Title
In Search of Sand: Debris Flows and Pacific Lamprey Habitat, Salmon River, California

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Abstract

The headwaters of Blind Horse Creek originate in the highest point of the Trinity Alps. It is a tributary to the South Fork Salmon River located in the Klamath National Forest. In the summer of 2021, wildfires burned 114,433 acres in the Salmon River watershed. For this subbasin of the greater Klamath River Basin (KRB), this was the greatest number of acres burned in a single year on record. The River Complex was a large-scale, high-severity wildfire that burned all around the South Fork Salmon River leaving steep drainages barren of any vegetation. The following year, 2022, summer rains brought 1-2 inches of rainfall to the landscape and triggered a debris flow within the Blind Horse Creek drainage. Although initially a major disturbance to the river system, over time the new sediment moving through the system deposited behind Large Woody Debris, boulders, and eddies, creating new beaches and sand bars distributed throughout the river. The delivery of fine sediments to streams post-fire can initially degrade salmonid-rearing habitat, however, these new sand deposits have the potential to be viable rearing habitats for other native fish species, such as Pacific Lamprey (*Entosphenus tridentatus*), and their larval stage, ammocoetes. Having a baseline of how the sediment is distributed throughout the system can indicate habitat change and distribution for these evolutionarily primitive and culturally significant fishes. Our work documents the current distribution of sediment and identifies potential lamprey rearing habitat through cross-sectional elevation surveys, facies map documentation, and the measurement of viable sand bars. The description of current site conditions after a large disturbance can help inform restoration strategies for the river and perpetuation of habitat for sensitive species such as salmonids and Pacific lamprey.

Introduction

The Salmon River and The Klamath River Basin

The Salmon River, located in remote and rugged northern California, is the second largest tributary to the Klamath River and maintains a large portion of habitat with high biological value. The 751 square mile watershed is over 98% owned and managed by the United States Forest Service. It has a natural, unregulated hydrograph, with no significant diversions, and is the largest cold-water contributor to the Klamath River (SRRC, 2019). This makes it a highly valuable habitat for cold-water-dependent species of anadromous fish (Stillwater Sciences, 2018). The Salmon River is fed by the high-elevation headwaters of its North Fork and South Fork. Flowing from the surrounding Marble Mountain Wilderness Area, the 37–mile–long North Fork is slightly smaller (27.16% of total watershed land area) than the South Fork (38.63% of total watershed land area) in watershed size and flow. The South Fork drains from the highest peaks of the northern Trinity Alps, and Salmon Mountains, flowing 39 miles to join the North Fork in the appropriately named Forks of Salmon (Kaufmann, 2022). From the combined forks to the mainstem river, the Salmon River later meets up with the Klamath River at the Siskiyou - Humboldt County line, where flow continues out to the Pacific Ocean. This configuration totals 100 miles and is the second-largest waterway nationally designated as Wild and Scenic from source to sea (Kaufmann, 2022).

Climate and Fire Shape the Landscape

The Klamath River Basin experiences a distinctive, Mediterranean-type climate seasonality characterized by wet, cool winters and dry, warm summers. A high inter-annual variation in precipitation is the norm, with most precipitation occurring between November and April, followed by a prolonged dry season from May through October. This regional variability of the region is attributed to steep elevational gradients and the proximity of the Klamath Mountains to the Pacific Ocean (Kauffman, 2022). On the Salmon River, intense localized summer rain showers frequently occur and have been associated with soil erosion and debris torrents (SRRC CWPP, 2021). The geology of the Salmon River results in landslides being a dominant geomorphic process, with debris flows occurring in areas characterized by granitic bedrock. From 1944 to 1988, 208 acres of the river's South Fork were scoured by debris flows (SRRC 2002), indicating the impact this process has on the system's morphology. High sediment inputs from landslides and debris flows, including post-wildfire debris flows, can affect the quality of anadromous fish habitat in the Salmon River and create shifts in habitat characteristics.

Historically, the watershed of the Salmon River and the larger KRB experienced frequent wildfires, which maintained important ecosystem functions (Knight et al., 2022). However, many decades of fire suppression and the cessation of natural and indigenous fires allowed fuel loads to increase, and wildfires now tend to produce greater burn severity. Drought may be an important factor in determining fire severity, and with increasingly more frequent hot and very dry summers, this raises the probability of enhanced wildfires following long durations and magnitudes of drought (Kane, 2017).

Anadromous Fish and Their Habitat

Anadromous fish species that are supported by the Salmon River watershed include summer and winter-run steelhead (*Oncorhynchus. mykiss*), coho salmon (*O. kisutch*), Pacific lamprey (*Entosphenus tridentatus*), spring and fall chinook salmon (*O. tchawytscha*), and green sturgeon (*Acipenser medirostris*), with the river contributing an estimated 376 miles of coldwater habitat (SRRC, 2002).

There are two distinct populations of Pacific lamprey that may occur in the Klamath River Basin, composed of spring-run individuals and fall-run individuals. Spring-run individuals are adults that migrate and immediately spawn, and the fall-run individuals migrate and then wait until the following spring to spawn (Anglin, 1994). Adults built nests to spawn, often in low-gradient riffles referred to as redds (Gunckel et al., 2009). Once hatched, the larval lamprey swim into the water column and are carried to areas downstream with finer substrates. They then burrow tail first into the softer sediments and begin filter feeding (Moyle et al., 2015). These larval lamprey are referred to as ammocoetes, and their survival at this stage is dependent on stream discharge and availability of the rearing habitat in which they will spend 5-7 years before migrating downstream to the ocean (Brumo, 2006).

