scour generally overlap with LW-present in all three sites (Figure 8). In Site 1, substantial scouring was primarily concentrated within the LW locations and at XS 18 (Figure 8b). In Site 2, more sporadic scouring patterns occurred compared with the other sites, with increased scour occurring within and slightly beyond the LW locations. Increased scour additionally occurred in Site 2 at XS 1 between 2016 and 2017 and at XS 5 in 2021 (Figure 8d). In Site 3, scouring predominantly occurred within the XS with LW-present, except for XS 1, XS 18–20 and XS 28 (Figure 8f). Across all sites, increased XS scour primarily occurred after 2016.

The magnitude of scour across the LW jam placements was strongly related to the volume of space the logs occupy in a given stream segment (VBR). As such, LW volume divided by the averaged bankfull area of the XS in contact with the LW times the length of the LW jam was related to the area normalized scour in these XS. We found that VBRs of 0.2–0.4 were associated with monotonic increases in scour (Figure 9a). Our observations for a LW jam with a blockage ratio of 0.6 indicate that scour consistently peaks when the VBR is somewhere between 0.35 and 0.5. However, our data is insufficient to infer scour for VBRs below 0.2 or above 0.6. We considered both a linear fit and a 2-degree polynomial fit to illustrate possible relationships between blockage ratio and scour (Figure 9a). The polynomial fit illustrates that the fit is not monotonically linear.

An annual curvilinear model between the VBR and XS area-normalized scour indicated that scour around the LW structures peaked in the later years of the study (2018–2020), 4–6 years after the LW introduction (Figures 9b and S10).

3.5 | Reach-scale surface sediment changes over time

Averaged over all the XS within each site, changes over the 7 years indicate modest fining of all sediment size fractions (D_{16}, D_{50} and

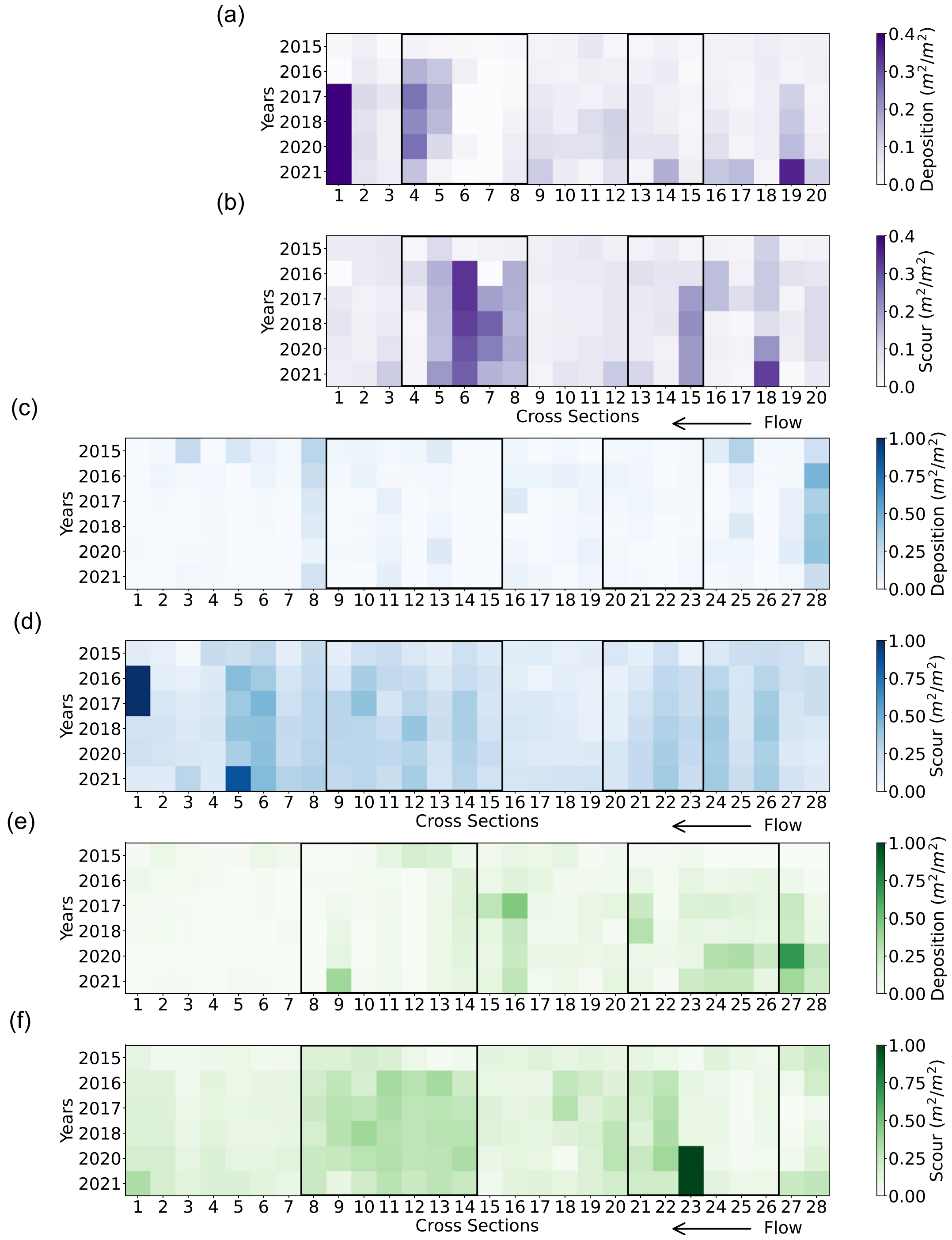

FIGURE 8 (a and b) Annual XS area-normalized deposition (m^2/m^2) and scour (m^2/m^2) in Site 1 from 2015 to 2021. (c and d) Annual XS area-normalized deposition (m^2/m^2) and scour (m^2/m^2) in Site 2 from 2015 to 2021. (e and f) Annual XS area-normalized deposition (m^2/m^2) and scour (m^2/m^2) in Site 3 from 2015 to 2021. Black outlines show the locations of the two logjams in each site. Darker colours signify more geomorphic change than lighter colours. Average distance between XS in Site 1 was 5.7 m, Site 2 was 3.2 m and Site 3 was 3.9 m.

