

THESIS

GEOMORPHIC IMPACTS OF LARGE WOOD RESTORATION IN AN URBAN
COLORADO STREAM

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2025

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ABSTRACT

GEOMORPHIC IMPACTS OF LARGE WOOD RESTORATION IN AN URBAN COLORADO STREAM

The effects of urbanization on river systems lead to degradation and simplification, reducing beneficial ecosystem functions. Prior to urbanization, many rivers in the Mountain West were geomorphologically complex, hydrologically interconnected, interspersed with large wood, and connected to their floodplains, providing numerous ecosystem services that led to functional resilience. Process-based restoration techniques are being implemented to reintroduce and support these lost functions in both rural and urban areas as an alternative to form-based restoration. Minimal research around process-based techniques has been done in urban systems and understanding how this approach impacts geomorphic response in varied biomes provides practitioners a basis to evaluate future projects. The objective of this study is to analyze the effects of a large wood process-based restoration in an urban Colorado corridor (Cache la Poudre River, Fort Collins, CO) by monitoring changes in 1) site erosion and deposition, 2) geomorphic unit heterogeneity, 3) large wood volume and porosity, 4) evaluate whether monitoring geomorphic units is an adequate metric of project success, and 5) to compare restoration techniques throughout the site by analyzing sediment changes. Additionally, I review and recommend monitoring methodologies and discuss how water policy affects restoration in Colorado. The site restoration included reconnecting the floodplain, reconstructing site bathymetry, and adding large wood to both the floodplain and active channel. Following restoration construction and one runoff season, digital elevation models were analyzed to delineate geomorphic units and compare restoration

approaches. iPad LiDAR was collected at six constructed large wood structures to determine volumetric and porosity changes. Sediment analysis shows net aggradation of sediment around structures, supporting the project goal of mitigating an impending head cut. Large wood analysis results varied based on structure location within the channel and with respect to other large wood structures. The accumulation and dispersion of wood throughout the site was captured by newly formed islands induced by restoration. Both the largest patch index and patch density heterogeneity metric either stayed consistent or increased after the runoff season. This restoration project demonstrates to policymakers the geomorphological, ecosystem, and social benefits while showcasing the low-risk nature of carefully designed process-based restoration using large wood. Greater utilization of large wood in urban restoration more broadly supports the ecosystem services that benefit the communities that live in and around the river.

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1. Introduction

The current context of river management is rooted in anthropocentric needs generally associated with conveyance, flood mitigation, and water rights. With a new ecological and climatic paradigm, approaches to river management are embracing a shift to holistic restoration practices benefiting human safety and environmental needs (Death, 2024, Wohl et al., 2005). Historically, rivers have been leveed and reconstructed into single-thread channels to limit overbank flow (Bechtol and Laurian, 2005). Historical river management also included the removal of wood from channels for increased navigation and decreased risk to nearby infrastructure (Wohl, 2014). However, channelization may lead to catastrophic failures through bank failing or overtopping, while also significantly reducing ecosystem services typically provided by complex channels, such as groundwater recharge and microhabitat formation (Sparacino et al., 2019, Opperman et al., 2010, Flitcroft et al., 2022, Flatley et al., 2018, Kondolf, 2011). Groundwater recharge stores water during drought, increases hydrologic floodplain connection, and decreases wildfire intensities (USFS, 2018). Diverse habitat formation supports diverse species compositions that provide resilience after large disturbances (Legleiter et al., 2003, Pugh et al., 2022, Petsch et al., 2023). Here resilience will be defined as the ability of a system to return to pre-disturbance conditions (Death, 2024). When large wood is kept in place or reintroduced to the channel, water is forced to move and shift, leading to bank erosion, pool scour, and local downstream deposition, all supporting aquatic micro and meso-habitats (Montgomery et al., 2003). Provided the appropriate technique and location, reintroducing these natural processes to degraded urban rivers can restore the multitude of benefits lost due to an emphasis on restriction and conveyance. Process-based restoration (PBR) is an umbrella term that describes restoration techniques and practices that

mimic natural processes. Beechie et al. (2010) define it as restoration that looks to reestablish original processes that maintain river and floodplain systems. According to Beechie et al. (2010), process-based restoration should satisfy four key criteria; restoration should remedy the origin of degradation, be consistent with historical physical and biological norms, align with the scale of environmental concerns, and clearly define outcomes.

1.1 Use of wood in restoration

Goals of PBR can be varied and based on project specifics but commonly include floodplain connection, and increasing biological and geomorphic diversity to increase resilience. Adding wood to the channel and floodplain is one approach to achieve those goals (Grabowski et al., 2019, Neuhaus and Mende, 2021, Larson et al., 2001, Anlanger et al., 2022, Cashman et al., 2018). Floodplain reconnection during restoration can happen a few ways: 1) lowering the floodplain elevation to enhance regular flow inundation; 2) ponding water behind a blockade, such as a dam, channel spanning wood structure, beaver dam analog; and less commonly 3) adding sediment to the channel bed to increase water surface elevations and more frequent floodplain inundation (Flitcroft et al., 2022, Pess et al., 2005). These methods tend to be used in conjunction with each other. For example, manual topographic grading may be implemented within a mainstem river to reduce erosion and add geomorphic complexity by building geomorphic units like riffles and islands. Additionally, wood would be placed at the upstream head of an island mimicking natural accumulation.

Geomorphic units are defined by River Styles (2024) as a landform-scale feature representative of formative processes, determining structure and function of a river. The number and size of geomorphic units has been linked to diverse species structure and fluvial complexity, which in turn builds ecological resilience. Considering the importance geomorphic complexity plays in healthy

river systems, measuring geomorphic unit heterogeneity is a suitable metric for determining project success when the stated goal is to enhance resiliency and biodiversity (Morrison et al., 2024, Thomson et al., 2001, Clarke et al., 2003, Ciotti et al., 2021).

The addition of wood during river restoration includes using on-site or outsourced logs to mimic natural log jams in low-risk areas to increase geomorphic complexity and hydrologic processes (Wohl et al., 2019). Wohl et al. (2019) outline the benefits, risks, and considerations for implementing large wood within river corridors, and provide examples for various intercontinental locations. Benefits of large wood implementation include but are not limited to increasing channel planform complexity, hyporheic exchange, and biodiversity. Risks of using large wood include increased backwater flooding, increased local erosion, infrastructure blockages and damages that can create hazards to recreational boaters and tubers. Some efforts mentioned for mitigation of these hazards include designing stable jams to capture mobile large wood, infrastructure designed to pass mobile large wood, and preventing beavers from building near intakes.

1.2 Urban restoration

About a third of US rivers have been impacted by changes in land use (Bernhardt et al., 2005), of which approximately one-third are located in urban corridors (Bernhardt et al., 2007). If the impacts are left unattended, then the reaches will continue to degrade in line with what Walsh et al. (2005) describe as the “urban stream syndrome.” Impacts of degraded urban rivers include flashier hydrographs, changes in sediment transportation regimes, elevated concentrations of nutrients and contaminants, altered channel morphology, and stressed/degraded instream aquatic ecology (Walsh et al., 2005, Shoredits and Clayton, 2013, Gurnell et al., 2007, Vietz et al., 2016). However, infrastructure near urban river corridors complicates restoration efforts. Many streams

are straightened to make room for new buildings, reducing the lateral space available for restoration (Shoredits and Clayton, 2013).

Process-based restoration (PBR) is being implemented around the world. Despite the plethora of diverse locations, caution around implementation in urban settings has left urban stream corridors with a limited scope of trusted restoration techniques (Ockelford et al., 2024). Blauch and Jefferson (2019) found that an increase in nearby impervious areas was correlated to increased wood mobility, validating fears of large wood-induced infrastructure damage. Restoration, in that case, did not include floodplain reconnection or energy dissipation techniques and points to the impacts of how systemic-catchment-wide issues make urban restoration tricky. Shoredits and Clayton (2013) note that degradation of urban rivers will continue unless the source of urbanization is mitigated. Understanding the limited feasibility around mitigating urbanization they point to addressing some pertinent symptoms of which include but are not limited to floodplain connection, runoff regimes, and wood and sediment loading. Cockerill and Anderson Jr. (2014) mention that public perception plays a large role in determining what a healthy river looks like and thus influences the types of projects implemented in urban corridors. While the approaches to urban restoration may be limited, urban rivers still require attention and restoration as they are a part of a larger system, affecting river health and habitat.

1.3 PBR in Urban Colorado

PBR projects in the United States can be found across the country with a large concentration in the Pacific Northwest (Blauch and Jefferson, 2019, B Rios-Touma et al., 2014, Larson et al., 2001). However, fluvial processes in high desert Colorado differ from those of the temperate Pacific Northwest and so restoration approaches vary and cannot be equally applied. Colorado experiences a semi-arid and arid climate in a majority of regions characterized by low precipitation, wide

temperature variations, and a snowmelt-dominated hydrograph. In contrast, the Pacific Northwest has a diverse climate ranging from temperate forests to semi-arid inland regions (Wohl et al., 2019). Restoration practices must consider the site's hydrograph, geology, historical use, policy, and disturbance regime (Montgomery and Buffington, 1997). When considering large wood implementation, different biomes have different tree species, which all degrade differently under various climatic conditions, making large wood restoration spatially dependent on the surrounding ecosystem (Harmon et al., 1986, Akita et al., 2014, Wohl et al., 2019). Project success directly results from how climate, resources, and ecology react to specific techniques.

Community and private sector organizations within Colorado are actively working to integrate large wood PBR into rivers. However, due to the perceived risk of flooding and damage to infrastructure, these projects have occurred primarily in rural, mountainous regions (Ockelford et al., 2024). Sackett (2023) notes that Colorado legislature requires restoration efforts to not negatively affect downstream users. This is generally interpreted as no decrease in the amount of water moving downstream to protect downstream water rights. While there are no guidelines on what type of restorations can be implemented, this policy can make certain practices more difficult since a large component of PBR involves removing artificially imposed conveyance through reshaping reaches and slowing water to support aquatic ecosystems (Sackett, 2023, Bouwes et al., 2016). While water policy and law are typically meant for upstream users diverting water for agriculture, it has been interpreted in restoration efforts to mean that ponded water will evaporate, impacting downstream users. This creates a barrier to process-based design and incentivizes traditional engineering options (Romero-Heaney, 2023). One of these traditional options is form-based restoration, which is a common among practitioners. However, this option has been shown within the Upper Colorado River to improve aesthetics but has been found to reduce wetland

hyporheic exchange and storage and fails to improve hydrologic and sediment processes (Cockerill and Anderson, 2014, Sparacino et al., 2019).

1.4 Study Objectives

This study evaluates the large wood river restoration within an urban river corridor applied on Cache la Poudre River (Poudre) in response to a head cut located near the Colorado State University Environmental Learning Center (ELC). In conjunction with the design objectives, this study evaluates changes in 1) site erosion and deposition, 2) geomorphic unit heterogeneity, 3) large wood volume and porosity, 4) evaluate whether monitoring geomorphic units is an adequate metric of project success, and 5) to compare restoration techniques throughout the site by analyzing sediment changes for process-based restoration in urban corridors. Subsequently, I review and recommend monitoring methodologies and discuss the ways in which policy affects restoration in Colorado.

2. Methods

2.1 Historical Background of the Study Site

The Cache la Poudre River runs from the Rocky Mountains to the South Platte River with a myriad of dams and water diversions. The Poudre is around 4,000 square kilometers (StreamStats, 2024) heading from the Rocky Mountain National Park. The river runs through the Poudre Canyon before flowing into the plains flowing towards Fort Collins, Colorado. The river typically provides around 50 percent of the water to Fort Collins, but this number is variable as it is dependent on the freshet (Handy, 2014). The water is stored in Horsetooth reservoir, 13 kilometers from Fort Collins and is treated before reaching users. Notably, the Poudre River flows west to southeast through the Environmental Learning Center (ELC), which is owned and operated by Colorado State University (CSU) (Figure 1). The land was originally a bison hunting ground for the Arapahoe and, after colonization, served as farmland, which was then donated to CSU in the 1960s (Poudre National Heritage, 2024). There are 10 dams or grade control structures between where the Poudre enters the Front Range and the ELC (Haworth and Bestgen, 2024). Haworth and Bestgen (2024) measured a 68–83 percent decrease in baseflow (November to April) and a 2–8 percent decrease in peak flows (May – October) between six structures. Reduction in baseflow reduces sediment transport and impacts river form and available aquatic habitat.