The conservation of Pacific Lamprey has not been a fisheries management priority in the United States (Close et al., 2002). Although these primitive fish share many of the same habitat characteristics as salmonids, lamprey have received little attention in the fisheries management system. Native Americans in the Columbia River basin have elevated the importance of restoring Pacific lamprey (*ksuyas*) populations and habitat; sharing similar geographical ranges and habitat characteristics, lamprey are sympatric with salmonids, as well, their decline is significantly correlated with habitat disturbance. This long-lived species plays an integral role in the food web, acting as a buffer for salmon as predators and may be an essential source of marine nutrients to oligotrophic watersheds (Close et al., 2002). Pacific lamprey continues to this day to be a culturally significant species for various tribes along the Pacific coast, harvested as a subsistence food source, Pacific lamprey is the link between food and tribal sovereignty with the land (Close et al., 2002).

The River Complex Fires and 2022 Debris Flows

The River Complex Fires began in July 2021 and were active for a total of 88 days, burning almost 200,00 acres (CalFire, 2022). In late July and early August, 2022, the mid- Klamath River Basin experienced isolated thunderstorms across the region, bringing about 1- 2 inches of rain. The region was already experiencing high temperatures in combination with drought, adding a high-severity fire has put pressure on the stability of the drainage slopes.

Drought prior to the summer of 2022 led to a moisture deficient landscape on a high-severity fire scar, resulting in heavy debris flows in multiple drainages within the 2022 Mckinney Fire and 2021 River Complex burn areas. No significant fish kill was documented on the Salmon River as a result of the debris flows, however, the debris flows which occurred in the mainstem Klamath River from the Mckinney Fire, resulted in a large number of fish dead. This is likely due to the fact that the Mckinney Fire was an active incident at the time and contributed higher levels of ash to the river once the storms began (SRRC, 2023).

Methods/ Study Approach

Our study area is located at the confluence of Blind Horse Creek and the South Fork Salmon River (Figure 1). The primary goal of our study was to document evidence of the 2022 debris flows, and to establish baseline data against which future changes (such as flushing out of fine sediment from the debris flow) can be measured in the future. From observed field conditions we inferred how sediment from the debris flow altered channel morphology and rearing habitat for the Pacific lamprey on both the South Fork of the Salmon River and Blind Horse Creek.

Literature Review/ Site Mapping

In preparation for the field, we researched literature related to historic and current conditions of the Salmon River including habitat availability and biotic community classification, specifically for native anadromous fishes (such as salmonids and lamprey) and the historic, current, and proposed management practices within the Salmon River basin, and within the entire Klamath River basin. We included literature on how the aftermath of wildfires can create the potential for widespread debris flows in de-vegetated drainages.

To visualize the extent of vegetation loss, we acquired Landsat- 8 satellite imagery before and after the 2021 River Complex. Scars from recent wildfires are visible on both sides of the South Fork Salmon River drainage, and the River Complex Fire which encircled our project area (Figure 2b). The image analysis known as the Normalized Burn Ratio (NBR) can provide an indication of fire extent and severity after calculating the difference between conditions immediately before and immediately after the fire. To calculate the difference NBR, we subtracted the post- fire NBR raster from the pre-fire NBR raster, resulting in the difference in Normalized Burn Ratio (dNBR). We classified the severity levels as: Unburned, Low Severity Burn, Moderate-Low Severity Burn, Moderate-High Severity Burn, and High Severity Burn, based on qualitative degrees of the vegetation (or lack of vegetation) that covers the landscape. In the footprint of our area of study the burn severity was categorized as High Severity Burn and Moderate-High Severity (Figure 2a).

Field Survey

We conducted three cross-sectional surveys at sites selected based on their proximity to Blind Horse Creek and the South Fork Salmon River (Figure 4). Two sites were surveyed on the South Fork, one above (41°05'27.44"N, 123°03'15.42"W) and one below the confluence with Blind Horse Creek (41°05'28.48"N, 123°03'16.98"W), with both cross-sections positioned at pool tail-outs (XS.A and XS.C). The Blind Horse Creek cross-section (XS.B), was located approximately 10 ft upstream of its outlet (41°05'27.04"N, 123°03'15.32"W). To our knowledge, this reach did not have any previous cross-sections recorded.

Additionally, we created a facies map to document the changes in bed material post-debris flows (Figure 5). The term *facies* refers to a mappable area of the streambed that can be delineated/mapped based on particle size, representing a distinct local depositional environment (Pettijohn, 1975). This type of mapping can be an extremely useful tool for describing current site conditions (Kondolf and Lisle, 2016). Our map covers the entire survey area (approx. 5,500 sq. ft) of documented bed material. During this exercise, we were particularly interested in the formation of new sand bars, created by the influx of sediment from the 2022 debris flows, which we identified as potentially suitable Pacific lamprey rearing habitat. We created the facies map by referencing extensive photographs taken on site, aerial imagery, and rough field sketches/notes. Distinct changes in bed material were also noted while recording elevations for our cross-sections and we used these to validate the scale of our drawing.

The dimensions of three of the more substantial deposits we encountered were calculated using a method outlined by Nystrom (2020), with the lengths multiplied by the average of 3 width measurements to yield total area (Figure 6). We measured the depths of the deposits from the surface of the water to the surface of the sand and from the top of the deposit to the original cobble bed material below (Table 1). These measurements allowed us to identify areas where the deposits were deep enough to be considered viable rearing habitat. Not only do lamprey ammocoetes need certain depths of substrate, but dewatering of rearing areas due to low flows can cause high mortality rates, especially early on in the larval stages. (Liedtke et al., 2015). Future surveys during various points of the annual hydrograph will need to occur to confirm that the measured deposits will in fact be submerged sufficiently even during low flow periods. According to Nystrom (2020), burrowing ammocoetes need fine grain deposits with a minimum depth of 3 inches. Required depths of burrowing material depend on the size and species of lamprey, with Pacific lamprey rarely needing substrate deeper than 6 in (Liedtke et al., 2015).