D_{84}). The coarse fraction (D_{84}) of Site 1 abruptly fined 1 year after the LW introductions in 2015 and moderately fined in succeeding years (Figure 10a). Modest fluctuations of fining and coarsening of the D_{50} and D_{16} in Site 1 occurred over the 7 years. All size fractions in Site 2 gradually coarsened between 2014 and 2018 but uniformly fined to the original grain sizes in the following years (Figure 10b). Modest interannual fluctuations of coarsening and fining trends for all size classes were observed in Site 3 between 2014 and 2021 (Figure 10c). Throughout all years and across all sites, coarse and fine sediment was present (Table S1). While the values of the D_{16}, D_{50} and D_{84} did moderately fluctuate, only a moderately significant temporal fining trend was found for D_{84} in Site 1 (Table S2).

3.6 | Cross-sectional-scale surface sediment changes over space

Sediment in all three reaches was relatively poorly sorted before the LW introductions, with median gradation coefficients ranging

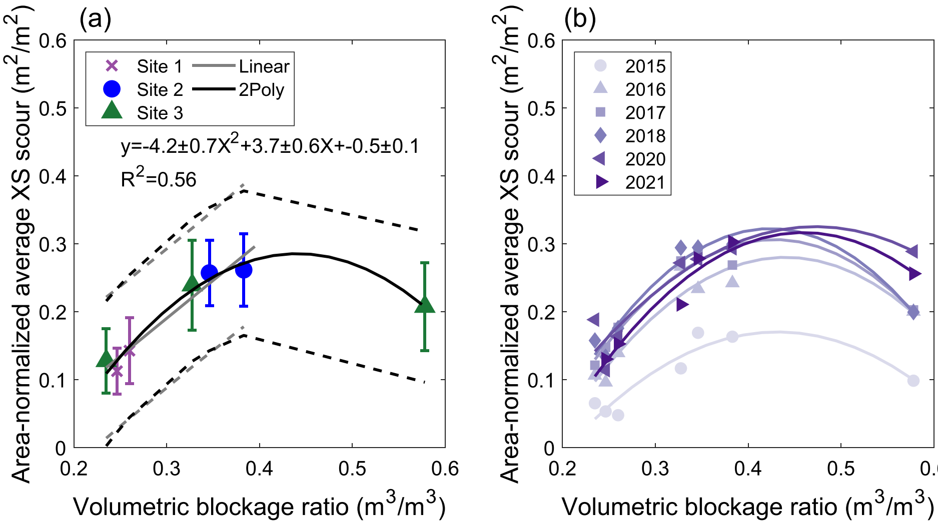

FIGURE 9 Volumetric blockage ratio (large wood [LW] jam volume/channel volume) as a function of mean area-normalized XS scour (m^2/m^2) around each LW jam. (a) Values per LW jam across 6 years; the line is a 2-degree fit with 95% confidence intervals (CIs); error bars represent the standard deviation in scouring (m^2/m^2). (b) Annual observations per jam. Lines indicate 2-degree annual fits (Figures 9a and S10).

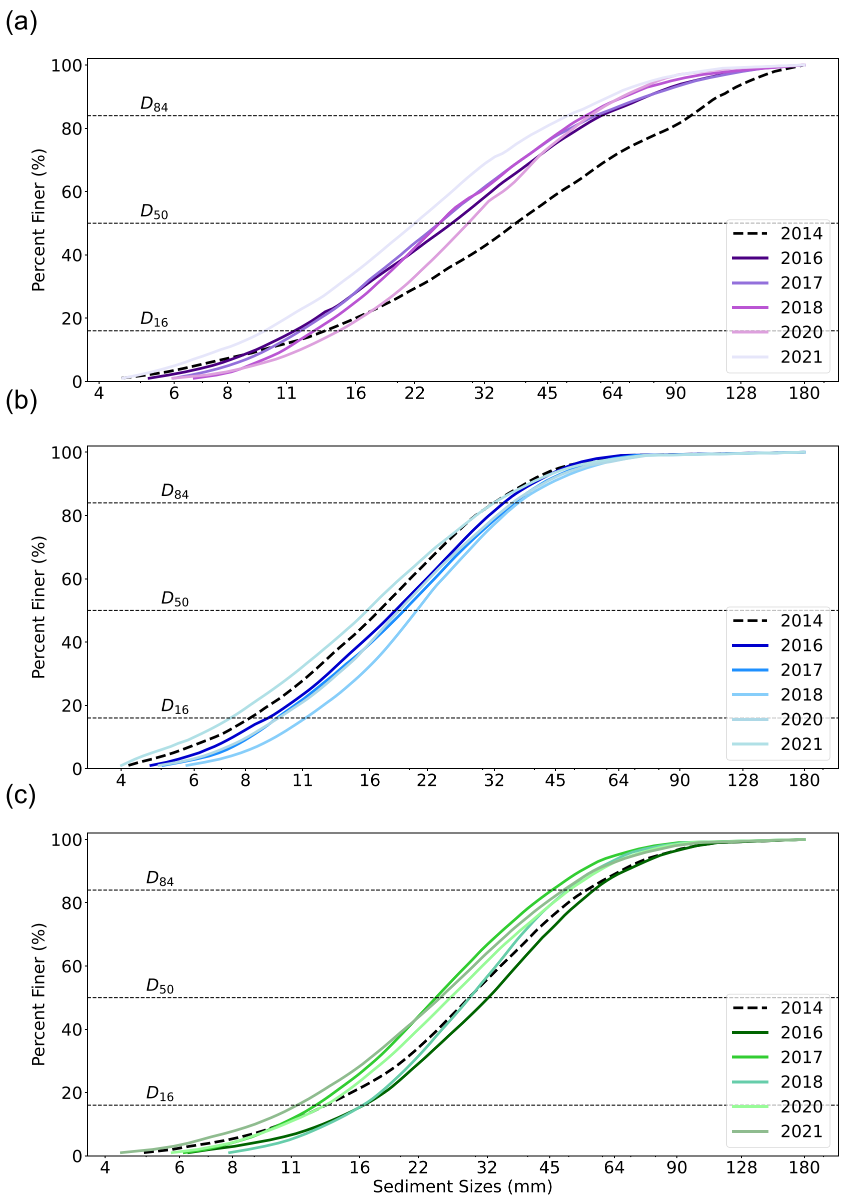

FIGURE 10 Annual reach-averaged cumulative frequency distributions for Site 1 (a), Site 2 (b) and Site 3 (c). The black dashed line is before the LW introduction (2014), and a decrease in line shade corresponds to sediment size distributions in succeeding years.

between 2.74 and 4.70 (Figure 11). In 2016, 1 year following the LW introductions, there was a 29%–49% decrease in the gradation of the surface substrate in all the sites, indicating an increase in sediment sorting. The median gradation coefficient remained within a range of 1.82–2.55 for all sites throughout the remainder of the monitoring period (Figure 11). However, in 2020 and 2021, we observed location-specific increases in the gradation coefficient across all sites, with some XS reaching values above 4.