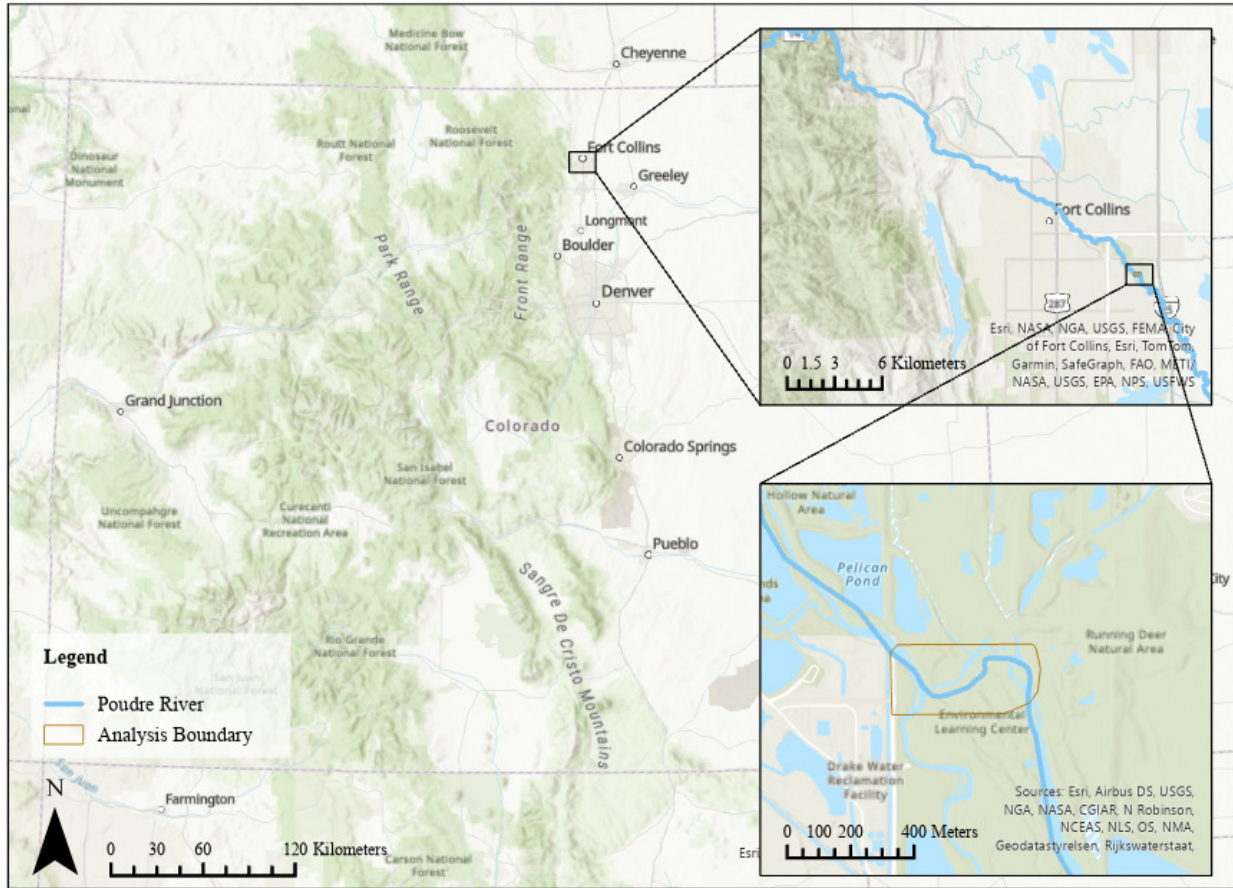


Figure 1. A topographic map of the northern Colorado front range highlights the Poudre river path and the location of the project site.

In 2013, a large storm resulted in a five-year flood (~140 CMS), which subsequently caused an avulsion within the Environmental Learning Center (ELC) along the Poudre (Figure 2). The avulsion in the new mainstem decreased channel length and steepened longitudinal slope to transport the same amount of water which caused the river to head cut. The head cut at the ELC posed a risk to a nearby low-head dam. The City of Fort Collins’s goal was to stop the head cut from impacting the dam and to retain environmental water rights by rewatering the avulsed mainstem. Therefore, they hired a private contractor to develop restoration designs. The contractor design included some process-based techniques with the goal of capturing sediment to stop the head cut and support ecosystem processes. In April 2023, the project construction was finished

and included lowering the floodplain in two locations, adding large wood to the channel and floodplain, installing two riffle structures, and regrading channel bathymetry to stabilize longitudinal slopes. A two-year storm (~ 55 CMS) occurred the summer after construction and transported sediment and wood throughout the site, providing a unique opportunity to assess the post-restoration geomorphic change, as most vegetation had not yet established.



Figure 2. Historical imagery of the Poudre River within the ELC around peak runoff. Top two images show multiple flow paths prior to avulsion. Bottom two images show channelization due to the 2013 Flood.

2.2 Restoration Description

Restoration efforts included a variety of process-based and traditional techniques. The upper portion of the active channel (Figure 8) included traditional restoration practices, while the downstream portion included large wood structures. A pool-riffle bathymetric form was implemented with two floodplain-spanning boulder riffles near the upstream reach. Floodplain connection was completed by lowering the north floodplain to inundate at the 2-year flood, and a swath near the first bend to inundate at the 5-year flood. The side channel inlet was lowered to

further secondary connections. Large wood structures were placed on the north floodplain and in the main stem and floodplain on the downstream bend.



Figure 3. Left: Downstream log structures. Right: Upstream log structures.

I described earlier how Beechie et al (2010) outlined four keys to successful restoration. The restoration implemented at the ELC does not address each one. For example, restoration should address the origin of degradation, however most restoration cannot address the origin of degradation. In this case, a major impact are the dams directly upstream of the site that limit sediment and restrict flow. The scale of a restoration that reverses these impacts are not always possible.

2.3 Survey

Topographic surveys were performed between May 2023 and January 2024 using an RTK GNSS Emlid system. In the Spring of 2023, ground control points were set using a combination of National Geodetic Survey (NGS) and Fort Collins local benchmarks; the control points were used as base station locations for the remainder of the field season. Tops of the banks were surveyed three times throughout the summer to observe erosion at river bends. Additionally a full site bathymetric survey was performed in September 2023 and used to build a surface that was later combined with drone imagery to create a complete DEM. The bathymetric survey was completed

by walking the length of the channel and surveying the thalweg, toe, and tops of the channel including any grade breaks. A bathymetric geomorphic unit delineation survey was performed in November 2023 when flows were below 0.3 CMS to access the thalweg. Further discussion of geomorphic unit delineation is found in later sections.

2.4 Drone Imagery

On November 29, 2023, a DJI Phantom 4 RTK drone was flown at the site, capturing aerial imagery at a 0.15-meter resolution. These data were brought into AgiSoft Metashape and processed into orthomosaic aerial imagery and a structure from motion (SfM) digital elevation model (DEM).

2.4.1 Workflow for SfM and orthomosaic data

Using the orthometric photo data obtained during the flight, a DEM and aerial image were created using the USGS workflow described by Over et al. (2021) with some modifications. Raw .jpg data were uploaded to Agisoft Metashape. Photo data were placed into one camera group, the camera was aligned, then camera positions for each image collected by the drone were uploaded. Default values suggested by Over et al. (2021) were applied to camera calibration and accuracy settings at which point the images could be aligned (Appendix A). Static structures within the site were used as ground control points (GCPs). Traditional ground control points (GCPs) were not used during the flight, but static structures were surveyed and used in lieu of GCP targets. Static structures include vertices of the inlet headwall, corners of a pedestrian bridge, and the tops of secured log jam poles. Suggested values described by Over et al. (2021) and the procedure for error reduction were applied to point data. After optimization, the image was converted to a point cloud, a DEM, and an orthomosaic. Suggested settings were applied to all products except for interpolation, which was left enabled.

2.4.2 Combined DEM

A bathymetric surface was created in AutoCAD Civil 3D using the survey performed in September. Survey points were converted to feature lines for the thalweg, toe and top of the channel (line between P_B points, Figure 4). The feature lines were then applied to a blank surface as break lines, which created a rough bathymetric surface. Since there are small discrepancies between the bathymetric surface and DEM surface (area defined by diagonal hatch, Figure 4) an intermediary surface was built. The tops of bank feature lines were offset 0.15 meters (distance between P_{S1} and P_{S2} , Figure 4) and placed on the SfM DEM where the topographic values could be extracted to line vertices. These top of bank elevation defined lines (between P_{S2} points, Figure 4) were pasted as new features into the bathymetric surface to ensure the SfM DEM and bathymetric surface aligned. Finally, the bathymetric surface and SfM DEM were pasted into a blank surface to be combined and exported into ArcGIS for further analysis.

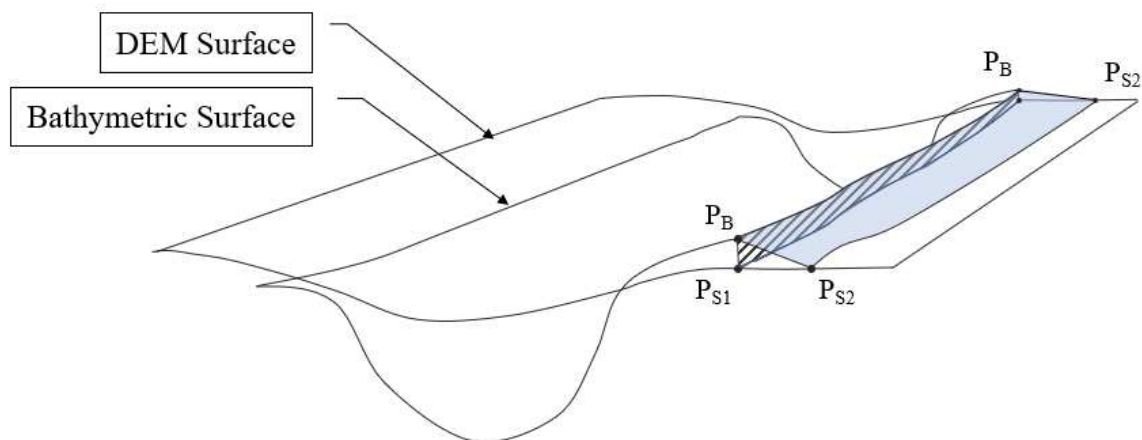


Figure 4. Diagram of how to combine bathymetric and topographic surfaces.

2.5 Error Calculations and DEM Adjustments

Random spatial error is intrinsic in surveying and can propagate through post-processing data. I tested the accuracy of the survey and SfM data by adding the two errors using error propagation

techniques (Equation 1) for x, y, and z factors (Lane, 2003). Root mean square error data are provided for each survey point in x, y, and z coordinates, and distance error is provided for each GCP from Agisoft Metashape.

Equation 1

$$\delta_x = \sqrt{\delta_{x_{\text{SfM}}}^2 + \delta_{x_{\text{Survey}}}^2}$$

Values ranged from 0.01 to 0.09 meters. The combined DEM was compared to the survey point values using the “Extract Values to Points” function in GIS. From here, the surveyed elevation was subtracted from the DEM elevation to obtain an elevation error. Even when observing the GCPs strictly, values ranged from 0.04 to 0.12 meters. Elevation values consistently varied between as-built conditions and SfM data. A difference in elevations was taken at a sidewalk to the west and a trail to the east. The difference was used to shift the DEM elevation manually, addressing the site-wide error.

2.6 Sediment Analysis

2.6.1 Pebble Count

A defining goal of the restoration project was to mitigate the head cut threatening the low-head dam by increasing sediment deposition. The contractor conducted a pre-restoration cross-sectional pebble count in April 2020 prior to construction and I reconducted the pebble count 7-months post-restoration in November 2023. The upstream section was taken at the bottom of the first riffle, and the downstream cross-section was taken at the first bend in the channel (Figure 5). Tape measures were placed across the channel and a blind point and pick method was used to measure sediment every 0.3 meters. Each piece of sediment was measured using a gravelometer and anything below 2 mm was recorded as fines but analyzed in calculations as 2 mm.



Figure 5. Locations of pebble counts overlain on a 2023 (post-construction) aerial.

2.6.2 Measuring restoration effects on sediment mobility

A RTK GNSS cross-sectional survey was conducted to capture sediment deposition near the downstream gravel bar near the large wood structures. The first survey was conducted on July 10th, 2023 with a repeat survey on January 9th, 2024. Using the as-built DEM and November post-restoration DEM, additional site-wide cross-sectional analyses were conducted. Each DEM was uploaded into ArcGIS Pro (3.3.0) for processing. I created a difference of DEM's (DoD) by subtracting the as-built DEM from the November DEM using the "Raster Calculator" function. Then I created a line shapefile and drew multiple lines across the site at locations of interest including bends, floodplains, log jams, and runs. Using the "Points along Lines" function, points were generated at 0.6 meter intervals along each cross-section. The "Extract Values to Points" function was then used to retrieve as-built and post-restoration elevation data for each point, which was exported as a .csv for analysis (Appendix B).

