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RESEARCH ARTICLE

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How does over two decades of active wood reintroduction result in changes to stream channel features and aquatic habitats of a forested river system?

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Abstract

Since the late 1980s and early 1990s, wood reintroduction has been a commonly assessed stream restoration technique. Many of the efforts have focused on short-term, localized physical changes and response of salmonids to wood reintroduction. Few have examined how long-term, spatially extensive increases in wood loadings alter stream channel morphology and the geomorphic processes responsible for these changes. We used before and after photos as well as a wood storage survey with tagged restoration logs in a small, low-elevation Western Washington watershed to characterize the effects of 23 years of wood additions. In the ∼6 km of wood placement we saw an increase in wood loading and channel-spanning logjams, which contributed to deeper and more frequent pools, a reduction in particle size, increases in sediment storage, reduced stream width, vegetation re-establishment in the riparian zone, and increased development and maintenance of floodplain channels. The largest geomorphic changes occurred due to restoration wood effectively storing pieces moving downstream. These findings imply that the cumulative habitat restoration actions and associated changes to stream habitat conditions are identifiable through comparison of historical and current photos as well as more quantitative habitat metrics. It also demonstrates that wood placement that simulates the function of large key, stable pieces accelerates habitat recovery within basins subjected to historic logging.

KEYWORDS

long-term monitoring, aquatic habitat monitoring, stream restoration, wood placement, wood storage survey

1 | INTRODUCTION

The geomorphic effects of wood in rivers and associated floodplains have been well documented, particularly over the last three decades (Abbe & Montgomery, 2003; Collins et al., 2012; Montgomery et al., 2003; Wohl, 2020; Wohl et al., 2019). Wood is an important component in the creation and maintenance of primary geomorphic features including stored sediment, floodplain channels, and pools, particularly in forested mountain streams (Collins et al., 2012; Montgomery & Abbe, 2006; Montgomery et al., 1995; Wohl & Scott, 2017). However, since ∼2600 BCE wood loadings in rivers have declined globally as a result of riparian harvest, conversion of floodplain forests to other land uses, and instream wood removal (Montgomery et al., 2003; Wohl, 2014). These causes have resulted in wood loadings that are currently much lower than historical levels in many watersheds worldwide (Martens et al., 2019, 2020).

Over the last several decades, increasing wood levels to more natural conditions has increasingly become a goal of habitat restoration (Stout et al., 2018). Common restoration practices include stopping the human removal of wood from channels, allowing wood to naturally accumulate in river systems, actively restoring wood abundance by reintroduction, and riparian protection and restoration (Palmer et al., 2014; Stout et al., 2018). Recently, protection of instream wood has increased in many river systems, although wood removal still occurs, particularly in larger river systems with infrastructure and in rivers used for recreational purposes (Wohl, 2014). Along with riparian protection, riparian restoration is widely recognized as an important means of increasing wood recruitment for long-term wood recovery (Meleason et al., 2003). However, even with changes to riparian areas due to restoration, increases in naturally recruited wood will not begin for 30–100 years (Beechie et al., 2000; Meleason et al., 2003) and recovery to natural wood loading levels is likely to take more than 200–250 years (Martens et al., 2019; Stout et al., 2018). Therefore, relying on passive riparian and stream recovery is unlikely to increase the quality of stream conditions in the near future.

Since the late 1980s and early 1990s, wood reintroduction has been a common stream restoration technique, gradually expanding from smaller, simple in-stream structures in wadable streams to engineered or constructed logjams in larger river systems (Abbe et al., 2018; Roni et al., 2008). Many of these efforts occurred under the auspices of salmon habitat restoration (Bernhardt et al., 2005). Fish habitat restoration research has focused on short-term, localized physical changes to wood reintroduction (Roni et al., 2015) and biological response of salmonids to wood reintroduction (Whiteway et al., 2010), including how relative abundance and density of salmonids have changed with increasing wood abundance (Bennett et al., 2016; Polivka & Claeson, 2020). More recent efforts have focused on multiple wood projects, such as in Europe, where the use of less costly soft engineering techniques (non-fixed wood structures), higher amounts of wood, and larger wood structures were more effective (Kail et al., 2007). These local, active placements of wood structures in Europe are considered an interim measure until passive restoration methods have increased recruitment sufficiently (Kail et al., 2007). However, there still is a lack of research on the geomorphic responses (e.g., pool spacing, sediment storage, and channel type) to long-term, spatially extensive, increases in wood loadings due to multiple decades of restoration effort.

This paper focuses on the following question: How have wood additions led to changes in stream channel characteristics (i.e., sediment storage, pool frequency and depth, streambed particle size, floodplain connectivity, riparian condition, and stream channel type), and what geomorphic processes caused such changes? We use before and after photos throughout the Deep Creek watershed, a wood storage survey incorporating tagged reintroduced wood, and geomorphic surveys of pools, sediment storage, and side channels. We hypothesize that variables altered by increased wood loadings such as local sediment storage, streambed particle size, channel width, roughness, bank condition, and riparian vegetation help create and maintain in-channel attributes and stream channel planform favorable to salmonids. Finally, we discuss how the cumulative restorative action of wood placement over the last 23 years has led to such changes in the Deep Creek watershed.

2 | BACKGROUND

2.1 | Study area

The Deep Creek catchment covers an area of 45 km^2 in the northwest portion of the Olympic Peninsula, Washington State, USA (Figure 1). The geology of Deep Creek is characterized by Crescent Formation volcanic rock in the upper catchment, resulting in steep, confined stream channels (Snavely et al., 1980; United States Forest Service et al., 2002). In contrast, glacial deposits, as well as marine sedimentary rocks, both of which are subject to intense erosion, dominate the middle and lower catchment (Snavely et al., 1980; United States Forest Service et al., 2002).

Precipitation occurs primarily as rain between October and May and averages 190 cm per year (United States Forest Service et al., 2002). Average daily streamflow is less than 2 m^3/s, but can exceed 40 m^3/s, with peak discharge around 57 m^3/s (W. Ehinger, Washington Department of Ecology, unpublished data). Flows during monitoring were typically less than 1 m^3/s. There are three vegetation zones in Deep Creek. Sitka spruce (*Picea sitchensis*) dominated the valley bottom while the lower to mid portions of the catchment is primarily western hemlock (*Tsuga heterophylla*). The silver fir (*Abies amabilis*) zone encompasses the headwaters of Deep Creek (United States Forest Service et al., 2002).

The known disturbance history of Deep Creek dates back to a series of fires in ~1308, ~1508, and several fires between 1895 and 1939 (United States Forest Service et al., 2002). Since the early 1900s, the primary land use in Deep Creek has been industrial forestry (United States Forest Service et al., 2002). During the 1900s, logging road construction and timber harvest increased landslide frequency, while "stream cleaning" activities removed in-channel wood.

The combination of increased landslide frequency and wood removal resulted in a simplified and degraded stream. Salvage logging following the 1939 fire was particularly intense and resulted in widespread watershed degradation. In the 1980s, poorly constructed mid-slope roads caused increasing rates of landsliding, including a large dam break flood event that scoured the upper channel network of Deep Creek. By the mid-1990s, when stream restoration began, Deep Creek had little instream wood, a lack of mature riparian vegetation, and a loss of floodplain connectivity due to stream channel incision from the lack of obstructions such as wood (United States Forest Service et al., 2002).