Lastly, we repeated photo points of Amy Fingerle (2022). Fingerle took photos about a week after the storms that caused the observed debris flows at three sites, including the confluence of the North and South Forks of the Salmon River, Methodist Bridge on the South Fork of the Salmon River, and the confluence of Blind Horse Creek and the South Fork Salmon River (Figure 3).

Discussion/Conclusion

Channel Morphology

The results from our cross-sections are intended to serve as the baseline for future surveys assessing morphological changes in the reach of study. Of note is the cross-section of Blind Horse Creek, showing incision with high banks on either side of the wetted bedrock channel. In one of the cross-sections taken for the South Fork of the Salmon River (XS.A) our measurements ended at the location of accumulated Large Woody Debris (LWD), instead of at the bankfull width. The LWD formations made the right bank inaccessible and future surveys should take this into consideration. Much of this log pile can be considered "coarse woody debris" (>10cm) using a classification outlined in Harmon and Sexton (1996) and it was the most significant pile we observed.

Habitat Characteristics

The results from the field show that the bed material of the South Fork Salmon River has been impacted by the debris flows from Blind Horse Creek and Rush Creek upstream. This reach of the river is predominantly alluvial with a cobble and gravel bed, and in our observations we found many of the interstitial spaces between the cobbles had been filled with medium to coarse grain loose granitic sands (approximately 0.2 mm-1.0 mm). In a few places we found that the new matrix sediment exceeded the pore space provided by the cobbled bed material and had built up into surficial patches or sand bars. For the deposits measured, we found that they ranged in depth (top of deposit to bedrock or cobbles below) from 0.3 ft to 1.0 ft. A summary of all measurements taken can be seen in Table 1. Both the depth of the deposit and its distance from the water surface level was recorded to ensure that the deposits were sufficient enough for the burrowing habits associated with Pacific lamprey ammocoetes. While the sand bars chosen for survey ranged from 0.2ft to 1.7ft below the water surface level at the time of our visit (November, 2023), we recommend that they be revisited during a period of base flow to make sure that they continue to be submerged. Specifically, Bar 3, is unlikely to remain inundated during low flow periods of the year. Using pacific lamprey larval habitat classifications outlined by Stillwater Sciences (2013) and shown in Table 2, we classify the new deposits on the South Fork Salmon River as a combination of Type I and Type II. In contrast, Blind Horse Creek at its outlet showed little to no obvious lamprey ammocoete habitat and should be classified as Type III, or unsuitable.

Many of the sand bars that we observed occurred in pools or directly behind obstacles in the channel such as LWD pile ups or boulders. Small scale studies show that distributions of larval Pacific lamprey often increase in areas characterized by patches where fine sediments tend to accumulate, such as the insides of bends and eddies (Torgerson and Close, 2004). It is tempting to say that the sand bars and substrate changes that we observed in this study mean there are likely to be viable populations of Pacific lamprey here in the future. However, it is important to consider the connectivity between habitat patches alongside the site specific qualifications of ideal habitat (Moser et al., 2021). Studies of larval lamprey abundance at varying spatial scales have suggested that the relationship between potential habitat and utilized habitat relies heavily on spatial context (Torgerson and Close, 2004). Also, the classifications of habitat addressed above were based solely on bed material and depth of deposits. Classifying the study reach as ideal ammocoete habitat requires additional information on other habitat characteristics, such as dissolved oxygen concentrations, food availability, and the organic and inorganic properties of the sediment. However, we believe that the presence of these sand bars warrants resources to be allocated to continue monitoring in this reach. Additionally, using an Electrofishing survey method will help to identify presence/absence of lamprey and contribute to knowledge of distribution throughout the region.

Sediment Dispersal

When comparing images taken in the weeks directly after the storms to those we took on site just over a year later, it is clear that much of the suspended fines visible from the earlier images have since washed out. Earlier photos show the dispersal of sediment introduced to the river from overland flow, most likely the fine-grained sediment driving higher turbidity. Recent photographs show residual material left behind both from overland flow inputs and coarser sediment and larger debris that were more likely introduced from the debris flows. We observed areas along the banks of the South Fork Salmon River with up to 26 inches of fluvial deposits, this observed coarse sediment material (gravel and boulders), is evidence of a high rate of transport, suggesting a categorization of the event to be a debris flood, a case of Stage 3 flow, as defined by Church and Jacob (2020, pg. 1):

> "In Stage 3, the entire streambed or a continuously connected portion of it becomes mobile and activity may extend to a depth of several median grain sizes below the surface as the result of momentum transfer by grain-grain collisions. In many instances, the channel itself is modified by erosion and sedimentation. *A debris flood is, then, a case of Stage 3 transport*."

In addition to Blind Horse Creek, other tributaries within the 2021 River Complex burn scar contributed to the increased sediment loading in the South Fork. On the north side of the drainage, approximately 167 yards upstream from Blind Horse Creek, Rush Creek flows into the South Fork Salmon River. We hiked approximately 300 yards through Rush Creek, after taking the Rush Creek Trail southeast and entering the channel at the trail bridge (41°05'30.26"N, 123°02'52.91"W). While walking southwest towards the confluence of Rush Creek and the South Fork, we observed large accumulations of woody debris (which appeared to be freshly deposited given the state of the finer branches), at the base of standing trees, a layer of mud provided an indication of the floodline, and unvegetated freshly deposited fine to medium grained sand accumulated on the banks. These suggested that another debris flood had occurred on Rush Creek (Figure 7). Thus, for a comparison of sediment dispersal, we need to go further afield to locate a reach that is less impacted by the 2021 River Complex and 2022 winter storms.