To determine changes in sediment, I created a denser series of cross sections 10 meters apart (Figure 6). Between each cross section I created polygons spanning one cross section to the next. I ran a raster statistic function on the DoD for each polygon. This calculated the average DoD cell value between each cross section within the November active channel as defined by grade breaks and vegetation boundaries.



Figure 6. Cross-sections used for sediment transport analysis, dark lines are cross sections and open circles are placement of log jams.

2.7 Delineation and comparison of geomorphic units

USGS EarthExplorer 2019 NAIPs imagery combined with the contractor's existing conditions topography was used for pre-restoration geomorphic unit delineation. Google Earth imagery combined with contractor as-built topography was used for as-built geomorphic unit delineation. Geomorphic units were delineated by using DEM datasets converted to 0.3 meter contour shapefiles and aerial imagery. Bathymetric post-restoration conditions were surveyed to the level of sediment size, and geomorphic form was determined using the River Styles framework (River

Styles, 2024). Delineation of above-water geomorphic units was completed using orthomosaic imagery and digital elevation data obtained through drone imagery. Units were predefined and included terraces, floodplains, ledges, lateral bars, in-channel bars, islands, side channels, chutes, pools, riffles, and wood using the River Styles approach. After delineation, patch types were dissolved and merged in ArcGIS so that one shapefile contained all patch types, and each type was one multi-patch polygon. The combined polygon shapefile was turned into a raster file with a cell size 0.15 meters. This resulted in numerous one cell patches. This is because of the process used to overwrite and combine overlapping patch areas in ArcGIS, where the method described above supports the delineation of micro patches, sometimes only 0.1 m². The “Polygon to Raster” function reinforces this inflation by requiring a raster cell size which promotes a false discretization of patches. There are a total of 8 patches, including the floodplain background on the left, while the right has approximately 45 (Figure 7).

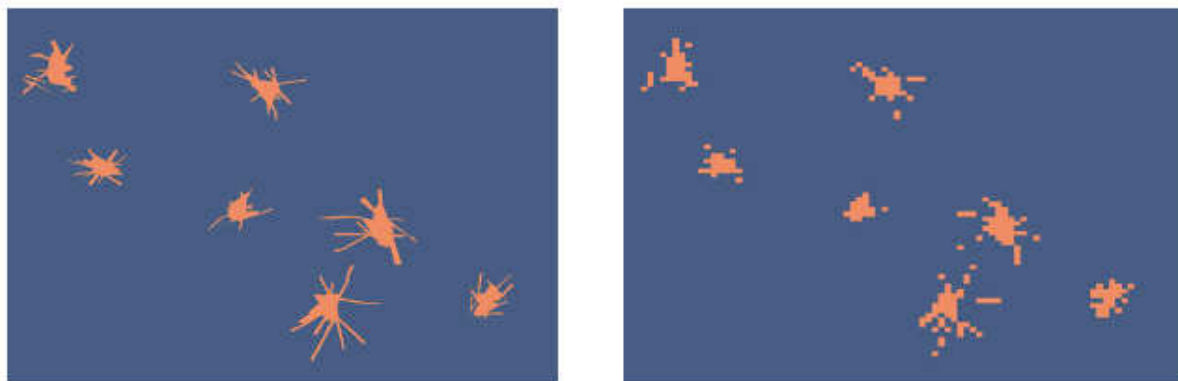


Figure 7. Left: Wood patch delineation as polygons in the north floodplain. Right: The same wood patch delineation as rasters after processing.

To fix this I manually went through and reassigned these singular cells to match the surrounding geomorphic unit to mitigate skewing in the statistical analysis. I projected all rasters from Northern Colorado State Plane to UTM Zone 13. This raster was then processed using R to calculate heterogeneity metrics. Heterogeneity metrics of interest follow Iskin and Wohl (2023)

methodology, which use several functions in the R package “landscapemetrics” including adjacency index, interspersion and juxtaposition index (IJI), largest patch index (LPI), patch density, aggregation index and Shannon evenness index (SEI) (Appendix C). The adjacency index measures spatial connectivity between the same patch type; high values indicate less fragmentation. IJI measures the mix of different patch types across the area of interest; high values indicate complex arrangements of patches. LPI measures the percent of area covered by the largest patch; high values indicate a significant portion of the area is dominated by one patch. Patch density measures the total number of a type of patch per 100 hectares; high values indicate high fragmentation. The aggregation index measures the clumping of patch types where high values indicate patches of the same type are spatially grouped. SEI measures the equal distribution of different patch types across the area of interest, where high values indicate that one patch type does not dominate the area.

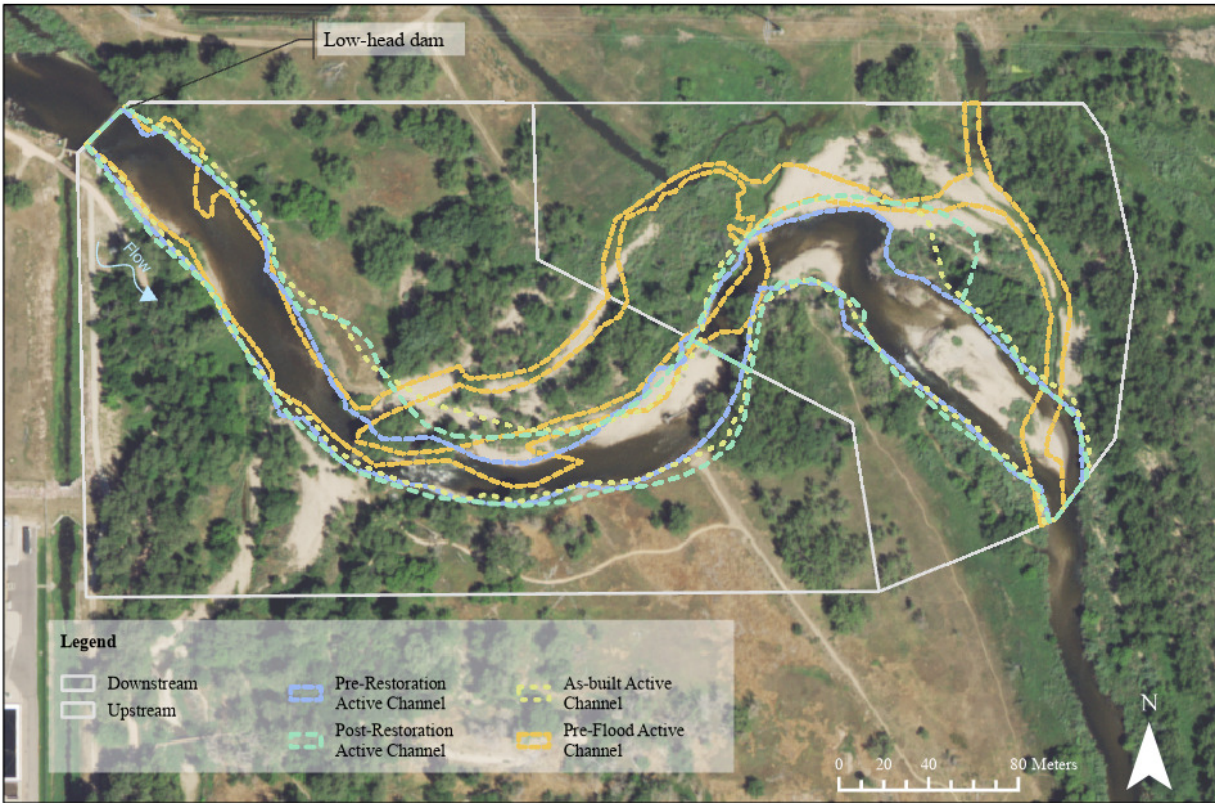


Figure 8. Area of analysis and the separation between up and downstream reaches as indicated by white line crossing the middle of the study area.

2.7.1 Comparison of site restoration

The two delineated areas seen in Figure 8 were compared spatially and temporally. Spatial analysis compared each heterogeneity metric between the upstream and downstream reach. Temporal analysis compared pre-restoration, as-built, and post-restoration metrics. To assess how restoration techniques effected the results within the active channel, I delineated the active channel based on established vegetation for each scenario. In areas where vegetation was absent or disrupted due to construction activities, I prioritized identifying breaks in the topographic grade. Each active channel delineation accompanied by the appropriate raster was used in the “Extract by Mask” ArcGIS Pro to isolate the area of interest for analysis. This resulted in six rasters per point in time to be analyzed; a full site, full active channel, full upstream, full downstream, full active channel

upstream, and full active channel downstream area for pre-restoration, as-built, and post-restoration conditions.

2.8 Changes to Large Wood

To measure the accumulation of wood on site, I evaluated the aerial extent of wood and changes in volumetric accumulation and porosity at six downstream wood structures. The aerial extent was calculated through the summation of wood patch area from the polygon shapes in the geomorphic unit delineation. Marshall et al. (2024) describes a method for measuring porosity and volume of large wood structures using handheld iPad LiDAR and CloudCompare. The method as described was applied to assess changes in the six large wood structures. Data were collected on July 10th, 2023, and October 5th, 2023, after the peak summer flow, using the iPad application Polycam. Six of the seven large wood engineered log jams (ELJs) downstream were scanned and exported as .obj files to CloudCompare; the seventh was omitted due to a lack of safe access. I aligned each structure with the respective pair and the flow-facing or "front" of each ELJ was extracted, ensuring the same delineation area was used for each pair. Because no ground control points (GCPs) were used during the scan, the reported changes in values are relative to each ELJ. I applied the methods outlined by Marshall et al. (2024) for calculating porosity, 2.5D, and 3D volumes.

Additionally, two game cameras (SpyPoint Flex) were placed on site to visually assess the changes in sediment and identify flows at which large wood transport occurred. One camera was placed at the boundary of the north floodplain grading looking upstream and one on a downstream ELJ looking downstream. Pictures were captured at 15 minute increments for the duration of the study.

3. Results

3.1 Sediment Analysis

The pebble count results show a post-restoration reduction in median sediment size and increased deposition of fine particles. After restoration, the upstream cross-section coarsened whereas the downstream cross-section became finer (Figure 9). The D_{50} measurement decreased at the upstream reach from 48.8 mm, very coarse gravel, to 21.7 mm, coarse gravel using the Wolman class size standard. The downstream cross-section increased a small amount from 43.4 mm to 47.1 mm resulting in no sediment class change. There was an increase in fines (2 mm or smaller) in the upstream sediment composition after restoration from 4% in 2020 to 25% in 2023. Despite a slight coarsening in D_{50} , there was an increase in downstream fines from 8% in 2020 to 12% in 2023. The increase in fines shows increased entrapment of small particles at these locations (Table 1).

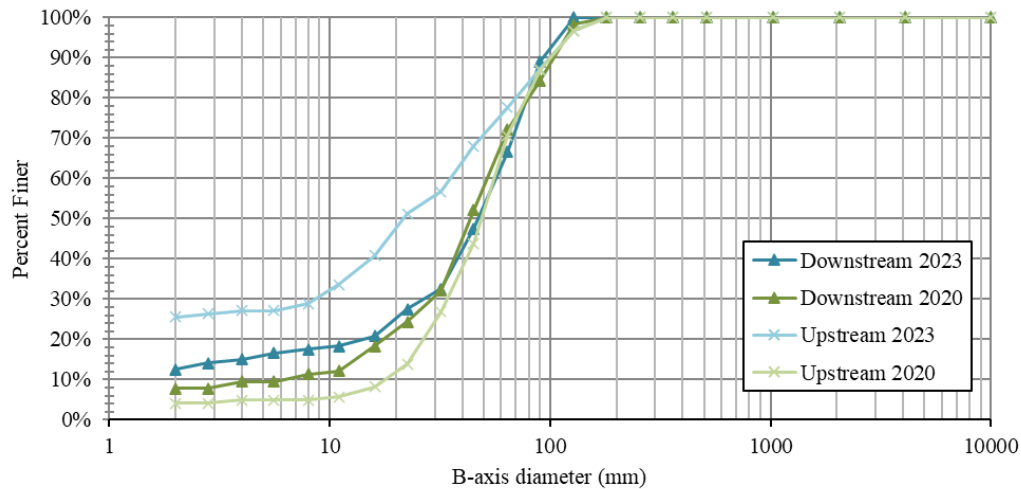


Figure 9. Bed sediment analysis at two cross sections for pre-restoration (2020) and post-restoration (2023). The green lines show pre-restoration (2020) sediment size results, while the blue lines show sediment size results for post-restoration (2023). Triangle markers indicate the downstream cross section while “x” markers the upstream cross section.

Table 1. Sediment diameters for each cross section for 2020 and 2023, bold values denote the D₅₀.

