GEOMORPHIC EFFECTS OF RESTORATION TO STAGE 0 ALONG DEER CREEK THROUGH SUMMER 2021

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EXECUTIVE SUMMARY

Key Points – The Story of Restoration Along Deer Creek

Context

The lower 2.5 km of Deer Creek was formerly a complex, multi-channel valley bottom, which probably supported a thriving aquatic and riparian ecosystem. Historical human impacts constrained and simplified the stream, taking away the physical integrity needed to support that ecosystem.

Restoration

Valley bottom restoration along Deer Creek had two objectives: 1) in the short-term, create a more complex, habitat-rich river corridor by adding large wood, removing artificial barriers near the stream, excavating high areas, and filling low areas; and 2) over the long-term, give the river the space and ingredients needed to kickstart natural processes that sustain that habitat-rich state. This study documents the initial 2016 restoration and a second phase of restoration in 2020.

What Has Happened Thus Far

Both phases of restoration met their short-term goal of creating a more complex, habitat-rich valley bottom, but differed in meeting their long-term goal. The initial phase of restoration in 2016 did not substantially kickstart natural processes that would sustain a complex state. However, the second phase of restoration in 2020 gave the valley bottom a much harder “kick”. In the year following the second phase of restoration, moderate flows have been able to rearrange both the channel bed and floodplain surfaces, creating side channels, scouring pools, and making the valley bottom even more complex and habitat-rich than it was immediately after restoration. This indicates that the second phase has been sufficient, so far, to meet the goal of spurring natural processes that will likely sustain the restored river corridor.

What Still Remains to Be Seen

This monitoring study only documents one year following the second phase of restoration, and flow during that year was only moderate compared to historical floods. More monitoring over a longer period with more floods will be needed to judge whether restoration along Deer Creek has sustainably restored a complex, habitat-rich state.

Recommendations for Future Monitoring

Some degree of future monitoring would help determine how to take lessons learned from Deer Creek and apply them to making future restoration projects more sustainable. However, it likely doesn’t need to be as intensive or as frequent as the monitoring documented in this report: it can be cheaper, faster, and more targeted, based on the foundation this monitoring has provided.

The 2.5 km of Deer Creek’s valley bottom (i.e., the flat-lying land around the stream) upstream from its confluence with the McKenzie River has been the site of three phases of stream restoration from 2016 through 2021. This restoration has reset the valley bottom topography, restoring Deer Creek from a confined, narrow stream that provided limited habitat for fish, bugs, and streamside vegetation to one that flowed across much more its valley bottom, with a much more complex and habitat-rich character.

This restoration style, known as valley bottom-reset, or process-reset, involves new and untested restoration techniques, so the McKenzie Watershed Council commissioned this study to evaluate implementation of this restoration style along Deer Creek. Restoration involved excavating material from high surfaces adjacent to the stream and using that material to fill in the stream channel, then placing hundreds of logs across the valley bottom. This restoration was not only meant to restore riverine habitat in the short-term by reshaping the valley bottom to a more habitat-rich condition: The primary goal was to restore natural processes, like floods that span the entire valley bottom and rearrange wood and sediment frequently enough to sustain habitat. These processes, known as geomorphic processes, because they reshape the Earth's surface (geo means Earth and morph means shape), are key to sustaining riverine habitat over the long-term. This report details a study of whether restoration along Deer Creek met these goals of restoring a complex valley bottom in the short-term and reactivating the geomorphic processes that will sustain riverine habitat over the long-term (Figure 1).

This report details monitoring of the effects of restoration along Deer Creek through summer 2021 to show how the restoration along Deer Creek affected geomorphic processes. This study builds off of previous monitoring through summer 2018, which is reviewed here but detailed in Scott and Collins (2019).

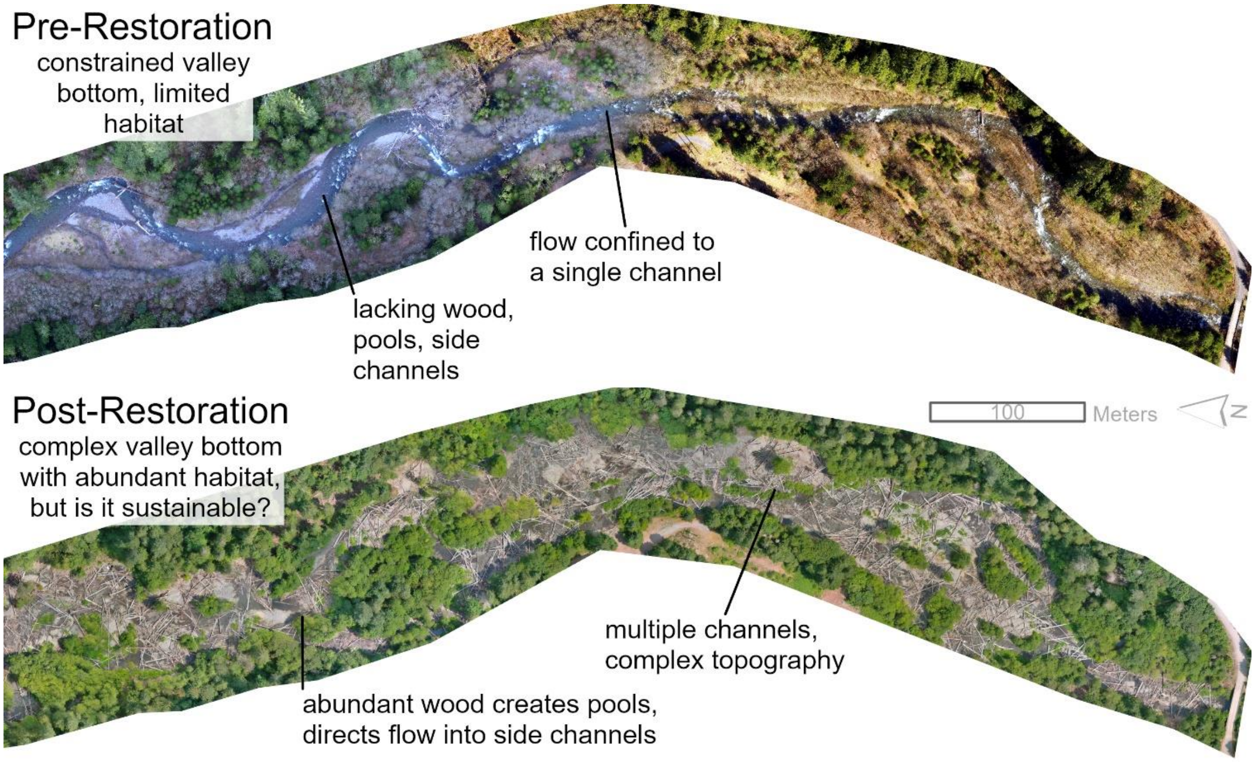


Figure 1: Aerial imagery showing pre- and post-restoration conditions along a portion of Deer Creek. Restoration successfully reset the physical characteristics of the valley bottom, restoring a substantial amount of habitat, but did it reactivate the geomorphic processes that will sustain that condition?

Each phase of restoration has focused on a different portion of the lower 2.5 km of Deer Creek: Phase 1 restoration, implemented in summer 2016, partially reset the valley bottom near the confluence with the McKenzie and upstream of the road bridge (upstream and downstream reaches in Figure 2). Phase 2 restoration occurred upstream of the road bridge and extended the restored area to just upstream of the Budworm Creek confluence (Budworm and upstream reaches in Figure 2). This study describes the outcomes of phases 1 and 2 of restoration along Deer Creek. This study does not discuss the third phase of restoration along Deer Creek, which restored the middle reach, just downstream of the road bridge, in summer 2021.

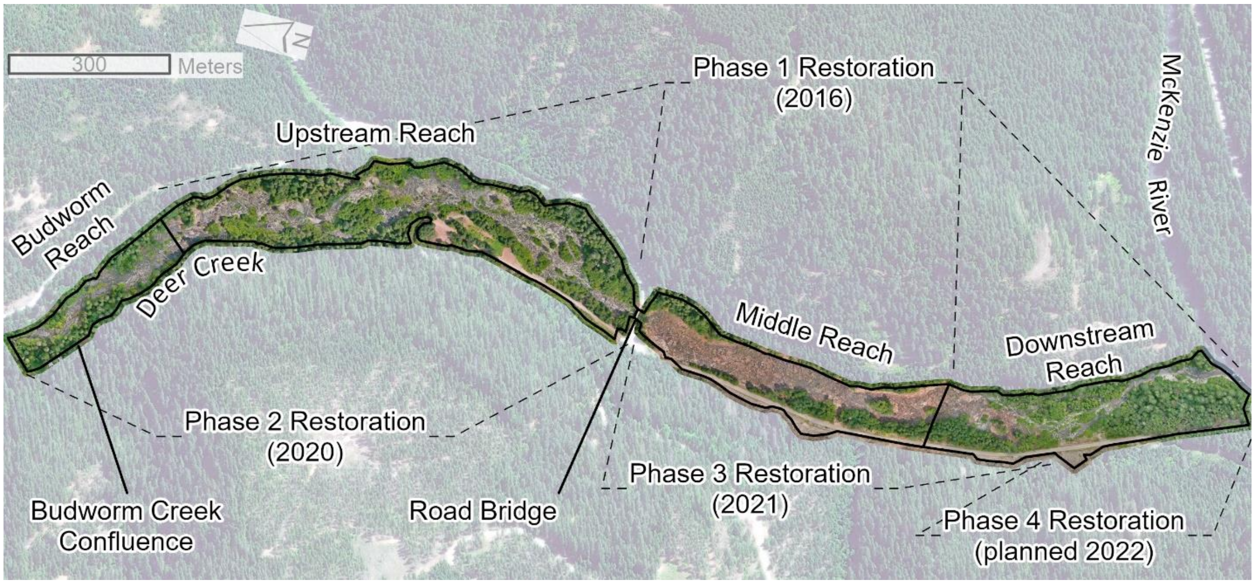


Figure 2: Map of the restored segment of Deer Creek. Dashed lines show the extent of each of the three phases of restoration. This report documents restoration phases 1 and 2 but does not discuss phase 3.

To evaluate the outcome of restoration along Deer Creek, I use metrics of geomorphic forms and processes. Each metric either reflects landforms that provide habitat, like pools, or reflects geomorphic processes that will sustain those habitat features. Geomorphic processes that rearrange and sustain habitat are mainly driven by the flow of water, usually during floods. Floods move sediment and wood around the valley bottom — this keeps pools from filling in, carves new side channels through the floodplain (i.e., the flat, vegetated land near the stream that frequently floods) as old ones vegetate and fill in, and deposits patches of gravel suitable for spawning. However, floods can only perform those beneficial functions when the river has both the room to move laterally across its valley bottom (i.e., space), sufficient amounts of wood to redirect flow across the valley bottom, and enough sediment to deposit on the channel bed (i.e., ingredients).

Figure 3 shows a portion of the restored segment of Deer Creek, highlighting examples of how the river corridor responded to restoration. The following text summarizes that change through time and applies broadly across the restored reaches.

In terms of its immediate effects on the valley bottom, phase 1 restoration:

- Gave the stream more space to move and increased the stream's utilization of that space. By regrading berms that formed terraces (i.e., high, dry surfaces) and filling portions of the channel, phase 1 restoration gave the stream more area over which it could actively move sediment, wood, and water. However, this effect was limited to the upstream reach.
- Increased the area over which the stream was actively reshaping the landscape and creating habitat by spreading flow over a larger proportion of the valley bottom and over more channels.

- Evened out the distribution of elevation across the valley bottom. By excavating high ground and filling low areas, phase 1 restoration evened out the area occupied by pools, shallower parts of the channel, overbank channels, floodplains, and terraces. That is, it flattened out the valley bottom, making it easier for water to spread across multiple channels and over the banks onto the floodplain.

- Created more side channels, or places where flow branches off the former main channel and runs across what used to be terrace or floodplain surface. Side channels, especially forested side channels or those with abundant large wood, are key habitat for salmonids.

- Dramatically increased the amount of large wood in the stream, which also helps provide salmonid habitat and food for the bugs that salmonids feed on. Through manual wood placement and tree tipping, phase 1 restoration tripled the amount of wood in the river corridor.

Flow, especially high flows, cause geomorphic processes. As such, I interpret changes observed along Deer Creek since restoration in the context of the flow history since restoration, indicated by a flow gage on nearby Lookout Creek. Since phase 1 restoration (summer 2016), two moderately high flows (approximately 1500 cfs, or cubic feet per second, on Lookout Creek) in 2017 slightly rearranged the valley bottom, but did not overtop the banks, which is necessary to rearrange the floodplain. Those flows were followed by a higher flow (approximately 2000 cfs on Lookout Creek) in 2019, which did overtop the banks and slightly rearrange the floodplain, but again had little overall geomorphic effect.

More specifically, river corridor geomorphic evolution over the four years between phases 1 and 2 of restoration was characterized by:

- Rearrangement of wood, the growth of vegetation, and only very limited rearrangement of floodplain surfaces, as most flows remained within the banks. This indicated limited lateral flow connectivity, or movement of flow between the channel and surrounding floodplain, which can enhance water quality and sustain riparian vegetation.

- Although the stream had more room to move, it wasn’t utilizing all of that space. In fact, the area over which the stream was actively reshaping the valley bottom consistently decreased following phase 1 restoration. This was primarily due to a lack of substantial erosion.

- Instead, the river corridor, at least under the moderate flows it experienced over this period, was experiencing moderate sediment deposition and the formation and growth of patches of emergent vegetation. Vegetation typically grows in a river on bars that form opposite eroding banks. However, in the case of Deer Creek, vegetation began the process of succession, or growth on newly deposited surfaces in the channel, even without floodplains having been eroded. This indicated a narrowing of the active channel and, overall, a low-energy, depositional environment. This vegetation wasn’t necessarily a bad sign, but it did signal a transition from the river providing habitat in the stream channel to more habitat on floodplains.

- During the first winter after phase 1, moderate flows rearranged the wood that had been placed across the valley bottom, aggregating it into more densely packed wood jams. Little to none of the wood placed in the valley bottom left the restored reaches, and after the first year of rearrangement, wood jams changed only slightly.

Phase 2 restoration again reset the valley bottom, further excavating high surfaces, filling low areas, and adding a tremendous amount of wood. Unlike phase 1 restoration, phase 2 restoration used improved restoration design techniques to more precisely excavated and filled areas to flatten out the valley bottom. Phase 2 also restored the Budworm reach, upstream of the original phase 1 restoration extent (while some trees were tipped in the Budworm reach prior to phase 2, phase 2 was the first major restoration action along the Budworm reach). This phase of restoration had very similar effects as phase 1: increasing the space available for the stream to move and its utilization of that space, evening out the distribution of elevation across the valley bottom, creating even more side channels, and increasing the amount of wood in the stream. However, these immediate effects were of a considerably larger magnitude than those due to phase 1.

In the year following phase 2 restoration, peak flows were again only moderate (approximately 1500 cfs on Lookout Creek). However, their effect on the valley bottom was dramatically greater and spread over a larger area than similar flows in 2017 and even the higher flow in 2019. Phase 2 restoration did what phase 1 restoration did not: After only a moderate flow in the winter following phase 2 restoration, water ran over the banks and substantially rearranged the floodplain, especially in the Budworm reach. This was likely due both to the more targeted and substantial earthmoving and the massive amount of wood that was placed in the channel.