2.2 | The Deep Creek restoration plan and wood treatments

Starting in the mid-1990s the Lower Elwha Klallam Tribe (LEKT) developed and implemented a watershed-scale restoration plan for Deep Creek (United States Forest Service et al., 2002). The restoration plan focused on reducing the rates of anthropogenic-caused landslides to background levels, recovering riparian forests to provide long-term adequate supplies of in-channel wood, adding wood to offset cumulative losses due to land use impacts, and increasing the amount of floodplain habitats. These physical habitat objectives were linked to biological factors that can limit salmonid survival, including abundance, growth, and productivity. For example, elevated landslide rates can cause mortality of juvenile salmonids due to scour-and-fill events, degradation of salmonid spawning habitat due to sedimentation, and loss of juvenile rearing habitat due to pool loss, floodplain disconnection, and overall channel simplification (Kemp et al., 2011). Reducing these impacts was an immediate goal in order to allow habitat-forming processes to recover naturally. Restoration projects were initiated in 1998 and have continued through the present.

In-channel wood placement was an obvious tool for restoration treatment because it influences many stream channel habitat-forming processes that affect salmonid life histories (Roni et al., 2008). Large wood is known to form pools, store gravels, and can reverse channel incision and improve floodplain connectivity (Abbe & Brooks, 2011; Wohl & Scott, 2017). Increases in floodplain connectivity may also increase formation of floodplain habitats known to be critical overwinter habitats for juvenile coho salmon (Martens & Connolly, 2014).

Restoration treatments implemented from 1998 to 2021 were designed to address the restoration plan objectives in the lower 5 km of Deep Creek. The majority of wood placement in Deep Creek focused on increasing wood loadings in order to increase low-gradient, mainstem habitat quality and quantity (Table 1). Approximately 15 of the 21 projects that were completed over the last 24 years were wood placement efforts. Initial treatments in Deep Creek were in-channel projects that relied upon ground-based wood placement techniques to create static features such as log weirs, sills, and logjams constructed of cut logs. These treatments were generally smaller in overall size, of low profile, and obstructed a relatively small

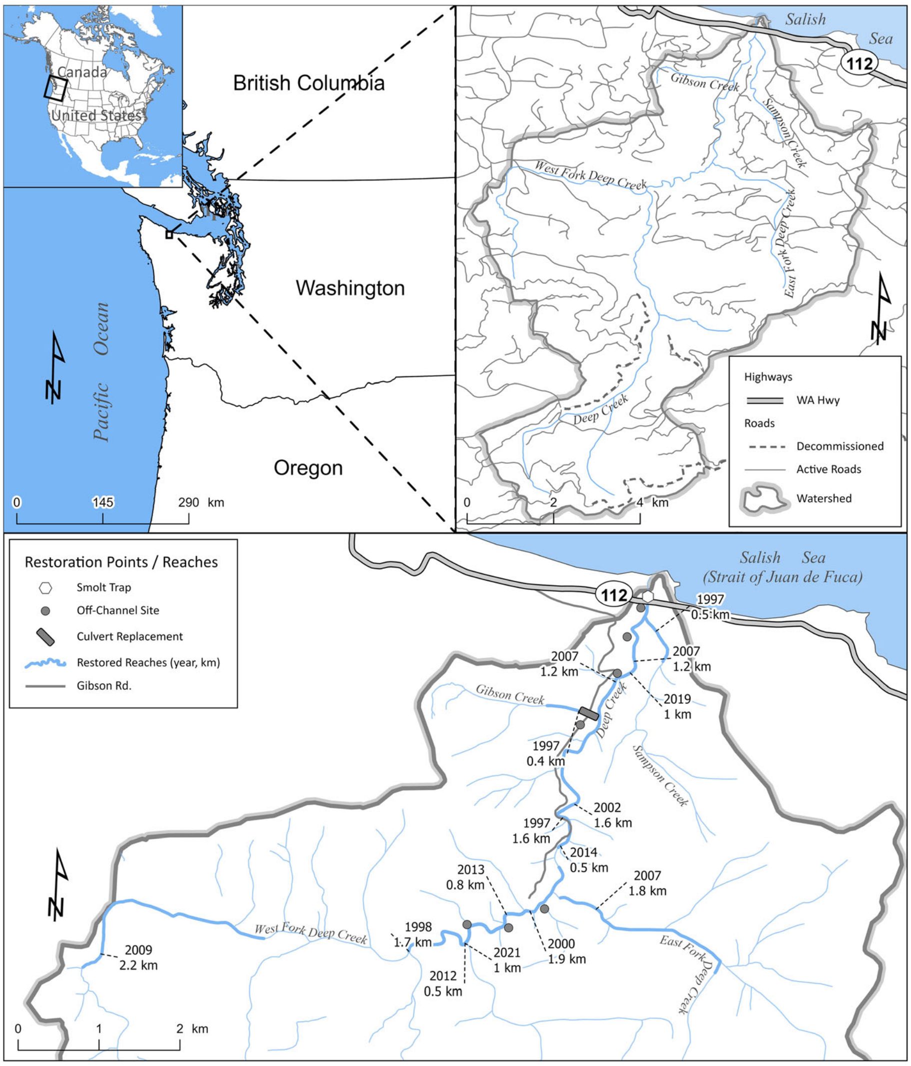

FIGURE 1 Deep Creek catchment and its location in Washington state, and the reach location and time period of wood addition treatments [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Deep Creek stream channel gradient (%) by river kilometer (rkm)

rkm	Average gradient (%)	Minimum gradient (%)	Maximum gradient (%)
0.0 to 0.9	0.00	0.00	0.00
1.0 to 1.9	0.62	0.01	1.86
2.0 to 2.9	0.60	0.01	1.57
3.0 to 3.9	0.58	0.01	1.04
4.0 to 4.9	0.64	0.35	1.12
5.0 to 5.9	0.86	0.14	2.96

percentage of the stream channel cross-sectional area. Some were also to protect the toes of deep-seated landslides from further erosion.

In 2002–2003, the first helicopter wood placement projects were implemented in Deep Creek, using heavy-lift helicopters to fly in key pieces of wood to both previously ground-based treated reaches and into inaccessible habitats. This technology resulted in new or larger jams (adding to ground-based treatments) or individual key pieces throughout a greater portion of the anadromous zone. By 2008, there was a shift away from ground-based wood treatments to helicopter placement of wood.

Additional wood treatments in Deep Creek did not occur for nearly a decade following the completion of ground-based and initial helicopter treatments. This was due to a combination of factors including the inability to procure restoration funds, implementing other project types (i.e., road decommissioning), and the perception that restoration treatments were mostly successful. Newer treatments from 2013 to 2021 exclusively used helicopter placements, addressing the difficulties of accessing treatment areas. Thus, in-channel restoration in Deep Creek was iterative and evolved over time in response to new techniques, as with other watersheds across the USA and beyond (Roni et al., 2015).

Deep Creek restoration efforts were affected by natural disturbance events. In upper Deep Creek, a high percentage of the relatively smaller, low-profile ground-based treatments began to degrade or move in response to large floods in the late 2000s (M. McHenry, personal observation). These movements result in larger aggregations of wood (i.e., full channel-spanning logjams) that had a greater effect on habitat features (i.e., conversion of stream channel types) downstream.

3 | METHODS

3.1 | Qualitative photo analysis

Approximately 80 photographs were taken in Deep Creek in June of 1997 prior to implementing the majority of habitat restoration actions. (Please see Data S1. Supporting information for more detail). The photos were taken at 40 reference locations at 100 m intervals, both mid-channel upstream and downstream views, beginning at river kilometer (rkm) 0.1 and extending upstream to rkm 4.0. These older Kodachrome slides were scanned to JPG format in 2020. The photo points were retaken at the same reference locations (within meters) in digital format during August of 2020.