Percentile	Upstream		Downstream	
	2020	2023	2020	2023
D _{min}	2.0	2.0	2.0	2.0
D ₁₀	17.9	2.0	6.1	2.0
D ₁₆	24.0	2.0	13.9	4.9
D ₂₅	30.5	2.0	23.3	19.9
D₅₀	48.8	21.7	43.4	47.1
D ₇₅	70.0	58.2	69.3	72.6
D ₈₄	84.5	80.3	89.1	83.2
D ₉₀	100.3	99.7	103.8	92.5
D _{max}	180.0	180.0	180.0	128.0

DEM differencing between as-built conditions and post-restoration (November) shows net aggradation at every cross-section except for cross-section 13, including cross-sections A, B, and C (Figure 10). The latter cross sections show consistent aggradation from as-built conditions until sometime between November and January, with net erosion at all three locations (Table 2). There was aggradation across the site except for cross-section 4, 5, and 13, which lost 1.1, 1.4, and 2.4 m³ of sediment, respectively. When examining sedimentation changes upstream and downstream, it's evident that the downstream reach exhibits a larger magnitude (-2.6 to 2.9 meters) and average value (0.14 meters) of sediment alteration compared to the upstream reach (ranges from -1.65 to 1.25 meters and has an average value of 0.08 meters) (Figure 10). Cross sectional sediment analysis shows that the area of highest erosion is at the bend near the in-channel ELJ's. The other location that on average had deposition was near either constructed riffle. Additionally, the location with highest erosion is near the in-channel ELJ's (Figure 11).

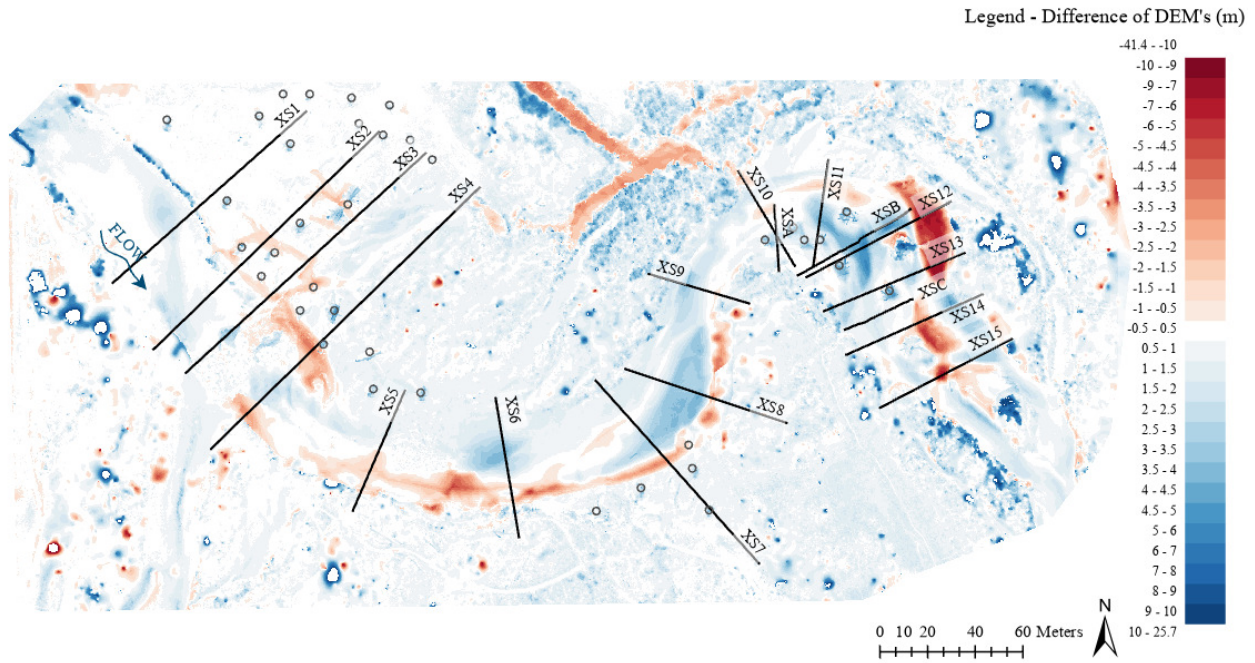


Figure 10. Difference of DEMs between as-built (April 2023) and post-restoration (November 2023) topography, where red denotes erosion and blue denotes aggradation. Open circles indicate locations of ELJ's.

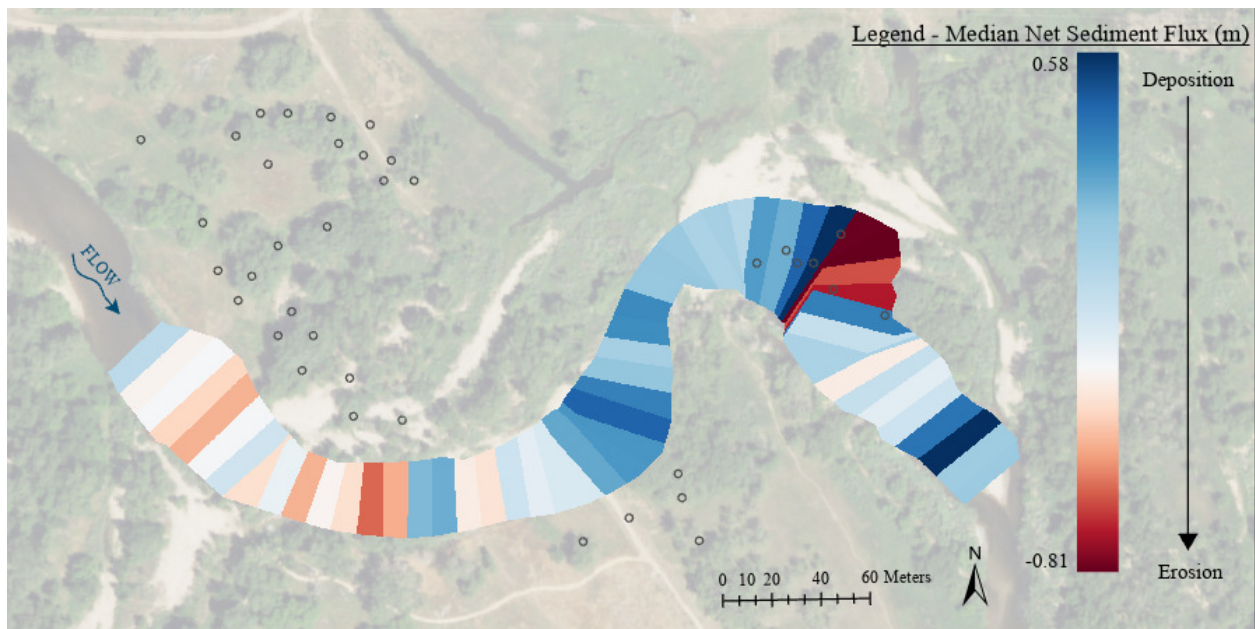


Figure 11. Result of sediment transport analysis shows scale of deposition (blue) to erosion (red) for each cross section based on average value of DoD within active channel. Open circles indicate locations of ELJ's.

Table 2. Net change in surface area of sediment at three cross sections over time.

Cross Section	April - July (m²)	July - November (m²)	November - January (m²)
A	3.95	1.45	-0.63
B	27.49	5.35	-6.10
C	4.73	3.49	-4.33

Areas of high erosion include the outer banks of each bend, the first near the emergent gravel bar (XS 7 and 8) and the other north of the downstream log structures (XS 12 and 13). Cross-sections 7 and 8 have a maximum vertical change of 2.4 meters and cross-sections 12 and 13 changed 1.2 meters vertically. Bank erosion of 2.7 linear meters occurred at the upstream outer bend (XS 7) between April and May, then another 1.2 linear meters between May and November. Erosion at the downstream bend cut into the bank upwards of 14.9 meters at cross-section 12. Other notable areas of erosion are the side channels on the northern floodplain (XS 1 through 4), which have eroded upwards of 0.6 m. Areas of high aggradation include sedimentation in the upstream riffle (XS 3), the emergent gravel bar, and the increased height of the lateral bar (XS A, B, and C) (Figure 10), aggrading upwards of 1.5 meters (Figure 12).

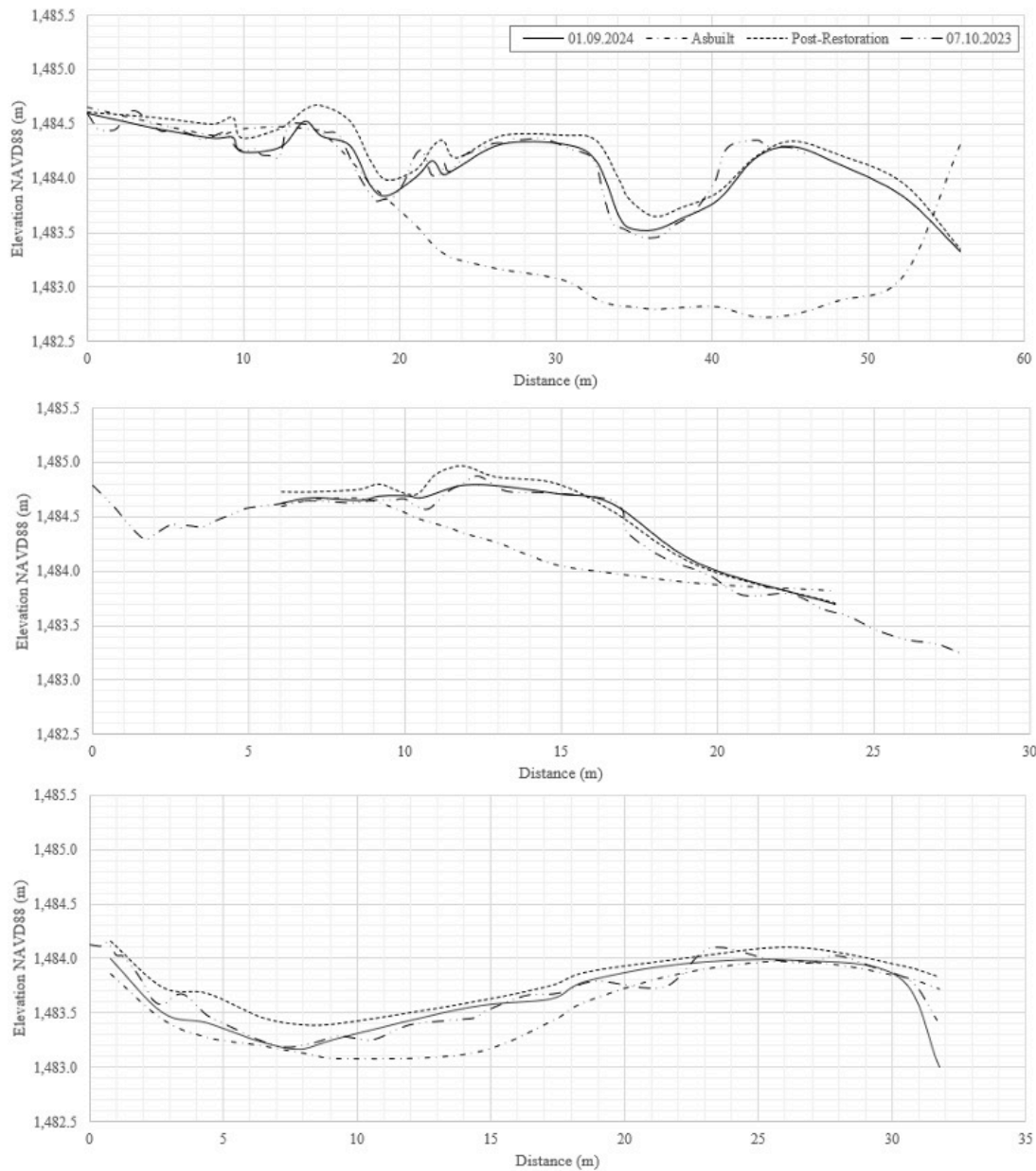


Figure 12. Elevation data for cross-sections A, B, and C.

3.2 Geomorphic Units

The number of geomorphic units increased over the study period. Pre-restoration delineation noted nine designated geomorphic units, while as-built and post-restoration delineation includes eleven (the addition of ledges and in-channel bars) (Figure 13). Pre-restoration, as-built, and post-

restoration results include 54, 100, and 186 patches, respectively. Excluding wood patches, the bar patch increased the most, a total of 12 more patches total between as-built and post-restoration.