More specifically, in the year following phase 2 restoration:

- Wood rearranged from a loose, distributed pattern to a pattern with more clumps of wood, or wood jams. This caused flow to plunge over these wood jams and scour out more pools. Sediment also deposited upstream of jams, forming more pools and likely forming spawning gravel patches. The increase in pools generally reflected a more complex in-channel habitat mosaic.

- Overbank flows and in-channel flows eroded banks and carved new channels in the floodplain, increasing the channel area along most of the restored reaches. That is, the river essentially gave itself more room to move, especially in the newly restored Budworm reach.

- Flows over the bank into floodplains and even terraces carved numerous forested side channels, which may provide new, high-quality habitat for fish. These overbank flows and newly carved side channels also disturbed the riparian forest and delivered key sediment and nutrients to it. This may enable new vegetation to grow on floodplains in the future, creating a more diverse and vibrant riparian vegetation community.

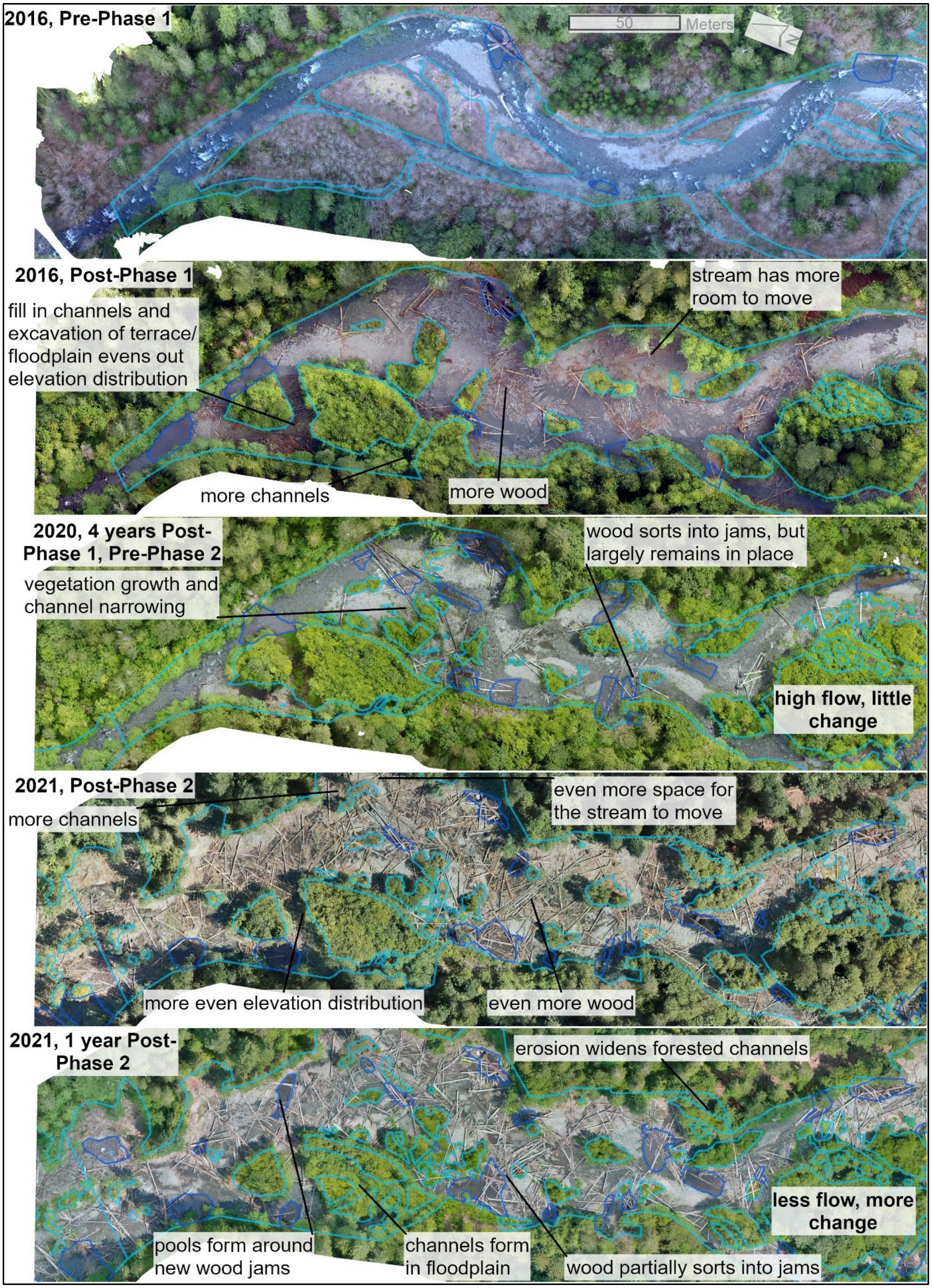


Figure 3: Deer Creek through time. Panels show the upper portion of the upstream reach. Light blue outlines channels and dark blue outlines pools.

Restoration along Deer Creek was not only intended to make the valley bottom more complex and habitat-rich — it was intended to reactivate the processes that will sustain that state in the absence of significant future human intervention. That means that restoration success is not only defined by what the river looks like, but whether it sustains that appearance through time, mainly by the natural process of the river moving across its valley bottom, moving water, sediment, and wood across both the channel and floodplain. Whereas the first phase of restoration restored the physical shape of the valley bottom to a more habitat-rich and diverse condition, the second phase of restoration crucially reactivated the processes that can sustain that restored condition into the future.

The question that still remains is: Will the beneficial natural processes reactivated by phase 2 restoration remain active over the long-term? More monitoring will be needed to answer that question, but it could likely be both less intensive and less frequent than the monitoring described here. Monitoring should be conducted based on the occurrence of high flows, not necessarily annually, and could use cheaper, more rapid methods that simply estimate conditions, as opposed to the more intensive methods used for this study.

This report is organized into three sections: First, this executive summary tells the story of how river restoration changed Deer Creek and is intended for a general audience. Following this summary, the main body of the report details the story of the restoration along Deer Creek, from the pre-restoration condition through to summer 2021, one year after the second phase of restoration. The main body of the report is intended for an audience familiar with river processes and some jargon specific to river science but provides key points summaries of each section that are written for a general audience. Throughout the main body of the report, you will find references to appendices that provide supporting information and are intended for an audience experienced in river science and the field, remote sensing, and statistical methods common to studies of restoration effectiveness.

INTRODUCTION: TELLING THE STORY OF RESTORATION TO A STAGE 0 CONDITION ALONG DEER CREEK

Key Points

- Deer Creek formerly supported a thriving valley bottom ecosystem, but due to historical human impacts, it lost the physical integrity needed to support that ecosystem.
- Restoration of Deer Creek sought to fix that loss of physical integrity by resetting the physical characteristics of the valley bottom, making it more complex. More complex river corridors tend to provide higher quality and more abundant habitat for the fish and vegetation that live around rivers. These messy river corridors also tend to better absorb disturbances, like wildfires or floods. Restoration also sought to provide the river with space to move around and the ingredients, like wood, that the river needed to sustain habitat far into the future.
- This report details a study of whether this restoration succeeded. Success, in this case, is defined by two factors: 1) The restoration needed to recreate a complex riverine landscape, with multiple channels, patches of vegetation, and lots of wood, and 2) the restoration needed to give the river both the space and the ingredients that it needs to sustain that complex landscape as the river naturally changes through time.

Deer Creek used to occupy a broad valley bottom and water likely flowed through multiple channels, with a more even mix of different landforms and the plant species that grow on those landforms, and with a thriving ecosystem, rich with different species of vegetation and animals, like salmon. Historical human interventions, like logging, road building, and construction of a power transmission corridor, constrained and simplified this diverse and messy landscape.

Heterogenous, messy river corridors tend to support abundant, high-quality, and resilient (i.e., able to absorb, or bounce back from, disturbances) physical habitat. In the channel, salmonids tend to benefit from more complex hydraulics (i.e., spatial patterns of flow depth and velocity) that create both slow- and fast-moving and both deep and shallow water (Hughes & Dill, 1990; Moore & Gregory, 1988; Peterson & Quinn, 1996; Quinn, 2018). This flow heterogeneity can also produce heterogeneous bed sediment, which benefits the macroinvertebrates that salmonids feed on (Benke & Wallace, 2003; Pilotto et al., 2016) and can help maintain gravel for salmonid spawning (Flannery et al., 2017; Hassan & Woodsmith, 2004). Zooming out from the channel, heterogeneity in the river corridor can increase lateral connectivity, driving water, sediment, and nutrients from the channel into the floodplain, which can help sustain vegetation that grows around the stream (Amoros & Bornette, 2002; Cadol & Wine, 2017). Together, heterogeneity and the connectivity it can create can make the river corridor more readily absorb disturbances (Fuller et al., 2019; Hall et al., 2018), recovering the physical template that underpins the riverine ecosystem faster after large floods or wildfires. In the case of forested rivers, large wood tends to play a crucial role in regulating the processes that maintain river corridor heterogeneity (Collins et al., 2012; Fausch & Northcote, 1992; Livers & Wohl, 2016). That is, wood is a crucial ingredient that allows natural processes to sustain the physical integrity that underpins river corridor ecosystems.

Historical human activities reduced Deer Creek's capacity to support the fish and other organisms that likely once thrived there. Since 2016, restoration along the lower 2.5 km of Deer Creek has attempted to not only improve the habitat of the animals and vegetation that live around the river, but also reactivate the natural processes that will sustain those living conditions. The historical impacts to the river not only degraded habitat, but largely stopped the important processes that maintain that habitat through time: processes like the development of multiple channels (Stefankiv et al., 2019), the accumulation of wood into jams that can provide salmonid habitat by creating pools, providing cover, and inducing deposition of spawning gravels (Jones et al., 2014; Latterell et al., 2006; Montgomery et al., 2003; Pfeiffer & Wohl, 2018), and the flooding that both delivers water, nutrients, and sediment to floodplains (Wohl et al., 2019) and rearranges the channel, creating and sustaining landforms like pools and spawning gravel.

Deer Creek's capacity to support a thriving riverine ecosystem is a function of both natural geomorphic processes and human interventions. This report details a study of the geomorphic status of Deer Creek through time. By monitoring valley bottom geometry, landform arrangement, vegetation characteristics, and changes in those factors through time, I show how restoration, operating in the context of the natural flows of water, wood, and sediment down Deer Creek, has both reshaped the valley bottom and potentially reactivated the geomorphic processes that are necessary to sustain a complex valley bottom and thriving ecosystem. Because it's too early to tell whether restoration has reactivated geomorphic processes over the long-term, I conclude this report by recommending future monitoring to determine whether restoration has put Deer Creek on a sustainable trajectory of maintaining its current state of complexity and high-quality habitat.

The restoration along Deer Creek, and, more generally, restoration designed to reset a valley bottom and kickstart the processes that will sustain a multi-channel, depositional character, is known as restoration to a Stage 0 condition (explained below). This restoration style is actively being developed, and systematic, critical evaluations of this restoration style's geomorphic effects are limited (Bianco, 2018; Scagliotti, 2019; Scott & Collins, 2019). By comparing the direct impacts of each phase of restoration with their effects on geomorphic processes, I identify key lessons learned from each phase that may guide future restoration towards a Stage 0 condition.

BACKGROUND

Deer Creek Geomorphic Context and Restoration Need

There is little direct evidence of what Deer Creek looked like or the ecosystem it sustained prior to human disturbance, but relict side channels and islands on terraces indicate that the restored segment used to be complex, with multiple channels and a diverse floodplain forest. Road building and forest harvest, beginning in the mid-19th century, more recent berm construction along the active channel, construction of an electricity transmission line that runs through the segment, and active wood removal has likely decreased wood supply and load, as well as artificially confined the channel. This likely produced the pre-restoration condition of a dominantly single thread channel with a single incised main channel and poor lateral connectivity (i.e., limited transport of water, sediment, and wood between the channel and floodplain). The exception to that state in the pre-restoration period was a large flood that reshaped the valley bottom in 1964 and produced a multithread channel that filled much of the valley bottom (Bianco, 2018), before roads were repaired and the stream again confined to a single thread.

Thus, restoration along Deer Creek was intended to help restore a multi-channel, depositional environment. The restoration segment (Figure 4) has a valley gradient of approximately 2% over its lower 2.5 km and a 60 – 150 m wide valley bottom (i.e., the relatively flat area around the stream bounded by the valley walls on either side). Upstream of its confluence with Budworm Creek, Deer Creek tends to be steeper and more confined. The area between Budworm Creek and Deer Creek's confluence with the McKenzie River is wide, relatively low gradient, and shows signs of former multi-channel, or anastomosing, characteristics. This makes it a prime target for restoration to a depositional, multi-channel valley bottom, a state known as Stage 0.

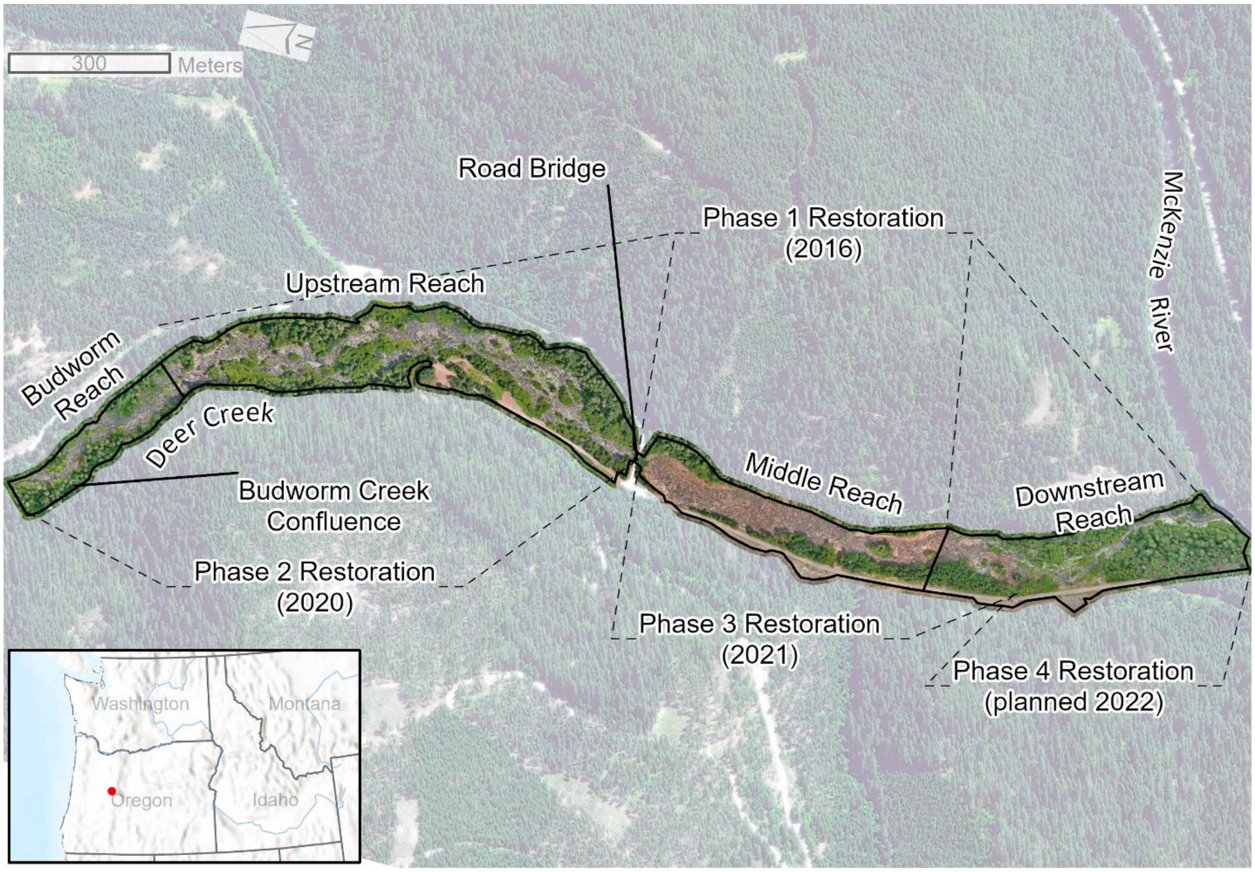


Figure 4: Map of the restored segment of Deer Creek. Inset shows map location.

