Mapping active and exposed coarse bars and fine sediment deposits in the restoration reach of the Trinity River, California

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Abstract

Exposed and active coarse sediment (>2 mm diameter) and fine sediment (≤2 mm diameter) deposits were mapped in summer 2023 on the Trinity River between Lewiston Dam and the North Fork Trinity River. The mapping was used to identify areas where fine sediment deposits are lacking, quantify the trajectory of change in coarse sediment storage since active bar mapping was last completed in 2014, and describe mechanisms for and limitations on coarse bar development. The upstream-most fine sediment deposit was mapped 2.04 river miles downstream of Lewiston Dam, indicating a deficit of fines in this reach. The deficit likely extends to river mile (RM) 89.92 near Steiner Flat, where areas of fine sediment deposit per unit channel distance triples relative to the upstream reach. Coarse bar areas increased 45% from 1,345,673 ft^2 in 2014 to 1,957,437 ft^2 in 2023; the number of mapped bars also increased from 302 to 392 in these years, which is a 30% increase that indicates bars were larger and more numerous in 2023 than the previous survey. Bar areas per unit channel distance increased from 29,262 ft^2/mile in 2014 to 49,256 ft^2/mile in 2023, and the cumulative areas of bars exhibited stepwise rises at stream junctions and gravel augmentation locations, suggesting gravel placements may effectively simulate natural supplies of sediment to the river. Coarse bars were most frequently associated with channel expansions followed by river bends, channel reconstruction projects, and bedrock forcings. Fine sediment deposits were commonly associated with the same forcings driving coarse deposits, except roughness from vegetation replaced constructed areas in importance. The main limitation on fine sediment deposits appears to be the under supply between Lewiston Dam and Steiner Flat, located 22.3 river miles downstream from the dam. Adding fine sediment near Lewiston and increasing channel complexity would help reverse the deficit by providing areas for deposits to reside within the active channel. Large wood additions and increased roughness from channel widening would also promote fine and coarse bar development. Large wood was the least frequently observed forcing mechanism for these sediment deposits due to its storage principally outside the active channel of the Trinity River.

Introduction

Alluvial deposits form in rivers where the sediment supply exceeds the transport capacity of the flow. The supply of coarse and fine sediments can originate from numerous sources, including the channel bed and banks, tributary streams, debris flows and landslides, and anthropogenic augmentations made to the channel, to name a few. The transport capacity of the flow is also influenced by many factors, such as hydraulic roughness from streambanks, bed sediments, bedrock, vegetation, wood, bar deposits, channel cross section and planform shape, variations in channel width, and the actual width itself. It is the dynamic interaction between the relative supply and transport of sediment that determines where and how long sediment deposits are formed and persist in a river channel through time (Hooke and Yorke, 2011).

Local perturbations in sediment supply and transport capacity can lead to sediments depositing as mid-channel, lateral, or transverse bars that generate form drag that promotes sediment sorting (Parker and

Peterson, 1980; Dietrich et al., 1989). The sorting causes fine grains to be winnowed from larger rocks and a coarse bed and hydraulically rough surface to form (Buffington and Montgomery, 1999). The higher roughness on the coarser, sorted bed increases intergranular friction angles and the critical flow for sediment entrainment, which promotes further deposition (Kirchner et al., 1990) and adjustment of the channel width through bank adjustments. From these, a positive feedback is created between an existing bar's roughness and form that helps maintain its size and position in quasi-equilibrium with the channel dimensions, sediment supply, and stream power (Lisle et al., 1993). Such equilibrium promotes gravel bar formation and maintenance and supports the biology of a stream by providing a gradient of water depths and flow velocities for fish to preferentially locate (Harrison et al., 2011), topography for hyporheic forcing (Marzadri et al., 2005), and exposed surfaces for plant establishment and growth.

Fine sediments that are winnowed from the bed or contributed directly to the channel by creeks or bank erosion can remain suspended in the flow or transported in long steps between low energy areas where they deposit. A primary area for storing fines is between gravel and cobbles in the subsurface area of a riverbed, and until this area fills or is nearly filled with fines, surface deposits of sand and silt can be rare to non-existent. As fines percolate in and fill void spaces in the bed, surface deposits of fines will increase in occurrence in low energy areas of the channel, including behind boulders, logs, amongst vegetation, within irregularities in streambanks, or in the lee of gravel bars. When in the wetted channel, fine sediment deposits are nursery areas for Pacific Lamprey (*Entosphenus tridentatus*) in their ammocoete life stage. Fines are also biologically important for partially filling spaces between gravels in the bed to degrees that reduce egg jiggling and mortality from abrasion (Merz et al., 2004), providing media for plant establishment and growth on bars and floodplains (e.g., Steiger et al., 2003), and preventing channel dewatering by reducing the hydraulic conductivity of the bed (Kolterman and Gorelick, 1995) and exchange of streamflow with the subsurface environment (Tonina and Buffington, 2007).

Where coarse or fine sediment supplies chronically exceed the transport capacity of the flow, detrimental effects can occur. For example, where fines are overly abundant, interstitial spaces in the bed can fill and block hyporheic exchange, suffocate and entomb salmon eggs and fry (Suttle et al., 2004), and reduce interstitial habitat in the bed for macroinvertebrate populations that reside there (Jones et al., 2012). Excess fines can also reduce the mean size and sorting of streambed sediments and lower the entrainment threshold of sediments (Wilcock, 2001), which can endanger salmonid embryos through bed mobility and scour (e.g., Buxton et al., 2015; Gaeuman et al., 2023). Coarse sediments in surplus can also lower the availability of instream habitat through aggradation of the channel, which can reduce bar relief and form a relatively featureless and steepened channel (Lisle, 1982).

Given their biological importance and responsiveness to variations in sediment supply and transport, monitoring the prevalence of coarse bars and fine sediment deposits in regulated rivers can inform adjustments to dam releases of flow and augmentations of sediment to benefit species. Gravel bar areas were first measured in the restoration reach of the Trinity River between Lewiston Dam at river mile (RM) 112.2 and the confluence with the North Fork (NF) Trinity River at RM 72.5 (hereafter "restoration reach") in Summer 2014 (McBain Associates, 2015). This paper reports on a repeat of this effort in Summer 2023 with some modifications, including the mapping exposed fine sediment deposits.

Environmental Setting

The Trinity River in northern California experiences a mediterranean climate that is characterized by long, hot summers and cool, wet winters. Flows in winter principally result from rainfall events as snow is stored in the upper watershed's mountainous terrain. Spring runoff is from snowmelt that drives a protracted high flow season and slow recession to summer baseflow that typically commences in late June to early August. Trinity and Lewiston dams disrupt these natural flows and trap all sediments from the upper watershed. Lewiston Dam is the downstream-most of the two structures and is located 112.2 river miles upstream of the Trinity River confluence with the Klamath River. Regulated flows at Lewiston include a static 450 cfs summer baseflow and 300 cfs winter baseflow and only deviates from these relatively high and low seasonal flows during the spring peak discharge that commences around April 15 annually and during releases to aide salmon in the Klamath River and accommodate tribal ceremonial float. The magnitude of the spring peak discharge is governed by the water year type (extremely wet, wet, normal, dry, and extremely dry) and restoration considerations made by the TRRP. The Program is restoring ecosystem processes in the restoration reach using channel reconstruction, river flows, and additions of sediment below Lewiston Dam. During the spring release, gravels (3/8 to 4-inch diameter) are typically added at one or more locations that include the Hatchery Site (RM 111.9), Weir Hole (RM 111.1), Cableway (RM 110.5), Sawmill (RM 109.6), and Upper and Lower Lowden Meadows (RMs 104.4 and 104.9; Figure 1). The additions attempt to mitigate for the dam's blocking sediments from the upper watershed, and along with channel rehabilitation work that includes bar construction, provides sediment to the river along with tributary inputs of gravels and fines.