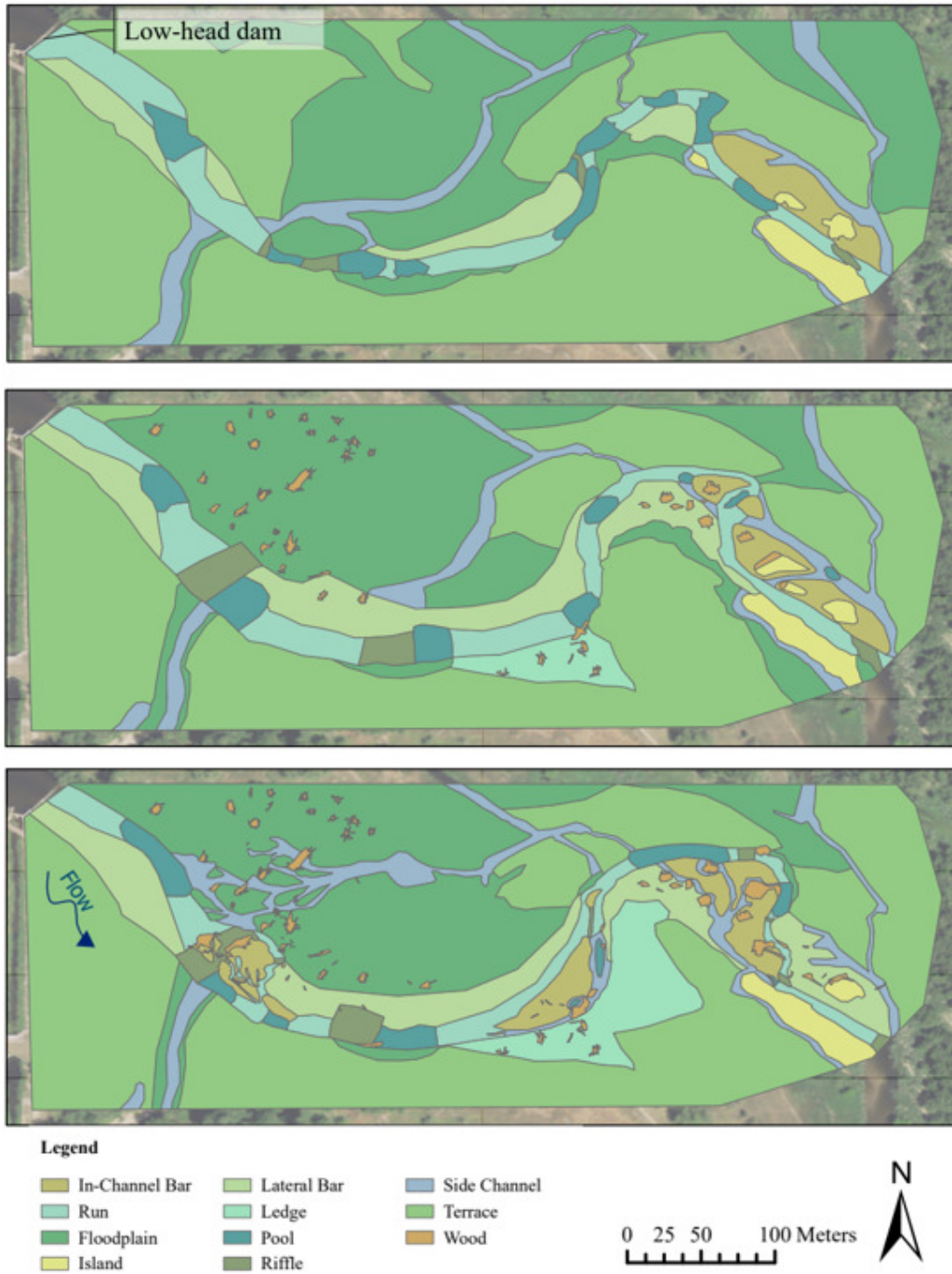


Figure 13. Geomorphic unit delineation of pre-restoration (top), as-built (middle), and post-restoration (bottom) conditions.

3.2.1 Full Site

3.2.1.1 Temporal shifts

Heterogeneity metrics for the entire site show little change across sampling periods except for patch density and the largest patch index (Table 3). The adjacency index and IJI remain relatively consistent across time. The largest patch index decreases by 25 percent between pre-restoration and post-restoration, and by 9 percent between as-built and post-restoration. This indicates the largest patches decrease in size due to construction. Construction increased patch density 153 percent, whereas change between as-built and post-restoration increased density by 67 percent. Aggregation index does not shift notably, indicating fragmentation and dispersal of patches did not greatly change. Shannon's evenness slightly increased, suggesting the site is moving towards a balanced distribution of patches. Changes in the upstream reach have similar trends with notable changes within the LP index, PD, and Shannon Evenness Index. LP decreases by 8 percent due to construction and 18 percent between construction and post-restoration. Patch density increases 243 percent from construction and continues to increase by 70 percent after runoff. SEI increases 14 percent after construction and increases by 5 percent after runoff. Downstream conditions do not shift much except for patch density, which increased 97 percent between pre-restoration and post-restoration and increased 59 percent between as-built and post-restoration. Adjacency, IJI, and aggregation indices did not change greatly and followed trends observed at the full reach scale.

Table 3. Geomorphic indices are analyzed across the entire reach.

Metric	Analysis Period	Upstream	Downstream	Full Site
Adjacency Index (%)	Pre-restoration	98.93	98.12	98.58
	As-built Conditions	98.76	97.83	98.36
	Post-restoration	98.07	97.48	97.78
Interspersion and Juxtaposition Index (%)	Pre-restoration	79.31	69.12	73.26
	As-built Conditions	78.43	72.72	77.45
	Post-restoration	77.82	74.28	80.09
	Pre-restoration	26.53	15.42	22.24

Largest Patch Index (%)	As-built Conditions	24.50	14.94	18.39
	Post-restoration	20.10	14.67	16.71
Patch Density (#/100 ha)	Pre-restoration	494.67	978.80	568.83
	As-built Conditions	1,698.31	1,216.85	1,442.34
	Post-restoration	2,885.49	1,930.90	2,407.20
Aggregation Index (%)	Pre-restoration	98.72	97.82	98.37
	As-built Conditions	98.47	97.50	98.10
	Post-restoration	97.75	97.10	97.50
Shannon Evenness Index (%)	Pre-restoration	0.63	0.70	0.64
	As-built Conditions	0.72	0.69	0.69
	Post-restoration	0.75	0.73	0.74

3.2.1.2 Spatial shifts

Similar to temporal trends, spatial trends show the greatest change in the LP and PD indices. Adjacency decreases slightly over time, but the difference between up and downstream remains reasonably consistent. There are consistently lower IJI values downstream compared to upstream, indicating higher complexity which is paired with the LP index being consistently higher upstream. Upstream patch density was lower than downstream patch density in pre-restoration conditions. Both increase following construction and runoff, but upstream patch density surpasses downstream and is 33 percent greater than downstream in post-restoration conditions. The aggregation index does not change greatly but is slightly lower downstream at all times. Shannon evenness index shifts dominance over time but remains relatively similar between the two areas of analysis (Table 3).

3.2.2 Active Channel

3.2.2.1 Temporal shifts

Analysis of active channel heterogeneity metrics across time (Table 4) show little change except for patch density and LPI. Construction decreases PD 39 percent, then increases 70 percent between as-builts and post-restoration, which is only a three percent increase from pre-restoration

conditions. LPI increases 11 percent between pre-restoration and as-builts then decreases 21 percent after the runoff season. Adjacency, IJI, and aggregation stay consistent across the entire reach. Similar trends were observed after separating the active channel into the upstream and downstream reaches. Most metrics were similar, except for patch density and the largest patch index. Largest patch index increased upstream but restored to post-restoration values. The downstream reach decreased with restoration and decreased post-restoration by a small amount. The largest patch index increased by 28 percent in the upstream reach in as-built conditions and decreased 20 percent to pre-restoration values after runoff, while the downstream reach maintains the 35 percent decrease seen between pre-restoration and as-builts. Patch density in the upstream reach decreases 59 percent during as-built and returns to pre-restoration values after runoff, but downstream decreases 17 percent and then exceeds pre-restoration values by 12 percent.

Table 4. Geomorphic indices analyzed within the active channel.

Metric	Analysis Period	Upstream	Downstream	Full Reach
Adjacency Index (%)	Pre-restoration	96.76	95.59	96.02
	As-built Conditions	97.80	95.19	96.49
	Post-restoration	95.97	94.32	94.99
Interspersion and Juxtaposition Index (%)	Pre-restoration	78.58	76.60	79.76
	As-built Conditions	75.79	70.94	76.76
	Post-restoration	76.60	71.52	77.35
Largest Patch Index (%)	Pre-restoration	17.64	29.39	12.67
	As-built Conditions	22.59	19.03	14.11
	Post-restoration	17.89	18.27	11.06
Patch Density (#/100 ha)	Pre-restoration	5,884.78	6,672.11	5,930.71
	As-built Conditions	2,411.24	5,569.61	3,601.48
	Post-restoration	5,535.24	7,486.57	6,129.15
Aggregation Index (%)	Pre-restoration	97.01	95.23	96.24
	As-built Conditions	97.86	94.74	96.54
	Post-restoration	95.85	93.87	95.01
Shannon Evenness Index (%)	Pre-restoration	0.72	0.87	0.84
	As-built Conditions	0.74	0.83	0.80
	Post-restoration	0.75	0.79	0.77

3.2.2.2 Spatial Shifts

Akin to the full site analysis, the adjacency and IJI index are slightly higher upstream but relatively consistent throughout the active channel. LPI was higher in the downstream active channel pre-restoration (29 percent of total area compared to 17 percent in the upstream); this changed during construction so that there was an approximately equal LPI up and downstream (23 and 19 percent respectively) and decreased slightly but was ultimately maintained after runoff (18 and 18 percent respectively). Patch density within the active channel has been higher in the downstream reach through time; the upstream immediately post-construction was about 130 percent less than downstream compared to 13 percent pre-restoration and 35 percent post-restoration. The aggregation index is slightly higher upstream, and the Shannon Evenness Index is marginally higher downstream.

3.3 Large wood analysis

Volume analysis of the six ELJ faces show that half decreased in volume at the face and half increased between July and October (Table 5) (Figure 14). Porosity values decreased in most ELJs except for ELJ 1 and 5, which increased by 0.9 and 10.4 percent, respectively. All other ELJs decreased between 0.9 and 5.4 percent, with ELJ 2 decreasing the most and ELJ 6 decreasing the least. Two of the six ELJs, located in a region of consistently high velocity, had an increase in porosity as a result of lost sediment and wood. Wood lost likely would have been slash and not large structural pieces. ELJs 2, 4, and 6 show an overall sediment and wood accumulation, subsequently decreasing porosity. ELJs 1 and 5 show a total loss of volume and increased porosity. ELJ 3 shows reduced porosity but slight volume loss (Table 5).

Table 5. Summary of porosity and 3D volume changes for each ELJ analyzed based on porosity and volume calculations. Porosity values can be found in Appendix D.

ELJ	Change in Porosity (%)	Change in Volume (%)	Notes
1	0.92	-63	Net loss of material
2	-6.72	31	Net gain of material and packing
3	-3.05	-1	Increased packing
4	-4.72	83	Net gain of material and packing
5	6.60	-15	Net loss of material
6	-1.40	16	Net gain of material and packing



Figure 14. Location of downstream ELJs.

Based on the aerial analysis, an increased amount of large wood was present throughout the site (Figure 13) after runoff. As-built conditions show 43 wood patches, and post-restoration conditions have 88. The two notable accumulations at the upstream riffle are around 160 m³ and 105 m³ and were approximated using the difference between the average and minimum elevation of the delineated ELJ and multiplying by the delineated area.

4. Discussion

4.1 Data Analysis

4.1.1. Sediment analysis

Based on a difference in DEMs (DoD), there are notable areas of aggradation and erosion along the Poudre at the ELC, specifically in areas dominated by wood. This suggests large wood is effective at increasing local sediment dynamics (Montgomery et al., 2003, Grabowski et al., 2019, Osei et al., 2015) and addresses my first objective. Erosion occurs along the outer bend of the flow path and deposition along the inside curve which results in an emergent bar near cross section 7 and 8. Additionally, aggradation occurs on the downstream lateral bar. Given the altered sediment dynamics in the watershed due to urbanization and hydrologic regulation, initiating bank erosion in low-risk zones can be beneficial and not seen as a project failure. This approach compensates for the sediment deficiency caused by upstream dams (Walsh, 2005, Gurnell, 2007, Vietz et al., 2016). The northern floodplain lost over half a meter of sediment at certain locations in a fashion resembling a head cut, due to a combination of wood placement, bare earth, and high flows occurring immediately after construction. While this head cut is not preferred, it does create several locations of energy dissipation within the floodplain as opposed to within the mainstem. These head cuts have also been halted by the floodplain spanning boulder riffle installed during construction. The overall fining in the channel is assumed to be due to the loss of fine sediment on the floodplain, as demonstrated by the pebble count. Confirmation of this would require particle tracing or sediment transport modeling. Increased fining in the upstream reach also shows that velocities have been reduced compared to previous years, likely due to the increased floodplain conveyance, relieving shear stress from the main stem. Additionally, the upstream pebble count

was collected below a plunge pool which will naturally have fine sediment deposition (Thompson, 2018). Cross-sections A, B, and C show aggradation throughout the summer. Most aggradation was measured during April and July surveys likely because sediment dropped out at the tail end of the peak flow in June, settling behind ELJs.