Process-Reset Restoration to a Stage 0 Condition along Deer Creek

Restoration along Deer Creek sought to restore a Stage 0 valley bottom condition. Stage 0, as defined in the context of the stream evolution model of Cluer and Thorne (2014), is exemplified by a multi-channel or wetland-dominated stream in a depositional valley bottom, with floodplain surfaces that are well connected to the channel, receiving inputs of water, sediment, nutrients, and wood. The specific technique used along Deer Creek is known as valley bottom process-reset style restoration using the geomorphic grade line (GGL) design method (Powers et al., 2019). Process-reset restoration effectively resets the form of the valley bottom to Stage 0 and provides sufficient roughness (i.e., resistance to flow) and wood to kickstart and sustain geomorphic processes that sustain a Stage 0 condition. The GGL method involves fitting a GGL to historical indicators of the pre-disturbance valley bottom to derive a valley surface that approximates the historical valley grade and is hypothesized to support a well-connected, multi-channel valley bottom. Once such a surface is determined, areas of the valley bottom that are higher than the grade line can be evaluated for excavation, and areas lower than the grade line evaluated for fill with excavated material. This method generally results in excavation of human-made berms, terraces, and portions of the floodplain, then infilling of portions of the channel (although deep portions are sometimes left as pools).

In addition to regrading the valley bottom, process-reset style restoration also commonly involves the placement of large quantities of loose, large wood and slash, both from on-site harvest (e.g., from excavating high surfaces) and from off-site locations. This large wood is typically placed without anchors, meaning that it is not restricted from mobilizing downstream. However, some logs are often buried or left interacting with the valley wall, which can reduce their ability to move downstream (Carah et al., 2014; Dixon & Sear, 2014; Merten et al., 2010).

Note that in this report, I refer to "channels," or low-lying areas where water flows most frequently, "floodplains," or areas where water flows during floods, and "banks," the relatively steeper areas that separate channels from floodplains. In a recently restored Stage 0 valley bottom, these features are often difficult to distinguish: banks are diffuse, small, and broken up, and channels sometimes grade gradually into floodplains, or overbank areas, making banks difficult to define at all. Flow can even move down-valley in unchanneled areas that lack defined banks. Fundamentally, channels, banks, and overbank areas look very different in a Stage 0 valley bottom than their counterparts in single-channel valley bottoms, especially just after a valley bottom-rearranging flood or process-reset restoration to a Stage 0 condition (Figure 5). While the terms "channel," "bank," and "overbank" are not ideal, I use them here in lieu of terms yet to be coined that may better capture the nature of these complex river-wetland corridors.

Figure 5: Picture of a channel and floodplain in a recently restored portion of Deer Creek. Note that it is difficult to discern the boundary between the channel and floodplain.

Both phases of restoration along Deer Creek had similar overall objectives but differed in approach and scope. While phase 1 restoration removed anthropogenic berms and filled in low portions of the channel, it did not reach the GGL-derived valley surface in many locations, as the GGL method was still in development at that time. It also only involved placement of a moderate quantity of large wood (planned placement was 200 logs per km), although 13 large conifers were also pulled over (felled without cutting off the rootwad) into the channel in the two years following restoration. Phase 2 restoration, in contrast, was designed using a LiDAR digital elevation model (DEM) that resolved even wetted portions of the streambed and using the recently developed GGL method. It was designed to reach the GGL-derived valley surface across a much larger area, and it involved approximately quadrupling the existing wood load. Phase 1 restoration targeted the downstream and upstream reaches, whereas phase 2 restoration targeted the upstream and Budworm reaches.

Timeline and Focus of This Study

Deer Creek has undergone three phases of restoration, with a fourth phase planned for 2022. Phase 1 took place in summer 2016, and phase 2 took place in summer 2020. Phase 3 had also originally been planned for 2020 but was delayed until 2021. This study required at least one year after restoration implementation to understand how Deer Creek responded to restoration. As such, because this study only documents change through summer 2021, phase 3 restoration was excluded from this study, and I do not present monitoring data from the downstream reach in summer 2021, as it would only reflect the immediate impacts of phase 3 restoration. Instead, while I focus on the upstream and downstream reaches' response to phase 1 restoration, I shift the focus of the report to the upstream and Budworm reaches to discuss the impacts of phase 2 restoration. This report also does not discuss the evolution of the middle reach, which was restored for the first time during phase 3 restoration (summer 2021).

EFFECTS OF RESTORATION ALONG DEER CREEK

Key Points

- Phase 1 restoration gave the river more room to move (i.e., fluvial process space), converted floodplains and terraces to channels that were split by vegetated islands, and added a substantial amount of large wood. These changes increased the total area over which riverine habitat could form and gave the river the ingredients it needed to form that habitat.
- In the four years between phase 1 restoration and phase 2 restoration, flows were moderate, and vegetation established in the channel. With only slight rearrangement of the bed during most flows, the physical characteristics of the river corridor remained mostly constant. Generally, there were no signs that phase 1 restoration had reactivated the geomorphic processes that would sustain the river corridor's complexity over the long-term.
- Phase 2 restoration mimicked the effects of phase 1 restoration, but to a much greater degree. It excavated a substantial amount of terrace and floodplain in the upstream reach, then used that material to fill the channel in both the upstream and budworm reaches. In essence, phase 2 gave the river even more room to move and even more of the ingredients necessary to sustain a habitat-rich valley bottom.
- In the year following phase 2 restoration, moderate flows substantially rearranged the valley bottom, creating new side channels, inundating terraces and turning them into floodplains, and creating new pools around large wood. That is, the river gave itself even more room to move, occupied more of that space, and developed an even more habitat-rich condition.

The following narrative describes how restoration towards a Stage 0 condition changed the geomorphic form and active processes of the restored portions of Deer Creek. This narrative follows the upstream and downstream reaches through summer 2020 (the downstream reach was restored again in summer 2021's phase 3 restoration, and so monitoring in that reach was discontinued for this study). From summer 2020 to summer 2021, this narrative focuses on the upstream and Budworm reaches, as the Budworm reach was first restored and the upstream reach was restored again (phase 2) in summer 2020.

This discussion focuses on changes in geomorphic units through time and relies primarily on geomorphic unit mapping of drone-derived aerial orthomosaics. A geomorphic unit is simply a class of landform (e.g., pool, floodplain), but I also differentiate geomorphic units by their biotic characteristics, specifically, canopy height (e.g., floodplain with high canopy versus floodplain with low canopy). In the following narrative, I commonly use "floodplain" to refer to both marginal floodplains (i.e., attached to terraces or valley walls) and patches of floodplain surrounded by the channel, which I also refer to more specifically as "vegetated islands." Appendix 1 provides a detailed definition of each geomorphic unit, the methodology used to map them, and a justification for the geomorphic unit definitions used in this study.

IMMEDIATE EFFECTS OF PHASE 1 RESTORATION — SUMMER 2016

Phase 1 restoration removed anthropogenic berms, filled in incised channels, and added a substantial amount of large wood to the upstream and downstream reaches. This phase of restoration changed geomorphic units (e.g., converted floodplain to channel) across 37% and 23% of the valley bottom area in the upstream and downstream reaches, respectively.

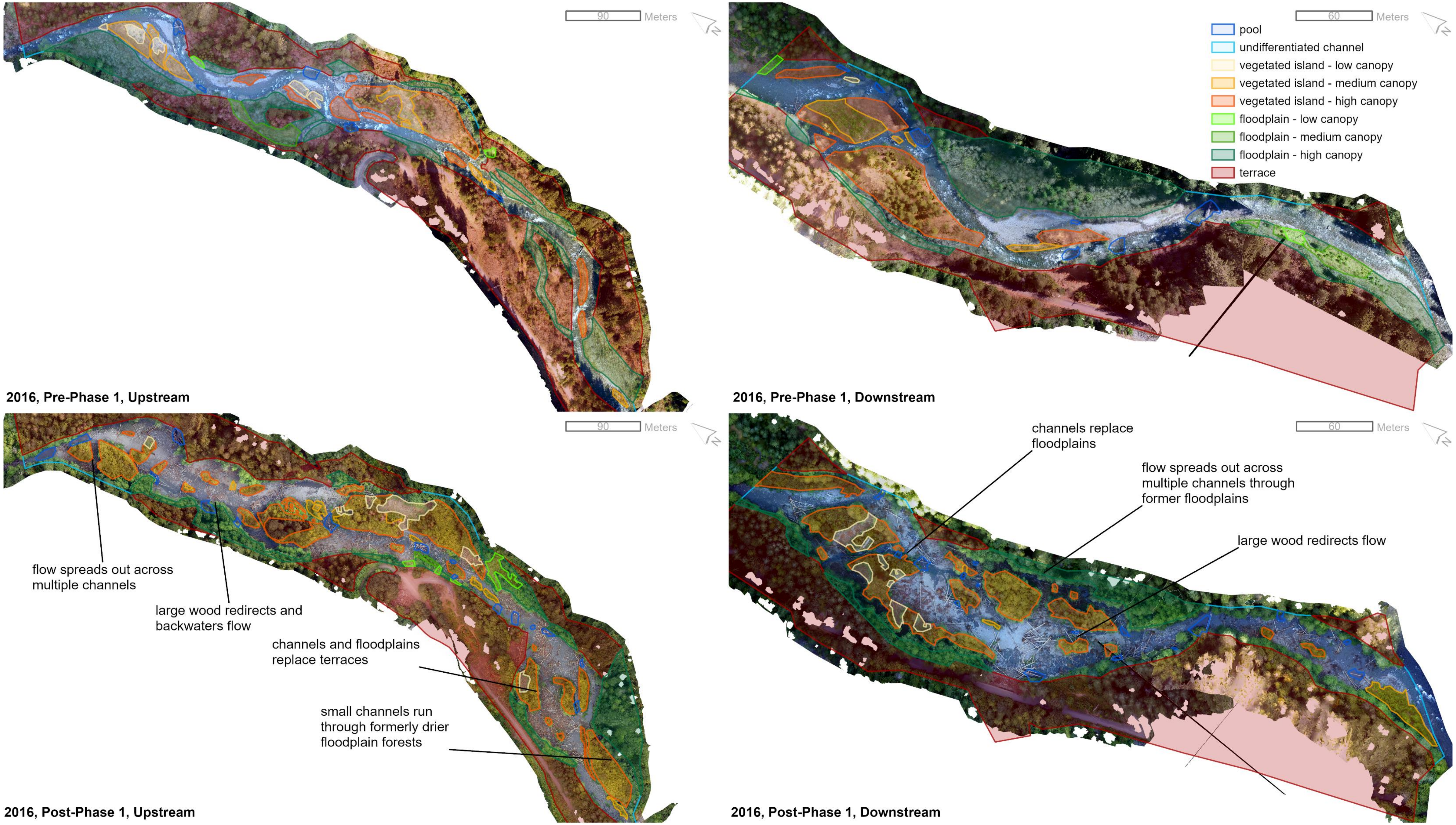
By converting area previously occupied by terraces into channel and floodplain, this phase of restoration gave the stream more room to move. It increased fluvial process space, or the ratio of non-terrace to total valley bottom area, in the upstream reach from 44% to 61% of the valley bottom. Fluvial process space, as used here, describes the proportion of the valley bottom that is liable to be subject to fluvial processes (i.e., similar to the definition of Ciotti et al., 2021). A river with more fluvial process space has more room to move across its valley bottom and develop fluvial landforms and habitat. In addition to increasing fluvial process space, this phase of restoration also increased the total channel area by converting floodplain surface to channel in both the upstream and downstream reaches. This spread flow over more of the valley bottom, increasing the utilization of fluvial process space, or the ratio of channel area to non-terrace area, from 47% to 52% in the upstream reach and 46% to 63% in the downstream reach.

Phase 1 restoration evened out the distribution of relative elevations across the valley bottom, likely increasing lateral connectivity, or the ability of flow, sediment, and wood to move between the channel and floodplain. Prior to phase 1 restoration, the valley bottom had a more confined channel and less floodplain. By removing berms and infilling portions of the channel, restoration evened out the distribution of surfaces with different elevations. While detailed elevation data needed to directly quantify this effect is absent, I can infer the relative abundance of different surfaces that tend to be of characteristic relative elevations. Typically, pools represent the lowest points, shallower areas, such as runs, glides, and riffles (referred to in this study as undifferentiated channel), are slightly higher, floodplains (including vegetated islands) are elevated above the channel, and terraces are elevated substantially above floodplains. I measure the evenness of these categories of elevation using the Simpson Diversity index (Somerfield et al., 2008). This Simpson Diversity index ranges from 0 to 0.8, with 0.8 indicating a perfectly even distribution of, in this case, relative elevations (see Appendix 1 for a more detailed explanation of this metric). Phase 1 increased the Simpson Diversity of relative elevations from 0.60 to 0.70 and 0.63 to 0.64 in the upstream and downstream reaches, respectively. Along with the increase in fluvial process space utilization, this indicated the distribution of flow over a larger area and a potential reduction in the amount of flow needed to inundate the floodplain (i.e., increased lateral flow connectivity).

A key aspect of phase 1 restoration was splitting the valley bottom up and creating a messier fluvial landscape. Phase 1 restoration increased the density of vegetated islands from 162 to 315 and 112 to 239 per km^2 in the upstream and downstream reaches, respectively. However, the conversion of substantial portions of floodplain and terrace to channel decreased the in-channel fragmentation (i.e., a decrease in the proportion of pool and undifferentiated channel patch perimeter length to area from 0.18 to 0.15 and 0.18 to 0.16 in the upstream and downstream reaches, respectively). That is, while the flow was split amongst more channels, those channels had yet to develop pools, bars, and elevation variability that would provide high-quality habitat — that would need to come from natural rearrangement of the channel bed by future flows.

Finally, the placement of loose large wood and tree tipping increased wood load (here, measured as the proportion of the channel and floodplain, or the non-terrace part of the valley bottom, covered by wood) from 3 to 8% and 4 to 7% in the upstream and downstream reaches, respectively. This wood was placed primarily in the form of large wood jams, or discrete accumulations of multiple logs. These wood jams were not anchored — they were free to adjust and move in future high flows. However, many logs extended from the channel into the floodplain, were buried, or were stacked up relatively high, extending above the bankfull stage (i.e., the vertical transition from the channel into the overbank, where flow begins to spill out into the floodplain).

These changes are illustrated in Figure 6.



2016, Pre-Phase 1, Upstream

2016, Pre-Phase 1, Downstream

channels replace floodplains

flow spreads out across multiple channels through former floodplains

large wood redirects flow

flow spreads out across multiple channels

large wood redirects and backwaters flow

channels and floodplains replace terraces

small channels run through formerly drier floodplain forests

2016, Post-Phase 1, Upstream

2016, Post-Phase 1, Downstream

Figure 6: Geomorphic unit maps showing the restored reaches of Deer Creek before and after phase 1 restoration. Annotations show examples of the primary, immediate effects of restoration.