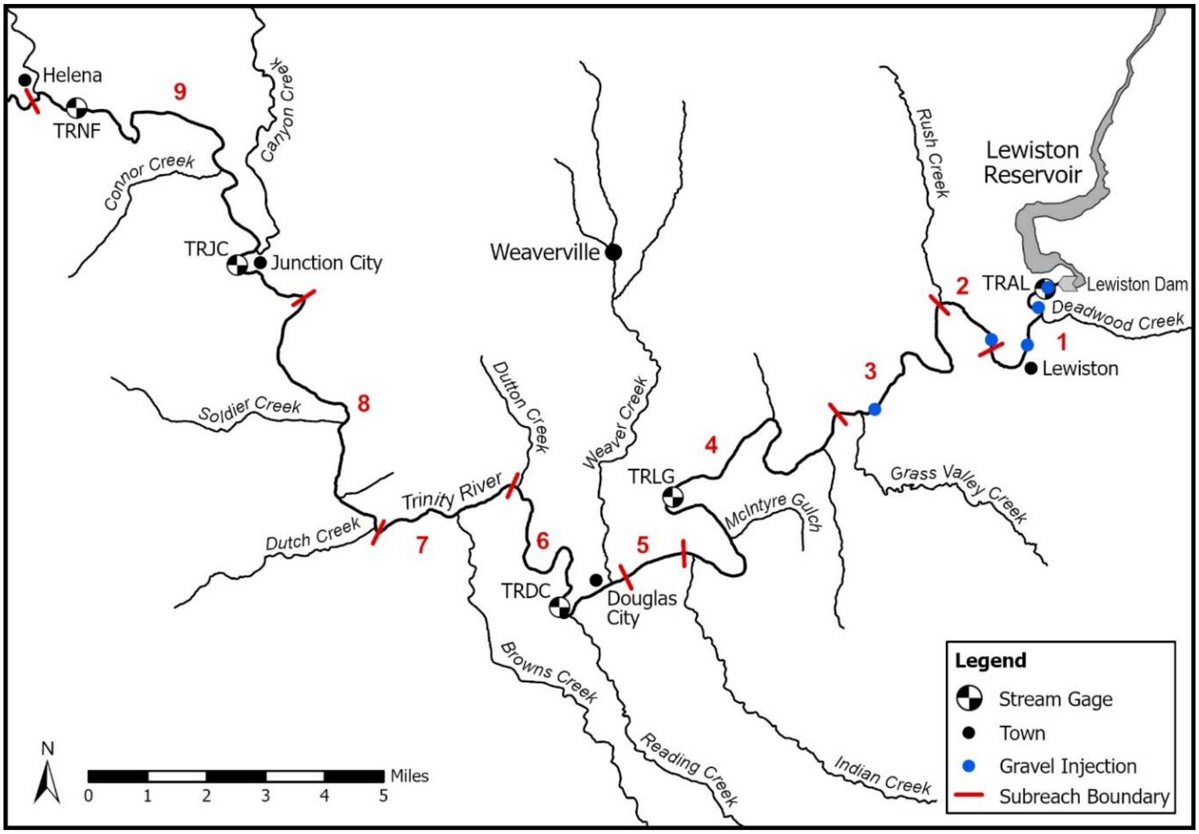

Figure 1. Restoration reach of the Trinity River from Lewiston Dam to the NF Trinity River where active, coarse bars were mapped in 2014 and 2023 and fine sediment deposits were mapped in 2023. Red numbers indicate geomorphic reaches with coarse bar area targets developed by McBain Associates (2015). The blue dots show where gravel additions are made to the channel using heavy equipment.

Previous Work

A census of exposed fine sediment deposits was not done before 2023. Before then, sand storage was estimated on the Trinity River by Wilcock et al. (1995) between Grass Valley Creek (RM 104.4) and Steel bridge (RM 99.0) and at 8 locations in the restoration reach by GMA (2003). Other sediment analysis or measurements that have occurred on the Trinity River include 1) coarse sediment budgeting (e.g., Gaeuman and Krause, 2011), 2) facies mapping (Alvarez et al., 2015), 3) tracer monitoring (Gaeuman and DeJuilio, 2022), 4) sediment transport monitoring with physical measurements (e.g., GMA, 2020a) and hydrophones (Marineau et al., 2016), and 5) bulk sampling of streambed sediments (GMA, 2020b). This work has improved understanding of sediment dynamics in the restoration reach but has limitations. For example, sediment budgeting uses multiple assumptions in estimating storage changes between several-miles long sections of river and provide no information on sedimentary features or habitat availability in the river. Spatial limitations also apply to the remaining approaches except facies mapping that was limited to only reporting the bed surface grain size that is larger than 84 percent of grains on the bed within the channel areas that conveys a discharge of 2,000 cfs in the restoration reach.

Active bar mapping performed by McBain Associates (2015) in 2014 and reported here for 2023 provide a census of sediment deposit areas that are exposed above the water surface at summer baseflow but have limitations as well. The 2014 mapping was restricted to coarse sediment deposits and analyses by McBain Associates (2015) found no correlation between bar areas summed for contiguous channel lengths of 656 ft (200 m) and reach average channel widths, shear stress, or volumetric additions of gravel made to the channel by the TRRP. The lack of correlation may have been due, in part, to the attempt to explain the occurrence of gravel bars over long channel distance when bars can instead associate with local controls.

Another potential reason for lack of correlation is error in the active bar area measurements and what the bar areas represent in some cases. Error in the area measurements can result to a small degree from field interpretation of what portion of a sediment deposit meets the criteria for being active (see below), or more significantly from how the area of the exposed bar may be affected by local roughness effects on the baseflow water surface elevation. For example, if aggradation increases the elevation of a pool tail, the water surface in the pool will rise and inundate a larger area of bars on the pool margins. In this case, absent bars aggrading about as much as the pool tail, the decreased area of the exposed bar will suggest that bar degradation has occurred when the bars may have remained static or aggraded, just not to the same degree as the pool tail. This example highlights a major assumption implicit in McBain Associates (2015) and this report, that the Trinity River channel is in dynamic equilibrium in space, with elevation adjustments on bars and nearby channel features being roughly equal when averaged over time.

Objectives

The objective of this report is to present the findings from active and exposed gravel and fine sediment bar measurements made in the restoration reach of the Trinity River in Summer 2023. Sub-objectives of this report are to

1) Compare the 2023 results to exposed, coarse active bar area measurements made in 2014 to determine the trajectory of coarse bar development in the Trinity River;
2) Explore causal factors for the observed spatial distribution and cumulative area of coarse and fine sediment deposits; and
3) Identify possible limitations on development of coarse and fine sediment deposits in the Trinity River channel.

Methods

Bar Identification

Active and exposed gravel bars are defined as coarse sediment deposits that are 1) primarily composed of bed surface grains >2 mm in diameter, 2) display a landward edge with exposed (out of water) areas of active fluvial transport and deposition, and/or 3) an outer edge bounded by the water surface at summer baseflow (450 cfs at TRAL, Figure 1). The wetted boundary of bars was further defined as the dry edge of the bar, excluding areas where water flows between particles that extend above the water surface. This and the McBain Associates (2015) study also defined bar areas with the following criteria:

- Bar surfaces must show evidence of active transport, including surface imbrication, particle sorting, and low grain embeddedness, with particles around half exposed above the ambient bed.
- Surface grains must predominantly be >2 mm in diameter by ocular estimate. Fine sediment deposits within a coarse bar were excluded from the area measurement unless fines existed as a thin layer on the coarse surface or were in a small (approximately ≤16 ft^2) area relative to the total area of the bar.
- The minimum bar width for measurements was 4 ft. This width was set by the estimated accuracy of the Global Positioning System (GPS) used in the 2014 mapping.
- The bar surface may be vegetated, but the vegetation cannot prevent sediment transport. Areas where vegetation traps sediment and prevents its mobilization are excluded. Areas where slugs of coarse sediment show evidence of active transport between stands of vegetation were mapped.
- Mapping of surfaces that meet these criteria was limited to areas within the bankfull channel of the river and side channels with 20% or more of the mainstem flow or on tributary deltas.

These criteria also applied to exposed fine sediment deposits (e.g., Figure 2) with the exceptions that rules for minimum area, particle imbrication, sorting, and embeddedness were not considered. Fine sediment deposits were located where accumulations of fines ≤2 mm composed ≥80 percent of the deposit area exposed the water surface. Fine sediment deposits could be surrounded by coarse sediments or vegetation but a wetted edge contacting the deposit was not required for a deposit to be mapped.

Figure 2. Coarse and fine sediment deposits mapped at RM 83.6 on the Trinity River in summer 2023 (left panel). The green area is a coarse bar and the yellow areas are fine sediment deposits. The coarse bar mapped here in 2014 is outlined in red. The right panel is an upstream view of a fine sediment deposit.