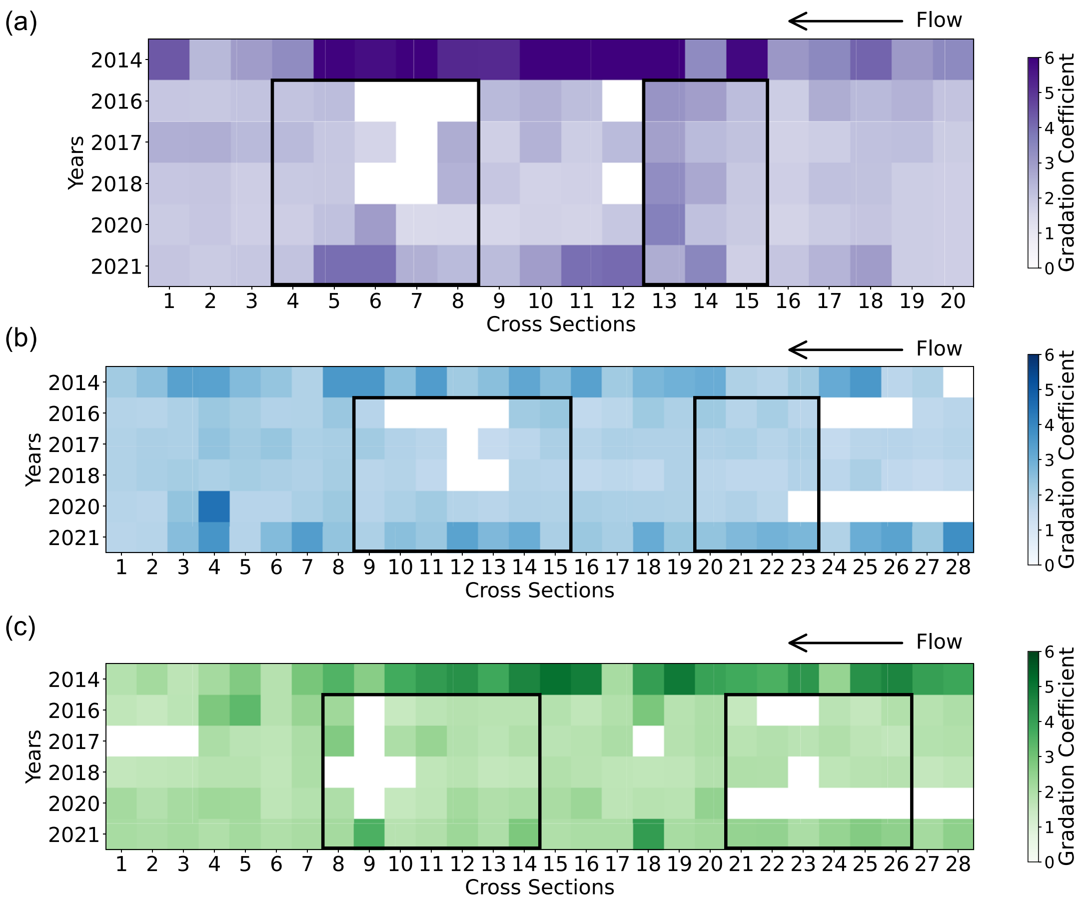

FIGURE 11 Annual XS gradation coefficients for Site 1 (a), Site 2 (b) and Site 3 (c). The black box indicates when (year) and where (XS) the large wood (LW) was present in each site.

TABLE 2 Scaled estimates for each explanatory variable from the linear mixed model outputs of scour and deposition. High variance inflation factors (VIFs) indicate multicollinearity between the covariates. However, multicollinearity wasn't present among the covariates. All values were exponentiated back onto the original scale for interpretation. Due to the transformation back from the log scale, estimate and confidence interval values less than 1 indicate a negative relationship and above 1 indicate a positive relationship. Non-significant variables are denoted with an *.

Model	Covariates	Estimate	Std. error	95% CI	VIF
Scour	Intercept	0.184	1.127	(0.155, 0.214)	-
	LW-present	1.388	1.068	(1.224, 1.549)	1.097
	Width	1.746	1.055	(1.593, 1.929)	3.252
	Depth	1.511	1.036	(1.416, 1.606)	1.186
	*D_{50}	1.032	1.037	(0.976, 1.115)	1.137
	Site 2	5.525	1.145	(4.417, 7.178)	4.621
	Site 3	3.371	1.116	(2.781, 4.157)	4.621
Deposition	Intercept	0.348	1.024	(0.254, 0.540)	-
	LW-present	1.355	1.173	(1.058, 1.849)	1.010
	*Width	1.197	1.138	(0.923, 1.446)	3.226
	Depth	0.603	1.089	(0.530, 0.708)	1.184
	D_{50}	0.872	1.089	(0.694, 0.959)	1.348
	Site 2	0.181	1.386	(0.087, 0.287)	4.517
	Site 3	0.290	1.306	(0.174, 0.445)	4.517

Abbreviation: LW, large wood.

3.7 | Influence of large wood on geomorphic processes

On the response scale, median estimated scour was found to be positively related to LW-present (95% CI = [1.224, 1.549]), stream depth (95% CI = [1.416, 1.606]) and stream width (95% CI = [1.593, 1.929]) (Table 2). No strong relationships existed between the median estimated scour and the D_{50} (95% CI = [0.898, 1.044]) (Table 2). The relative influence of width ($\beta = 1.746$) and stream depth ($\beta = 1.511$) was larger than the relative influence of LW-present ($\beta = 1.388$) and D_{50} ($\beta = 1.032$) on median estimated scour (Table 2). Between the sites, Sites 2 ($\beta = 5.525$) and 3 ($\beta = 3.371$) underwent more median estimated scour than Site 1, assuming all other variables were constant.