We compared the 1997 and the 2020 photographs to qualitatively assess geomorphic and habitat responses to wood additions over time (see Supporting Information for all photos). The reference point photos and associated field notes were used to identify multiple stream characteristics. Stream characteristics included the stream channel type (Beechie et al., 2006; Montgomery & Buffington, 1997), general riparian conditions, and the presence or absence of floodplain channels. In-channel characteristics included a qualitative assessment of wood volume, the dominant streambed substrate size, the amount of sediment storage, the frequency of pools, and overall pool area. In all cases, photos and field notes were taken and an assessment was made by the same individual to minimize any observer bias and error.

Stream channel type for each 100 m reach was identified. If stream channel type according to either Montgomery and Buffington classification system (Montgomery & Buffington, 1997) or the Beechie large river classification system (Beechie et al., 2006) changed then it was noted. The Beechie classification system was only used if a reach went from a single thread to multi-thread channel since there is no corresponding channel type in the Montgomery and Buffington classification system. Wood accumulation change was identified as either no change, increased, or decreased, and the major type of accumulation (logjam, spanning wood, engineered logjam, etc.) was noted (Abbe & Montgomery, 2003). Stream substrate change was noted through identification of the dominant substrate type (organics, sand, gravel, cobble, boulder, or bedrock). If there was a dramatic change, such as a channel type change, then features and trends were noted, including gravel bars, forested islands, and streambed fining and sorting. Changes to sediment storage, pool area, or pool depth was noted as either increased, decreased, or remaining the same. Floodplain channels were either present or not present, and riparian area was noted by the most dominant change.

3.2 | Wood storage survey

We carried out a wood storage survey in 2020 in the lower 5.5 km of Deep Creek. We organized the survey by reference point and proceeded from downstream to upstream over a period of eight survey days in August and September. We identified all wood that had been placed in the system, as well as those pieces naturally recruited in order to quantify how wood accumulation and associated stream channel characteristics changed over time with the restorative actions. All placed wood was mapped and individually tagged with a numbered 2-inch aluminum disk the same year it was placed. The wood storage survey attempted to locate all pieces of large wood within the current active channel of Deep Creek. Wood was measured as either single pieces (snags) or aggregations of wood (logjams). We used a minimum piece size of 30 cm in diameter and >3 m in length for both snag and logjam measurements. Logjams were classified as any aggregation of wood with a piece count greater than two.

We used a Trimble Geoexplorer with individual data dictionaries to record wood and stream channel habitat metrics during the survey. For snags, we recorded the tree species, basal diameter, top diameter, root diameter, total length, decay factor, and tag number if present. For logjams, we identified the type (channel-spanning, meander, bar apex, bar top), size (surface area and volume), number of wood pieces, and origin (natural versus restoration). Differences between restoration and naturally recruited wood was determined by a combination of presence of tags, species, and characteristics of wood observed. We had intimate knowledge of the wood placement details over time. Restoration wood was all of conifer origin and consisted of sawn logs (both ends cut) and rootwads. Rootwads were cut on one end and were either Douglas fir (*Pseudotsuga menziesii*), Sitka spruce or western hemlock, and were consistently ∼15 m in length, with diameters ranging from 46 to 81 cm. All other wood not meeting these criteria were considered of natural origin. Other information collected focused on the function of the wood encountered, including whether the individual piece (or multiple pieces or jams) was contributing to channel functions. Those criteria include no effect, storing gravel, forming pools, creating off-channel habitat, and contributing to floodplain connectivity.

During the stream channel morphological survey, we recorded pool location, surface area, maximum depth, outlet depth, and pool-forming factor (bedrock, roots of standing tree, channel bed, snag, and logjam). We calculated residual pool depth for each pool by subtracting the outlet depth from the maximum depth for each pool. For floodplain channels, we recorded their location using GPS and classified its type (side-channel, overflow channel, alcove, or excavated pond). We also classified the floodplain channel forming function (natural wood, restoration wood, other). The wood and morphological metrics used allowed us to conduct an assessment of how wood impacted stream morphology within the watershed. We summarized metrics of pool size and logjam intensity for 500 m reaches. We also used scatter plots to look for potential correlations. We avoided formal statistical analysis because of the small sample size ($N = 11$ reaches).

3.3 | Assumptions, limitations, and inferences

The qualitative nature of the photo analysis, coupled with the limited potential to interpret photographs due to limited perspective and detail, provides enough information to identify only the relative magnitude of change. We also recognize the potential bias in conducting observations more than two decades apart. A shift in perspective on the part of the observer over this time could influence how sites are interpreted, and the desire for a positive outcome in terms of restoration success could lead one to exaggerate changes, even if subconsciously. Lastly, the photos between years were generally taken within several meters of each other; however, where significant channel changes occurred, such as a stream channel avulsion, the differences are larger. Due to these limitations, we cannot infer causation from our results; however, we can determine if the results are consistent with our hypotheses, and attempt to rule out plausible alternative hypotheses where possible. Despite these limitations and constraints, we attempt to build on the original work because of the unique timescale of the study, which is longer than the majority of other works on similar themes.

4 | RESULTS

4.1 | Qualitative photo analysis

We documented multiple qualitative stream channel changes in Deep Creek associated with wood additions between 1997 and 2020 (Figure 2a,b). Wood loadings were observed to have increased extensively in the lower 3.0 km (rkm 0.0 to 3.0) of Deep Creek (Figure 2a). There was also an increase in riparian vegetation in the lower 3.0 km. The number and size of riparian zone trees increased within the lower 2.0 km. New secondary channels were evident in several locations in 2020 (Figure 2a). Forested islands (four) also developed in specific areas of Deep Creek throughout the lower 4.0 km (Figure 2a). Both observed pool area and depth increased for many segments between rkm 2.0 and 3.0, often coupled with increased sediment storage and substrate fining (Figure 2b). Observed pool area increases and substrate fining also occurred in the lower 1.0 km of Deep Creek (Figure 2b).

Figures 3–7 are examples of some of these changes. Between rkm 0.0 and 1.0 we observed that extensive wood accumulation resulted in a visual change from a plane-bed dominated reach to a forced pool–riffle sequence (Figure 3a,b). The creation of an anastomosing stream reach occurred where a mid-channel engineered logjam was created between rkm 0.3 and 0.5, and new channels formed (Figure 2a). Channel narrowing and vegetation recruitment on the stream banks and gravel bar areas also resulted from the change in wood accumulation (Figures 2a and 3b).

For rkm 1.0 to 2.0 there were several significant changes associated with the increase in wood accumulations. A deep-seated landslide from rkm 1.5 to 1.6 revegetated due to the construction of a wood revetment along the toe of the failure on the east bank of Deep Creek (Figure 4a,b). The revetment allowed riparian vegetation, particularly red alder (*Alnus rubra*), to establish on the placed wood as well as the stabilized hillslope (Figure 4b). The wood pieces, combined with the stabilization of the landslide, resulted in a narrower active channel, riparian encroachment and a decrease in the observed width-to-depth ratio through the reach (Figures 2a and 4b). Secondary channels now occur in the majority of Deep Creek between rkm 1.5 and 2.0 (Figure 5a,b).