Mapping Protocol

Active bars of coarse sediment and fine sediment were mapped using methods in McBain Associates (2015) that are reproduced here with only slight modifications. The duplication of methods provides a means to directly compare results from the 2014 and 2023 mapping. In both years, field mapping was performed from Lewiston Dam to the NF Trinity River (Figure 1). In 2023, fieldwork was conducted in seven days from August 28 through September 29, except active areas on Rush Creek delta were mapped on October 13. River flows on dates that bars were mapped varied within narrow ranges at each mainstem flow gage (Table 1) so provided a common datum for mapping exposed sediment deposits through the duration of fieldwork.

Training was held the first day of mapping to familiarize personnel with protocol and ensure data were collected in the same manner by all crews. The training area extended from the base of Lewiston Dam to Old Bridge at Lewiston on August 28, 2023 and involved pacing bar edges to properly locate the water's edge and landward side of bars, identify fine sediment deposits within the boundaries of coarse bars or elsewhere in the channel, estimate percentages of fines, and identify formative features (see below).

Fieldwork was thereafter performed by two or three-person crews transiting the river near the channel margins in separate rafts and stopping at each deposit that met criteria for mapping. An Eos Arrow 100 Global Navigation Satellite System (GNSS) with sub-meter receivers paired to iOS data collectors running ESRI Field Maps was used to log the position in space of each bar's margin while pacing their outline. Bar edges were predominantly logged in sub-foot accuracy every two feet of horizontal distance. We nonetheless maintained the minimum 4 ft width requirement for coarse, active bar measurements for comparability to results in McBain Associates (2015). In some cases, overhead vegetation decreased the accuracy of the GNSS position to 6 ft or greater. When this occurred, an alarm alerted the user and flagged the bar for later review in the office. The review used aerial photography (Table 1) taken July 12, 2023 to correct inaccurate positions that might have been logged. The corrections were made by adjusting polygon traces of bar edges to reflect the position and size of the affected bars more logically and accurately.

Table 1. Discharges at United States Geological Survey (USGS) gages on the Trinity River when active bar mapping was performed.

Date	USGS gage location[1,2]					Reach mapped
	TRAL	TRLG	TRDC	TRJC	TRNF	
7/12/2023	456	465	519	540	679	Aerial photography taken on this date
8/28/2023	460	468	467	489	545	Map Lewiston Dam to Old Lewiston Bridge
9/18/2023	468	460	457	469	508	Map Old Lewiston Bridge to Fenceline
9/20/2023	461	466	460	478	518	Map Fenceline to Indian Creek
9/22/2023	456	462	456	476	513	Map Indian Creek to Lorenz
9/27/2023	456	468	464	487	540	Map Lorenz to Evans Bar
9/28/2023	458	467	463	484	542	Map Evans Bar to Junction City Campground (CG)
9/29/2023	453	466	461	484	536	Map Junction City CG to NF Trinity River
10/13/2023	452	453	466	486	528	Map Rush Creek Delta

[1] TRAL is the Trinity River at Lewiston; TRLG is the Trinity River at Limekiln Gulch; TRDC is the Trinity River at Douglas City; TRJC is the Trinity River at Junction City; TRNF is the Trinity River above the NF Trinity River.

[2] Discharges are in cubic feet per second (cfs)

Field Data Collection

Several pieces of information were collected at each coarse sediment bar and fine sediment deposit that was mapped. The information included a representative picture of the bar, date and time of measurement, the person's name who paced the bar edge, the bar type as gravel or sand, the percentage of fines (≤2 mm) visually estimated on the bar surface, the apparent primary feature responsible for the deposit's formation, and other pertinent information, including local effects on bar development, quality of the GPS signal, and any secondary formative features that were observed. A photograph of each mapped feature was generally taken looking upstream to show a conspicuous aspect of the deposit, including its formative feature, interaction with vegetation, and position in the channel. Ocular estimates of the percentage of fines were determined in conversation between paired individuals in the field unless the value was apparent, such as on a sorted gravel bar or fine sediment deposit with only sand present.

Formative features within the active channel that appeared responsible for an exposed sediment deposit forming were logged during field data collection. Formative features included bedrock, channel confinement, channel expansions, constructed or associated with construction of a channel rehabilitation project (e.g., HVT and McBain Associates, 2021), tributary deltas, forced meanders such as where the river channel enters a gradual bend and interacts with the valley walls, river bends where the channel abruptly changes course, roughness from an island in the river, alluvial meander bends, or roughness from vegetation or wood (Table 2). These formative features used in the current effort differed somewhat from those considered by McBain Associates (2015). On occasion, bars could be associated with multiple formative features, but it was the dominant feature that was assigned to each bar. For example, a bar deposited behind a bedrock outcrop in a widened section of river would be assigned to the bedrock because it is flow separation in the boulder's lee that formed the deposit in its particular location.

Table 2. Description of formative features associated with observed coarse gravel bars and fine sediment deposits (modified from McBain Associates, 2015).

Formative feature	Description
Bedrock	Bedrock outcrop causing sediment deposition on the up or downstream side.
Channel confinement	Reduction in channel width that locally reduces sediment conveyance from backwatering.
Channel expansion	Increase in channel width that shallows flow and reduces sediment transport by lowering the energy grade and increasing dissipation of shear stress on the granular bed.
Constructed	Areas where mechanical rehabilitation resulted in constructed widening, increased complexity, or roughness that promotes bar deposition.
Delta	Sediment deposit associated with a delta formed by inputs of sediment from a creek and the river (see Buxton and Bradley, 2022).
Alluvial meander	Gradual channel bend formed by cut bank erosion and sediment deposition inside a bend.
Forced meander	Sharp bend in the channel forced by the interactions with immobile features (bedrock, valley walls, etc.) at the valley scale.
River bend	Like forced meander but at a local scale.
Island	Areas near islands where sediment deposits occur. Islands are former medial bars or relic floodplains that are stabilized with vegetation and largely maintain their size and position within the channel.
Vegetation	Bars that form from increases in hydraulic roughness from nearby vegetation.
Wood	Naturally contributed or deposited large wood existing as single pieces or aggregates of pieces that result in bar formation up or downstream of the structure. Bars associated with wood placed or constructed as jams in the channel are considered constructed features.

Post processing of the mapping results occurred the morning following each day's field measurements and involved confirming or modifying the formative feature for the deposit as seen from the aerial photography versus observations on the ground. The bar outline was also modified in some cases where the bar shape was illogically mapped due to poor GPS coverage or the mapped outlines of a bar crossed one another.

Error Estimation

Several potential sources of error can influence the position and area of a bar mapped in the field. These include strength of the GPS signal, interpretation of a bar's outline, and delineation between coarse and fine sediment deposits. To evaluate the total error from all sources, five bars were mapped by both crews to determine the total actual error in the bar outlines and areas. The repeat bar measurements were made on August 28 and September 18, 20, and 28 at RMs 111.64, 109.98, 109.96, 104.11, and 81.11.

Data Analyses

The mapping results were assessed with an aim to postulate reasons for change in coarse bar areas between 2014 and 2023 and to identify areas where fine sediment deficits exist below Lewiston Dam. For these objectives, GIS maps of delineated areas were developed showing the change in size, shape, and position of bars between surveys. The areas of coarse bars and fine sediment deposits were also cumulatively summed in the downstream direction from Lewiston Dam and plots were used to discern the influence of tributary inputs and gravel augmentations on observed areas and percentages of fines on gravel bar surfaces. Coarse bar areas were also binned within geomorphic subreaches that McBain Associates (2015) delineated by channel confinement, slope, and the location of tributary junctions (Table 3). The total area of coarse bars in each bin was compared both between the 2014 and 2023 surveys and to gravel storage targets by reach proposed by McBain Associates (2015). Coarse bar areas were compared to active channel widths measured every 0.01 river mile in the restoration reach from the 2023 aerial photography. The widths were measured in GIS as the distance perpendicular to the channel centerline between active channel banklines traced on the aerials, with the active channel defined in Osterkamp and Hedman (1982). Lastly, fine sediment deposits were assessed for their cumulative area, size, and frequency below the dam. Active bar and fine sediment deposit areas were also binned by forcing mechanism to identify their hierarchy in association with the number and area of coarse bar and fine sediment deposits in the restoration reach.

Table 3. Geomorphic subreaches proposed by McBain Associates (2015) and updated herein.

Subreach	Distance below Lewiston Dam (miles)	Reach length (miles)	Channel confinement[1]	Energy grade[2]
1	0 – 3.29	3.29	Moderate	0.0032
2	3.29 – 4.20	0.91	Low	0.0014
3	4.20 – 8.15	3.95		0.0022
4	8.15 – 16.50	8.35	High	0.0023
5	16.50 – 17.50	1.00	Moderate	0.0024
6	17.50 – 22.95	5.45		0.0026
7	22.95 – 25.65	2.70	High	0.0026
8	25.65 – 30.90	5.25	Low	0.0017
9	30.90 – 40.50	9.60		0.0024

[1]Channel confinement characterized in McBain Associates (2015). [2]Energy grade is the average water surface slope at 450 cfs modeled with SRH-2D by Bradley (in progress) on channel bathymetry surveyed in 2022.