EVOLUTION BETWEEN PHASE 1 AND PHASE 2 RESTORATION — SUMMER 2016 TO SUMMER 2020

The geomorphic effects of any stream restoration are a function of the driving forces that reshape the river corridor. In particular, the magnitude of high flows determines how much the river corridor may evolve from year to year. Higher peak flows should lead to more dramatic and widespread change, whereas lower peak flows should produce less change. Here, I use flow measurements on nearby Lookout Creek as a proxy for flow along Deer Creek (see Appendix 2 for justification of this flow proxy).

In the four years following phase 1 restoration (i.e., before phase 2 restoration again reset the valley bottom), peak flows were only moderate (Figure 7). Flow only exceeded the 50% annual exceedance probability (AEP) flood (also known as a 2-year recurrence interval flood) once during this period, on April 8, 2019. Based on observations of overbank flow indicators (e.g., pushed leaves or fine sediment in the floodplain), this April 8, 2019 flow was the only one that substantially inundated the floodplain. Also notable, flows from summer 2019 to summer 2020 were unusually low, never exceeding 1,000 cfs on the Lookout Creek gage.

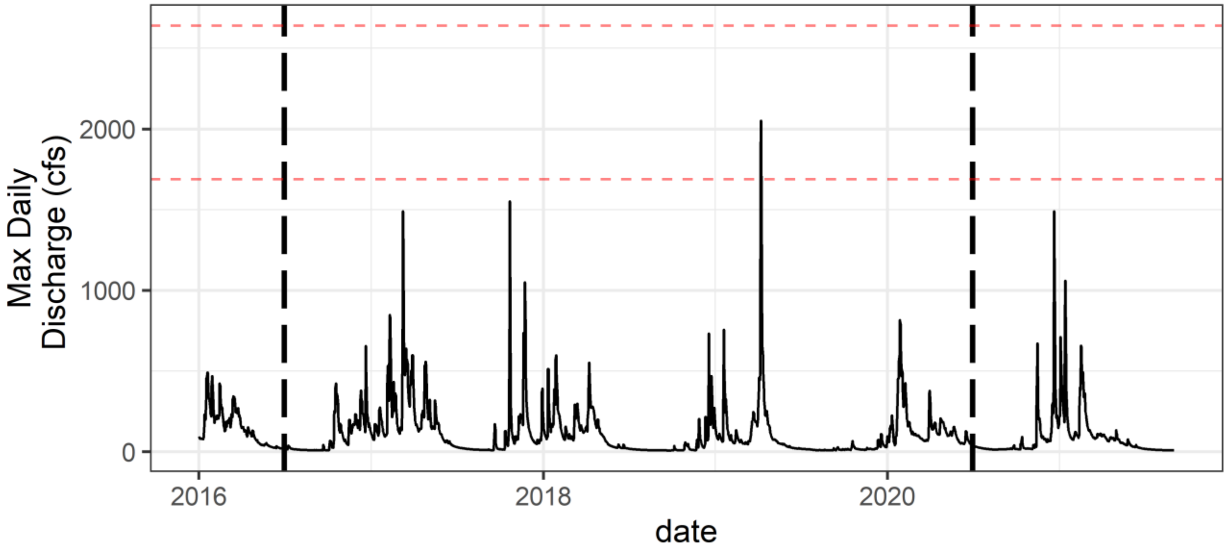


Figure 7: Maximum daily discharge along Lookout Creek over the study period. Dashed black lines show the timing of restoration phases 1 and 2. Dashed red lines show the 50% annual exceedance probability (AEP) and 20% AEP floods for Lookout Creek (also known as the 2-year and 5-year recurrence interval floods, respectively).

These moderate flows were generally insufficient to drastically alter the valley bottom. Change in geomorphic units was generally limited to 10% or less of the total valley bottom area from year to year and decreased slightly through time as the reach adjusted to its new topography and roughness (Figure 8). The dominant mode of change in the 4 years following phase 1 restoration was vegetation establishment in the active channel.

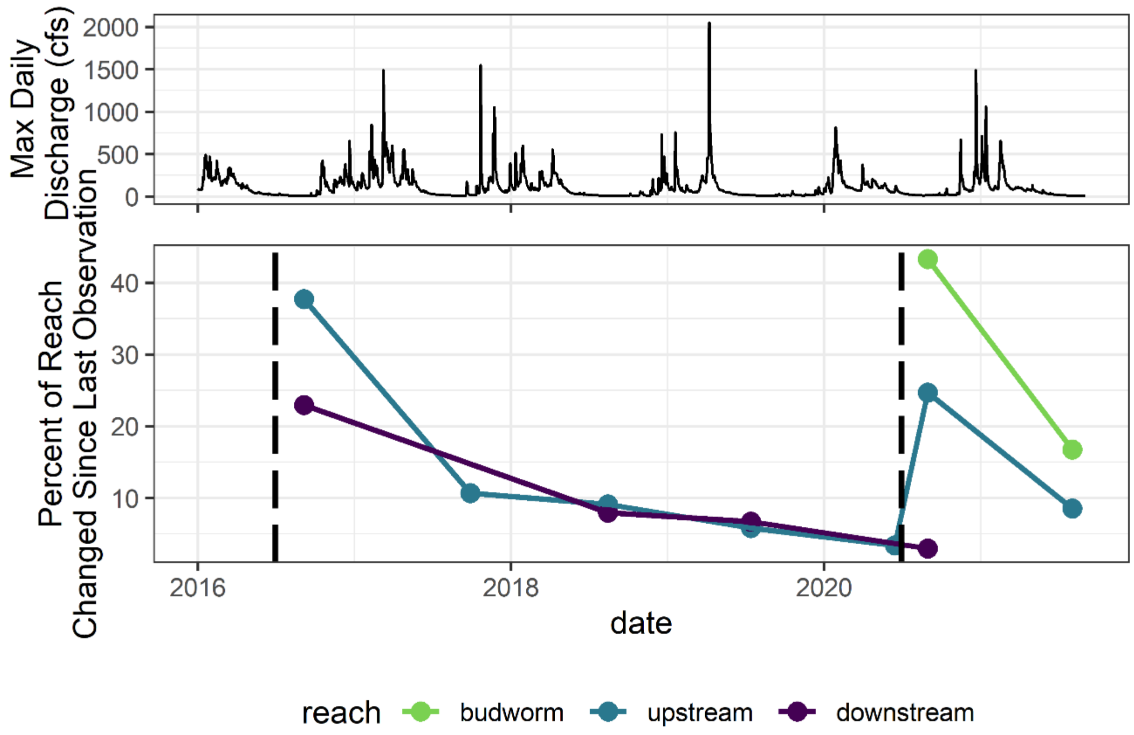


Figure 8: Extent of change of geomorphic units since the preceding observation. Higher values indicate that a higher proportion of the valley bottom area changed from one geomorphic unit to another since the last observation. Dashed black lines show the timing of restoration phases 1 and 2.

This vegetation growth led to a narrowing of the active channel in many places. Bank erosion was minimal, likely due to a combination of a lack of high flows (Figure 9A) and additional roughness provided by wood. Thus, the total amount of terrace along the valley bottom remained constant, maintaining the total fluvial process space over this period (Figure 9B). A decrease in channel area and no change in terrace area resulted in a decrease in the utilization of fluvial process space (Figure 9C). The lack of significant change in geomorphic units also led to a lack of change in the evenness of relative elevations across the valley bottom (Figure 9D).

The only exception to the general lack of geomorphic change across the valley bottom was the incision of multiple floodplain overbank channels (i.e., channels that activate during flows that inundate the floodplain, but do not fully connect to the low-flow channel network; Figure 10) during the 2018/2019 season, likely during the April 8, 2019 flood. Similar signs of floodplain overbank channel activation were not visible during other surveys.

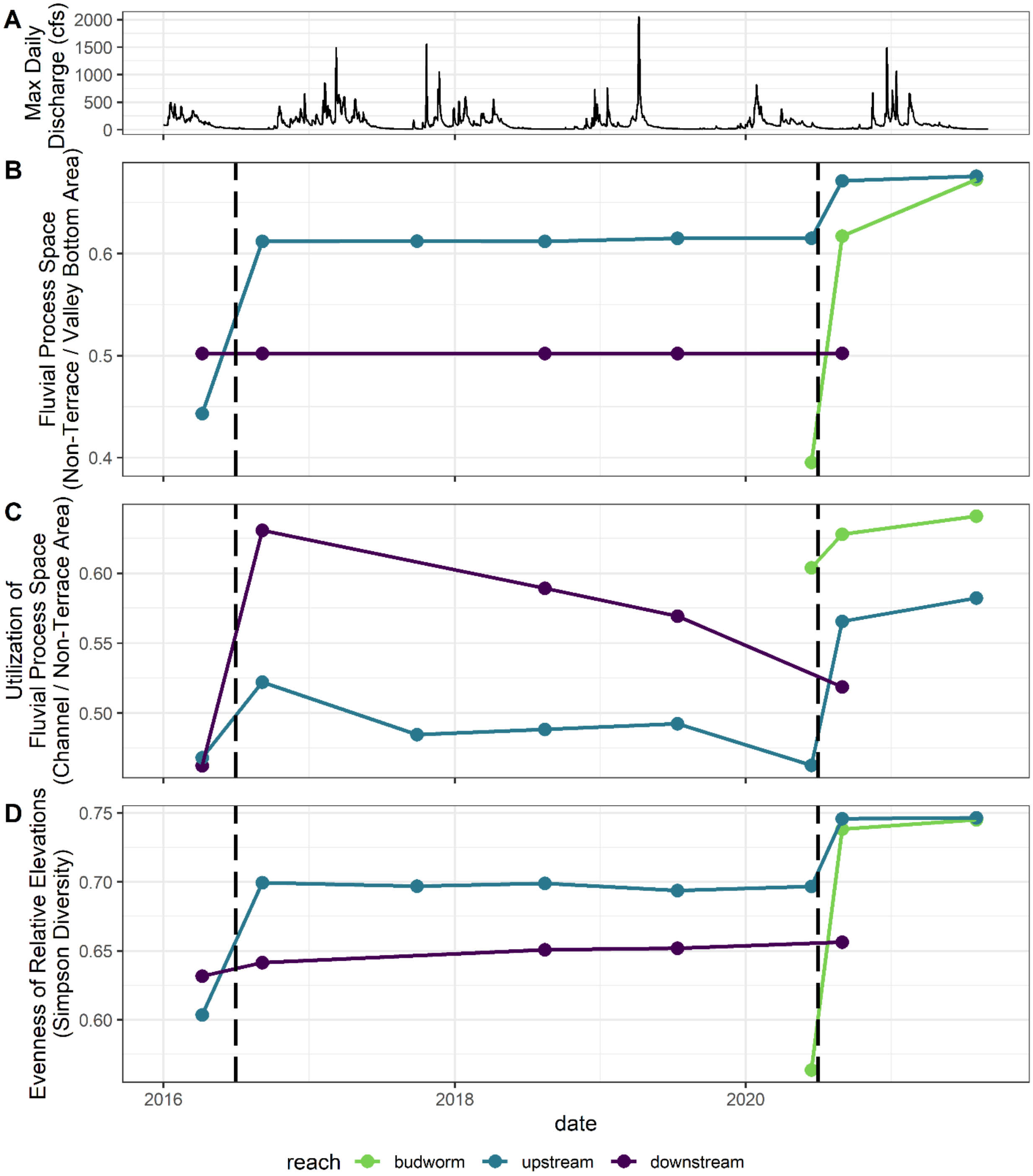


Figure 9: Fluvial process space, utilization of that space, and the evenness of relative elevations across the valley bottom, all in the context of max daily flows on Lookout Creek. Dashed black lines show the timing of restoration phases 1 and 2.

Figure 10: Picture of a floodplain overbank channel in the upstream reach that was reactivated during a flood shortly after phase 2 restoration (August 2, 2021).

Vegetation established in dispersed patches in shallow areas or where sediment deposited around large wood. Vegetation establishment occurred between every observation, even through the high flow of April 2019. However, vegetation establishment was especially dramatic between summer 2019 and summer 2020, likely due to the abnormally low flows that year (Figure 11A). This led to a continual increase in the density of vegetated islands (Figure 11B), which further fragmented the active channel (Figure 11C), creating a more complex channel landscape[1], but restricting flow to a smaller proportion of the valley bottom.

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[1] in-channel fragmentation, as measured here, could result either from an increase in bank edge (e.g., due to an increase in vegetated islands) or an increase in bed elevation heterogeneity (i.e., variations between pools and the rest of the channel). Pool abundance remained largely constant during this period (Figure 11D), with the exception of a slight rise in pool abundance in the upstream reach in the pre-phase 2, summer 2020 survey (this was likely caused by higher flows during that survey, not a real trend in pool creation). If pool area did not change significantly, then the increase in in-channel fragmentation was likely caused by an increase in vegetated island density.

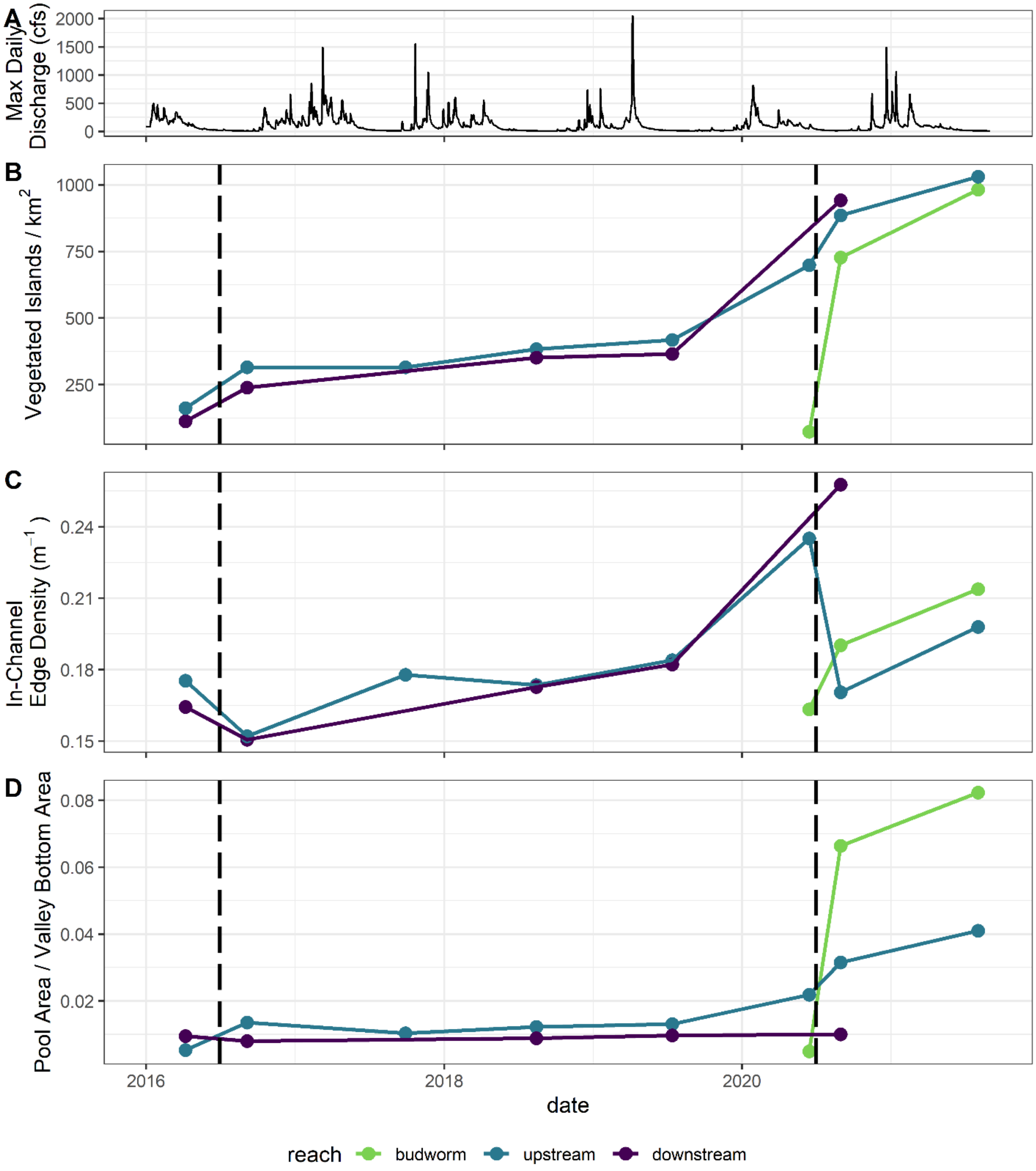


Figure 11: Vegetated island density (count per area), in-channel fragmentation (edge density, or total pool and undifferentiated channel perimeter length divided by channel area), and pool area across the valley bottom, all in the context of max daily flows on Lookout Creek. Dashed black lines show the timing of restoration phases 1 and 2.