Implications for restoration and fisheries management

As wildfires become more extreme, especially in the state of California, river restoration planning will need increasingly to consider the impacts of fire and post-fire debris flows (Bixby et al.; Dunham et al., 2003, 2015; Howell, 2006). Events such as the 2022 debris flows are likely to continue occurring in the future and pose interesting challenges and opportunities to fisheries managers on the Salmon River. We recommend that cross sectional elevations, facies maps, and surficial patch measurements continue to be re-measured as the sediment introduced from this event is distributed over time. Having an estimate of how long the sand bars created by this event remain, may help us determine whether or not these initially disruptive debris flows actually create new habitat opportunities for Pacific lamprey larvae.

Hatch and Whiteaker (2009) speculate that Pacific lamprey have poor homing abilities, and that populations fluctuate based on source-sink dynamics. This means that metapopulations on tributaries may be established from larger populations on main rivers, and that there is an extremely stochastic quality to the distribution of lamprey (Moyle et al., 2015). It also indicates that occasional extinctions of metapopulations may occur in tributaries (sinks) due to episodic environmental disturbances and may be the reason that lamprey have been observed in streams with very little ideal habitat (Moyle et al., 2015). If this is the case on the Salmon River, populations of Pacific lamprey on the Klamath River or the Mainstem of the Salmon River may be a source population for the South Fork Salmon River. While the "sink" populations on the South Fork may fluctuate due to disturbances such as the 2022 debris flows, a strong driver of whether the new habitat is utilized is the stability of the source populations. This indicates that even if the sand bars we observed in our study are not permanent, a metapopulation may be established if the source population is maintained. As mentioned before, lamprey have not historically been afforded the same attention in restoration efforts as other more charismatic anadromous fish. We recommend that Pacific lamprey be made a management priority, with further research needed on the longer-term dynamics of sediments introduced through debris flows and their impacts on the distribution of lamprey.

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Plan and profile of Klamath river, California and Oregon (below Keno): Scott River to mile 22, Trinity River to South Fork, Salmon River and South Fork to Grizzly Creek, North Fork of Salmon River to Russian Creek, and South Fork of Smith River, California—Digital Maps and

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Appendix. Figures and Tables