4.1.2 Large wood change

Large wood jam faces placed in areas exposed to unobstructed flow demonstrated a net decrease in volume and increased porosity, addressing my third objective. In contrast, ELJs that were partially sheltered or to the side of the main flow demonstrated a net gain of material and decreased porosity. This shows a threshold below which there is insufficient velocity for transport and above which there is sediment/wood loss due to high velocities. Something to consider is that the delineation of wood accumulated at the front end is difficult to separate from sediment accumulation as there is a layering of wood and sediment. Values do not measure only the change in wood but also the change in sediment. This is because the changes in sediment can obfuscate the changes in wood as it covers the newly accumulated wood or fills in the gaps between newly accumulated wood. Hence, wood volume analysis cannot be separated from sediment. ELJ 3 was an anomaly in categorization because there was reduced porosity and increased volume, demonstrating accumulation as well as pore packing (Figure 15). This is likely due to the placement of the ELJs with respect to other structures and flow paths. In Figure 16, ELJ 3 is sheltered from flow by ELJ 1, 2 and 4. While the flow impacts from ELJ 2 do push velocities towards 3, velocities move along the south side of the ELJs and not towards the front face, which allows sediment and debris to drop out. I expected that the dropping of sediment and wood at this structure would increase volume, but there was a net decrease. Considering the change in volume was one percent, this indicates that smaller debris was likely lodged in microhabitats, decreasing

porosity while not significantly shifting the volume. This, paired with the likelihood of sediment loss at lower flows, could result in a small net volume loss. There is little literature about how placing large wood structures in series affects sediment and debris transport. Addy and Wilkinson (2016) identified and measured areas of erosion and deposition along a gravel bed island where several ELJs had been placed in series. These areas aggraded no more than 1 meter and eroded no more than 0.6 meters. While the difference of DEM's is useful, there is little mention of how relative structure placement impacts geomorphic change.

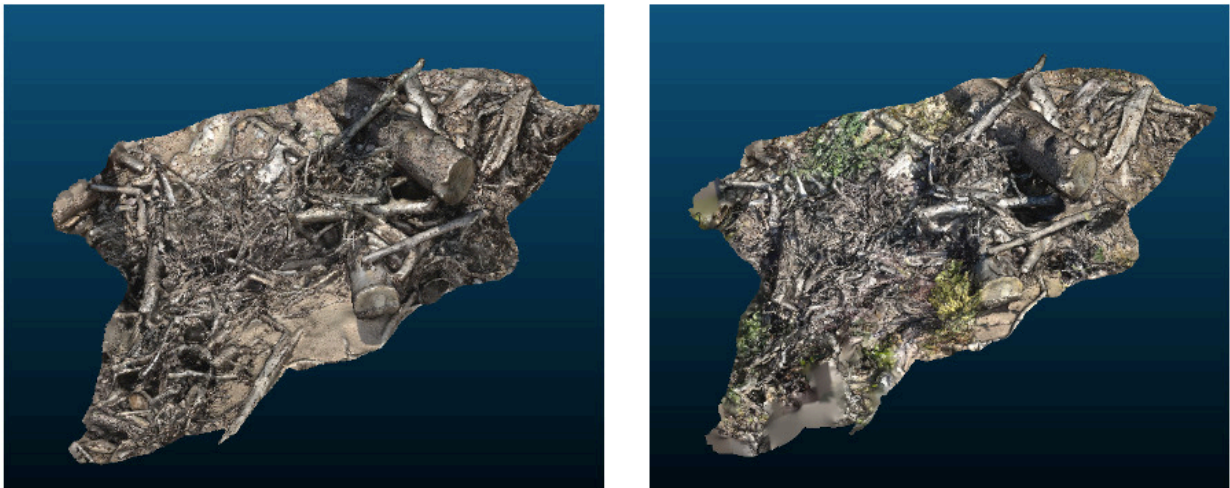


Figure 15. Left. SfM rendering of the front face of ELJ 3 in July 2023. Right: SfM rendering of the front face of ELJ 3 in October 2023. Changes in small woody debris and vegetation presence as it affects volume and porosity calculations.

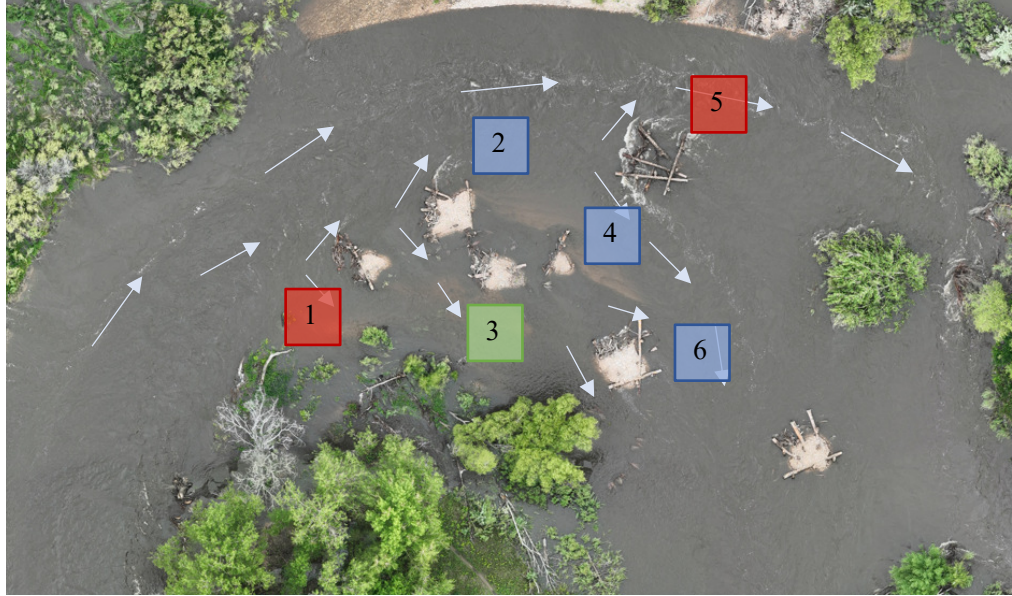


Figure 16. Predicted flow vectors (light blue arrows) at peak flow in response to placement of large wood in the channel. Structures with red outlines indicate a net loss of material due to placement in the flow field, structures with a blue outline indicate a net gain of material with increased packing, while structures with green outlines indicate increased packing and a minimal net loss of volume.

Due to the lack of as-built volume and porosity data it is difficult to ascertain how these structures changed between April and June. These ELJs had void space filled with fine sediment during construction, so total wood volume in each structure would have required data acquisition during implementation. Porosity is commonly calculated using visual assessments, which have been shown to correlate within less than 10 percent error compared to SfM calculations and found to be around 66 percent accurate for most experiments (Spreitzer et al., 2020, Marshall et al., 2024). While porosity analysis with a trained eye can be reliable, using a method void of personal bias allows for reliable and repeatable processes regardless of field experience. Aerial analysis of wood shows an increase in total wood on site, omitting the effects of porosity from ELJs. It is important to note that the resolution of aerial imagery impacts the definition of the delineation. Externally sourced wood accumulation can be identified at the upstream riffle by comparing as-built conditions, aerial imagery, and game camera imagery (Figure 17). Without the implementation of

the riffle, key log pieces may have been transported downstream and been unable to further accumulate wood (Blauch and Jefferson, 2019).



Figure 17. Imagery of flows where wood transport can be identified and was captured by the upstream riffle.

4.1.3 Geomorphic units

There was net sediment accumulation throughout the site, as indicated by the emergence of gravel bars and net aggradation at cross sections throughout the reach. A 323% (569 to 2,407 patches per 100 ha) increase in patch density across the full site means greater complexity of geomorphic units for various biological and hydrologic processes inside and outside the active channel, addressing my second objective. Considering the large increase in LPI and PD from as-built to post-restoration values, shifts in these metrics are likely to continue increasing even if the rate of change decreases (Randle et al., 2015). A feature not weighted in the analysis is the beneficial quality of individual geomorphic units. When discussing river restoration and floodplain reconnection goals, having a large floodplain area is notably better than a terrace. This sort of hierarchy is omitted from the quantitative conversation. There are many methods that can be applied to convert qualitative hierarchies to a quantitative analysis (Martin et al., 2020). Implementing a ranking system of preferred geomorphic units prior to delineation and then weighting the values accordingly could be a more accurate metric of project success. For example, in this scenario, increasing terrace area is not a project goal, but increasing floodplain area is, terraces would be scored with a one and

floodplains with a two. Using the scores as normalized multipliers, patch density would increase based on the number of preferential geomorphic units making practitioners choose which metrics are prioritized.

Most geomorphic unit indices did not greatly change from pre-restoration to post-restoration conditions, addressing my fifth objective. This could be due to many reasons, hypothesized factors include:

1. The need for quantitative definitions of geomorphic units to consistently delineate areas (Jowett, 1993),
2. The metrics analyzed are not appropriate descriptions of site dynamics (Poole et al., 2007),
3. That work done on-site was not enough to make significant changes (Cockerill and Anderson, 2014), or
4. Prior to construction, the site had reached maximum diversity for specific indices due to limits on hydrologic and sediment processes (Bernhardt and Palmer, 2007).

Iskin and Wohl (2023) selected several rivers with low human impact but varied characteristics. They calculated patch heterogeneity metrics for each site to better understand how these metrics correspond to different systems. Rivers analyzed in Iskin and Wohl (2023) have a higher aggregation index and SEI compared to the ELC. Adjacency index is higher at the ELC as is the patch density in the active channel. IJI and patch density are approximately equal to non-urbanized locations. Patch density values are higher in the active channel due to the smaller analyzed area; because of this, I will focus on values for the entire site. While patch density values are similar to those reported in Iskin and Wohl (2023), the numbers are higher than those bounding the hydrologic and planform regime analysis. Comparing the ELC with the other measured sites, the values exceeded all patch density planform ranges as described by Iskin and Wohl (2023). IJI

results were in the straight or beaver planform range prior to construction, while as-built and post-restoration values were more in line with a braided or meandering planform. SEI values prior to construction were aligned with the beaver meadow planform, and post run-off values were closer in range to either the beaver or straight planform.

4.1.3.1 Restoration Practice

The fourth objective aimed to compare the results of different restoration techniques on the active channel and such results varied. Upstream had a greater aggradation index, adjacency, and IJI, while downstream patch density and Shannon evenness were higher. The downstream reach shows greater sediment transport and notable increases in patch density and evenness metrics. The two reaches cannot be held entirely separate. Still, they can be viewed outside of the spatial attachment by understanding that shifts in sediment transport would occur regardless of whether the two reaches were linked. The combination of changes between the upstream and downstream geomorphic unit indices and sediment budget show that in-channel wood has a significant effect on increasing geomorphic unit diversity and instigating geomorphic change as seen in Anlanger et al., 2021 where flow and morphological diversity significantly increases. Kail et al. (2007) note that large hard-engineered structures show fewer natural channel features, but of the projects, the majority showed rapid improvement in the hydromorphological status of sites. The ELC case study shows that adding large wood structures to the channel increases sediment dynamics and patch density, correlated with increased geomorphic complexity and floodway resilience. Restoration also successfully entrapped large wood on site, halting large wood transport, which is a primary concern of large-wood restoration critics (Grabowski et al., 2019, Chin et al., 2008, Ruiz – Villaneuva et al., 2016, Wohl and Scott, 2017, Wohl et al., 2016).

4.2 Monitoring Methods

4.2.1 Current Monitoring Methods

Project evaluation should be achieved through the collection of high-quality information, defined as representative data gathered with sufficient replication over an appropriate time and spatial scale relevant to project objectives, emphasizing the importance of obtaining pre-restoration data for setting a baseline (England et al., 2021). As an example, FACStream is a framework for providing a functional assessment of Colorado rivers. The framework provides metrics for health assessments, recommendations for project goal setting, and strategies for reaching project goals (Johnson et al., 2015). Recommendations include obtaining sufficient and appropriate pre-restoration data to set a baseline understanding of the site. Shoredits and Clayton (2013) note that in addition to the impacts of the “urban stream syndrome”, the lack of long-term monitoring documentation impinges on the ability of practitioners to implement new restoration methods successfully. They go on to state that little knowledge of project success criteria can be due to “inadequate project design with no clearly stated or quantified goals, a lack of funding for subsequent monitoring programs, or reluctance to disclose failures”.