Results and Discussion

Measurement Error

Repeat measurements of bar and deposit areas were made by separate crews on five bars. The error in the repeat measurements was 0.2 to 1.6% on four bars with an average area of 14,413 ft^2 and 26.2% on one bar with an area of 307 and 416 ft^2 in the repeat measurements. This indicates that minor discrepancy in pacing the outline of a bar can lead to large error in area delineations when the bar is small (Figure 3). Results indicated that bar area measurements were repeatable with overall good accuracy with the lesson that extra care be used to map smaller deposits.

Figure 3. Repeat measurements of a large coarse bar (green) and a small fine sediment deposit (yellow) made on September 18 at RM 110.0. The difference in area between the fine deposit measurements was 26.2% and the coarse bar areas differed by 0.2%. The fine sediment deposit shown here is the upstream-most deposit of fines in the restoration reach. The aerial photography pictured is from July 12, 2023 when the daily average flow at Lewiston Dam was 456 cfs.

Coarse Bar Areas

The total area and number of active, coarse bars in 2023 (1,957,437 ft^2; 392) was 611,764 ft^2 or 45% higher than in 2014 (1,345,673 ft^2, 302; Figure 4, top panel). The overall area difference between surveys includes an 87,856 ft^2 bar at the downstream end of the restoration reach at the outlet of the NF Trinity River that was measured in 2023 survey but ignored in 2014. Excluding this bar from the 2023 data, the percent increase in gravel bar area between surveys is 39% and the total coarse bar area per unit channel distance was 47,045 ft^2/mile in 2023, which compares to 29,262 ft^2/mile in 2014. The 2014 and 2023 active bar survey data are available for download in GIS format (Buxton and McSloy, 2024).

Inflections in the total bar area per unit channel distance were common at tributary confluences in 2014 and 2023 (Figure 4, Table 4). Reflecting the overall larger area of bars in the more recent survey, the normalized areas were higher in the more recent survey (Table 4). Inflections in the rate of increase in bar area also occurred at gravel augmentation locations, between which bar areas decreased from 81,785 ft^2/mi between the Hatchery and Weir Hole sites to 45,661 ft^2/mi between the Sawmill and Lower Lowden Meadows sites (Figures 1 and 4). These findings and those for the tributaries (Table 4) respectively reflect the 79,000 cubic yards of gravel additions that have been made upstream of Grass Valley Creek since 2006, several channel reconstruction projects undertaken in the past decade, and sediment contributions by tributaries, which may have accelerated from wildfires accelerating watershed erosion in recent years (Buxton, 2021). Increases in bar area between surveys were often observed as mobile patches of gravel entering vegetated areas, new bars forming in open channel and marginal areas, and gravel deposits being constructed or naturally formed in channel reconstruction areas (Appendix A). Conversely, decreases in bar area between the 2014 and 2023 surveys notably reflected the conversion of active areas to immobile areas from bar fossilization by vegetation, tight packing and cementation of bar surfaces, and erosion and/or inundation of bars by flow. Presentation of river reaches with notable changes in active bar areas between survey years is available in pdf format (McSloy and Buxton, 2024).

Table 4. Cumulative coarse bar areas per unit channel distance between tributary confluences where inflections in the rate of increase were observed in the 2014 and/or 2023 surveys.

River mile start	River mile end	2023 rate of increase (ft^2/mile)	2014 rate of increase (ft^2/mile)
112.2 (Lewiston Dam)	104.4 (Grass Valley Creek)	55,890	46,271
104.4 (Grass Valley Creek)	95.6 (Indian Creek)	25,057	12,330
95.6 (Indian Creek)	79.2 (Canyon Creek)	50,405	---
	81.1 (Oregon Gulch)	---	23,322
81.1 (Oregon Gulch)	72.5 (NF Trinity River)	62,469	---
79.2 (Canyon Creek)		---	56,731

In nearly all geomorphic subreaches, coarse active bar areas in 2023 increased above that measured in 2014. The areas divided by channel distance were 1.1 to 16.7 times higher in 2023 in reaches 1-4 and 6-9; only in reach 5 was the value higher in 2014 (21.3 ft^2/ft versus 17.5 ft^2/ft in 2023; Table 5). In total, a higher number of bars and a significantly larger total bar area was mapped in 2023 (392 bars, 1,957,737 ft^2) than 2014 (376, 1,345,673 ft^2), indicating bar sizes increased following the initial survey, as reflected in the median size difference between years (22,112 ft^2 in 2023, 14,919 ft^2 in 2014). The bar expansions were coincident (or caused by, see below) with an observed increase in the active channel width between surveys, as explained later.

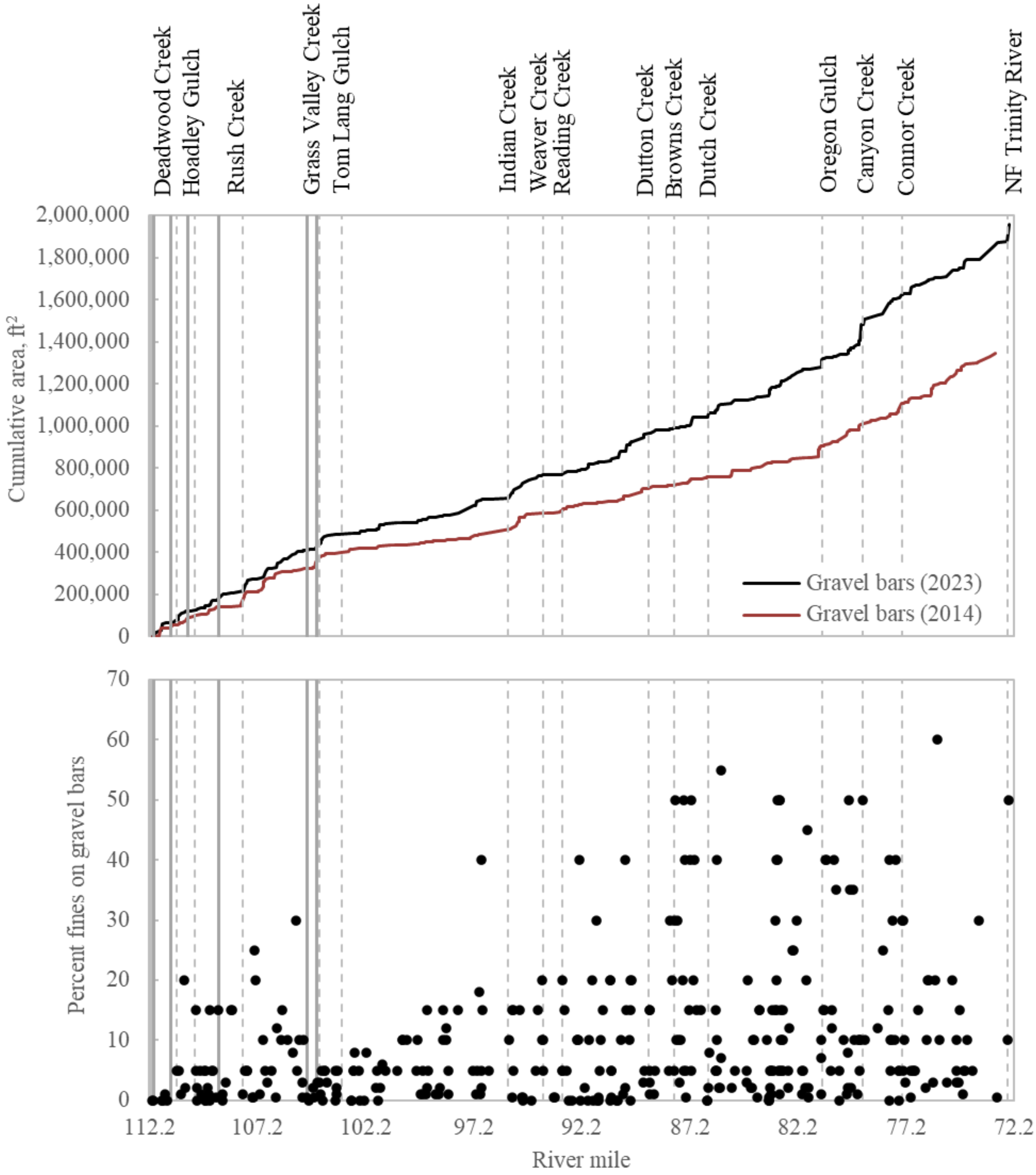

Figure 4. Cumulative coarse, active bar areas measured in 2014 and 2023 (top panel) and percentage of fines estimated on coarse bars that were surveyed on the Trinity River (Figure 1). The dotted horizontal lines show the locations of tributaries, and the solid grey lines show gravel augmentation locations.