On the response scale, median estimated deposition had a strong positive relationship with LW-present (95% CI = [1.058, 1.849]) and a strong negative relationship with stream depth (95% CI = [0.530, 0.708]) and the D_{50} (95% CI = [0.694, 0.959]) (Table 2). No strong relationship was found between median estimated deposition and stream width (95% CI = [0.923, 1.446]) (Table 2). The relative influence of LW-present ($\beta = 1.355$) was found to be larger than that of the D_{50} ($\beta = 0.872$) and stream depth ($\beta = 0.603$) on median estimated deposition (Table 2). Between the sites, Sites 2 and 3 both underwent less median estimated deposition compared with Site 1.

4 | DISCUSSION

The goal of this study was to investigate the geomorphic response of small mountain streams to LW introductions in terms of the processes that influence channel geometry and surface substrate. Peak flow conditions were moderate to high over the duration of the study, exceeding bankfull stage multiple times with streamflow rates up to 160% of bankfull flow across sites. Geomorphic change was evident 1 year after the LW introduction, being modestly related to relative streamflow size and duration. Geomorphic change peaked around 3–4 years after the restoration project in all sites, with the smaller sites (Sites 2 and 3) experiencing a larger magnitude of changes than the larger site (Site 1). Scouring was found to be highest in channel XS with wood, while deposition was found to be highest in areas adjacent (upstream and downstream) to XS with wood. However, across the sites evaluated here, scouring was highest at intermediate values of VBRs (i.e., LW jam volume to stream volume). Over time, scouring increased for all three sites, whereas deposition increased in Sites 1 and 3 and decreased in Site 2. LW movement was greatest in the largest site, relative to the smaller sites. Differences in geomorphic response across sites are attributed not only to differences in LW configuration but also to intrinsic differences across sites in terms of channel size, episodes of channel bank erosion, channel confinement and underlying lithology.

As previously documented in various studies on natural occurrences of LW in both small streams (Buffington et al., 2002; Collins, Montgomery, & Haas, 2002; Montgomery et al., 1995; Richmond & Fauseh, 1995; Webb & Erskine, 2003) and large river systems (Abbe & Montgomery, 1996), as well as in studies examining LW introductions in small streams (Flannery et al., 2017; Pess et al., 2022) and large river systems (Brooks et al., 2006), our findings align with the observation that the addition of LW contributes significantly to vertical channel adjustments and the formation of pool habitats (Webb & Erskine, 2003). We also found increased sediment deposition upstream of LW jams (Abbe & Montgomery, 1996; Faustini & Jones, 2003; Nakamura & Swanson, 1993; Ryan, Bishop, & Daniels, 2014; Webb & Erskine, 2003; Welling, Wilcox, & Dixon, 2021; Wohl & Scott, 2017). However, across our three sites, there was variability in the amount of geomorphic change driven by the amount of wood introduced as it relates to the channel size.

Blockage ratios (Gippel et al., 1996; Kail, 2003; Webb & Erskine, 2003) and LW jam height (Mao et al., 2008) have been used as metrics to quantify the amount of wood interacting with the flow and to quantify the relationship between wood amount and pool formation. In this study, we modified these and developed the VBR, which describes the total volume of wood occupying the channel along three dimensions. We use this volumetric ratio because, in a wood jam, flow interaction with channel obstructions is complicated, and any single individual XS is unlikely to capture this. Our results indicated that although LW jams are associated with scouring, the relationship between the VBR and scour may not be linear. Peak amounts of scour occurred for only intermediate levels of VBRs, and we found that the amount of scouring decreased for the VBR above 50%, which we suggest is linked to increases in overbank flow upstream of the wood jam and reduced available shear stress for scouring downstream when flows enter the floodplain (Webb & Erskine, 2003). These observations were at the LW jam scale, which does not represent overall patterns at the reach scale that appear to be related to channel size. Our findings suggest that for our focal system in western Oregon, where there is at least minor floodplain habitat on one or both banks, wood loadings and LW jams that block 50% or more of the channel volume may have more limited scouring effects, suggesting a potential point of diminishing returns. While low scouring near log jams with blockage ratios above 50% was found at our sites, this high blockage ratio could promote scouring outside the channel during overbank flow conditions. This process could over time facilitate changes in channel pattern, including the development of multi-thread channels.

While the best fit for our data in the relationship between scour and VBR was non-linear, our interpretation relies on a high leverage point that indicates a potential blockage ratio threshold in regard to scour. While this relationship may not necessarily apply to other systems where researchers have not found an inflection or maximum geomorphic change for intermediate wood loadings (Addy & Wilkinson, 2019; Livers & Wohl, 2021) or under different channel constraints such as lower floodplain connectivity, it held true for our sites during this time frame. The evidence here for declining scour at higher ratios, which we attribute to flow and energy dispersal on the floodplain, may be relevant to LW restoration efforts that are focused more on creating increased engagement with floodplains than creating additional scour. Although we did not explicitly measure off-channel flow, our data suggests that if restoration goals in a wood addition study include greater flow connectivity with side channels and flood plains, jams should block at least 50% of the channel volume in the target area in small headwater streams. This interpretation warrants greater exploration, as it is important to explore the non-linear relationship over a broader range of wood volumes and channel sizes.

Channel size exerts a primary control on the amount of sediment scour regardless of stream discharge. Reach-scale scour was substantially larger in the smaller sites (Sites 2 and 3) than the larger site (Site 1) for all years, even though all three streams experienced very similar hydrologic regimes during the 7 years. Increased stability of LW pieces in the smaller sites (Dixon & Sear, 2014; Gurnell et al., 2002; Warren & Kraft, 2008) may promote higher scour during high flows. In contrast, scour could be limited in larger sites during high flows because LW pieces have the potential to float and have limited contact with the channel bed. Wood size relative to the channel size influences wood stability or mobility (Dixon & Sear, 2014; Gurnell et al., 2002; Warren & Kraft, 2008). Consistent with findings in other studies (Dixon & Sear, 2014; Ruiz-Villanueva et al., 2016), we observed greater wood movement in the larger site compared with the smaller sites. As such, we found evidence of the control channel size has on scouring. However, no evidence was observed of the influence of channel size on deposition.