The emergence of vegetation in the channel indicated the beginnings of the process of vegetation succession, whereby vegetation begins growing on newly exposed portions of the valley bottom. Vegetation succession generally increases the evenness of canopy heights across the valley bottom (i.e., as vegetation establishes, it produces a more even mix of low, medium, and high canopy heights). I measure this using the Simpson Diversity index applied to the distribution of vegetation canopy heights mapped across each reach. This index ranges from 0 to 0.66, with 0.66 indicating a perfectly even distribution. The increase in evenness over time observed along Deer Creek following phase 1 restoration (Figure 12) indicates a steady, continual process of vegetation succession via vegetated island emergence, especially considering the lack of floodplain erosion or other processes (e.g., windstorms toppling trees) that would decrease the abundance of more mature forest (i.e., high canopy heights).

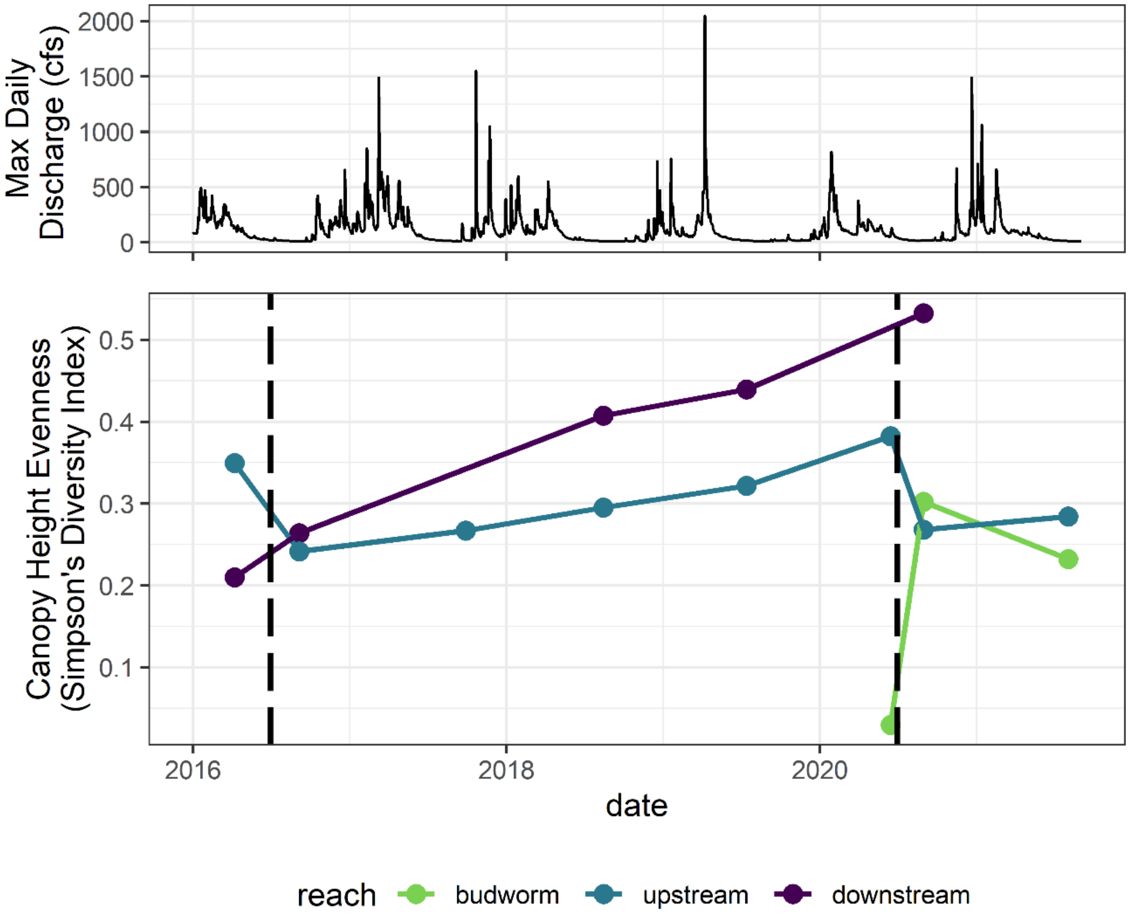


Figure 12: Evenness of vegetation canopy height across the valley bottom through time in the context of max daily flows on Lookout Creek. Dashed black lines show the timing of restoration phases 1 and 2.

Over this time period, wood rearranged slightly, as loose logs racked on wood jams. Based on repeat observations of the downstream-most wood jams in each study reach, I suspect that few to no logs mobilized downstream of the study reaches. These downstream-most jams did not mobilize or even significantly change during this period, and there were no signs that flow overtopped these jams sufficiently to transport logs over them. Some logs may have entered the upstream reach from upstream, but such input was not sufficient to substantially alter wood area in the reach.

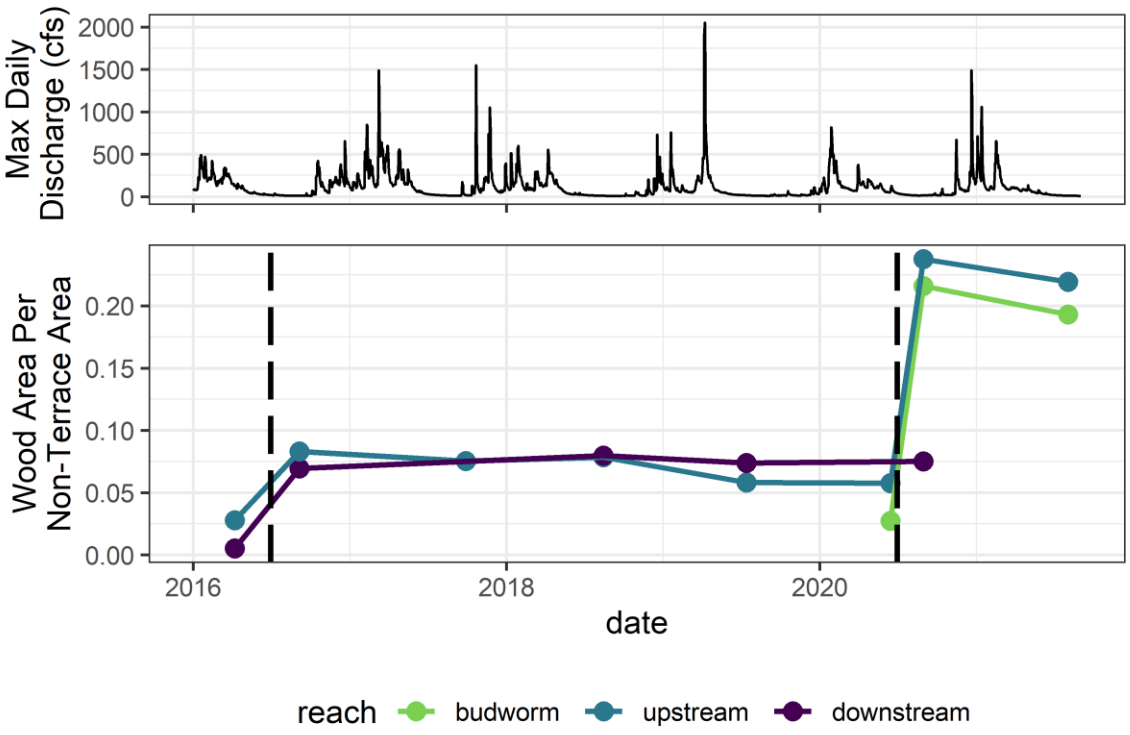
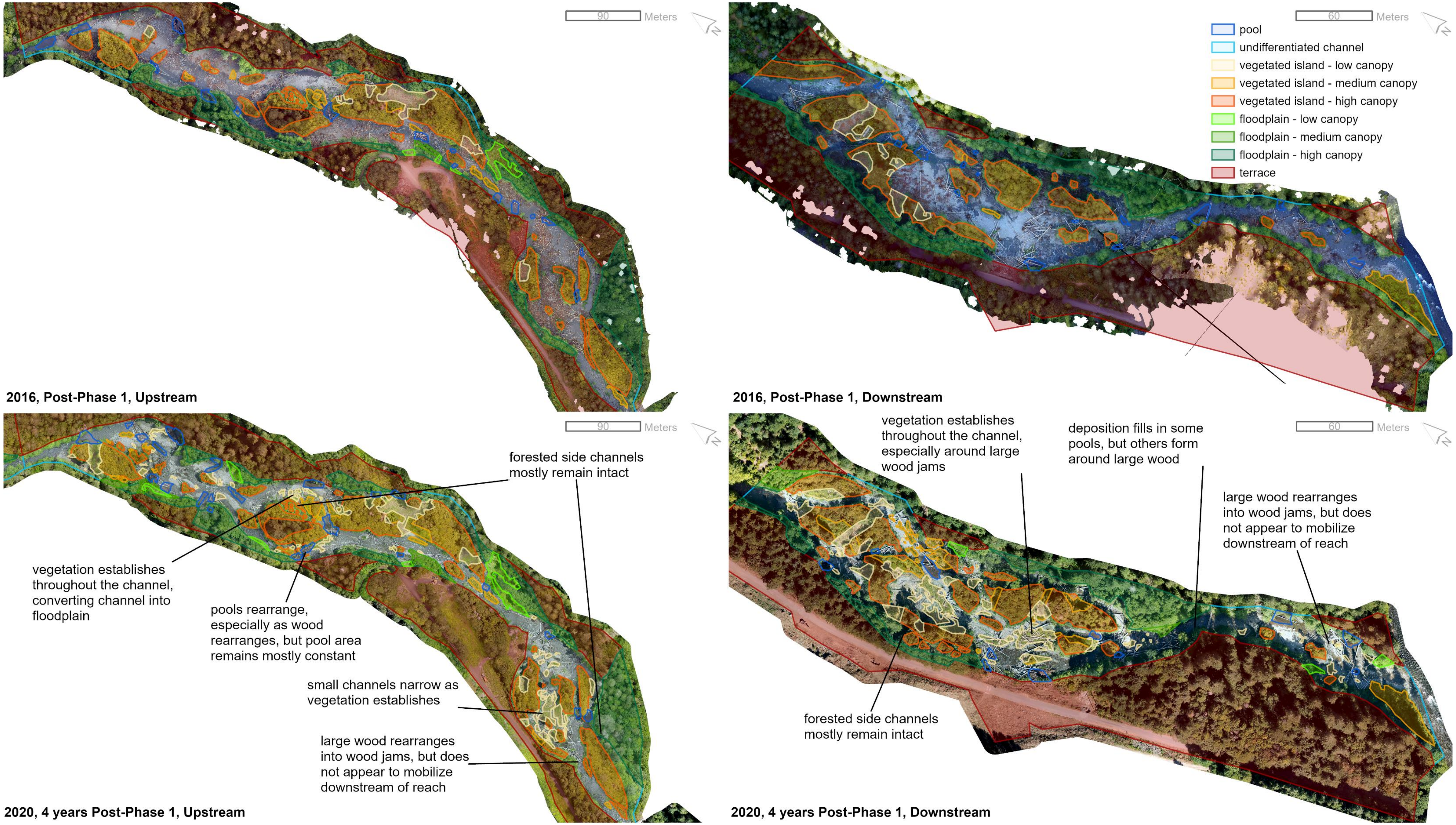


Figure 13: Large wood load, as measured by the proportion of the non-terrace area of the valley bottom covered by wood, through time. Dashed black lines show the timing of restoration phases 1 and 2.

The overall pattern of vegetation establishment and lack of geomorphic unit change during this period indicates that despite the occurrence of a moderately high flow, geomorphic processes such as side channel formation and maintenance, pool scour and development, and robust delivery of water, sediment, and nutrients to floodplain forests had not been sufficiently reactivated. While phase 2 restoration has made it impossible to determine the long-term effects of phase 1 restoration, I hypothesize based on these limited observations that the restored reaches may have been on a trajectory of returning to a simpler, less habitat-rich state than was present just after phase 1 restoration. That is, phase 1 restoration did not seem to provide the river the sufficient ingredients needed to kickstart the geomorphic processes that could sustain such a complex valley bottom. However, that return may have taken a considerable amount of time, and whatever stable state the valley bottom may have taken over the long-term may still have been more complex and habitat-rich than the pre-restoration condition.

These changes are illustrated in Figure 14.



2016, Post-Phase 1, Upstream

2016, Post-Phase 1, Downstream

forested side channels mostly remain intact

vegetation establishes throughout the channel, converting channel into floodplain

pools rearrange, especially as wood rearranges, but pool area remains mostly constant

small channels narrow as vegetation establishes

large wood rearranges into wood jams, but does not appear to mobilize downstream of reach

2020, 4 years Post-Phase 1, Upstream

vegetation establishes throughout the channel, especially around large wood jams

deposition fills in some pools, but others form around large wood

large wood rearranges into wood jams, but does not appear to mobilize downstream of reach

forested side channels mostly remain intact

2020, 4 years Post-Phase 1, Downstream

Figure 14: Geomorphic unit maps showing the restored reaches of Deer Creek just after phase 1 restoration and 4 years after phase 1 restoration (i.e., just before phase 2 restoration). Annotations show examples of how each reach evolved over this time period.

IMMEDIATE EFFECTS OF PHASE 2 RESTORATION — SUMMER 2020

The rest of this narrative focuses on the upstream and Budworm reaches (the locations of phase 2 restoration), and now excludes the downstream reach, which was restored during phase 3 in summer 2021.

Phase 2 restoration was similar to phase 1, but both the cut and fill operations and wood placement were of a much higher magnitude. Excavation of high surfaces was almost entirely focused on the upstream reach, and excavated material was used to fill portions of the channel in both the upstream and Budworm reaches. This excavation and fill resulted in geomorphic units changing across 25 and 43% of the upstream and Budworm valley bottoms, respectively (Figure 8). However, note that this extent of change does not capture areas where channels were simply infilled (i.e., elevation increased) without a corresponding change in geomorphic unit.