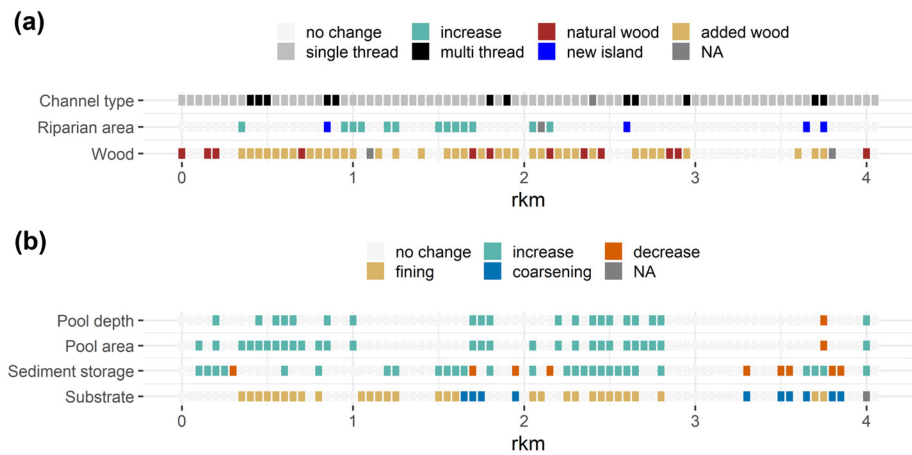

FIGURE 2 (a) Representation of the changes to reach-scale elements of Deep Creek from 1997 to 2020 using photo points from rkm 0.0 to 4.0.
(b) Representation of the changes to in-channel elements of Deep Creek from 1997 to 2020 using photo points from rkm 0.0 to 4.0 [Color figure can be viewed at wileyonlinelibrary.com]

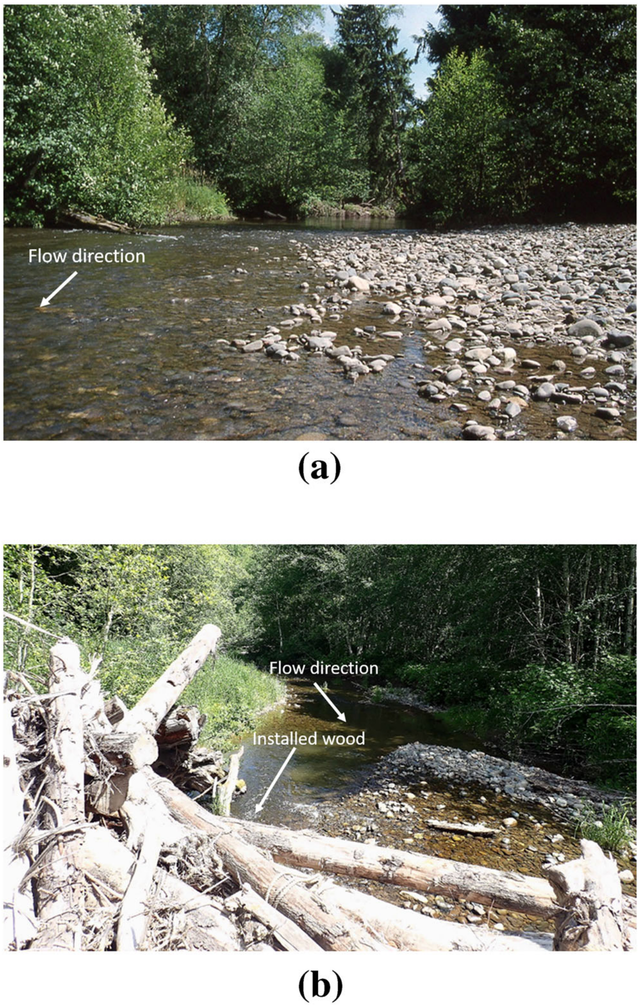

FIGURE 3 (a) Photo points of Deep Creek, rkm 0.0 to 1.0. Plane-bed channel in 1997. (b) Photo points of Deep Creek, rkm 0.0 to 1.0. Forced pool-riffle channel in 2020. Note increased wood and reduced substrate size in 2020 [Color figure can be viewed at wileyonlinelibrary.com]

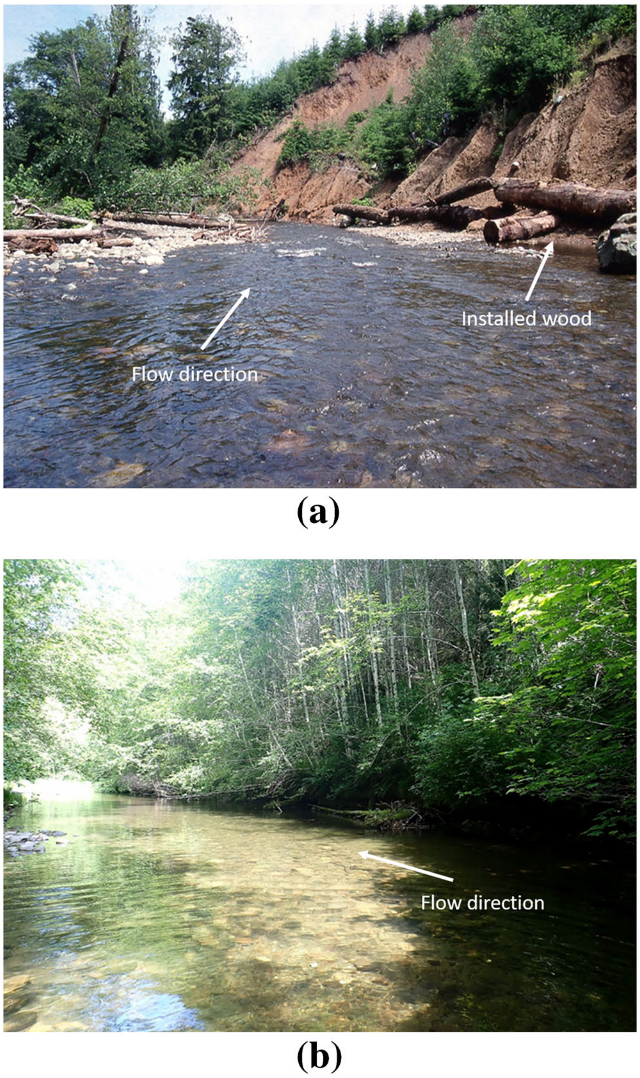

FIGURE 4 (a) Photo points of Deep Creek, rkm 1.0 to 2.0. Deep-seated landslide in 1997. (b) Photo points of Deep Creek, rkm 1.0 to 2.0. Deep-seated landslide revegetation and stabilization in 2020 [Color figure can be viewed at wileyonlinelibrary.com]

Approximately 400 m of Deep Creek between rkm 2.0 and 3.0 was converted from a cobble-dominated substrate with a widened channel and a lack of pools to a reach with reduced streambed particle size, noticeable wood accumulations, and increased pool area (Figure 6a,b). Observed bar deposits are now gravel rather than cobble, and channel narrowing, along with vegetation encroachment, are common. Pools have become more frequent and larger in observed surface area. Wood accumulation areas include channel-spanning logjams at rkm 2.2, 2.7, and 2.8 (Figure 2a). Side channels also now exist at rkm 2.2, 2.4, 2.6, and 2.9 (Figure 2a).

The Deep Creek reach with the identified fewest observed changes was between rkm 3.0 and 4.0. This reach of Deep Creek was identified during restoration implementation as less suited to be treated with the addition of wood. Thus, with the exception of wood placement at rkm 3.7 to 3.9, where the valley begins to widen, there was not significant wood placement. The only changes observed in this reach are associated with an engineered logjam associated island at rkm 3.7, where a side channel and forested island have formed (Figure 2a,b). The area with the logjam has increased sediment storage, streambed fining, increased wood accumulation, and a decreased width-to-depth ratio (Figure 7a,b).