While most studies focus on vegetative and biotic indices, the foundation of monitoring multiple points in time to assess change is applicable to geomorphic metrics. Pess et al. (2005) state that monitoring needs to come from a clear hypothesis of outcomes. They outline a step-by-step program including 1) identifying project objectives, 2) developing project hypothesis, 3) formulating the experimental design, 4) selecting physical/biological parameters, 5) selecting appropriate spatial scales to monitor, 6) determining monitoring frequency and duration, and 7) analyze and report. They also provide several examples of appropriate biological and physical parameters to measure. Of the physical parameters, some include channel and floodplain

morphology, sediment and wood storage, surface and subsurface flows, and spatial composition of vegetation. Weber et al. (2018) developed programmatic monitoring and evaluation (ProME), which is a system for coordination and standardization of surveys with systematic cross-project comparisons. This includes a series of principles and goals that aim to account for complexity, uncertainty and long-term change, support collaborative learning and adaptation, verify to what extent restoration has been achieved, and identify why the effects occurred. Roni et al. (2019) evaluate several programmatic monitoring techniques, including before and after, extensive post-treatment, intensively monitored watersheds, and programmatic approaches. The study shows that the best option is dependent on the questions looking to be addressed, the scale of inference, and the spatial-temporal scale where response is expected. For the assessment of the ELC, remote sensing techniques are recommended. Similar to previous papers, monitoring for physical or biological parameters is recommended. Some physical parameters include channel and floodplain morphology, meso-habitats, large wood, sediment, flow, and water quality. They emphasize that the best monitoring method is one that addresses project goals. Notably, there is not one way that any of the above literature suggests monitoring floodplain restoration. Each of them points to the fact that since each project is different and likely have different objectives, applying one method would be ineffective and costly.

4.2.2 Implications for Monitoring

Determining the success of projects with broad objectives can be challenging. This exposes a common issue in restoration efforts: goals lack specificity regarding who benefits, what changes are expected, and when they are expected to occur. Utilizing measurable indices alongside quantifiable changes within set timeframes offers valuable insights into restoration efficacy.

I recommend using an amalgamation of suggested practices where indices evaluated should align with project objectives determined by stakeholders and practitioners. To ensure effective monitoring, it is essential to establish monitoring protocols prior to design and allocate adequate resources to the project budget (Bernhardt et al., 2007, Kondolf et al., 2007, Bernhardt et al., 2005, Roni et al., 2019, Pess et al., 2005). Monitoring should prioritize quantifying project goals and include pre-restoration data for comparison. Studies note the importance of obtaining pre-restoration data that includes parameters that will be used to monitor the outcome (England et al., 2021, Weber et al., 2018, Roni et al., 2019). Suggested monitoring techniques for projects with an objective towards increased geomorphic complexity and biodiversity should acquire detailed topographic/bathymetric and orthomosaic data, and iPad LiDAR of large wood structures if applicable. This level of detail should be acquired immediately post-construction and subsequently conducted based on reoccurrence intervals to capture the dynamic nature of restoration outcomes. Geomorphic unit delineation as a monitoring technique has conflicting results as many of the metrics measured did not greatly change at this spatial and temporal time scale. Considering the remote nature of the analysis, the project area should not greatly impact the level of detail but will impact the level of post-processing effort.

It is equally important to recognize the constraints around placing quantitative goals on PBR projects by assigning a metric of success. Restoration can lead to various outcomes, some of which may seem like failures. For example, rivers that adjust laterally, widen, or erode might be perceived as failing, but in reality, they are readjusting and managing new inputs, similar to how a body maintains homeostasis. When scientists and practitioners communicate openly with the public, projects can be implemented that support process-based restoration, even if they may look messy and unappealing. This approach aligns project goals and objectives more closely with those

outlined by Palmer et al. (2005), which describe guiding principles for an ecologically successful restoration; 1) project should be based on guiding image of dynamic healthy rivers that are site specific, 2) the ecological condition must be measurably improved, 3) the system must increase in resilience for minimal adaptive management, 4) construction should not inflict lasting harm, and 5) project metrics before and after construction must be completed and shared with the public.

4.3 Policy

As noted previously, there is apprehension around placing large wood in urban active channels due to concerns of damage to downstream infrastructure. While endless studies demonstrate the benefits of large wood in these corridors, public perception and risk have undeniably halted policy from accepting this type of restoration technique. In the case of the ELC, there are two distinct types of large wood structures on the site. The upstream ELJs at the north floodplain are built to mimic natural ELJs. The downstream ELJs resemble something closer to log cabins, this is because in order to be implemented they had to withstand the 100-yr flood. The ELJs are around 240 meters upstream from the nearest bridge and would encounter a multitude of bends and gravel bars before reaching infrastructure. To allow for natural structures at restoration sites and remove the risk to bridges and culverts, Lassetre and Kondolf (2011) recommend creating wood-passible infrastructure. This alternative is demonstrated by a project along the Big Thompson in Colorado, where advocacy by practitioners and compromise by state agencies afforded large wood placement and floodplain connection near bridges (deRosset, 2024).

Even if large wood implementation was separate from process-based restoration, policy makes enacting these techniques in urban settings difficult. As water is brought onto the floodplain, there is a higher percentage of inundation (Bouwes et al., 2016), which has a chance to creep toward houses, businesses, and municipalities, posing a risk to nearby infrastructure. Buildings being

placed right near the river can be traced back to the use of rivers for conveyance and irrigation. Since towns and cities sprung up around these agricultural hubs it limits the abilities of practitioners to implement floodplain restoration. Practitioners can either find river reaches that are not near infrastructure (as is the case at the ELC), purchase the land of the infrastructure at risk, or find other techniques for implementing project goals. Acquiring land near the restoration site is not uncommon; however, there are some socio-political considerations. Commonly low-income and minority communities have homes in and near urban river corridors, specifically in areas that are prone to flooding (Bergemann, 2022, Yale E360, 2020). Therefore, stakeholders need to be mindful when implementing this option so as not to displace already marginalized communities.

Colorado water rights state that holding or diverting water in a project is subject to a water-court case. Since many floodplain restoration projects attenuate some amount of flow or support local groundwater recharge, water rights need to be considered. In 2023 Senate Bill 270 was supposed to provide guidance and amendments on restoration implementation, but lawmakers removed much of the wording that would have addressed large woody debris, floodplain reconnection, and beaver dam analogues (BDA's). This means that division engineers who approve these projects now decide if practitioners need to prove water changes to downstream users (Sackett, 2023). Sackett (2023) describes a floodplain restoration project within Colorado where 13 BDA's were proposed and denied by the division engineer because increased ponding would allow for increased evaporation and negatively impact downstream users. While it's important to consider the impact on downstream water users, the goal of process-based restoration is to create a system that sustains and regulates itself. However, natural regulation doesn't always align with human needs.

Additionally, most Colorado rivers are regulated, which raises questions about the effectiveness of process-based restoration when nearby dams restrict flow, sediment, and wood transport.

5. Conclusion

River restoration practices are evolving towards a process-based framework. This can be seen throughout the United States and Europe. Colorado's applications of this technique focus on rural or mountainous locations with a low risk of flooding and infrastructure damage. However, this framework is essential to apply in urban corridors as urbanization continues to degrade rivers. Assessment of the restoration indicate that site-wide cross-sectional analysis shows net sediment accumulation on site, mitigating the head cut. DEM comparison between as-built and post-restoration data show that large wood structures used in restoration promote geomorphic complexity and dynamic sediment transport. ELJ results varied as placement within the channel and with respect to other structures appeared to be a primary indicator of front-end sediment and wood accumulation. Constructed and emergent geomorphic structures captured wood throughout the site limiting downstream transport. Geomorphic units delineated through aerial imagery and DEMs between pre-restoration, as-built, and post-restoration data measured changes in geomorphic complexity. Analysis of the heterogeneity metrics shows that certain indices are increased while the majority remained the same, indicating insufficient evidence for using this technique as a means of urban restoration monitoring. This analysis demonstrates the need for increased pre-restoration data and long-term monitoring, without which there will be little data to support the implementation of novel restoration projects. Demonstrating to policymakers that adding wood to the site did not cause downstream infrastructure damage and did not increase dangerous flooding will pave the way for future projects.

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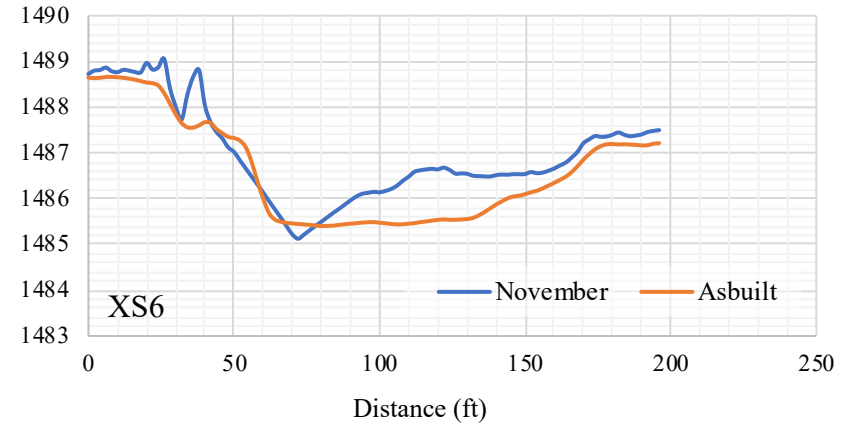
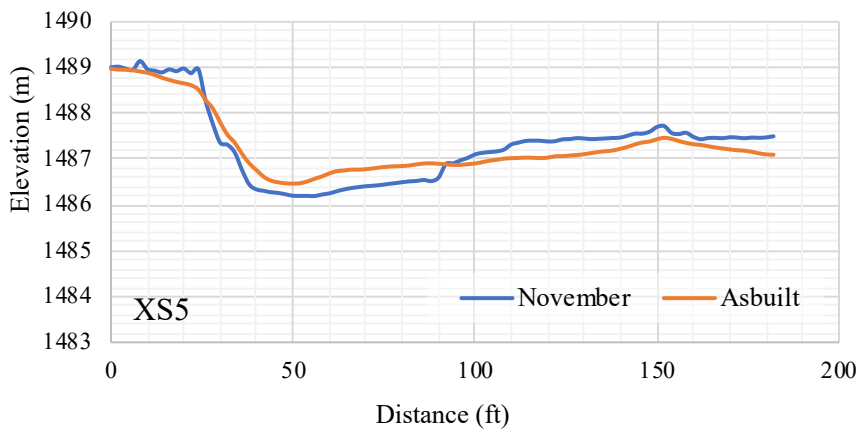
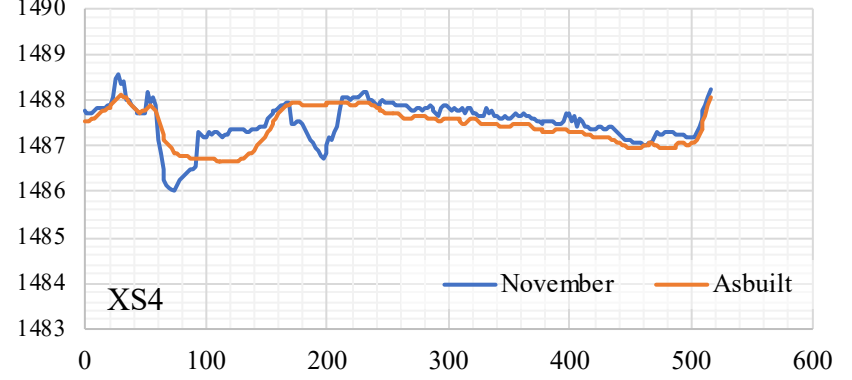
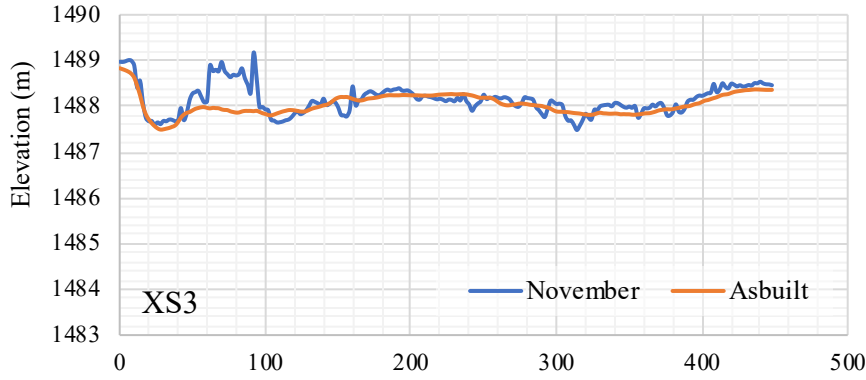
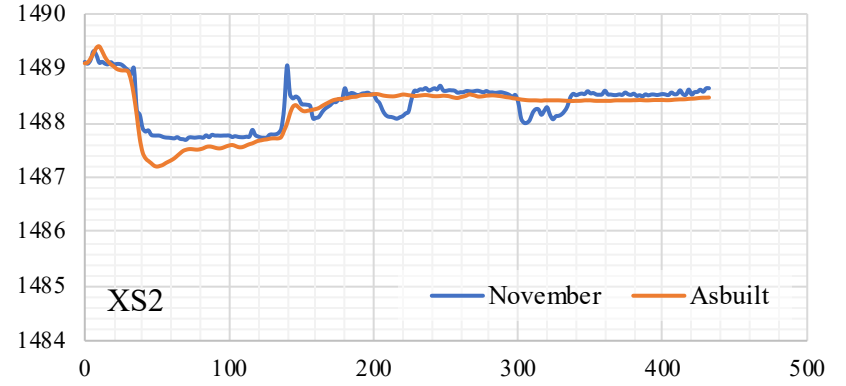
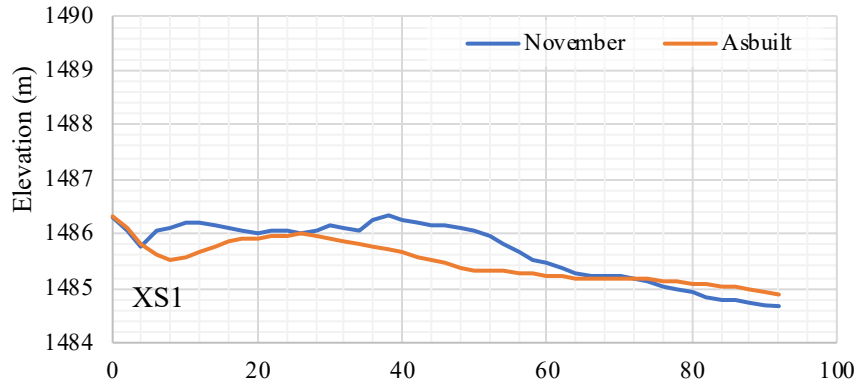
Appendices