Similar to phase 1, phase 2 restoration increased fluvial process space (the proportion of the valley bottom not occupied by terrace), the utilization of that space (the proportion of fluvial process space occupied by the channel), and the evenness of relative elevations (Figure 9). The increase in the evenness of relative elevation neared the maximum value for this evenness metric (0.8), indicating that further increases in lateral hydrologic connectivity would probably lead to a decrease in this metric as terraces become rare across the valley bottom and other, lower surfaces begin to dominate. Also similarly to phase 1, phase 2 restoration increased the density of vegetated islands, further splitting the flow among more channels (Figure 11B). Phase 2 restoration fragmented the channel in the Budworm reach (Figure 11C), likely because it increased pool abundance (Figure 11D). However, in the upstream reach, the substantial increase in undifferentiated channel area actually reduced in-channel fragmentation, similar to phase 1 restoration.

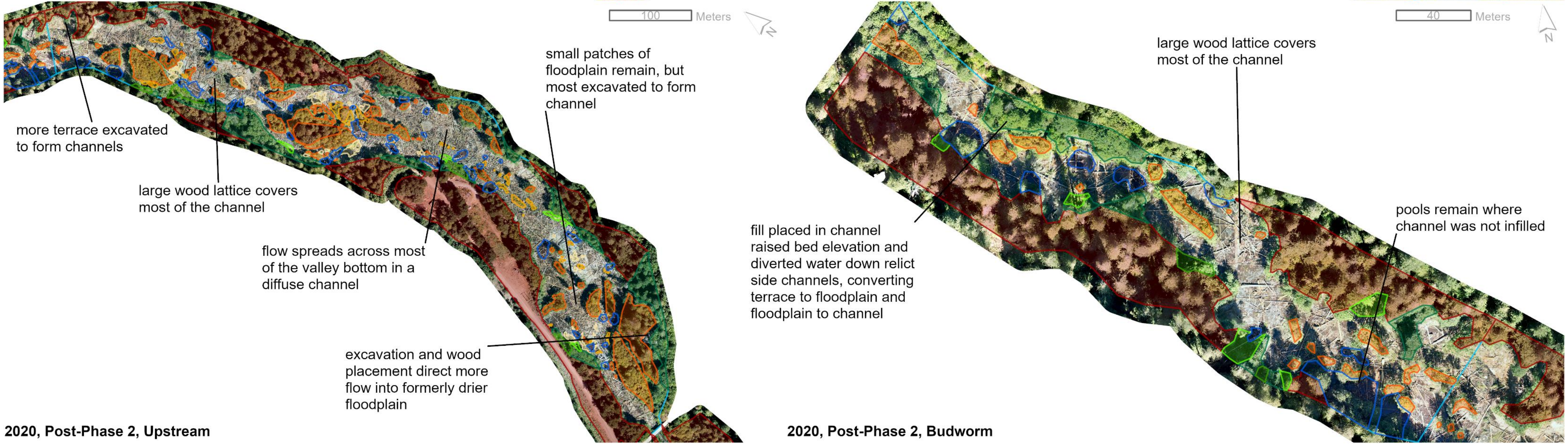
Perhaps the most noticeable change, phase 2 restoration increased wood load by a factor of 4 in the upstream reach and a factor of 7 in the Budworm reach (Figure 13). This dramatic wood addition not only differed in quantity from phase 1, but also in its spatial pattern (Figure 15). Instead of placing wood as discrete jams, wood was placed in what I refer to as a wood lattice, or a wood assemblage characterized by high wood density (i.e., lots of wood per unit area), but a low degree of aggregation (i.e., spread out, not sorted into discrete jams).

Figure 15: Orthomosaic imagery showing the wood lattice placed as part of phase 2 restoration. Wood is highlighted in brown for clarity.

These changes are illustrated in Figure 16.

2020, Pre-Phase 2, Upstream

2020, Pre-Phase 2, Budworm



more terrace excavated to form channels

large wood lattice covers most of the channel

flow spreads across most of the valley bottom in a diffuse channel

small patches of floodplain remain, but most excavated to form channel

excavation and wood placement direct more flow into formerly drier floodplain

large wood lattice covers most of the channel

fill placed in channel raised bed elevation and diverted water down relict side channels, converting terrace to floodplain and floodplain to channel

pools remain where channel was not infilled

2020, Post-Phase 2, Upstream

2020, Post-Phase 2, Budworm

Figure 16: Geomorphic unit maps showing the restored reaches of Deer Creek before and after phase 2 restoration. Annotations show examples of the primary, immediate effects of restoration.

EVOLUTION AFTER PHASE 2 RESTORATION — SUMMER 2020 TO SUMMER 2021

In the year following phase 2 restoration, peak flow at Lookout Creek only reached approximately 1,500 cfs, less than the approximately 2,000 cfs peak that occurred between phase 1 and phase 2 (Figure 7). While I lack direct measurements of flow on Deer Creek, based on timelapse imagery showing flow stage, flows in 2020/2021 were likely at least slightly lower in peak magnitude than flows from 2016 to 2020 (Figure 17). However, the geomorphic impact of this moderate flow was much greater than that of similar flows that occurred in the four years prior to phase 2 restoration, and it occurred over a large extent (16% and 9% of the valley bottom for the Budworm and upstream reaches, respectively; Figure 8).

Figure 17: Timelapse camera photographs in the downstream reach (unaffected by phase 2 restoration) from the April 2019 and December 2020 peak flows. Note that while flow stage only appears to be slightly lower in the December 2020 image, vegetation-induced roughness was likely considerably higher during that flow, so a given discharge would be expected to produce a higher stage during that flood.

In both the Budworm and upstream reaches, I found abundant evidence of floodplain inundation, including overbank sand deposition (e.g., Figure 18), leaves and sticks racked on living vegetation (e.g., Figure 19), channel incision into formerly unchanneled floodplain, scour and deposition on the floodplain, and channels that had been newly incised into floodplain and even terrace surfaces. This indicates substantial transfer of not only water, but also sediment and likely organic matter to the floodplain.

Figure 18: Picture looking upstream on a floodplain with recent overbank sand deposition (August 2, 2021).

Figure 19: Picture looking downstream at racked wood and fine organic matter on a floodplain margin, indicating inundation of the floodplain (August 3, 2021)

The fact that the floodplain inundated much more in December 2020 than it did in the higher flow of April 2019 indicates that phase 2 restoration successfully lowered the discharge at which the floodplain inundates, or the floodplain flow threshold. The floodplain flow threshold is a function of the hydraulic conveyance of the channel, or, in other words, how well the channel conveys water downstream.

Channels with higher hydraulic roughness, or resistance to flow, or channels with lower cross-sectional area, will tend to have a lower floodplain flow threshold, all else being equal. Phase 2 restoration both decreased channel cross-sectional area, especially in the Budworm reach, by filling in the channel and added a substantial amount of hydraulic roughness in the form of large wood, which pushed more water over the banks, increasing lateral hydraulic connectivity.

The large wood added during phase 2 restoration played a key role in the geomorphic evolution observed following restoration. While the initial placement took the form of a wood lattice, many logs in the lattice were transported downstream, racking on other logs and forming wood jams (Figure 20), overall decreasing the total wood area in both reaches (Figure 13). Based on timelapse camera footage (Figure 21), this rearrangement of wood occurred relatively quickly: during the peak flow on December 20, 2020, flow crested the approximate bankfull stage around 3:00am, and many of the logs visible in the timelapse frame had mobilized downstream by approximately 11:00am, while the flood waters remained elevated, likely near or above bankfull stage until 11:00pm that evening (Figure 22). This means that wood jams were formed with enough time for them to have a substantial effect on erosion and deposition. Wood rearrangement appeared to form more discrete jams in the Budworm reach compared to the upstream reach, possibly due to the narrower valley bottom in Budworm resulting in a higher flow depth (and thus a higher likelihood of log floating).

Large wood jams appeared to dominantly form around logs that in some way interacted with less mobile elements in the valley bottom, usually living trees or the valley walls. I hypothesize that the placement of many logs into floodplain forests helped keep the wood lattice from substantially mobilizing downstream, instead forming discrete jams that were able to split up flow across the entirety of the restored reaches.

Figure 20: Orthomosaic imagery showing wood rearrangement from just after phase 2 restoration to 1 year after phase 2 restoration. Wood is highlighted in brown for clarity. Note that while both images show a wood lattice, some discrete jams, or denser accumulations of wood, have formed in the lattice in the year following restoration.

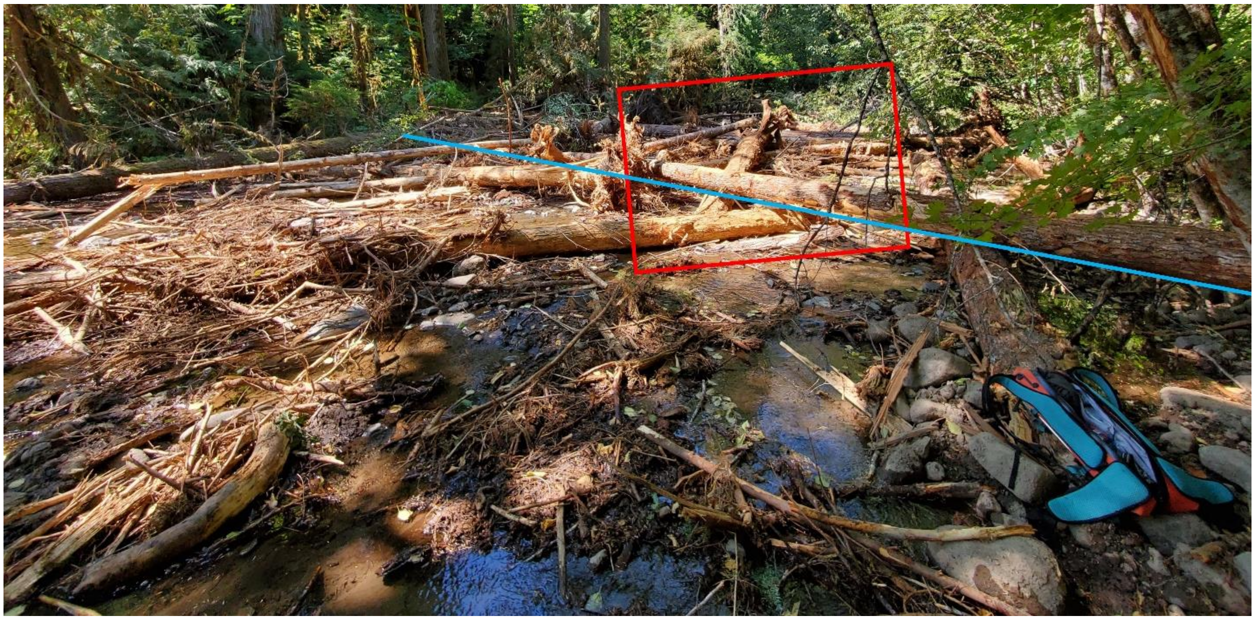


Figure 21: Picture looking upstream from just right of the timelapse camera that captured the stills shown in Figure 22. Red box shows approximate field of view of timelapse camera. Blue line shows bankfull stage.

Figure 22: Timelapse stills showing wood reorganization during the December 20, 2020 flood.

In addition to wood interacting with flow across the valley bottom, the high flows in 2020/2021 were also reshaping a very different river corridor geometry, one that was likely much closer to the valley surface derived from the geomorphic grade line analysis performed for phase 2 restoration. Filling in the channel, especially in the Budworm reach, was likely partly responsible for pushing more flow into the floodplain.

For the first time since restoration began, geomorphic processes (i.e., not direct human intervention, although these processes are the result of such intervention) converted terrace into floodplain and even areas wetted at low flows, thus increasing fluvial process space (Figure 9A). The creation of new channels on floodplain surfaces (e.g., Figure 23 through Figure 25) also increased the utilization of that fluvial process space (Figure 9B). These changes had only a small effect on the overall evenness of relative elevations (Figure 9C), possibly because that evenness was close to its maximum value already following phase 2 restoration. Given this high evenness, direct evidence of flow moving between the low flow area and the floodplain provides a better look at lateral hydrologic connectivity than does the evenness of relative elevations, especially given that we lack high-resolution topography data that could otherwise shed light on lateral connectivity.

Figure 23: Picture looking upstream at a newly formed side channel branching off into the floodplain (August 3, 2021).

Figure 24: Picture looking downstream at a channel inlet newly carved into a former floodplain surface (August 2, 2021).

Figure 25: Picture looking left at a newly scoured area wetted at low flow on what was formerly a floodplain surface, taken just downstream of Figure 24 (August 2, 2021).

Overall fragmentation of the valley bottom also increased substantially during the year following phase 2 restoration. Channel incision into floodplains and vegetated islands further split up the flow, increasing vegetated island density (Figure 11B). As wood jams formed from the wood lattice, they began to develop plunge pool scour and sediment deposition in their backwaters that created new pools and expanded existing pools (Figure 11D). This pool development and channel incision into floodplain surfaces increased the fragmentation of the active channel as well (Figure 11C). Broadly, this increase in vegetated island density and in-channel fragmentation indicates a more heterogeneous flow field across the restored reaches.

A key factor in overbank flow incising channels through floodplain surfaces appeared to be the location and characteristics of large wood jams. Multiple newly formed side channels had large wood jams in the channel they branched off from. These jams appeared to have backwatered flow and directed it into the floodplain, potentially concentrating flow enough to incise through floodplain surfaces.

The higher in-channel roughness provided by large wood and flow spreading out over a wider area also appeared to induce substantial gravel deposition (e.g., Figure 26). However, significant trends in bed surface grain size were difficult to distinguish (see Appendix 3).

Figure 26: Repeat photographs looking upstream from the upstream-most wood placement in the Budworm reach. Compare bed conditions from August 29, 2020 (left, dominantly cobble bed), to August 3, 2021 (right, dominantly sand to gravel bed).

One notable exception to the pattern of substantial reworking of the valley bottom was the left side of the channel in the upstream reach across from the hairpin turn in forest road 782. Here, a forested channel appeared to have not been inundated with flow sufficient to move the leaves and other fine organic detritus laid down in Fall 2020 (Figure 27). This indicates a transition from channel to floodplain in this area, as many other forested channels upstream, downstream, and across the valley bottom from this location were inundated during the last high flow enough to move fine organic detritus. This now relict channel is in one of the widest portions of the valley bottom, where a substantial amount of formerly floodplain surface was turned into channel by phase 2 restoration. It is possible that in this area, clearing rightward of this channel was sufficient to divert flow away and towards the right side of the valley bottom, even during a flow that overtopped the banks along most of the valley bottom.

Figure 27: Picture of the left forested channel across from the hairpin turn in forest road 782 looking upstream (August 4th, 2021). Note the fallen leaves in the channel that have not been moved significantly by flow.

These changes are illustrated in Figure 28.