4.2 | Wood storage survey

We measured 2954 total logs. of which 1197 (∼41%) were of restoration origin. Log distribution peaked at rkm 5.0, 4.0, 1.5, and 1.0 at ∼500 logs/km or greater (Figure 8a). Over 75% of the current logjams are the result of restoration efforts (Figure 8b). However, those logjams have retained much of the natural wood that has fallen into Deep Creek and been mobilized downstream (Figure 8a). Logjams/km peak in several locations along Deep Creek, including rkm 5.0, 4.5, 4.0, 1.75, 1.5, and 1.0 at over 20 logjams/km (Figure 8b). In channel segments lacking logjams and associated stable key pieces, there is negligible wood.

The overall number of snags/km increases in the downstream direction, with the majority of snags identified as racked or loose pieces of wood on logjams (Figure 8c). Peak counts of snags over ∼30/km occur at rkm 2.0, 1.75, 1.5, and 0.25 (Figure 8c). Key pieces are distributed in the lower 2.5 km of Deep Creek, with the vast majority in the lower 0.25 km (Figure 8c).

Pool length/km varied between a low of 500 m/km and a high of 875 m/km (Figure 8d). While variation in length was relatively minimal, pool-forming factors switched from being dominated by bedrock

FIGURE 5 (a) Photo points of Deep Creek, rkm 1.0 to 2.0. Secondary channel looking downstream in 2020. (b) Photo points of Deep Creek, rkm 1.0 to 2.0. Secondary channel looking upstream in 2020 [Color figure can be viewed at wileyonlinelibrary.com]

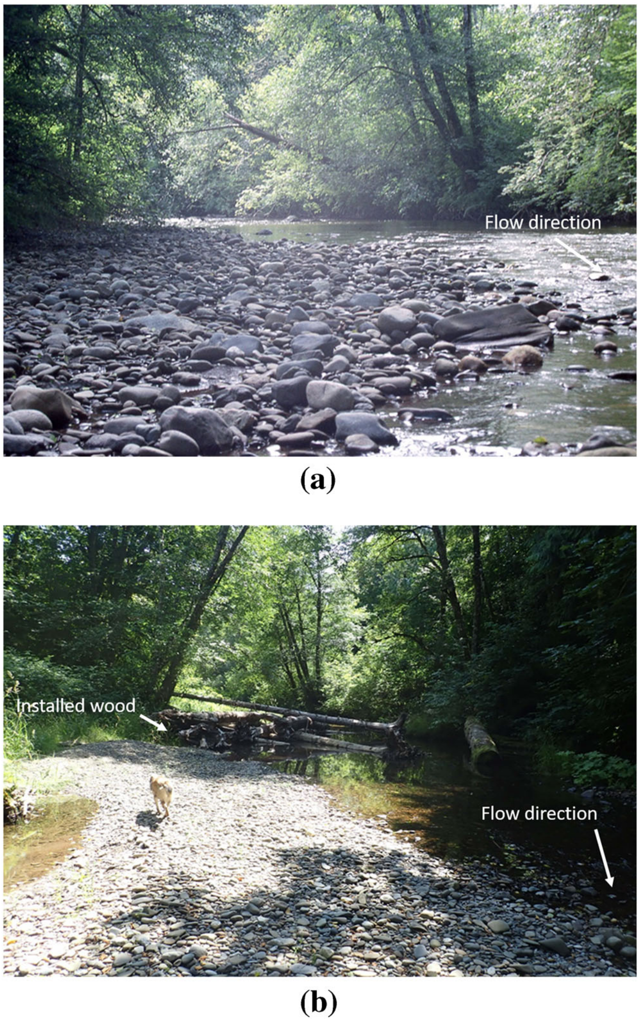

FIGURE 6 (a) Photo points of Deep Creek, rkm 2.0 to 3.0. Plane-bed channel in 1997 prior to wood placement. (b) Photo points of Deep Creek, rkm 2.0 to 3.0. Forced pool-riffle [Color figure can be viewed at wileyonlinelibrary.com]

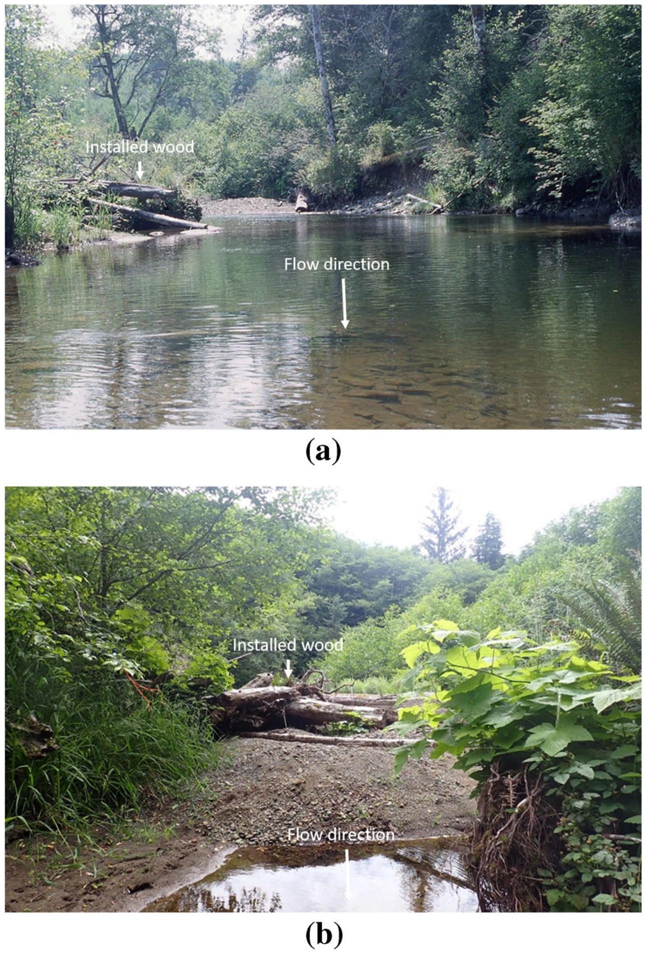

FIGURE 7 (a) Photo points of Deep Creek, rkm 3.0 to 4.0. Photo from 1997. Channel with wood and reduced streambed particle size in 2020. (b) Photo points of Deep Creek, rkm 3.0 to 4.0. Increased sediment storage and vegetation in 2020 [Color figure can be viewed at wileyonlinelibrary.com]

in the upper 3 km to being dominated by restoration logjams in the lower 3 km (Figure 8d). Restoration logjams were also a major contributor to pool formation between rkm 4.0 and 5.5 (Figure 8d). Floodplain channels/km were consistently near 5/km throughout the extent of the study reach, with the exception of rkm 1.5, where the density of floodplain channels was over 15/km (Figure 8e). Over 90% of the floodplain channels in Deep Creek were formed by restoration wood (Figure 8e).