Reference Maps

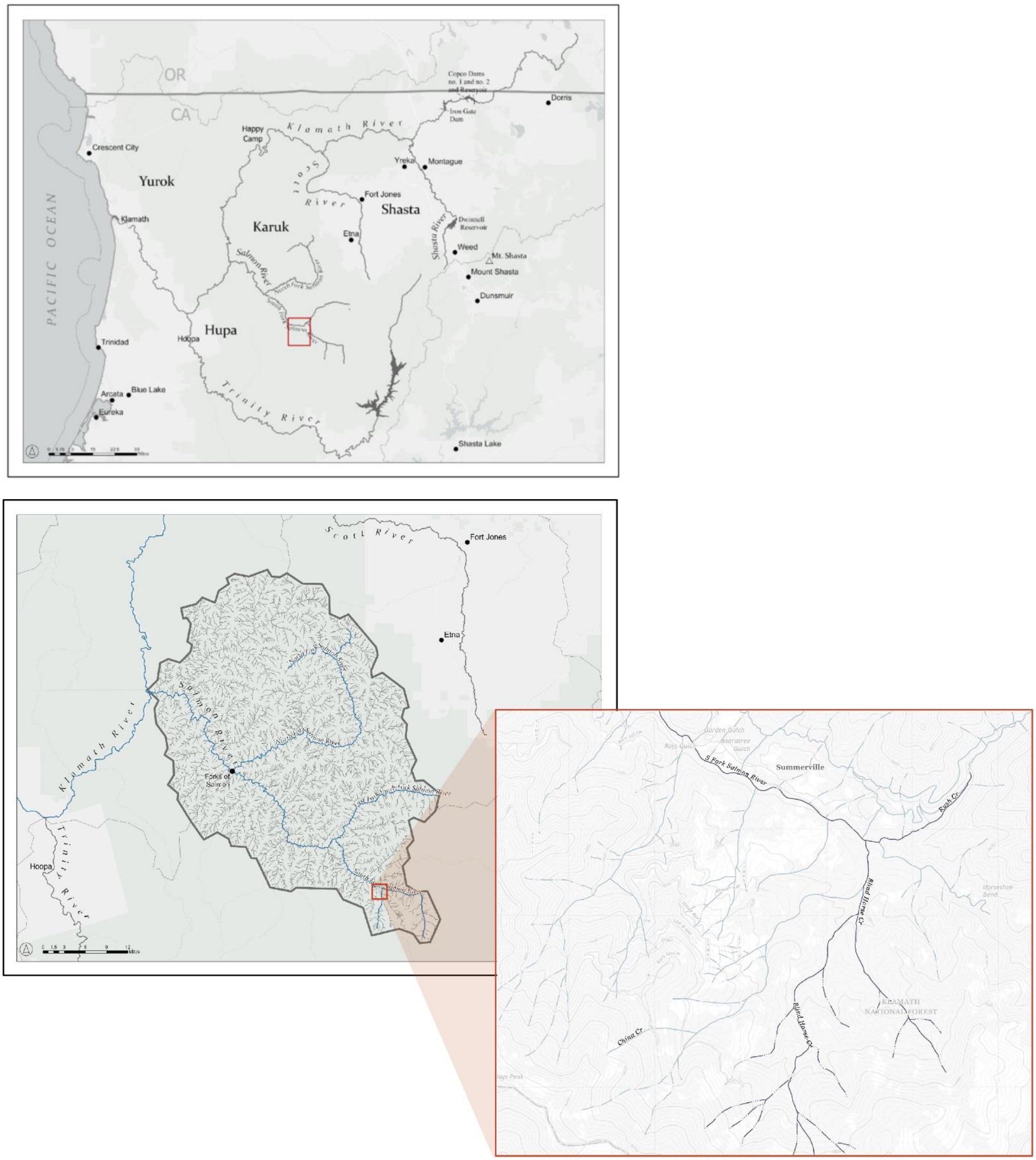


Figure 1. Reference maps depicting geographic area at the regional scale (top), watershed scale (middle left), and reach scale (bottom right).

Burn Severity Index

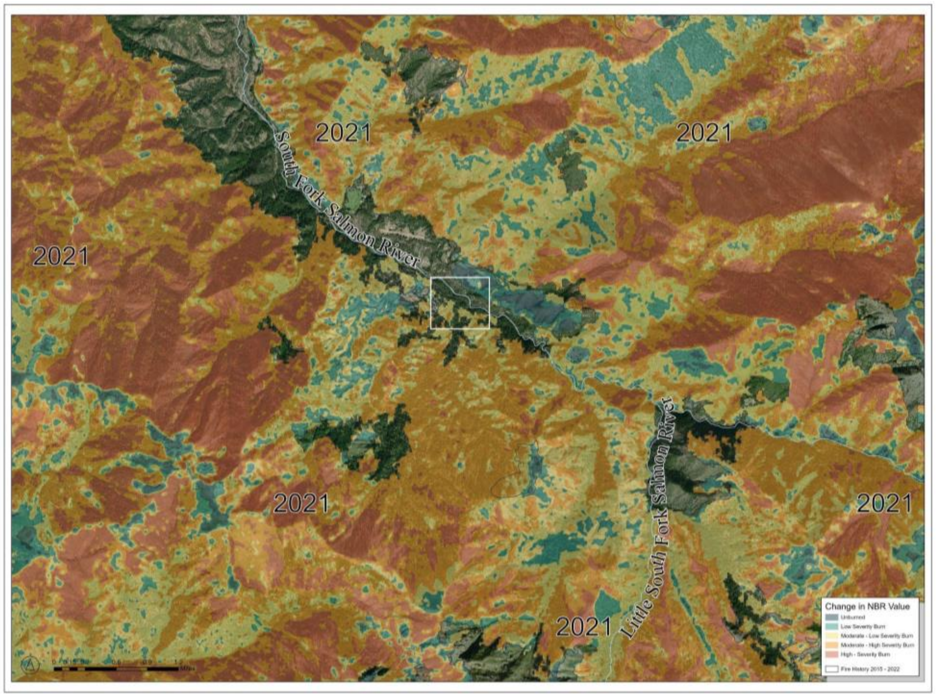


Figure 2a. Normalized Burn Ratio image analysis, showing severity of the burn scars surrounding our study reach. This map was created using Landsat-8 imagery from 2019 and 2021. This map indicates the extent of vegetation loss that occurred because of fires that burned after 2019. Our area of study has fire scars categorized as High Severity and Moderate-High Severity burns.

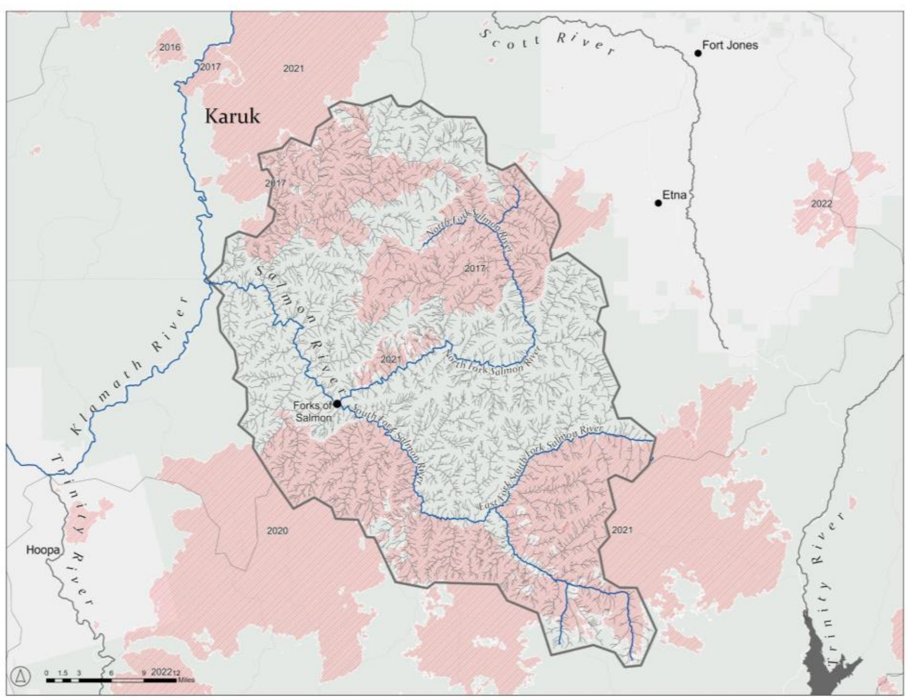


Figure 2b. Map showing burn extents of the 2021 River Complex and other recent fires. Multiple recent fires have occurred in the areas surrounding our study reach.