Table 5. Coarse active bar areas for geomorphic subreaches of the Trinity River below Lewiston Dam. Values in parenthesis were measured in 2014. Bold values satisfy target storage areas.

Subreach	Reach length (miles)	Total number of coarse bars	Median bar area (ft^2)	Total bar area (ft^2)	Unit bar area (ft^2/ft)	Targeted unit bar area (ft^2/ft)
1	3.29	40 (36)	1,783 (1,518)	182,712 (142,073)	**10.5** **(8.9)**	8.9 – 11.8
2	0.91	5 (3)	1,734 (3,789)	24,024 (861)	**5.0** **(0.3)**	0.3 – 3.6
3	3.95	40 (42)	3,031 (2,422)	266,894 (251,639)	**12.8** **(11.8)**	11.8 – 21.3
4	8.35	58 (49)	1,377 (1,001)	179,383 (92,107)	**4.1** (2.1)	3.6 – 8.9
5	1.00	10 (16)	7,864 (2,099)	92,521 (96,897)	17.5 **(21.3)**	21.3
6	5.45	54 (48)	1,813 (635)	217,162 (119,673)	**7.5** **(4.3)**	4.3 – 8.9
7	2.70	33 (31)	631 (1,001)	81,024 (47,028)	**5.7** (3.6)	4.3 – 8.9
8	5.25	71 (37)	1,494 (1,109)	227,359 (101,213)	8.2 (3.6)	11.8 – 21.3
9	8.76	81 (114)	2,385 (1,345)	686,358 (494,182)	**14.8** (10.8)	11.8 – 21.3

Active Channel Widths and Coarse Bar Areas

The area of coarse bars summed for every 0.10 river mile in the restoration reach was plotted against the average active channel width averaged over this same distance. A linear regression of the data indicated that bar areas increased 38 ft^2 for every foot that the active channel widened (Figure 5). Considerable scatter existed in these data, as bar areas varied 4-orders of magnitude for a given channel width and exhibited a low correlation (r^2=0.02), yet bar areas were almost exclusively large (>1,000 ft^2) in areas of the active channel that were >150 ft wide. These results highlight that bar size and placement involve complex sediment supply and transport interactions with channel slope and morphology that a single variable, such as channel width, cannot fully explain.

Active channel widths measured every 0.01 river mile slightly decreased with downstream distance at a rate of 0.3 ft/river mile while coarse bar areas increased at a rate of 177 ft^2/river mile. Although there is considerable scatter in both trends, active channel widths normally increase with downstream distance and drainage area in both alluvial and bedrock channels (Montgomery and Gran, 2001), but the reverse occurs in the restoration reach despite the drainage area increasing by 418 square miles from Lewiston Dam to the NF Trinity River. One explanation could be the stabilizing effect of riparian vegetation on stream banks that may render flow releases from Lewiston Dam and tributary accretions of flow and sediment incapable of widening the channel in proportion to the increase in discharge that occurs with downstream distance. Reduction of the peak flood magnitude by flood regulation by Trinity and Lewiston dams is another potential explanation, and both possibilities are important topics for further investigation.

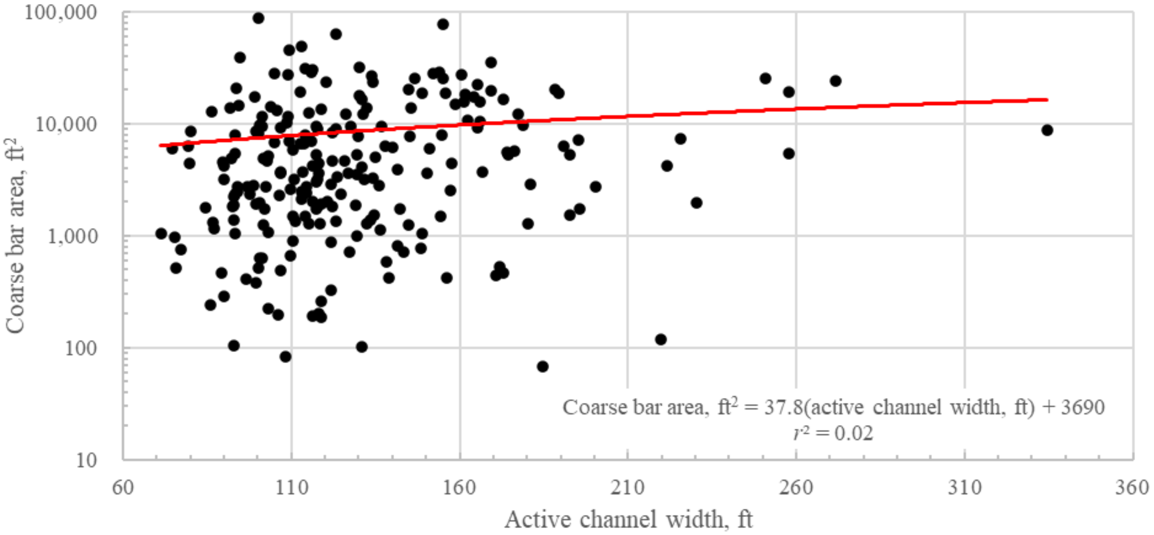

Figure 5. Coarse bar areas summed every 0.10 river mile versus the average active channel width for this same distance for the restoration reach of the Trinity River.

Percent Fines on Coarse Bar Surfaces

The percentage of fines on gravel bar surfaces varies from zero to 60% downstream of Lewiston Dam (Figure 4, bottom panel). Starting at the base of the dam, fine sediments are almost completely absent until Deadwood Creek, which typically produces large amounts of fines during rainfall events from nearly 80% of the watershed area being burned in the 2018 Carr fire (Buxton, 2021). Upstream of this confluence, fines are in such deficit that the high hydraulic conductivity of the channel causes flow to go subsurface in many areas (Figure 6). The transitions from surface to subsurface flow act as sieves and Chinook smolt mortalities have been observed in these stranding areas.

Figure 6. Lack of fine sediments near Lewiston Dam leads to high hydraulic conductivity in the gravel bed causing surface flows to go subsurface in places. Sieves are created where this occurs, and juvenile salmon mortality was observed at sieve locations. Lewiston Dam is visible in the center of picture.

Hoadley Gulch is the next tributary below Deadwood Creek and is also a large contributor of fines due to impacts from the Carr Fire. The percentage of fines consequently rises to 20-30% at this location before markedly decreasing at Lowden Meadows. Here, large augmentations of fine sediment-free gravels have been made since 2010, which appears to cause most of the fines delivered to the reach to be stored in the bed, which is a largely unfilled reservoir as indicated by the surface percentage of fines hovering around 5% on the coarse bar surfaces in this reach (Figure 4, bottom panel). From Lowden Meadows, fine sediments steadily increased in prevalence on the coarse bar surfaces until Browns Creek, downstream of which the range of percentages was largely consistent to the end of the restoration reach (Figure 4).

Fine Sediment Deposits

The total area and number of fine sediment deposits in the restoration reach was respectively 79,970 ft^2 and 116, making the average area of the deposits 689 ft^2 (Figure 7, top panel). For comparison, the area and number of coarse sediment deposits was 1,957,437 ft^2 and 392 (4,993 ft^2 average; Figure 4, top panel). The mapped deposits were 70% less prevalent and over 7 times smaller in area than coarse bars.

The upstream-most fine sediment deposit was mapped 2.04 river miles downstream of Lewiston Dam at a location 980 ft downstream of Old Bridge at Lewiston and 500 ft downstream of Hoadley Gulch (see Figure 3), indicating a strong deficit of fines upstream of this location. Notably, no deposits were observed between this location and Deadwood Creek (Figure 7), which makes significant contributions of fines to the river in winter when flows released from Lewiston Dam are a static 300 cfs (Figure 8). The lack of deposits in this reach likely reflects the in-bed storage of fines from Deadwood Creek and the effectiveness of high dam releases in moving these materials downstream. Therefore, lacking a source of fines upstream of Deadwood Creek, fine sediment contributions and changes in storage will continue to be episodic unlike that of a normal functioning channel (Buxton, 2021; Figure 8).