The number of constructed logjams increased over time in Deep Creek (Figure 9). The proportion of logjams that were identified as meander jams was the largest, followed by channel-spanning and bar apex jams (Figure 9). A comparison between constructed and natural logjams reveals a difference in the distribution of logjam type ($\chi^2 = 11.2$, $p = 0.05$) (Figure 10). Meander and channel-spanning jams make up 75% of all constructed jams in Deep Creek (Figure 10). Natural jams have a relative even distribution between channel-spanning, drift/bar, and meander jams. Channel-spanning jams constitute approximately 25% of the jam type, regardless of whether they are constructed or natural jams. Logjam type by location was dominated by meander jams, with the

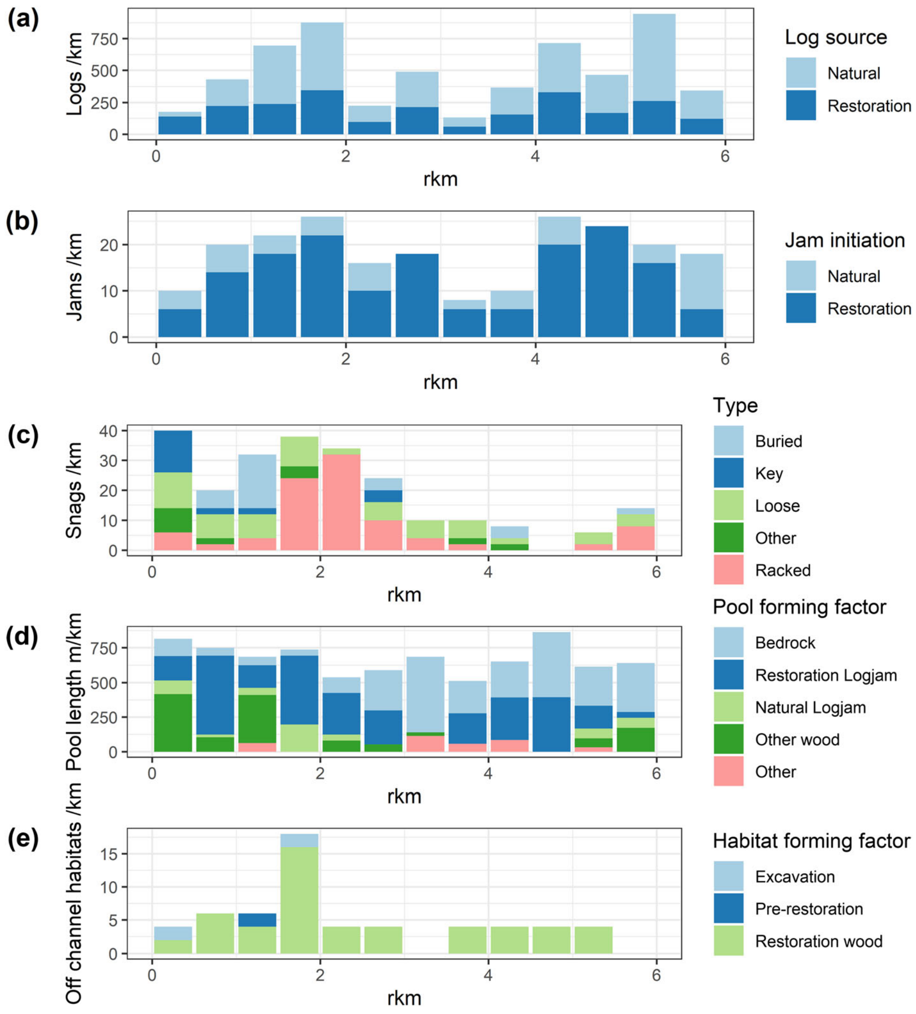

FIGURE 8 Deep Creek wood storage and associated stream characteristics. (a) Restored and natural logs/km. (b) Restored and natural logjams/km. (c) Snags number/km and associated type. (d) Pool length/km and associated pool-forming factor. (e) Floodplain channels/km and associated habitat-forming factor [Color figure can be viewed at wileyonlinelibrary.com]

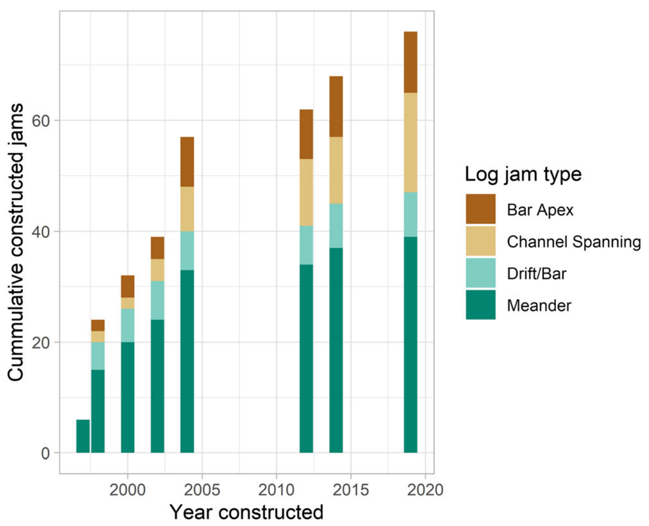

FIGURE 9 Deep Creek cumulative constructed logjams between 1998 and 2021 [Color figure can be viewed at wileyonlinelibrary.com]

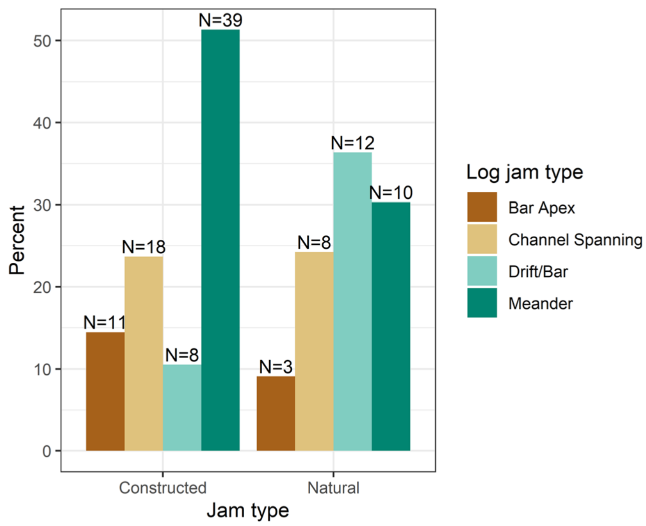

FIGURE 10 Deep Creek natural versus restored logjam type [Color figure can be viewed at wileyonlinelibrary.com]

exception of the lower 1 km, which was dominated by channel-spanning logjams (Table 2).

Pool length varied by pool-forming factor (Figure 11a), with bedrock pools averaging the longest length, but all factors generating fairly similar pool lengths. Jam type was dominated by channel spanning and bar apex jams (Figure 11b). Restoration-initiated jams created larger jam areas than natural jams (Figure 11c). Jam area correlated well with wood-formed pool length (Figure 12a), but not as well with total pool length (Figure 12b). Wood-formed pool length also increased with the number of jams per kilometer and total pieces of wood per kilometer in the lower portion of Deep Creek, but less so in the upper portion (Figure 12c,d).