The orientation of LW and local characteristics such as channel curvature and lithology likely influenced deposition patterns across sites. Stream XS with LW jams oriented perpendicular to the flow in Site 1 (XS 4–8, 13–15) and Site 3 (XS 21–26) or located in curved stream segments in Site 3 (XS 8–14) had annual increases in deposition (Welling, Wilcox, & Dixon, 2021). Conversely, Site 2, which is relatively straight and had LW jams placed parallel to the flow, had annual decreases in deposition. Another consideration is the lithological differences across sites. Sediment in the channel of Sites 1 and 3 includes basalt and sandstone, while sediment in the channel at Site 2 includes primarily sandstone. The reduced sediment competence of the sandstone results in higher amounts of this type of sediment leaving the system (as observed in Site 2). In contrast, sites with basalt (Sites 1 and 3) are less friable (Fratkin, Segura, & Bywater-Reyes, 2020; O'Connor et al., 2014) and have the potential to retain (deposit) more sediment in the channel.

While the presence of LW in larger natural systems promotes channel widening (Nakamura & Swanson, 1993) or lateral channel migration (Keller & Swanson, 1979; Nakamura & Swanson, 1993), the effects of LW in terms of channel width in small systems are not clear. Some studies have reported channel width increases after LW restoration (Pess et al., 2022), while others have reported channel width decreases (Flannery et al., 2017). In our case, we found minor, if not negligible, changes in channel width over the 7 years for all three sites. The minor channel widening may be attributed in part to added bank stability associated with the presence of bedrock outcrops in the channel banks of Sites 1 and 3.

Increased sediment sorting after LW introductions led to the creation of coarse and fine sediment patches across the XS, resulting in a heterogeneous streambed structure. Because coarse and fine sediment were consistently observed in all three reaches throughout the years, alongside increased sediment sorting after the LW introductions, these results imply sediment was arranged in patches of comparable sizes following the wood addition. While the introduction of LW directly increased sediment sorting initially, local processes are only one factor in stream sediment dynamics. Given that streams in the coast range are mainly coupled with frequent sediment input from the hillslopes (Benda et al., 2005; Brummer & Montgomery, 2006) and the moderate to high flow conditions observed over the duration of this study (7 years), in all study reaches, it is probable that upstream mass-wasting events delivered additional unsorted material to these reaches (Fratkin, Segura, & Bywater-Reyes, 2020; Hassan et al., 2005). In this case, sediment inputs and associated transport of sediment downstream could have likely led to a decline in sediment sorting over the years. Some locations near the log jams additionally showed increased gradation coefficients or poor sediment sorting in the years just following the LW introductions, potentially due to the LW movement. Overall, although we found clear evidence for sediment sorting at wood jam sites soon after wood addition, further research at the riverscape scale is needed to establish conclusive findings on sediment sorting patterns over space and time and the interactions and long-term drivers associated with LW introductions and sediment dynamics.

Overall, 7 years of monitoring indicated that changes in scouring, deposition, depth, width and sediment sorting continued in all sites. While some studies have shown that instream changes dimmish after 3 years (Krall et al., 2019), our study suggests that LW additions promote changes over longer periods, similar to observations of natural systems (Crispin, House, & Roberts, 1993; Faustini & Jones, 2003; Goodman et al., 2023). Seven years of data collection captured key channel-forming flows, highlighting the power of longer monitoring periods.

5 | CONCLUSION

Overall, 7 years of monitoring indicated that LW jam additions led to initial changes in scouring, deposition, depth, width (to a lesser degree) and sediment sorting across all three of our Oregon headwater replicate sites. But responses were not limited to the first few years. We found that the streams continue to change across a range of moderate to high flows. While some studies have shown that instream changes diminish after 3 years (Krall et al., 2019), our study suggests that LW additions promote changes over longer periods, similar to observations of natural systems (Crispin, House, & Roberts, 1993; Faustini & Jones, 2003; Goodman et al., 2023). While scour associated with wood loadings has been widely documented, we found that deposition and sediment sorting were also key geomorphic processes influenced by LW additions. Even though there was net overall scour and some of that material left the study reaches, most of the deposition occurred locally, and the deposition was a critical part of the whole-reach response. Deposition balanced scour to varying degrees within our study reaches, but even when there was only a small amount of net material loss, the process of scour and deposition led to sorting that created substrate patches. This study also found that while larger obstructions generally increase their effectiveness, the relationship between blockage volume and channel change does not appear linear, suggesting a limit if the goal is to maximize stream channel scour. In our case, peak scouring response occurred when the LW jam volume encompassed about 40% of the stream channel volume. Overall, this work suggests that the amount of geomorphic change is driven by the amount of wood introduced as it relates to the channel size. Continuous monitoring is key because geomorphic response is dynamic and influenced by unpredictable hydrologic forcings.

ACKNOWLEDGEMENTS

This research was supported by the Fish and Wildlife Habitat in Managed Forests Research Program of the College of Forestry, Oregon State University. We express our gratitude to the dedicated contributions during 7 years of field data collection of Ameilia Yaeger, Russel Bair, Joey Tinker, Melissa Mauk, Ellen Luedloff, Cedric Pimont, Will Potter, Jaime Ortega and Jonah Nicholas. Constructive discussions with Ivan Arismendi and statistical support from Dustin Gannon also greatly contributed to the analysis of this study. We also thank the thoughtful reviews by Dan Scott and George Pess.