The cumulative area of fine sediment deposits showed a steep rise just downstream of Rush Creek and then increased at steady rate until Steiner Flat at RM 89.92 (Figure 7, middle panel). Downstream of RM 89.92, the rate more than tripled for an unknown reason. However, dividing cumulative areas by channel distance shows that rates of area increase changed at several locations on the river. The initially high rate between Hoadley Gulch and about a mile downstream of Rush Creek flattened to near zero before steepening at Dutton Creek until just upstream of Oregon Gulch, where the rate generally matches the overall trend that is downstream of Dutton Creek for the remaining distance to the NF Trinity River (Figure 7, bottom panel). Like Deadwood Creek, Hoadley Gulch and Rush Creek contribute significant amounts of fine sediment to the river (Buxton, 2021), but sediment retainment ponds on Grass Valley Creek and accretions in flow from Indian, Weaver, and Reading creeks increases the transport capacity of the river at a rate that causes the cumulative area to balance with the downstream distance on the river. That rate rises significantly beginning near Dutton Creek, which because of the small size of its watershed (4.7 mi^2) suggests that the visually higher channel complexity that occurs from bedrock outcrops and large boulder areas provides a comparatively greater number of low energy areas for fine sediment deposits to reside compared to upstream reaches. The steep rate of area increase is maintained until just upstream of Oregon Gulch, where the Trinity River simplifies into a relatively featureless and primarily alluvial channel with fewer bedrock or boulder-controlled sections, again limiting areas for fine sediment deposits to reside until the NF Trinity River. At this confluence, a large (3,694 ft^2) fine sediment deposit has formed by materials contributed by the North Fork, which raises the deposit area per river mile value to its highest in the restoration reach at this location.

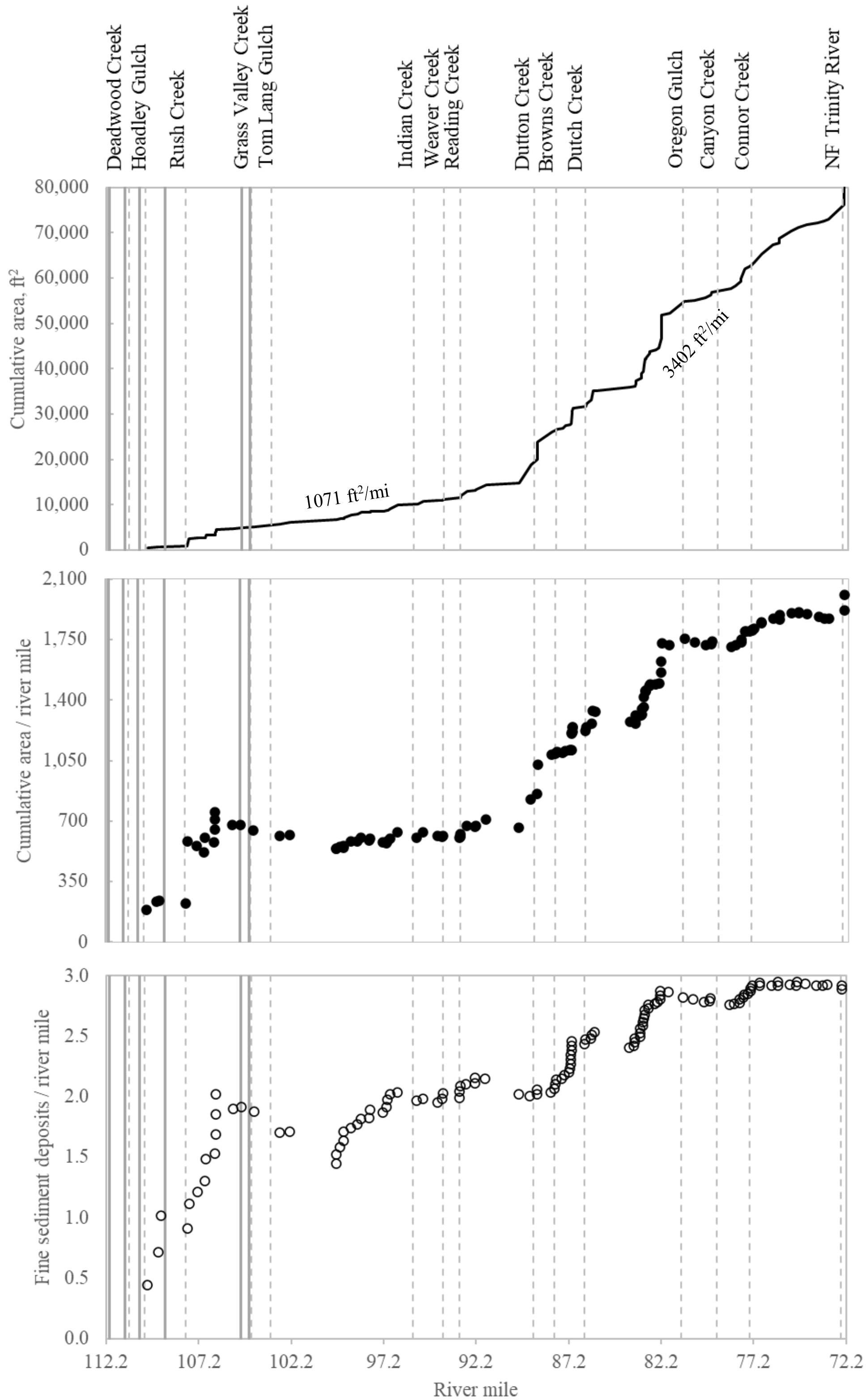

Figure 7. Cumulative area of fine sediment deposits exposed above the 450 cfs baseflow water surface in the restoration reach of the Trinity River in 2023 (top panel). The cumulative area and count of deposits per river mile are shown in the middle and bottom panels, respectively. The dotted horizontal lines show the locations of tributaries, and the solid grey lines show gravel augmentation locations.