Photographic Comparisons

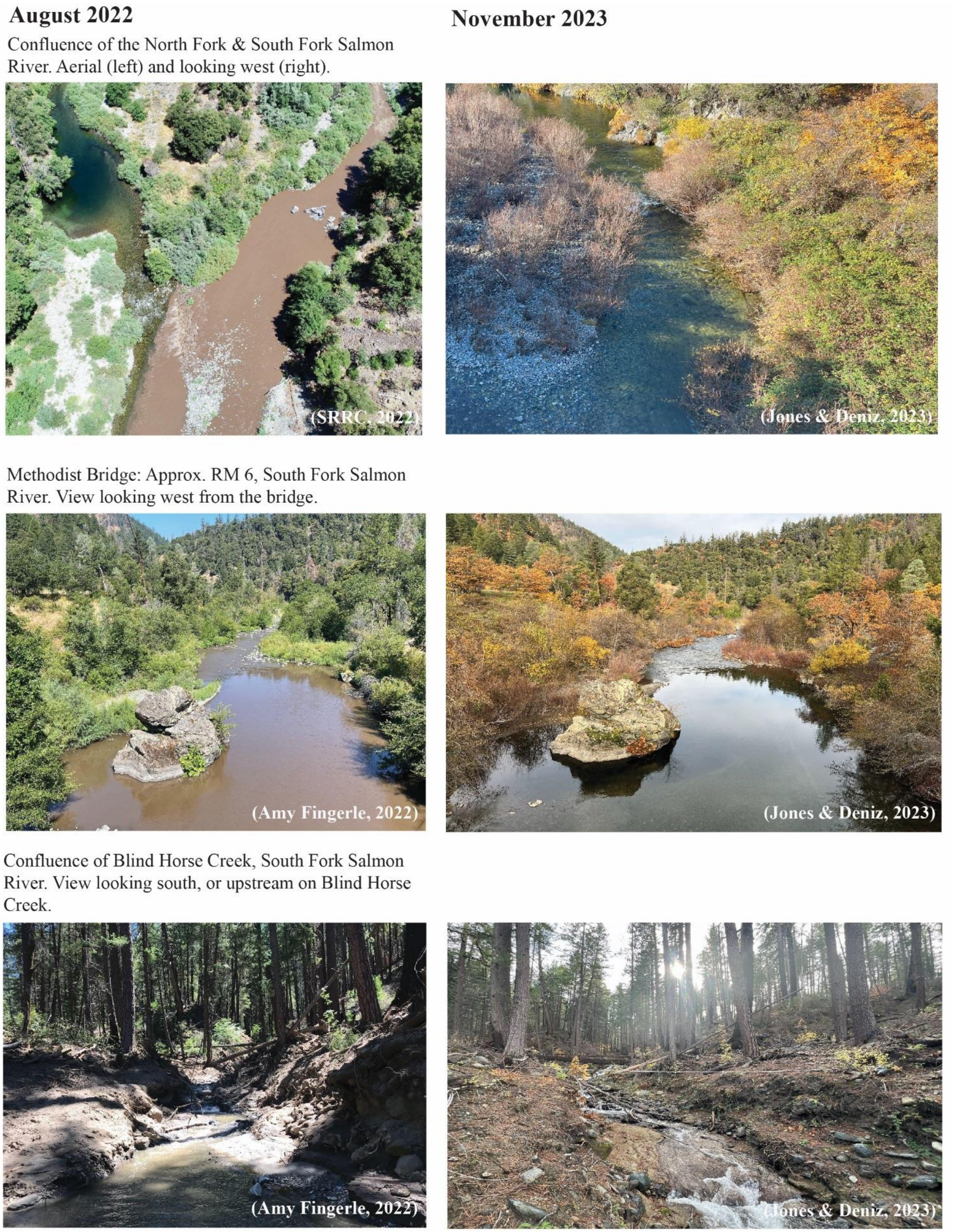
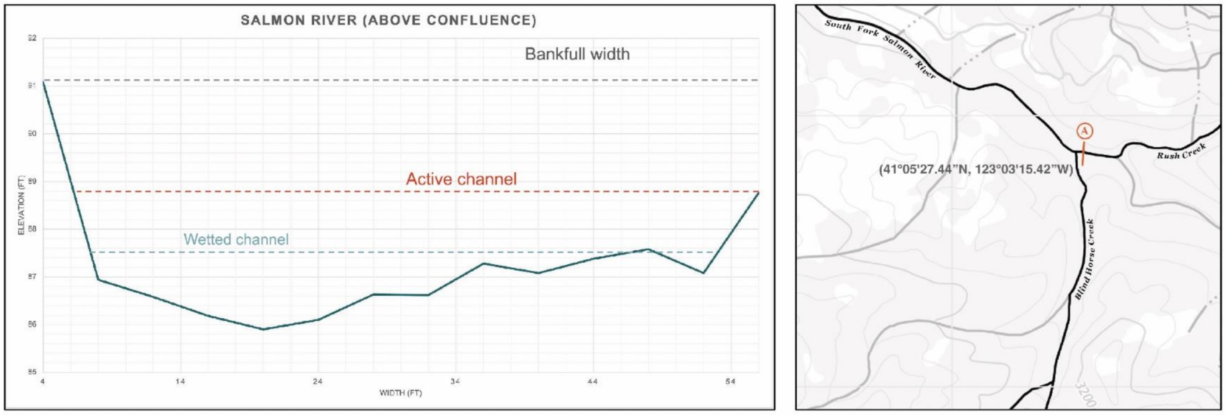