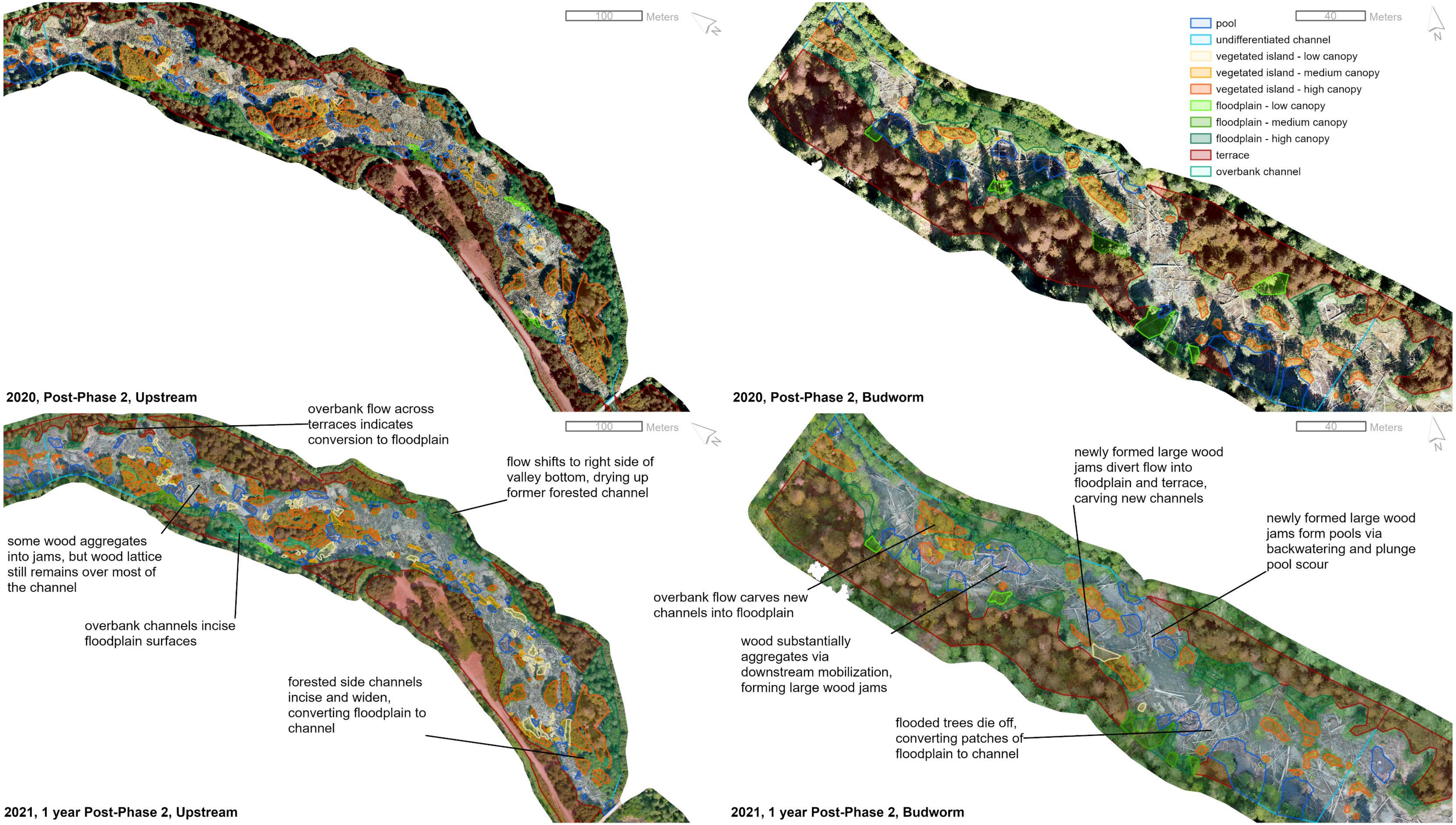


Figure 28: Geomorphic unit maps showing the restored reaches of Deer Creek just after phase 2 restoration and 1 year after phase 2 restoration. Annotations show examples of how each reach evolved over this time period.

CONCLUSIONS: DID RESTORATION ALONG DEER CREEK ESTABLISH A STAGE 0 CONDITION?

Key Points

- Phase 2 restoration effectively reset the valley bottom and kickstarted the processes that could sustain the new valley bottom character over the long-term.
- It is not clear whether wood placement versus earthmoving was more important in producing the effects observed following phase 2 restoration.
- While the restored reaches are now effectively in a Stage 0 condition and show signs of active processes that will sustain that condition, the long-term sustainability of this condition is still an open question.

This monitoring study was very fortunate to have captured flows of similar magnitude both before and after phase 2 restoration. Because the geomorphic response to an only moderately high flow after phase 2 restoration was so much greater than the geomorphic response to similar or even higher flows before phase 2 restoration, I can confidently conclude that phase 2 restoration substantially reduced the threshold discharge required for a geomorphically effective and floodplain-inundating flow. Phase 2 restoration met the short-term goal of immediately resetting the valley bottom to a multi-thread character, creating a more complex riverine landscape with more fluvial process space and abundant large wood. After a year of monitoring, it appears that phase 2 is also beginning to meet the long-term goal of giving the river both the space and the ingredients that it needs to sustain the geomorphic character of a Stage 0 reach.

This likely resulted from a combination of the following factors:

1. The high density and lattice-like placement of large wood, which likely provided substantially more flow resistance and diverted flow over the banks.
2. The higher evenness of relative elevations across the valley bottom, higher utilization of fluvial process space, and the higher proportion of the valley bottom that was likely close to the geomorphic grade line-derived valley surface.

Given that phase 2 restoration simultaneously added roughness in the form of large wood and brought the valley bottom closer to the GGL-derived valley surface simultaneously, I cannot robustly distinguish which of these two factors was dominantly responsible for the substantial geomorphic change caused by only a moderate flow observed in the first year following restoration. However, observations of side channel inlets and wood rearrangement in summer 2021 indicate the critical importance of the large wood assemblage in shaping the geomorphic evolution following phase 2 restoration.

While coming closer to the GGL-derived valley surface, effectively filling in the channel, may have helped inundate the floodplain, large wood likely caused focused flow diversions onto the floodplain that helped carve discrete channels, helping spur the avulsions that resulted in forested channel development during the 2020/2021 season. The close proximity to wood jams of many of the pools that formed in the year following phase 2 restoration also indicates the importance of wood in locally rearranging the channel bed. I hypothesize that without the substantial large wood addition and the rearrangement of the wood lattice, especially in the Budworm reach, floodplain flows may have been more diffuse, possibly even too diffuse to incise new channels in the floodplain, and the in-channel flow field may have been more homogenous, thus less likely to scour pools and deposit bars.

Future monitoring along Deer Creek will not be able to tease apart which of the factors above was most responsible for the geomorphic response to phase 2 restoration. That will likely require experimental and field studies explicitly examining the roles of valley bottom topography and wood in shaping patterns of erosion and deposition in complex, multi-channel streams.

However, another key question remains that future monitoring can answer: will restoration along Deer Creek continue to meet the long-term goal of sustaining a Stage 0 valley bottom?

RECOMMENDATIONS FOR FUTURE MONITORING

Key Points

- Future monitoring can effectively determine whether the current Stage 0 condition along Deer Creek will be sustained in the future.
- Monitoring should at least focus on whether wood and vegetation remain spread across the valley bottom and active channel, as both are key to regulating flow in a way that will maintain the Stage 0 valley form.
- To detect potential departures from a sustainable geomorphic trajectory (e.g., a return to pre-restoration conditions), monitoring could also collect data on bed sediment size, pool and other channel bedform abundance, and overall channel planform.
- Monitoring data collection does not necessarily need to be done annually: it should be done only after a set period of time (based on vegetation growth rates) or after flows that would be expected to substantially alter the valley bottom. I recommend surveying the river corridor after any flow over 1,500 cfs on Lookout Creek and no longer than 3 years following the last monitoring observation, if no flows over 1,500 cfs occur. Both the flow threshold that triggers monitoring data collection and the maximum time between monitoring observations could be adjusted (likely upwards) in the future based on monitoring observations.

Monitoring through 2021 has shown that the Phase 2 restoration has reactivated desirable geomorphic processes, namely floodplain erosion, sediment aggradation in the channel and on the floodplain, side channel development, and wood-induced local scour and deposition. However, monitoring has not gone on long enough to determine if this process reactivation will be sustained into the future. In the absence of continued geomorphic processes that will sustain the multi-channel, habitat-rich form of the valley bottom, it is possible that Deer Creek could revert to its pre-restoration state, with a simpler, less habitat-rich, and less resilient character, especially over multiple decades, after much of the wood placed during phase 2 restoration may have decayed or mobilized downstream.

Future monitoring to address the long-term sustainability of restoration along Deer Creek can use more sporadic and lower cost monitoring methods than have been applied for this study. Whereas previous monitoring focused on detecting the signal of geomorphic process reactivation, future monitoring should focus on two things: 1) simply determining whether those processes remain active at beneficial magnitudes as the site continues to evolve, and 2) whether there are continued wood inputs to sustain the current forms and processes present along Deer Creek, especially if wood mobilizes downstream. While sediment, flow, and vegetation are also key factors that will determine long-term restoration success, there have bene no indications that the system is deficient in terms of its sediment or flow regimes or in terms of its riparian vegetation community, so monitoring likely won't need to focus on those factors unless there arises a compelling reason to do so.

The geomorphic processes needed to sustain a Stage 0 condition along Deer Creek stem from roughness and fluvial process space. Roughness helps maintain high lateral connectivity of sediment and water, and fluvial process space spreads flow energy over a large area. Together, these two key factors can maintain a depositional, multi-channel valley bottom and help absorb disturbances, such as extreme floods or fires. Assuming no future human alterations that would again artificially confine the stream, fluvial process space should remain constant or increase through time, unless the stream incises, which would limit lateral hydraulic connectivity and transition floodplains back into terraces. However, wood and vegetation are not guaranteed to continue to maintain the roughness needed to split flow into multiple channels, locally accelerate and decelerate flows enough to cause local pool scour, maintain spawning gravel patches, and create new forested channels as old channels infill or vegetate.

Given the importance of wood and fluvial process space, future monitoring should first focus on these two factors. However, if possible, future monitoring should also look to establish the geomorphic trajectory of the valley bottom, which may provide early indications of long-term project failure. This would involve tracking key characteristics of the valley bottom, including:

- bed sediment size (an early indicator of potential incision and a direct indicator of spawning habitat)
- channel bed vertical heterogeneity, namely in terms of the relative abundance and spatial distribution of pools, shallower areas of the channel, and, if/when they become more readily recognizable, riffles and bars that directly affect water quality (temperature, dissolved oxygen)
- channel planform, namely the degree to which flow splits across the valley bottom, which can regulate both lateral hydraulic connectivity and the presence of forested channels

Table 1 lists these recommended metrics and potential methods that could be used to collect data for each metric. These metrics simplify the monitoring process used in this study and are more focused on detecting the trend in these geomorphic characteristics. By focusing on trends, not absolute values, these methods can save data collection and analysis costs while still indicating whether geomorphic processes that are likely to sustain the Stage 0 condition along Deer Creek remain active. I recommend refining these methods based on monitoring priorities and funding availability if future monitoring is planned.

Table 1: Recommended metrics for future monitoring and recommended data collection methods.

METRIC	DATA COLLECTION METHODS
Wood load and function	For wood load: Drone survey to obtain an orthomosaic, then estimate wood load using point sampling of orthomosaic For wood function: qualitatively describe the wood assemblage (i.e., wood lattice vs jams), note locations in the drone orthomosaic of wood-induced backwatering, pool scour, diversion of flow into side channels, bar deposition, vegetation establishment For wood input (long-term, especially if wood begins to mobilize downstream or decay substantially): field survey to qualitatively assess local wood recruitment and wood supply from upstream
Fluvial process space and utilization	For fluvial process space: walk floodplain surfaces to check for signs of inundation after flows expected to inundate the floodplain, check for terrace to floodplain conversion or vice versa For fluvial process space utilization: map channel centerlines in drone orthomosaic (may be useful to supplement with ground truthing during floodplain walk) and note locations where new channels form and old channels infill and vegetate
Bed sediment size	Sample randomly distributed points or plots across the valley bottom in the field to visually categorize grain size (into, e.g., sand, gravel, cobble, boulder, bedrock categories) Or, if drone imagery is high enough resolution, sample points in the drone imagery and categorize grain size (would likely be lower cost than field surveys)
Channel bed vertical heterogeneity	Map the location of pools and, if feasible, riffles and bars, using a combination of drone orthomosaic interpretation and field ground truthing.
Channel planform	Count the number of vegetated islands identified by channel mapping, or compute the number of channel nodes, or places where channels diverge or come together

If tracking wood mobilization off-site (i.e., into the McKenzie) becomes a priority, I recommend installing multiple timelapse cameras near the confluence with the McKenzie to track whether or not wood floats downstream during floods. Cameras would likely need to be maintained on an annual basis. To supplement direct observations, I would also recommend tracking whether flow overtops the downstream-most jams near the confluence with the McKenzie and if those jams ever mobilize or lose wood. If they do, or if flow overtops them, then it is possible that wood was transported into the McKenzie.

The interval for monitoring data collection should not be regular, but instead should be based on the processes likely to cause change across the valley bottom: sporadic high flows and vegetation establishment. To monitor vegetation establishment, data collection should be completed at least every 3 years, based on the rate at which vegetation established following phase 1 restoration. This interval could be adjusted upwards if vegetation establishes slower than expected. To monitor the effects of high flows, data collection should occur after flows of a magnitude that is likely sufficient to rearrange the valley bottom. Given that the flow in 2020 that substantially rearranged the valley bottom was only 1,500 cfs on Lookout Creek, I recommend setting that discharge as a threshold: if a flow over 1,500 cfs on Lookout Creek occurs in a given year, I recommend collecting monitoring data, as the valley bottom may have changed substantially. This flow threshold could be adjusted upwards if future monitoring reveals that higher flows are necessary to substantially rearrange geomorphic units across the valley bottom.

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APPENDIX 1: METHODS

I used geomorphic unit mapping to compute the metrics presented in this study. Geomorphic unit mapping relies on both a set of geomorphic unit definitions, which I refer to as a geomorphic unit schema, and a way of segregating the landscape into units based on that schema.

I used a geomorphic unit schema designed to identify patches of the valley bottom with different relative elevations and canopy cover, as well as distinguish between deep (i.e., pools) and shallow portions of the channel. Definitions were also based on the available data and feasibility of mapping the valley bottom, given the abundance of wood and geomorphic heterogeneity. The schema included the following geomorphic units:

- Terrace: quasi-planar surface showing no morphologic or vegetative signs of recent inundation, including terrace benches (i.e., terraces not on the valley margin)
- Floodplain: quasi-planar, quasi-horizontal surface showing morphologic and/or vegetative signs of recent flood inundation, categorized by canopy height into low (< 1 m), medium (1 – 5 m), and high (> 5 m) canopy
- Vegetated Island: floodplain surfaces surrounded by the channel, categorized by canopy height into low (< 1 m), medium (1 – 5 m), and high (> 5 m) canopy
- Overbank Channel: channel (i.e., displaying bed and banks and typical fluvial bedforms) on a floodplain or vegetated island surface whose upstream-most elevation is closer to that of the surrounding floodplain or vegetated island surface than the nearby channel and that shows morphologic or vegetative evidence of being recently reshaped by overbank flow (i.e., is not a relict channel)
- Pool: deep, concave-up, and baseflow-wetted portions of the channel
- Undifferentiated Channel: shallower portions of the channel, including bars, riffles, runs, and glides

I also mapped the area occupied by downed, dead wood visible in drone imagery where that wood intersected non-terrace geomorphic units (i.e., I did not map wood solely resting on terraces). This enabled me to compute normalized wood load as the ratio of wood area to non-terrace valley bottom area. This wood load estimate is underbiased, as I missed a considerable amount of downed wood that was completely obscured by vegetation in the floodplain.