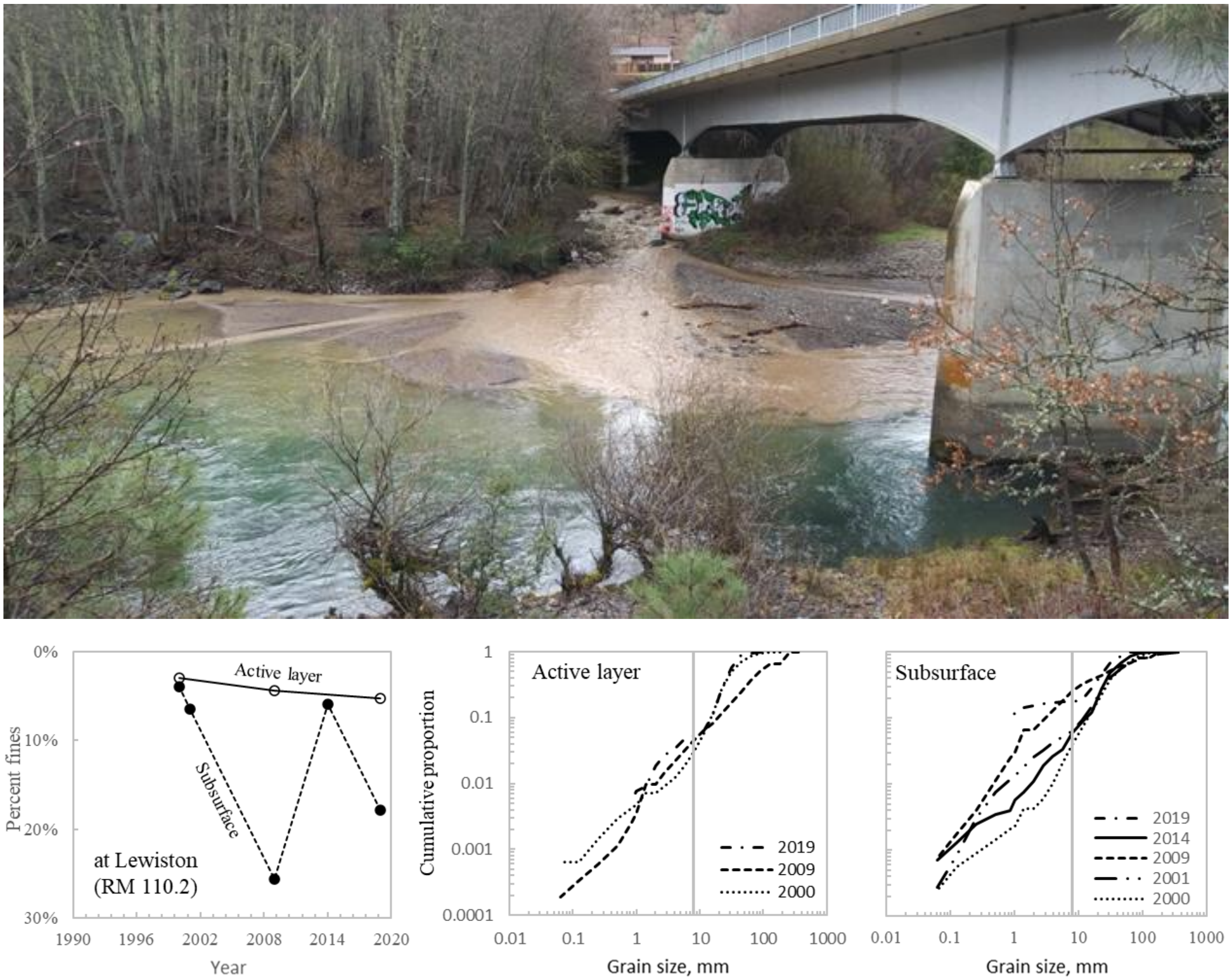

Figure 8. Confluence of Deadwood Creek and the Trinity River near Lewiston Dam in winter 2019. Sediment-free flow released from the dam and episodic contributions of fines from Deadwood Creek cause large variations in the percentage of fines near Lewiston, as shown in bulk samples of sediment taken in this reach near Old Lewiston Bridge. In the bulk sampling (bottom inset figures), the active layer extends from the bed surface vertically to a depth equal to the c-axis of the grain size that is larger than 84 percent of grains on the bed. The subsurface domain extends below the active layer to a depth of around one foot (Buxton, 2021).

Increases in the frequency of fine sediment deposits generally align with tributary junctions and channel constraints, such as confinement by hillsides. Downstream from the first fine sediment deposit that was encountered, the number of deposits per river mile remains low at around one per river mile until Rush Creek, where the frequency doubles (Figure 7, bottom panel). The frequency then decreases gradually to ~1.5 deposits per mile at gravel augmentation locations at Lowden Meadows, which aligns with the lowered percentages of fines on coarse bars in this reach (Figure 3). The frequency of deposits continues to decline in Limekiln Gulch where the river is constrained by hillsides and simplified in how the wetted channel during summer baseflow occupies nearly the entire unvegetated area of the valley bottom. Near the downstream end of this reach, the frequency increases rapidly until just upstream of Indian Creek, where values flatten between 1.96 and 2.15 deposits/river mile. This range was observed until Browns Creek, where the frequency rises to 2.5 deposits/river mile, which is maintained until the Chapman channel rehabilitation site at RM 83.6, which is the upstream end of the lower-valley suite of valley-wide mechanical restoration projects that have been constructed yearly since 2017. These projects have increased the complexity of the river and made fine sediments in floodplain areas accessible to the flow, and both factors are coincident with a steep rise in fine sediment storage until RM 81.83, located at the upstream end of the Oregon Gulch channel rehabilitation site. From here downstream to the end of the restoration reach at the NF Trinity River at RM 72.5, the river is relatively simplified and entrenched, resulting in the number of fine sediment deposits per river mile and their cumulative area remaining steady or slightly declining with channel distance until the confluence with the NF Trinity River (Figure 7, top panel).

Forcing Mechanisms

Channel expansions were the dominant mechanism forcing coarse bar and fine sediment deposits (Tables 6 and 7). This results because the water depth lowers with channel width at a given slope and shear stress is expended to overcome skin friction that increases with channel width. These adjustments cause sediment to more easily fall from transport and deposit as coarse bars or fine sediment deposits. Therefore, coarse and fine sediment deposits could be most significantly increased by widening the active channel of the Trinity River in areas where these deposits are rare or absent.

River bends were the next most prominent mechanism associated with coarse and fine sediment deposits because bends cause flow energy to be consumed by form drag and turbulence that leads to gravel deposition often in high relief bars with sufficient lee areas for deposition of fines. For coarse bars only, channel rehabilitation projects and forced meanders were the next most prominent mechanisms. Wood had the least significance in forcing coarse deposits because most wood in storage outside the active channel of the Trinity River. In descending order, the largest average coarse bar area was associated with deltas at tributary outlets, alluvial meanders, and channel expansions because these are landscape-scale rather than local features of the Trinity River (Table 6, Figure 9). The smallest average areas were associated with forcing mechanisms that function locally, including roughness from vegetation, channel confinement, and large wood, in ascending order (Table 6). In comparison, the order of highest to lowest prevalence of forcing mechanisms by count observed in 2014 was channel expansions, forced meander, bedrock, constructed, channel confinement, alternating bars, deltas, islands, wood, and bridge piers.

Table 6. Count and area of coarse bars by forcing mechanism.

Forcing mechanism	Count	Percentage by count	Area (ft^2)	Percentage by area	Average area (ft^2)
Channel expansion	169	43.1%	918,478	46.9%	5,435
River bend	51	13.0%	242,955	12.4%	4,764
Constructed	44	11.2%	184,967	9.4%	4,204
Bedrock	34	8.7%	110,435	5.6%	3,248
Forced meander	21	5.4%	108,382	5.5%	5,161
Island	18	4.6%	87,277	4.5%	4,849
Vegetation	18	4.6%	14,533	0.7%	807
Delta	16	4.1%	219,745	11.2%	13,734
Channel confinement	7	1.8%	6,194	0.3%	885
Alluvial meander	6	1.5%	47,372	2.4%	7,895
Other[1]	6	1.5%	14,011	0.7%	2,335
Wood	2	0.5%	3,087	0.2%	1,544
Totals	392	100.0%	1,957,437	46.9%	4,993

[1] Includes side channel inlet and outlet areas.

After channel expansions and river bends, vegetation and bedrock were the most prominent mechanisms forcing fine sediment deposits (Table 7). These mechanisms were often observed functioning in concert with coarse sediment bars. For example, several fine sediment deposits were observed in the lee of bedrock outcrops within the perimeter of large coarse bars. In these cases, it is the form roughness from the bar but more importantly the lee area formed by the outcrop that is responsible for the fine deposit existing where it does. In several locations, fine sediment deposits in the "other" category were observed at the entrance to side channels, suggesting the constriction of flow and decrease in sediment transport at these locations may lead to side channel failure. The largest fine sediment deposits were associated with delta features due to their expanse for generating form roughness and the presence of vegetation for generating additional flow roughness (Table 7, Figure 9). Constructed features exhibited the next largest average area. In these cases, deposits were wholly associated with the channel reconstruction performed in the Chapman reach of the Trinity River (RM 83.12-85.95) in 2021-2023. In this area, construction greatly increased the complexity of the channel, forming lee areas for fine sediments to deposit. Downstream of this rehabilitation site, the channel is relatively simplified and fine sediment deposits comparatively rare (Figure 7).

Table 7. Count and area of fine sediment deposits by forcing mechanism.

Forcing mechanism	Count	Percentage by count	Area (ft^2)	Average area (ft^2)
Channel expansion	36	31.0%	32,372	899
River bend	15	12.9%	7,101	473
Vegetation	15	12.9%	7,398	493
Bedrock	12	10.3%	7,445	620
Other	10	8.6%	2,913	291
Delta	9	7.8%	10,007	1,112
Constructed	6	5.2%	6,221	1,037
Forced meander	6	5.2%	3,647	608
Island	4	3.4%	763	191
Alluvial meander	3	2.6%	2,102	701
Channel confinement	0	0.0%	0	---
Wood	0	0.0%	0	---
Totals	116	100.0%	79,970	643

[1] Includes side channel entrances, channel complexity, and unknown forcings.