CONFLICT OF INTEREST STATEMENT

The authors of this paper are not aware of any conflicts of interest. The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Madelyn M. Maffia https://orcid.org/0009-0004-1913-4647
Catalina Segura https://orcid.org/0000-0002-0924-1172
Dana R. Warren https://orcid.org/0000-0001-5282-7972

REFERENCES

Abbe, T. & Brooks, A. (2011) Geomorphic, engineering, and ecological considerations when using wood in river restoration. In: Simon, A., Bennett, S.J. & Castro, J.M. (Eds.) *Geophysical monograph series*. Washington, D. C.: American Geophysical Union, pp. 419–451 https://doi.org/10.1029/2010GM001004

Abbe, T.B. & Montgomery, D.R. (1996) Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research and Management*, 12(2-3), 201–221. Available from: https://doi.org/10.1002/(SICI)1099-1646(199603)12:2/3<201::AID-RRR390>3.0.CO;2-A

Addy, S. & Wilkinson, M.E. (2019) Representing natural and artificial in-channel large wood in numerical hydraulic and hydrological models. *WIREs Water*, 6(6), e1389. Available from: https://doi.org/10.1002/wat2.1389

Bair, R.T., Segura, C. & Lorion, C.M. (2019) Quantifying the restoration success of wood introductions to increase coho salmon winter habitat. *Earth Surface Dynamics*, 7(3), 841–857. Available from: https://doi.org/10.5194/esurf-7-841-2019

Bates, D., Maechler, M., Bolker, B. & Walker, S. (2010) Package 'lme4'.

Benda, L., Hassan, M.A., Church, M. & May, C.L. (2005) Geomorphology of steepland headwaters: the transition from hillslopes to channels. *JAWRA Journal of the American Water Resources Association*, 41(4), 835–851. Available from: https://doi.org/10.1111/j.1752-1688.2005.tb03773.x

Brooks, A.P., Howell, T., Abbe, T.B. & Arthington, A.H. (2006) Confronting hysteresis: wood based river rehabilitation in highly altered riverine landscapes of south-eastern Australia. *Geomorphology*, 79(3-4), 395–422. Available from: https://doi.org/10.1016/j.geomorph.2006.06.035

Brummer, C.J., Abbe, T.B., Sampson, J.R. & Montgomery, D.R. (2006) Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. *Geomorphology*, 80(3-4), 295–309. Available from: https://doi.org/10.1016/j.geomorph.2006.03.002

Brummer, C.J. & Montgomery, D.R. (2006) Influence of coarse lag formation on the mechanics of sediment pulse dispersion in a mountain stream, Squire Creek, North Cascades, Washington, United States. *Water Resources Research*, 42, 2005WR004776. Available from: https://doi.org/10.1029/2005WR004776

Buffington, J.M., Lisle, T.E., Woodsmith, R.D. & Hilton, S. (2002) Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Research and Applications*, 18(6), 507–531. Available from: https://doi.org/10.1002/rra.693

Collins, B.D., Montgomery, D.R. & Haas, A.D. (2002) Historical changes in the distribution and functions of large wood in Puget Lowland rivers. *Canadian Journal of Fisheries and Aquatic Sciences*, 59(1), 66–76. Available from: https://doi.org/10.1139/f01-199

Crispin, V., House, R. & Roberts, D. (1993) Changes in instream habitat, large woody debris, and salmon habitat after the restructuring of a coastal Oregon stream. *North American Journal of Fisheries Management*, 13(1), 96–102. Available from: https://doi.org/10.1577/1548-8675(1993)013<0096:CIIHLW>2.3.CO;2

Dingman, S.L. & Dingman, S.L. (2015) *Physical hydrology*, Third edition. edition. Long Grove, Illinois: Waveland Press, Inc.

Dixon, S.J. & Sear, D.A. (2014) The influence of geomorphology on large wood dynamics in a low gradient headwater stream. *Water Resources Research*, 50(12), 9194–9210. Available from: https://doi.org/10.1002/2014WR015947

DOGAMI. (2011) Oregon Department of Geology and Mineral Industries Lidar Program Data. https://doi.org/10.5069/G9QC01D1

Dolloff, C.A. & Warren, M.L. (2003) Fish relationships with large wood in small streams. *American Fisheries Society Symposium*, 37, 179–193.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., et al. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, 81(2), 163–182. Available from: https://doi.org/10.1017/S1464793105006950

Faustini, J.M. & Jones, J.A. (2003) Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology*, 51(1-3), 187–205. Available from: https://doi.org/10.1016/S0169-555X(02)00336-7

Flannery, J., Stubblefield, A., Fiori, R. & Shea, C. (2017) Observations of channel change from constructed wood jams on a forested gravel-bed stream. *Transactions of the American Fisheries Society*, 146(1), 181–193. Available from: https://doi.org/10.1080/00028487.2016.1235615

Foote, K.J., Biron, P.M. & Grant, J.W.A. (2020) Impact of in-stream restoration structures on salmonid abundance and biomass: an updated meta-analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, 77(9), 1574–1591. Available from: https://doi.org/10.1139/cjfas-2019-0327

Fratkin, M.M., Segura, C. & Bywater-Reyes, S. (2020) The influence of lithology on channel geometry and bed sediment organization in mountainous hillslope-coupled streams. *Earth Surface Processes and Landforms*, 45(10), 2365–2379. Available from: https://doi.org/10.1002/esp.4885

Gippel, C.J. (1995) Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering*, 121(5), 388–395. Available from: https://doi.org/10.1061/(ASCE)0733-9372(1995)121:5(388)

Gippel, C.J., O'Neill, I.C., Finlayson, B.L. & Schnatz, I. (1996) Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. *Regulated Rivers: Research and Management*, 12(2-3), 223–236. Available from: https://doi.org/10.1002/%28SICI%291099-1646%28199603%2912:2/3%3C223::AID-RRR391%3E3.0.CO;2-%23

Goodman, A.C., Segura, C., Jones, J.A. & Swanson, F.J. (2023) Seventy years of watershed response to floods and changing forestry practices in western Oregon, USA. *Earth Surface Processes and Landforms*, 48(6), 1103–1118. Available from: https://doi.org/10.1002/esp.5537

Gurnell, A.M., Piégay, H., Swanson, F.J. & Gregory, S.V. (2002) Large wood and fluvial processes: large wood and fluvial processes. *Freshwater Biology*, 47(4), 601–619. Available from: https://doi.org/10.1046/j.1365-2427.2002.00916.x

Gurnell, A.M. & Sweet, R. (1998) The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms*, 23(12), 1101–1121. Available from: https://doi.org/10.1002/(SICI)1096-9837(199812)23:12<1101::AID-ESP935>3.0.CO;2-O