To map geomorphic units, I used a combination of field ground truthing and interpretation of remote sensing data, including: a 6 ft resolution LiDAR digital elevation model (DEM) from 2008, a 1 m resolution bathymetric LiDAR DEM from 2018, and approximately 3 cm structure-from-motion (SfM) derived drone orthomosaics and digital surface models. Drone orthomosaics were collected in April 2016 (just before phase 1 restoration), September 2016 (just after phase 1 restoration, September 2017, August 2018, July 2019, June 2020 (before phase 2 restoration), August 2020 (just after phase 2 restoration) and August 2021. Ground truthing involved walking the valley bottom and taking georeferenced notes and photographs coincident the 2018 – 2021 drone surveys. I mapped geomorphic units in ArcGIS Pro by manually drawing polygons around geomorphic units based on the aforementioned definitions. I used ground truthing and the SfM-derived digital surface model to differentiate canopy heights of floodplain and vegetated island surfaces.

I computed the abundance (area divided by valley bottom area) and total perimeter length of all geomorphic unit patches to compute geomorphic heterogeneity metrics, described in Table 2.

Table 2: Geomorphic heterogeneity metrics, definitions, and units.

GEOMORPHIC HETEROGENEITY METRIC	DEFINITION	UNITS
Vegetated island density	Count of vegetated islands divided by valley bottom area	# islands / km^2
In-channel edge density	Perimeter length of all pool and undifferentiated channel patches divided by the total area of all pool and undifferentiated channel patches	m / m^2
Pool abundance	Area of all pools divided by total valley bottom area	-
Fluvial process space	Area of non-terrace geomorphic units divided by total valley bottom area	-
Utilization of fluvial process space	Area of undifferentiated channel, pool, and overbank channel units divided by area of non-terrace units	-
Evenness of relative elevations (Simpson Diversity Index)	Probability of two randomly selected points being in geomorphic units of different inferred relative elevations Relative elevation classes were ranked by geomorphic unit as pool (lowest), undifferentiated channel, overbank channel, floodplain/vegetated island, or terrace (highest). Simpson diversity index was computed as $1 - \sum_{i=1}^{R} p_i^2$, where r is the total number of classes and p_i is the proportion of area occupied by the ith class. With 5 possible classes, this index can range from 0 to 0.8, with 0.8 representing complete evenness.	-
Canopy height evenness (Simpson Diversity Index)	Probability of two randomly selected points being in floodplain or vegetated island units with different canopy heights With 3 possible classes, this index can range from 0 to 0.66, with 0.66 representing complete evenness.	-

To compute the spatial extent of change in geomorphic units (i.e., the proportion of the valley bottom that changed from one geomorphic unit to another from observation to observation), I overlaid a 5 by 5 m grid of points across the valley bottom, extracted the geomorphic unit that point covered to each point, and tallied the number of points that changed from one geomorphic unit to another from observation to observation.

APPENDIX 2: ASSESSMENT OF LOOKOUT CREEK AS A FLOW ANALOG FOR DEER CREEK

Lookout Creek is a 62 km^2 (comparable to Deer Creek's 59 km^2) watershed adjacent to Deer Creek that ranges in elevation from 436 to 1622 m (comparable to Deer Creek's range of 1,055 to 1,628 m) and likely experiences a similar climatic regime. With its similar location and drainage topography, USGS gage 14161500 on Lookout Creek makes a suitable flow analog for Deer Creek.

I compared flows along Lookout Creek to ranked stages inferred from timelapse imagery of Deer Creek during high flows from November 2020 to February 2021 to determine if peak flow magnitude on Lookout Creek was comparable to stage peaks observed along Deer Creek. Of the 5 flow peaks during this period, 3 had timelapse-based rankings that matched with their relative magnitude as measured by the Lookout Creek gage (Figure 29). All peak flows matched with measured peak flows on the Lookout Creek gage within a few hours. The discrepancy between the two highest peaks and their timelapse-based ranking may have stemmed from the fact that the highest peak (December 20, 2020) substantially rearranged wood near the timelapse camera, potentially changing the stage-discharge relationship there (e.g., there could have been more backwatering on subsequent peak flows, so the timelapse-observed stage could have been higher, despite there being less total discharge). However, the temporal alignment and general agreement in relative magnitude between timelapse-observed peaks and peaks on the Lookout Creek gage indicates that it is a suitable flow analog for Deer Creek.

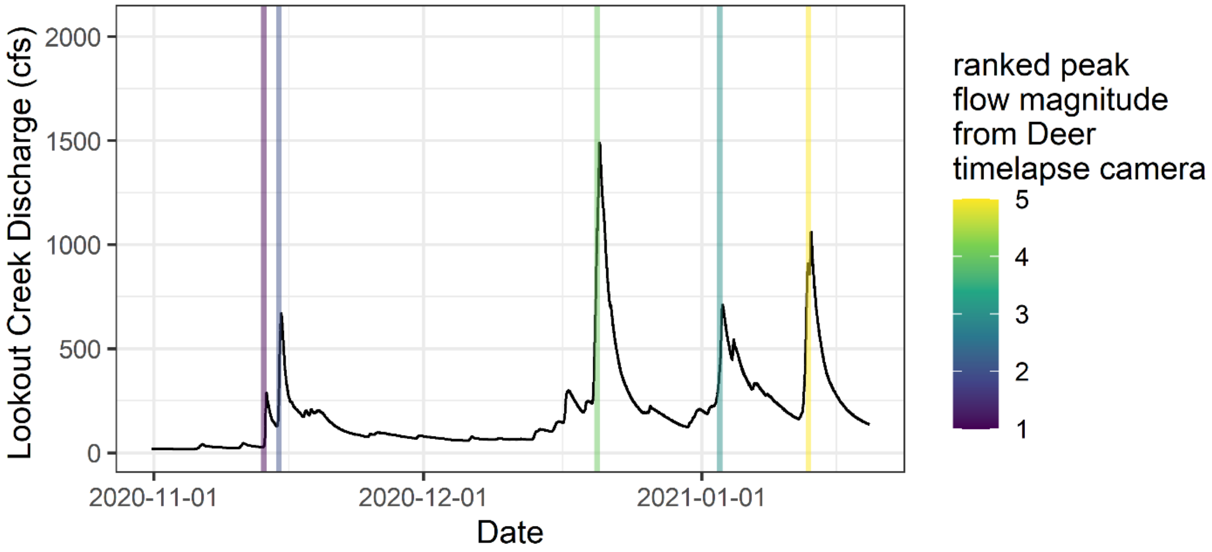

Figure 29: 15-minute discharge on Lookout Creek (gage 14161500). Vertical lines are plotted at the date and time of peak flows observed in hourly timelapse imagery along Deer Creek and are colored by their ranking of lowest to highest stage, as inferred from timelapse imagery.

APPENDIX 3: BED SURFACE GRAIN SIZE

Bed surface grain size is difficult to accurately quantify in a complex, multi-channel, and wood-rich valley bottom such as the restored portion of Deer Creek. Two separate efforts have been made to quantify bed grain size along Deer Creek: I have conducted transect surveys to estimate reach-scale bed surface grain size in the upstream and Budworm reaches from summer 2019 to summer 2021. Forest Service staff have also conducted separate transect surveys in the upstream reach from fall 2017 to summer 2020 (prior to phase 2 restoration). Both transect surveys estimate grain size in the active channel.

My transect surveys were coincident with my drone surveys in 2019, 2020, and 2021. Transects were systematically randomly spaced along valley centerlines at 50 m intervals throughout portions of the upstream and Budworm reaches (Figure 30). Along each transect, where it crossed the channel (pool or undifferentiated channel geomorphic units), I recorded the length of patches of median bed surface grain size classified as sand (< 2 mm), gravel (2 – 64 mm), cobble (64 – 128 mm), boulder (> 128 mm) or bedrock. Sample size was 7 transects in the upstream reach and 6 in the Budworm reach.

Forest Service transects were placed along the valley bottom in only the upstream reach and recorded both dominant and sub-dominant substrate classes. Data presented here shows only the dominant substrate class, and some transects were missing data. Sample size was 10 in 2017, 6 in 2018, and 10 in 2020.

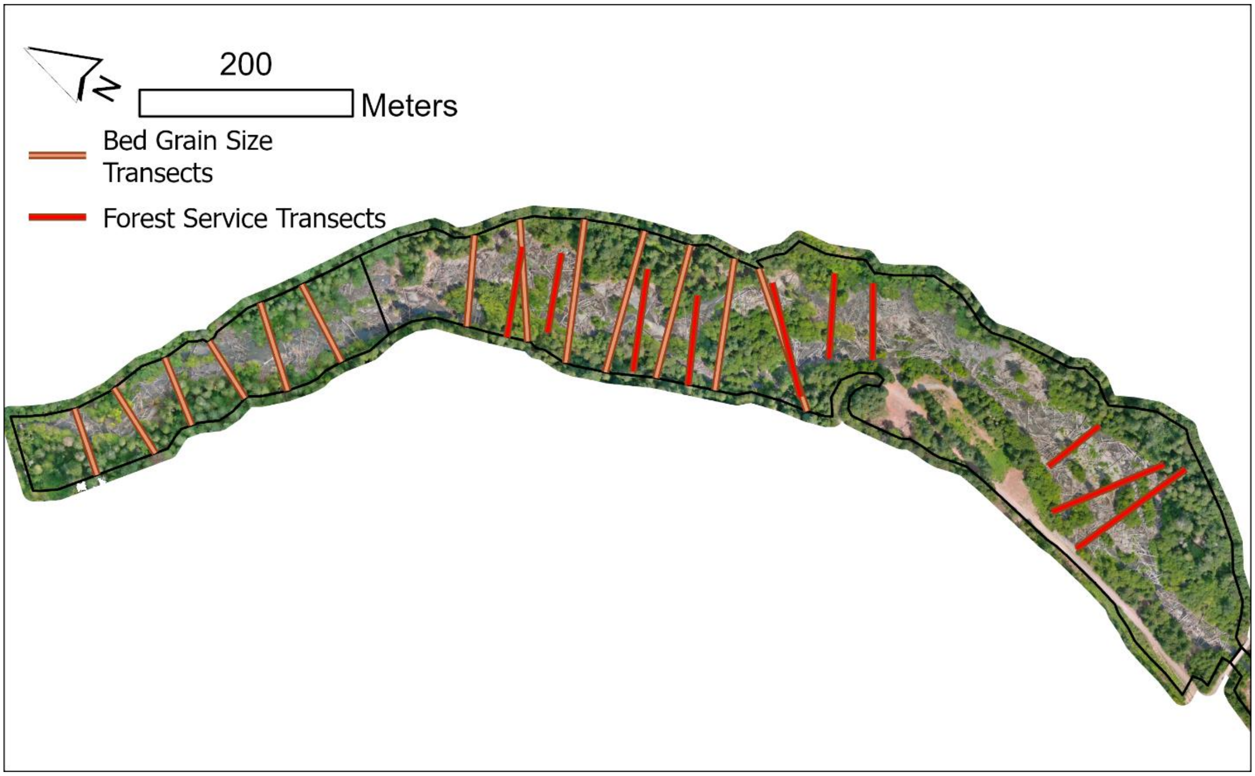

Figure 30: Transects used to estimate reach-scale bed surface grain size.

The data from these transect surveys displays a high degree of variability, likely due to a low sample size. As such, it is difficult to discern significant trends in bed grain size from these data. However, I present them here for informative purposes (Figure 31).

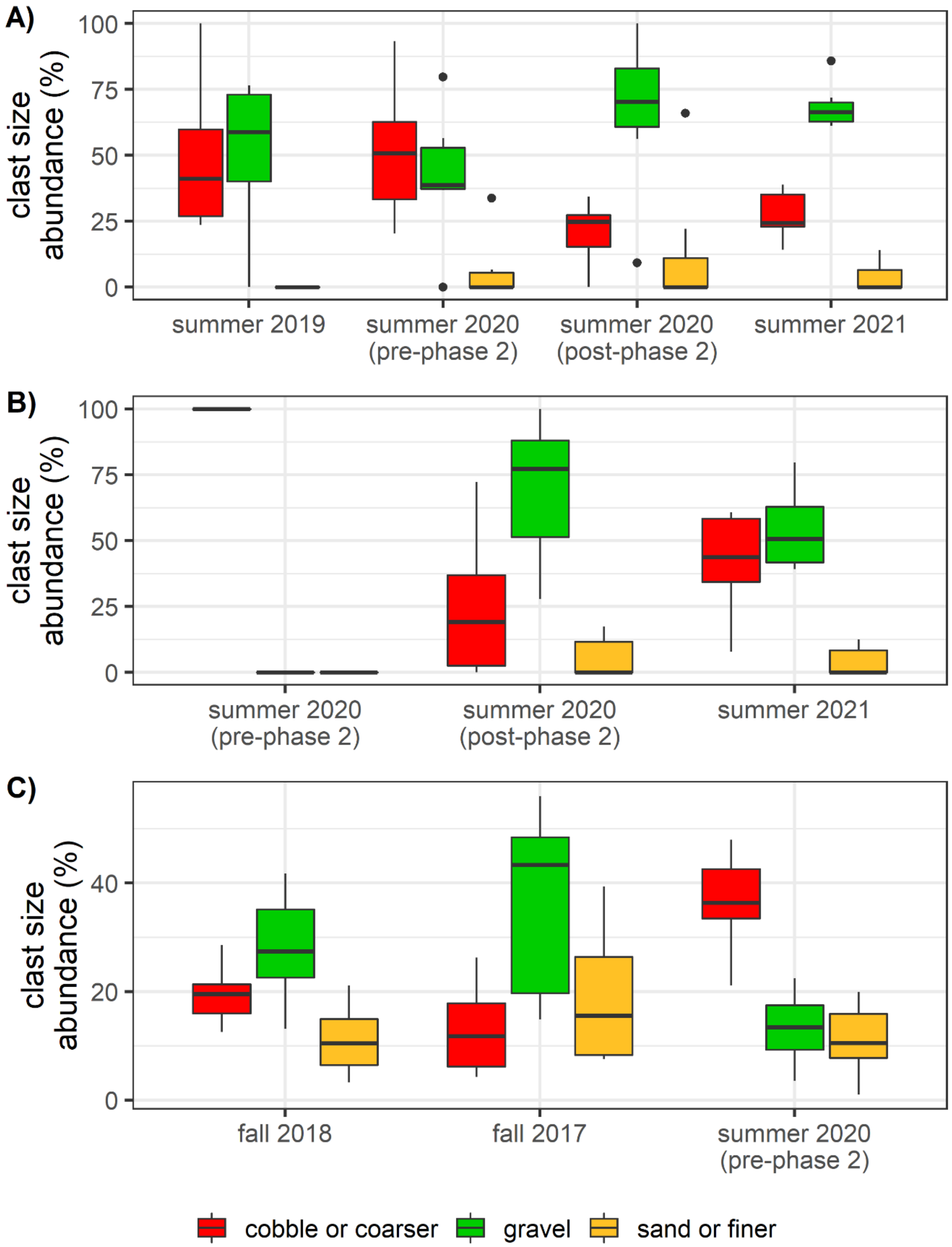

Figure 31: Boxplots summarizing transect-based survey data for my transects in the upstream reach (A) and Budworm reach (B) and Forest Service transects in the upstream reach (C). Bold horizontal line indicates median, box indicates 25th to 75th percentiles (i.e., interquartile range), lines indicate 1.5 times the interquartile range, and dots indicate observations outside 1.5 times the interquartile range.