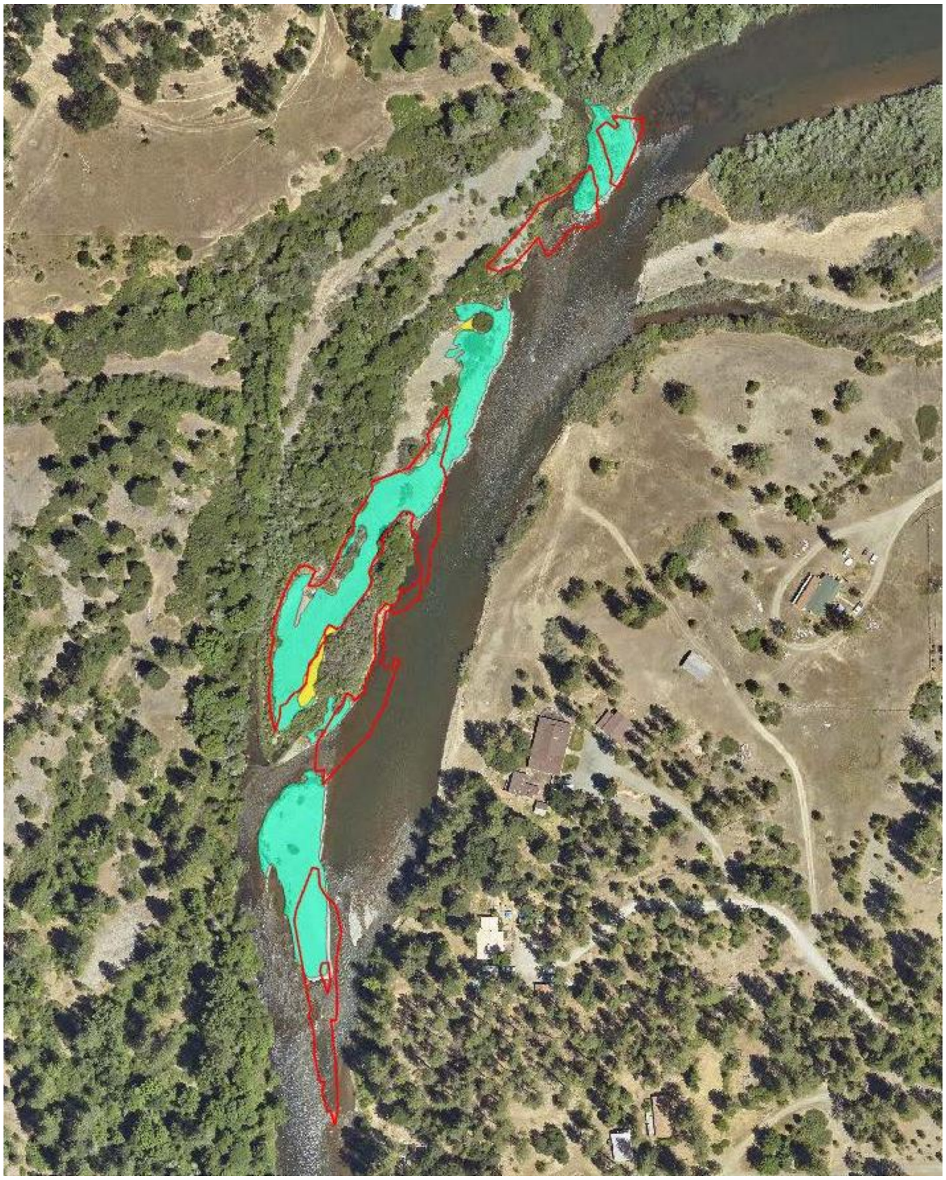

Figure 9. Delta expansion at Rush Creek confluence between RM 107.6 and 108.4. The green shading indicates active coarse bars and the yellow shading shows fine sediment deposits mapped in 2023. The red outlines show coarse, active bars mapped in 2014.

Summary and Recommendations

Fine sediment deposits are wholly absent for just over two river miles downstream of Lewiston Dam, indicating the absence of fine material for promoting physical processes and providing lamprey rearing habitat in this reach. Adding fine sediments during moderate to high flows near Lewiston will help alleviate this deficit and should be undertaken when permissible to do so. A program for monitoring the size distribution of streambed sediments and fine sediment transport rates and turbidity should be implemented before and after the additions are made to ensure benefits of this restoration action are realized without over-supplementing this component of the river ecosystem.

Coarse sediment deposit areas in 2023 increased by nearly half that measured in 2014, indicating substantial gains in bar areas and sediment storage in the restoration reach in this period. If fine sediment additions are implemented, gravel transport rates and travel distances will likely increase to further distribute coarse sediment that could lead to the need to increase augmentations rates. There is an also a need to update coarse bar area targets proposed by McBain Associates (2015) and develop target areas for fine sediment deposits. A sub-group of the TRRP physical workgroup is currently working on these tasks with results expected before year's end.

Coarse and fine sediment deposit areas could be most significantly increased by widening the active channel of the Trinity River in areas where sediment deposits are rare or completely lacking. This action would also promote mid-channel bar development that would help retain large wood in the channel and increase channel complexity and bar development. Restrictions in channel width from bank stabilization by riparian vegetation appears to limit bar development in the restoration reach. This conclusion derives from the finding that active bars were most often located where channel width expansions occurred, and bars were few or absent in reaches with vertical banks and relatively narrow channel widths. Active channel widths measured every 0.01 river miles in the restoration reach decreased at a rate of 0.3 ft/river mile while coarse bar areas increased at a rate of 177 ft^2/river mile despite drainage area and flood magnitudes increasing with distance downstream. This suggests an over-stabilized channel may be limiting width adjustments and bar development in the lower river.

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Appendix A. Examples of bar area changes between the 2014 and 2023 surveys.

Figure 1A. Conversion of a coarse, active bar in 2014 to an immobile area in 2023 by vegetation encroachment and grain cementation and packing at RM 102.9 at Poker Bar. The red lines indicate the coarse bar area surveyed in 2014 and the green shading is a coarse, active bar and the yellow shading is a fine sediment deposit surveyed in 2023. This format applies to the full appendix. Flow is to the left.

Figure 2A. Erosion and inundation of a coarse, active bar observed in 2014 to a relatively small, vegetated island in 2023 between RMs 78.7 and 78.8. Flow is to the left.

Figure 3A. Expansion of a coarse, active bar by mobile gravel entering a wooded area at Bucktail pool near RM 105.4. Flow is to the left.

Figure 4A. Marginal bar expansion near Dutch Creek from deposition of coarse and fine sediments at RM 86.3. Flow is towards the top of page.

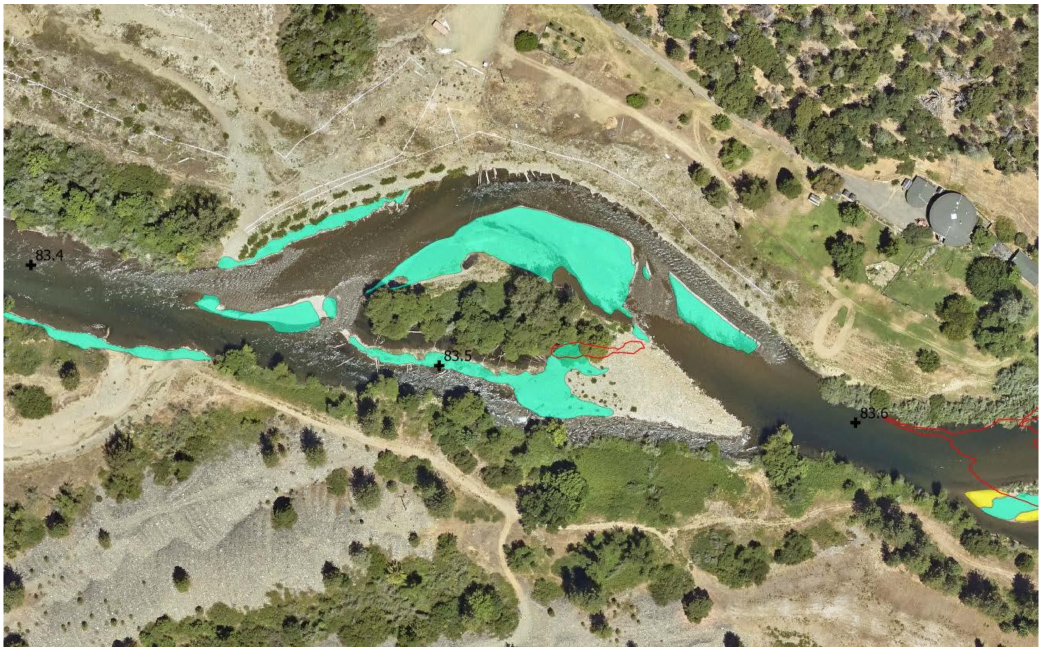

Figure 5A. Example of coarse, active bar area increases from channel reconstruction at the Chapman Ranch rehabilitation project at RM 83.5. Flow is to the left.