TABLE 2 Deep Creek logjam type by river kilometer (rkm)

rkm	Meander	Channel spanning	Bar apex	Drift/bar top
0.0 to 0.9	4	6	2	3
1.0 to 1.9	12	5	7	0
2.0 to 2.9	11	2	0	1
3.0 to 3.9	3	0	3	3
4.0 to 4.9	7	3	2	5
5.0 to 5.9	10	5	0	4

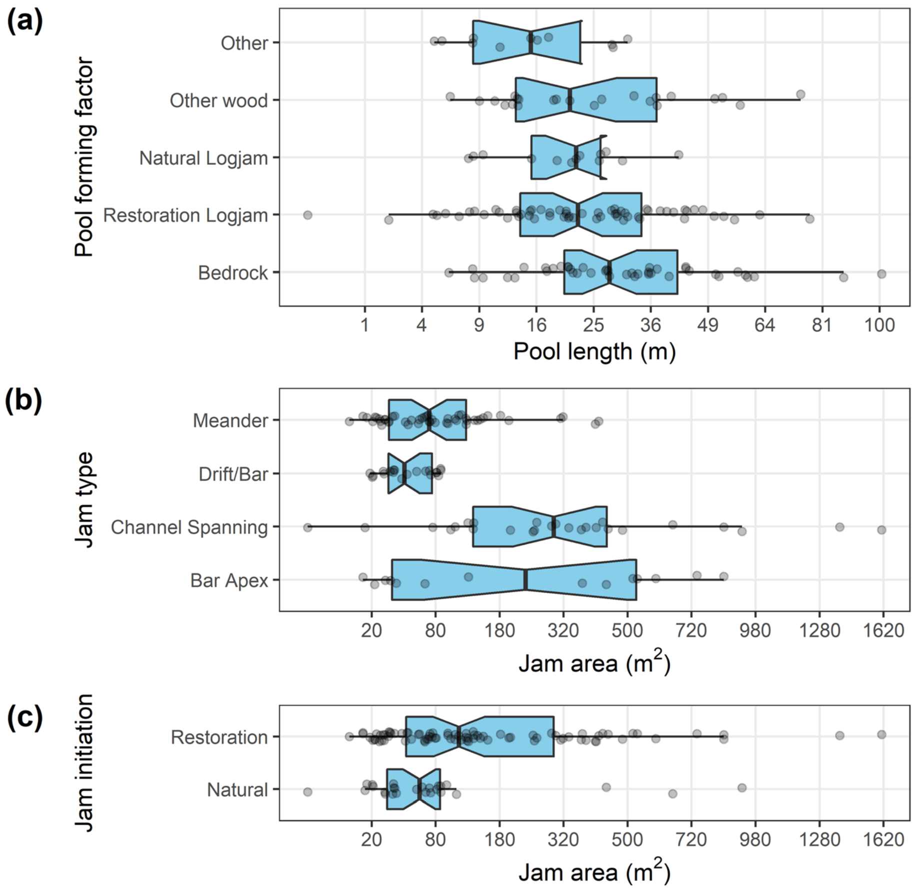

FIGURE 11 Individual pool and jam characteristics broken down by type. For all plots we used a box plot with the data points overlayed and jittered slightly horizontally for easier viewing. Non-overlapping notches indicate a statistically significant difference with an alpha of 5% (McGill et al., 1978). (a) Pool length by pool-forming factor. (b) Jam area by jam type. (c) Jam area by jam initiation type (restoration or natural) [Color figure can be viewed at wileyonlinelibrary.com]

5 | DISCUSSION

Observed changes in the stream channel characteristics of Deep Creek were, in part, due to long-term, continuous, and extensive wood additions. Before and after observations and photo points, and a post-restoration wood storage survey qualitatively and quantitatively aided to capture changes to the stream channel characteristics of Deep Creek due to wood additions. We hypothesize that wood additions aided in the observed changes in pool depth and pool frequency. Wood is critical in maintaining the pool quantity, frequency, and quality in forested settings (Montgomery et al., 1996). Pool length per kilometer in the lower 2 km of Deep Creek tended to be higher than in other reaches and was associated with higher densities of logs and snags (Figure 8b,c).

A downstream transition in pool-forming factors from bedrock-dominated to logjam-dominated in the lower 3 km (Figure 8d), coincided with increased sediment storage and substrate fining, a decrease in stream power, and ultimately changes to stream channel type (Figure 2a,b). Sediment storage due to wood loadings can determine whether a section of stream is alluvial or bedrock (Abbe et al., 2019; Montgomery et al., 1996). Alluvial channels in forest mountain drainages can be highly correlated with a combination of logs that are large, or “key” pieces, plus the occurrence of valley- or channel-spanning logjams (Abbe & Montgomery, 1996, 2003; Montgomery et al., 1996). The valley or channel-spanning logjams can store sediment at the same order of magnitude as what is annually exported as bedload (Abbe & Montgomery, 2003; Welling et al., 2021). A few channel-spanning logjams can store a disproportionate amount of the total sediment stored in a stream reach (Andreoli et al., 2007; Welling et al., 2021). Deep Creek included 26 channel-spanning logjams, with over 60% of all channel-spanning logjams occurring in the lower 3 km (Table 2). This density of channel-spawning logjams correlated with the observed fining of the streambed as well as an increase in sediment storage (Figure 2b).

The wood storage survey also identified that natural wood recruitment occurred and was captured by restoration-initiated logjams, resulting in additional increased wood loading. Natural log accumulation in Deep Creek was highest in areas upstream of restored

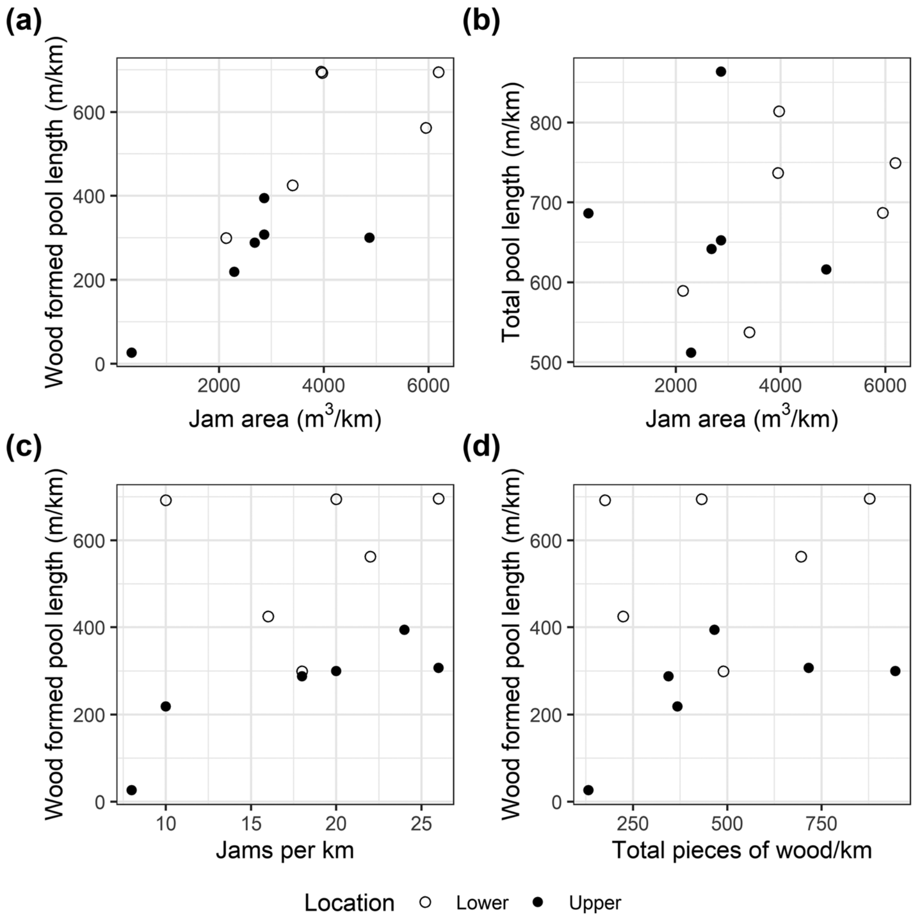

FIGURE 12 Relationship between reach-based summaries of pool area and logjam intensity. (a) Jam area versus pool area (formed by wood). (b) Jam area versus total pool area. (c) Jams versus pool area (formed by wood). (d) Total pieces of wood versus pool area (formed by wood). Point type indicates location in the basin (lower = rkm 0 to 3; upper = rkm 3 to 6)

logjams (rkm 4.0 to 6.0) or upstream of restoration logjams and areas of highest snag density (rkm 0.0 to 2.0) (Figures 8a–c). These restoration-initiated logjams captured natural wood that would otherwise have moved downstream. Sedimentation upstream of the structures can decrease the mobility of natural wood by reducing gradient and flow depths and allowing natural pieces, particularly those with rootwads, to embed themselves further reducing their mobility (e.g., Abbe & Brooks, 2011; Abbe & Montgomery, 1996; Abbe et al., 2019). Natural wood recruitment in these downstream portions of streams from upstream and nearby bank erosion and upstream drift can result in significant downstream accumulations of wood (Steeb et al., 2017).