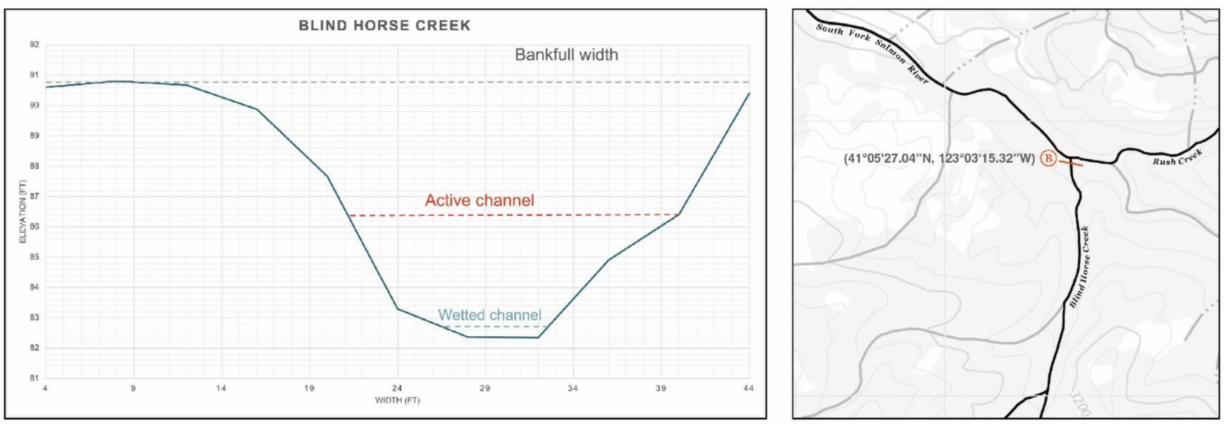
Figure 3. Photo point recreations, based on Amy Fingerle's photographs from August 2022, as well as aerial photography provided by the Salmon River Restoration Council.

Cross-sectional elevation profiles:

XS. A



XS. B



XS. C

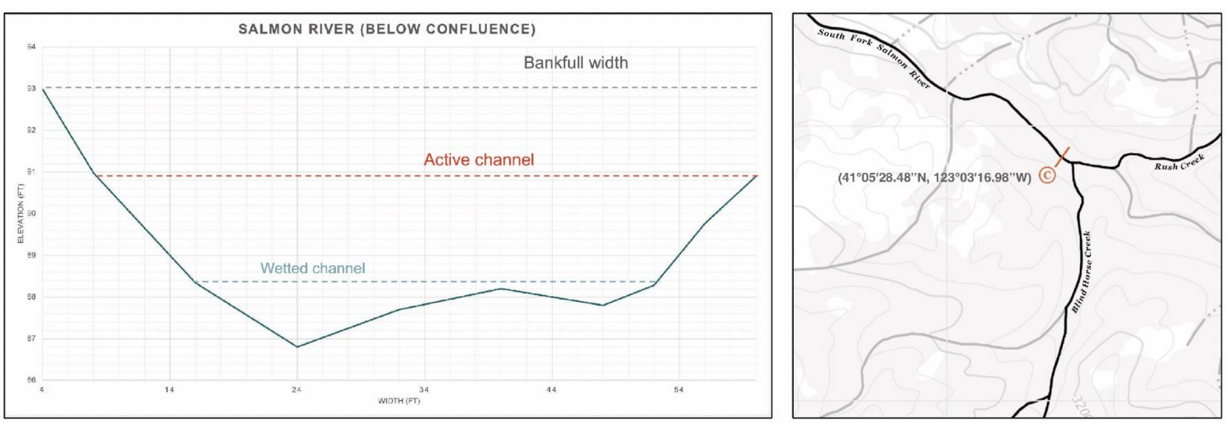


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Figure 4. Cross-sectional profiles showing elevations of 3 sites above, in, and below Blind Horse Creek. Elevation on the vertical axis was determined based on the benchmark elevation of 100ft for the auto-level. Width on the horizontal axis refers to the distance in feet from the benchmark on the left bank. Note: Left and right bank designations determined looking downstream. Coordinates given for left bank survey location.