Hallbert, T.B. & Keeley, E.R. (2023) Instream complexity increases habitat quality and growth for cutthroat trout in headwater streams. *Canadian Journal of Fisheries and Aquatic Sciences*, 80(6), 992–1005. Available from: https://doi.org/10.1139/cjfas-2022-0189

Hassan, M.A., Church, M., Lisle, T.E., Brardinoni, F., Benda, L. & Grant, G.E. (2005) Sediment transport and channel morphology of small, forested streams. *Journal of the American Water Resources Association*, 41(4), 853–876. Available from: https://doi.org/10.1111/j.1752-1688.2005.tb03774.x

Hilderbrand, R.H., Lemly, A.D., Dolloff, C.A. & Harpster, K.L. (1997) Effects of large woody debris placement on stream channels and benthic macroinvertebrates. *Canadian Journal of Fisheries and Aquatic Sciences*, 54(4), 931–939. Available from: https://doi.org/10.1139/f96-334

House, R.A. & Boehne, P.L. (1986) Effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon. *North American Journal of Fisheries Management*, 6(1), 38–46. Available from: https://doi.org/10.1577/1548-8659(1986)6<38:EOISOS>2.0.CO;2

Jones, K.K., Anlauf-Dunn, K., Jacobsen, P.S., Strickland, M., Tennant, L. & Tippery, S.E. (2014) Effectiveness of instream wood treatments to restore stream complexity and winter rearing habitat for juvenile coho salmon. *Transactions of the American Fisheries Society*, 143(2), 334–345. Available from: https://doi.org/10.1080/00028487.2013.852623

Julien, P.Y., 2018. *River mechanics*, 2nd ed. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781316107072

Kail, J. (2003) Influence of large woody debris on the morphology of six central European streams. *Geomorphology*, 51(1-3), 207–223. Available from: https://doi.org/10.1016/S0169-555X(02)00337-9

Keller, E.A. & Swanson, F.J. (1979) Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes*, 4(4), 361–380. Available from: https://doi.org/10.1002/esp.3290040406

Keys, T.A., Govenor, H., Jones, C.N., Hession, W.C., Hester, E.T. & Scott, D.T. (2018) Effects of large wood on floodplain connectivity in a headwater Mid-Atlantic stream. *Ecological Engineering*, 118, 134–142. Available from: https://doi.org/10.1016/j.ecoleng.2018.05.007

Kondolf, G.M. & Wolman, M.G. (1993) The sizes of salmonid spawning gravels. *Water Resources Research*, 29(7), 2275–2285. Available from: https://doi.org/10.1029/93WR00402

Krall, M., Clark, C., Roni, P. & Ross, K. (2019) Lessons learned from long-term effectiveness monitoring of instream habitat projects. *North American Journal of Fisheries Management*, 39(6), 1395–1411. Available from: https://doi.org/10.1002/nafm.10381

Lisle, T.E. (1986) Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. *Geological Society of America Bulletin*, 97(8), 999. Available from: https://doi.org/10.1130/0016-7606(1986)97<999:SOAGCB>2.0.CO;2

Livers, B. & Wohl, E. (2021) All logjams are not created equal. *Journal of Geophysical Research - Earth Surface*, 126(8), e2021JF006076. Available from: https://doi.org/10.1029/2021JF006076

Máčka, Z., Krejčí, L., Loučková, B. & Peterková, L. (2010) A critical review of field techniques employed in the survey of large woody debris in river corridors: a central European perspective. *Environmental Monitoring and Assessment*, 181(1), 291–316. Available from: https://doi.org/10.1016/S0341-8162(98)00120-9

Mao, L., Andreoli, A., Comiti, F. & Lenzi, M.A. (2008) Geomorphic effects of large wood jams on a sub-antarctic mountain stream. *River Research and Applications*, 24(3), 249–266. Available from: https://doi.org/10.1002/rra.1062

Marcus, W.A., Marston, R.A., Colvard, C.R., Jr. & Gray, R.D. (2002) Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology*, 44(3-4), 323–335. Available from: https://doi.org/10.1016/S0169-555X(01)00181-7

Martin, D.J. & Benda, L.E. (2001) Patterns of instream wood recruitment and transport at the watershed scale. *Transactions of the American Fisheries Society*, 130(5), 940–958. Available from: https://doi.org/10.1577/1548-8659(2001)130<0940:POIWRA>2.0.CO;2

Montgomery, D.R. & Buffington, J.M. (1997) Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin*, 109(5), 596–611. Available from: https://doi.org/10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M. & Pess, G. (1995) Pool spacing in forest channels. *Water Resources Research*, 31(4), 1097–1105. Available from: https://doi.org/10.1029/94WR03285

Nakamura, F. & Swanson, F.J. (1993) Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. *Earth Surface Processes and Landforms*, 18(1), 43–61. Available from: https://doi.org/10.1002/esp.3290180104

O'Connor, J.E., Mangano, J.F., Anderson, S.W., Wallick, J.R., Jones, K.L. & Keith, M.K. (2014) Geologic and physiographic controls on bed-material yield, transport, and channel morphology for alluvial and bedrock rivers, western Oregon. *Geological Society of America Bulletin*, 126(3-4), 377–397. Available from: https://doi.org/10.1130/B30831.1

ODFW. (2014) Mill Creek (Siletz) Effectiveness Monitoring Proposal [WWW Document]. Or. Dep. Fish Wildl. Salmon. Life Cycle Monit. URL https://odfwlcm.forestry.oregonstate.edu/lcm-restoration-effectiveness-monitoring

Osei, N.A., Harvey, G.L. & Gurnell, A.M. (2015) The early impact of large wood introduction on the morphology and sediment characteristics of a lowland river. *Limnologica*, 54, 33–43. Available from: https://doi.org/10.1016/j.limno.2015.08.001

Palmer, M.A., Hakenkamp, C.C. & Nelson-Baker, K. (1997) Ecological heterogeneity in streams: why variance matters. *Journal of the North American Benthological Society*, 16(1), 189–202. Available from: https://doi.org/10.2307/1468251

Palmer, M.A., Hondula, K.L. & Koch, B.J. (2014) Ecological restoration of streams and rivers: shifting strategies and shifting goals. *Annual Review of Ecology, Evolution, and Systematics*, 45(1), 247–269. Available from: https://doi.org/10.1146/annurev-ecolsys-120213-091935