Stream channel narrowing through vegetation recruitment was also evident through photo points and observation (Figure 2a). Narrowing occurred in the lower 3 km, where log frequency and snag frequency were highest (Figure 8a,c). Protection of riparian areas, in combination with increased frequencies of wood and debris jams, allows vegetation and wood to work together, which can lead to channel narrowing as well as greater heterogeneity in the longitudinal profile of a stream (Abbe & Montgomery, 2003; Mao et al., 2020; Montgomery & Abbe, 2006; Opperman & Merenlender, 2004).

Increased frequencies and duration of wood obstructions can lead to fundamental shifts in larger features. including forested islands, and alter overall stream channel type (Beechie et al., 2006; Montgomery & Buffington, 1997; Mongtomery et al., 1995). New floodplain channels were observed to have formed in over one-third of the lower 4 km of Deep Creek because of restoration wood (Figures 2a and 8e). Floodplain channels can be strongly associated with the presence of wood and logjams (Abbe & Brooks, 2011; Abbe & Montgomery, 1996; Sear et al., 2010). Wood jams retained against riparian vegetation apparently can help a channel bifurcation to originate, persist, and remain active (Bertoldi et al., 2015; Collins & Montgomery, 2002). Historically, it is hypothesized that the association between logjams and floodplains resulted in decreasing the frequency of floodplain turnover, and increasing the overall age and size of riparian trees in the Pacific Northwest (Collins et al., 2012). This can vary with several factors, including the size of stream, climate, disturbance regime, and decay rate of downed wood (Wohl et al., 2019).

Both vegetation and large wood can determine the shape and dynamics of island-braided river systems (Buffington & Montgomery, 1999; Mao et al., 2020), which are often the highest expression of ecosystem integrity within fluvial systems (Francis et al., 2008; Mao et al., 2020). Physical modeling experiments have shown that the inclusion of vegetation, specifically vegetated stream banks, changes wood dynamics in terms of the wood quantity that is stored and the depositional patterns that develop (Bertoldi et al., 2015). Vegetated banks increased channel stability, reducing lateral erosion, and promoted the formation of stable wood jams (Bertoldi et al., 2015). Deep Creek developed several similar traits to what is observed in island-braided systems, particularly in the lower 3 km with stream channel narrowing, wood recruitment, and stable wood jams.

Gravel bar stability and increased vegetation influence were also evident in Deep Creek. Vegetation exerts a strong morphological control within the channel by stabilizing gravel bars (Comiti et al., 2011). One of the mechanisms for island development, after gravel bar stabilization, is the rapid rooting and sprouting of flood-deposited trees (Gurnell & Bertoldi, 2020). In these cases, large wood can play an important role in stabilizing bar surfaces and trapping fluvial sediments, wood, and plant propagules to construct small "pioneer" islands (Edwards et al., 1999; Gurnell & Bertoldi, 2020). Pioneer islands can provide shelter for further vegetation development and sediment retention, and can result in larger forested island development or floodplain extension (Gurnell & Bertoldi, 2020). Gurnell and Petts (2006) proposed that river island development would be most extensive in reaches of intermediate width, where intermediate rates of tree growth would be sufficient to support island development under intermediate levels of unit stream power.

There is a joint impact of riparian woodland and large wood on river channel form and dynamics (Bertoldi et al., 2015; Collins et al., 2012). Wood is produced by standing trees, and both the riparian and wood recruitment and deposition drive a "large wood cycle" (Collins et al., 2012) that may extend over centuries but is easily broken (Bertoldi et al., 2015). We hypothesize that stream channels similar to Deep Creek have a higher probability for island development due to the fact they fall into the intermediate-range size where tree growth and wood size are sufficient to initiate island formation and expansion. One of the key mechanisms that allows wood to have a long-term influence on stream channel form and dynamics in the presence of riparian vegetation is increased wood retention (Bertoldi et al., 2015; Collins & Montgomery, 2002). Increased wood storage can result from a number of processes, including drifting of wood into riparian areas where it is retained, and incorporation of wood pieces into increasingly large jams as they become stable and riparian vegetation becomes denser and more mature (Bertoldi et al., 2015). Wood remobilization becomes less frequent and retention increases due to the increasingly large accumulations of wood, rather than by the retention of isolated wood pieces (Bertoldi et al., 2015).

There were several limitations to our study. The use of qualitative data alone can make the identification of geomorphic changes difficult—particularly, less obvious changes over long time periods. To reduce the potential for observation error, we had the same individual take photos at the geo-referenced locations in 1997 and 2020. In addition, we focused on obvious large-scale geomorphic changes that could be checked with data from the wood storage survey. Another limitation is the single year of quantitative wood data. Having multiple years of wood storage data either at regular intervals, before and after restorative actions, or before and after large-scale flow events, would have allowed us to understand the specific mechanisms that drove the changes documented in 2020. Doing similar work in a control watershed, with no treatment effects, during the same time interval will also allow us to better understand the potential signals from long-term wood additions.

6 | CONCLUSIONS

This study evaluated the geomorphic response of a dynamic gravel-bed river to 23 years of wood additions. In over 50% of the 6.0 km that had been treated, we observed increased wood loadings, more channel-spanning logjams, deeper and more frequent pools, a reduction in particle size distribution, increased sediment storage, reduced stream width, vegetation re-establishment in the riparian zone, and increased development and maintenance of floodplain channels. The largest geomorphic changes occurred in the lower 2.0 km of Deep Creek, in part, due to wood being recruited, mobilized, and routed downstream. These findings imply the cumulative habitat restoration actions and the associated changes to stream habitat conditions are identifiable through comparison of historical and current photos as well as more quantitative metrics produced by the wood storage survey. Such cumulative benefits may only occur at larger extents and longer time periods. River restoration is often measured typically only for a brief time period, such as 3–5 years, and at smaller extents such as less than 1 km (Palmer et al., 2010).

The cumulative restoration efforts in Deep Creek, and the associated geomorphic changes, are an example of anthropogenic impacts that triggered the need for process-based watershed restoration. Process-based restoration includes four principles: (1) addressing the root causes of degradation; (2) incorporation of physical and biological site potential; (3) the scale of restorative actions appropriately scaling to the environmental problem(s); and (4) a clear link between expected outcomes and ecosystem dynamics. The lack of wood in Deep Creek resulted in a simplified stream channel, and increasing wood loading was considered an important first step towards habitat recovery. Many years of restorative actions were necessary due to the magnitude of wood loss over time. Site potential was incorporated during the wood placement, and the allowance and understanding that wood would accumulate throughout the stream, rather than just specific locations. The scale of wood introduction was at the watershed-scale, similar to natural processes of wood recruitment. Lastly, the implementation of a wood storage survey was necessary because wood inputs are dynamic and change over time.

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DATA AVAILABILITY STATEMENT

The data analyzed in this study are available from the corresponding author upon request.

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