Facies Map

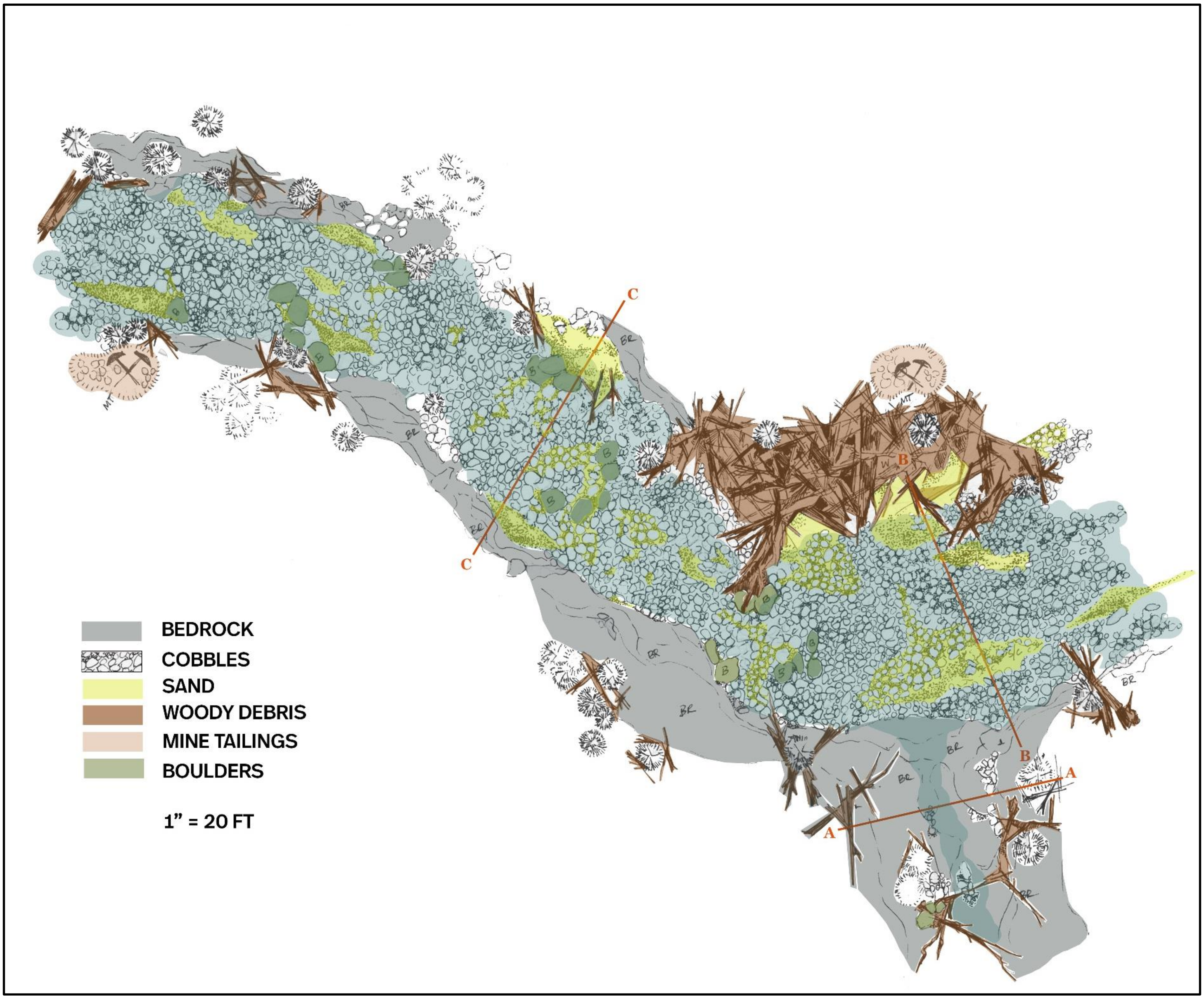

Figure 5. Facies map documenting bed material along study reach. This was hand drawn, using photographs taken from the site, aerial imagery, and field notes as reference. Drawn to a scale of 1:20.

Sand Bar Measurements

Bar 2

Figure 6. Example of measurements taken for each bar (image of bar 2). The 3 width measurements were averaged and multiplied by the length to determine area estimates.

Bar 1

Bar 3

Station	Length (ft)	Width 1 (ft)	Width 2 (ft)	Width 3 (ft)	Average Width (ft)	Area (ft²)	Depth of deposit to water surface (in)	Depth of deposit (in)
Bar 1	16.00	5.65	7.77	4.00	5.81	92.91	20.40	7.20
Bar 2	12.80	2.20	6.00	3.00	3.73	47.79	15.60	3.60
Bar 3	21.00	4.00	7.00	6.00	5.67	119.00	2.40	12.00

Table 1. Bar areas and depths.

Rearing Habitat type	Dominant substrate	Particle size range (mm)	Notes for classification
Type I: Preferred	Silt with or without organic matter	0.004-0.062	Finer grained sediment (such as clay) is not suitable unless loosely packed and mixed with significant fraction of organics.
	Fine to medium grain sand with a significant fraction of silt/organic matter.	0.063-0.50	Substrates dominated by coarse-grained sands (< 2 mm) are only considered Type I if they contain a significant fraction of organics/silts.
Type II: Acceptable	Medium grain-coarse sand with little or no silt/organic matter	0.25-2.0	Considered acceptable only if mixed with gravel and small cobble substrates if other habitat characteristics are highly suitable. Unsuitable if hard-packed.
	Fine gravel with significant fraction of fine sand/silt/organic matter	2.0-8.0	Substrates dominated by medium-gravel (8-16 mm) may be categorized as Type II if they are loosely packed and contain a significant fraction of organics/silts.
Type III: Not suitable	Clay	<0.004	Clays only acceptable if loosely packed and contain significant fractions of silt and/or organics, and other habitat characteristics are suitable.
	Medium-coarse gravel	8-64	Generally considered unsuitable. Though ammocoetes have been documented in gravel substrates, it is considered marginal habitat.
	Small cobble or larger, includes bedrock	>64	

Table 2. Substrate characteristics used to assess lamprey ammocoete habitat suitability. Adapted from Stillwater Sciences (2013).

Photos from Rush Creek

Figure 7a. Large woody debris pile up on Rush Creek. Note the steep bedrock banks with cobbles and small boulders deposited upstream of the log jam. View looking north (upstream).

Figure 7b. Active erosion of the noncohesive bed material that makes up Rush Creek's channel and fine grain deposits seen on the outer edges of the active channel, indicates significant transport throughout the tributary. View looking south (downstream)

Figure 7c. The channel is made of noncohesive sediments suggesting high rates of bed material transport throughout the incised channel. View of left bank (looking downstream).

Figure 7d. Evidence of scour on the left bank (looking downstream) from exposed roots.

Figure 7. Photos taken while hiking Rush Creek, showing evidence of a debris flow and flood occurring on the tributary, likely from the 2022 storms.