Parker, C., Henshaw, A.J., Harvey, G.L. & Sayer, C.D. (2017) Reintroduced large wood modifies fine sediment transport and storage in a lowland river channel: large wood modifies fine sediment transport and storage. *Earth Surface Processes and Landforms*, 42(11), 1693–1703. Available from: https://doi.org/10.1002/esp.4123

Parker, G., Klingeman, P.C. & McLean, D.G. (1982) Bedload and size distribution in paved gravel-bed streams. *Journal of the Hydraulics Division*, 108(4), 544–571. Available from: https://doi.org/10.1061/JYCEAJ.0005854

Pess, G.R., McHenry, M.L., Liermann, M.C., Hanson, K.M. & Beechie, T.J. (2022) How does over two decades of active wood reintroduction result in changes to stream channel features and aquatic habitats of a forested river system? *Earth Surface Processes and Landforms*, 48(4), 817–829. Available from: https://doi.org/10.1002/esp.5520

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. Available from: 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 Drôme River, France. *Catena*, 35(1), 19–39. Available from: https://doi.org/10.1016/S0341-8162(98)00120-9

Popovic, G., Mason, T.J., Drobniak, S.M., Marques, T.A., Potts, J., Joo, R., et al. (2024) Four principles for improved statistical ecology. *Methods in Ecology and Evolution*, 15, 2041–210X.14270. Available from: https://doi.org/10.1111/2041-210X.14270

Powell, D.M. (1998) Patterns and processes of sediment sorting in gravel-bed rivers. *Progress in Physical Geography*, 22(1), 1–32. Available from: https://doi.org/10.1177/030913339802200101

PRISM Climate Group. (2014) Oregon State University, https://prism.oregonstate.edu, data created 4 Feb 2014, accessed 20 Jan 2022.

Richmond, A.D. & Fauseh, 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. Available from: https://doi.org/10.1139/f95-771

Roni, P., Beechie, T.J., Bilby, R.E., Leonetti, F.E., Pollock, M.M. & Pess, G.R. (2002) A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. *North American Journal of Fisheries Management*, 22(1), 1–20. Available from: https://doi.org/10.1577/1548-8675(2002)022<0001:AROSRT>2.0.CO;2

Roni, P., Hanson, K. & Beechie, T. (2008) Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management*, 28(3), 856–890. Available from: https://doi.org/10.1577/M06-169.1

Ruiz-Villanueva, V., Piégay, H., Gurnell, A.M., Marston, R.A. & Stoffel, M. (2016) Recent advances quantifying the large wood dynamics in river basins: new methods and remaining challenges: large wood dynamics. *Reviews of Geophysics*, 54(3), 611–652. Available from: https://doi.org/10.1002/2015RG000514

Ryan, S.E., Bishop, E.L. & Daniels, J.M. (2014) Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado. *Geomorphology*, 217, 73–88. Available from: https://doi.org/10.1016/j.geomorph.2014.03.046

Torizzo, M. & Pitlick, J. (2004) Magnitude-frequency of bed load transport in mountain streams in Colorado. *Journal of Hydrology*, 290(1-2), 137–151. Available from: https://doi.org/10.1016/j.jhydrol.2003.12.001

Walker, G.W. & MacLeod, N.S. (1991) *Geologic map of Oregon*. US Geological Survey. Reston, Virgina.

Warren, D.R. & Kraft, C.E. (2008) Dynamics of large wood in an eastern U.S. mountain stream. *Forest Ecology and Management*, 256(4), 808–814. Available from: https://doi.org/10.1016/j.foreco.2008.05.038

Wasserstein, R.L., Schirm, A.L. & Lazar, N.A. (2019) Moving to a world beyond "$p < 0.05$.". *The American Statistician*, 73, 1–19. Available from: https://doi.org/10.1080/00031305.2019.1583913

Webb, A.A. & Erskine, W.D. (2003) Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. *Geomorphology*, 51(1-3), 109–126. Available from: https://doi.org/10.1016/S0169-555X(02)00327-6

Welling, R.T., Wilcox, A.C. & Dixon, J.L. (2021) Large wood and sediment storage in a mixed bedrock-alluvial stream, western Montana, USA. *Geomorphology*, 384, 107703. Available from: https://doi.org/10.1016/j.geomorph.2021.107703

Whiteway, S.L., Biron, P.M., Zimmermann, A., Venter, O. & Grant, J.W.A. (2010) Do in-stream restoration structures enhance salmonid abundance? A meta-analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, 67(5), 831–841. Available from: https://doi.org/10.1139/F10-021

Wohl, E. & Beckman, N.D. (2014) Leaky rivers: implications of the loss of longitudinal fluvial disconnectivity in headwater streams. *Geomorphology*, 205, 27–35. Available from: https://doi.org/10.1016/j.geomorph.2011.10.022

Wohl, E. & Jaeger, K. (2009) A conceptual model for the longitudinal distribution of wood in mountain streams. *Earth Surface Processes and Landforms*, 34(3), 329–344. Available from: https://doi.org/10.1002/esp.1722

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D.N., Comiti, F., Gurnell, A.M., et al. (2019) The natural wood regime in rivers. *Bioscience*, 69(4), 259–273. Available from: https://doi.org/10.1093/biosci/biz013

Wohl, E. & Scott, D.N. (2017) Wood and sediment storage and dynamics in river corridors: wood and sediment dynamics in river corridors. *Earth Surface Processes and Landforms*, 42(1), 5–23. Available from: https://doi.org/10.1002/esp.3909

Wolman, M.G. (1954) A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union*, 35(6), 951–956. Available from: https://doi.org/10.1029/TR035i006p00951

Yazzie, K.C., Torgersen, C.E., Schindler, D.E. & Reeves, G.H. (2023) Spatial and temporal variation of large wood in a coastal river. *Ecosystems*, 27(1), 19–32. Available from: https://doi.org/10.1007/s10021-023-00870-0

SUPPORTING INFORMATION

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

How to cite this article: Maffia, M.M., Segura, C., Lorion, C.M., Suring, E. & Warren, D.R. (2024) Restoring streams with large wood: An analysis of geomorphic changes 7 years post-restoration in small coastal streams. *Earth Surface Processes and Landforms*, 1–18. Available from: https://doi.org/10.1002/esp.6041