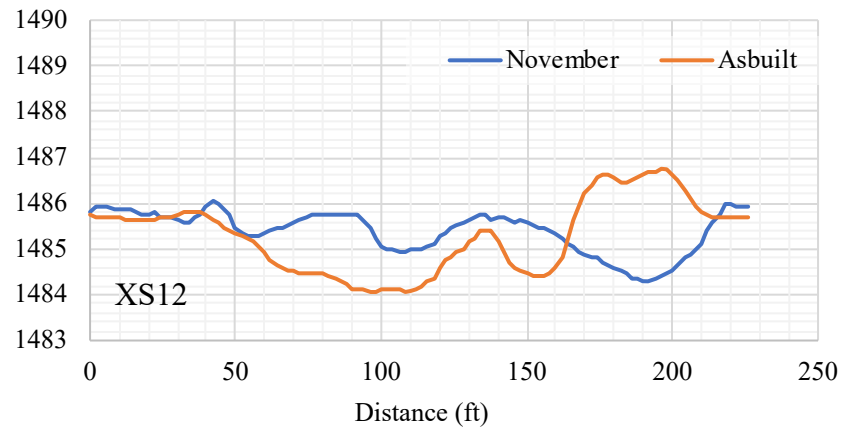
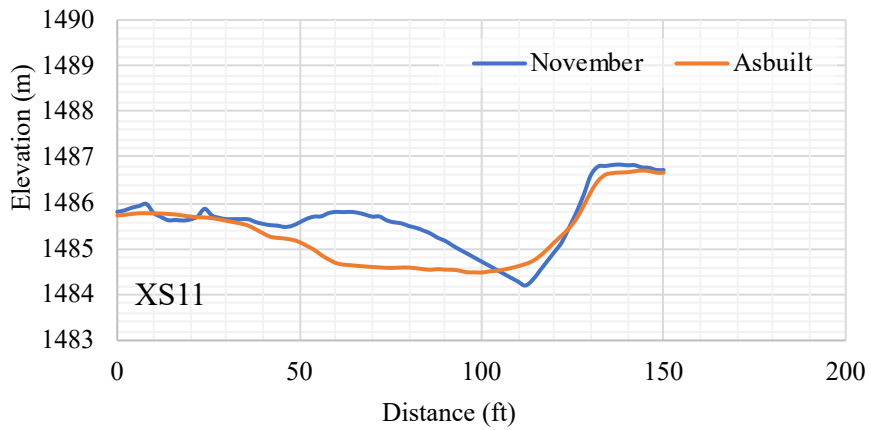
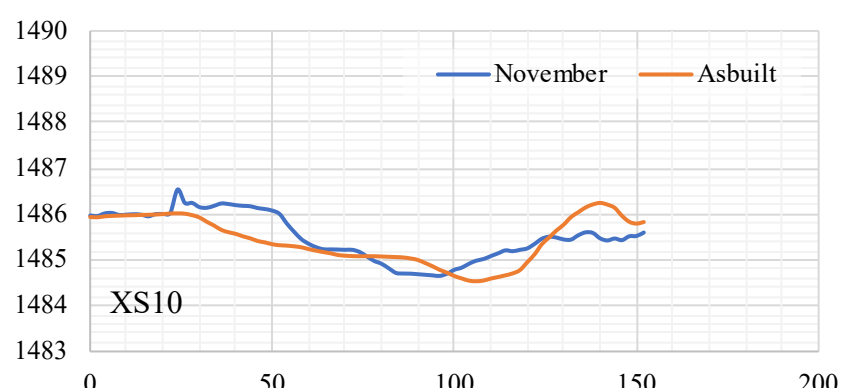
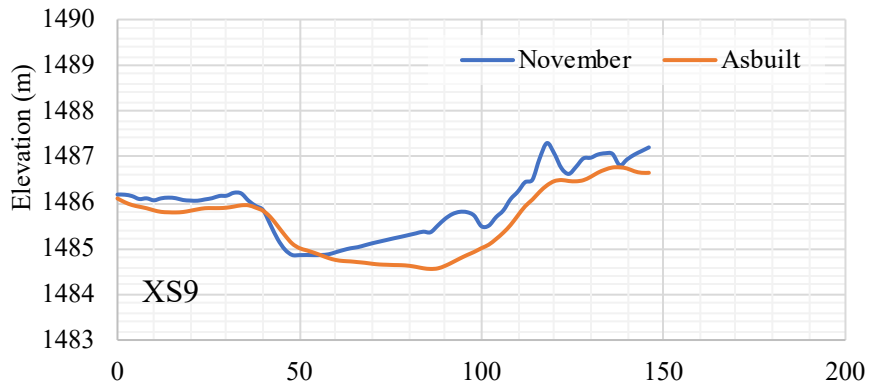
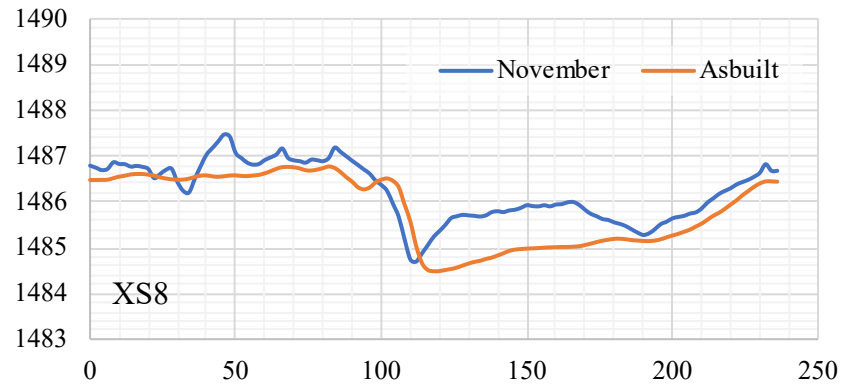
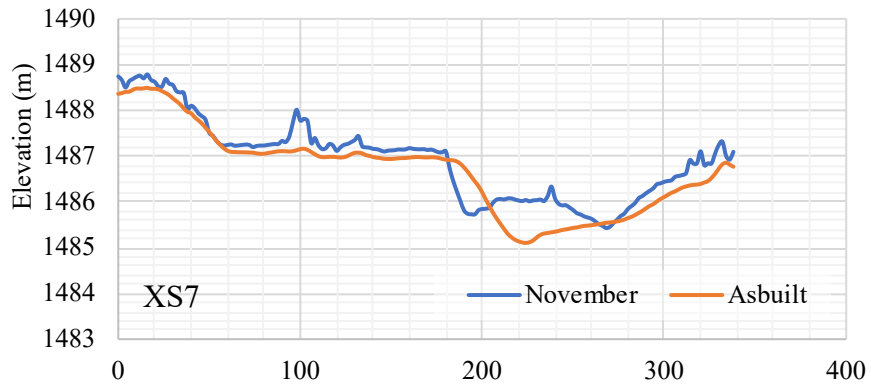
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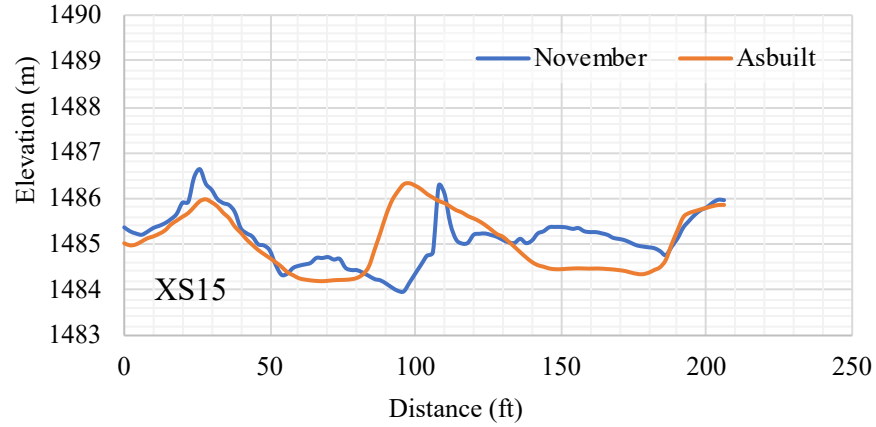
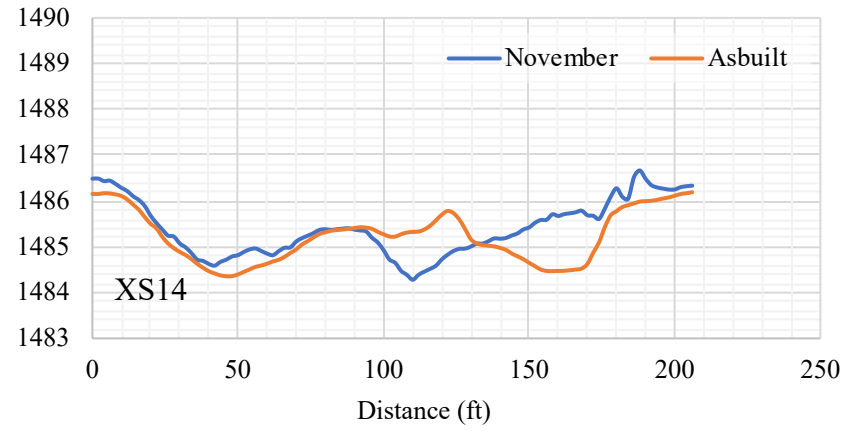
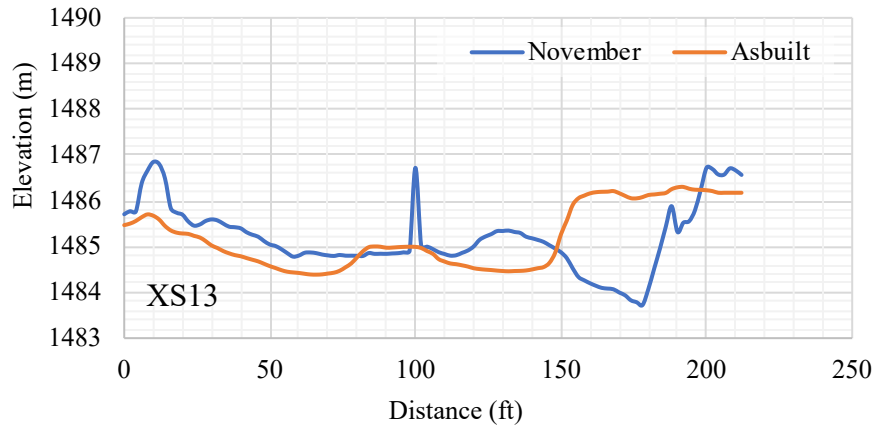
Brief overview of Over et al values from Table 1.

Image setup and alignment		
GPS offset lever arm	0.1/-0.15/1.25	meters
Camera Accuracy	0.1/0.15	meters
Tie point accuracy	1	pixels
Add ground control points (optional)		
Marker Accuracy	0.02/0.03	meters
Image coordinate accuracy	0.5	pixels
Error reduction and bundle adjustment		
Tie point accuracy	0.1-0.3	pixels
Export and File Naming		
Resolution size	0.25	meters

Appendix B

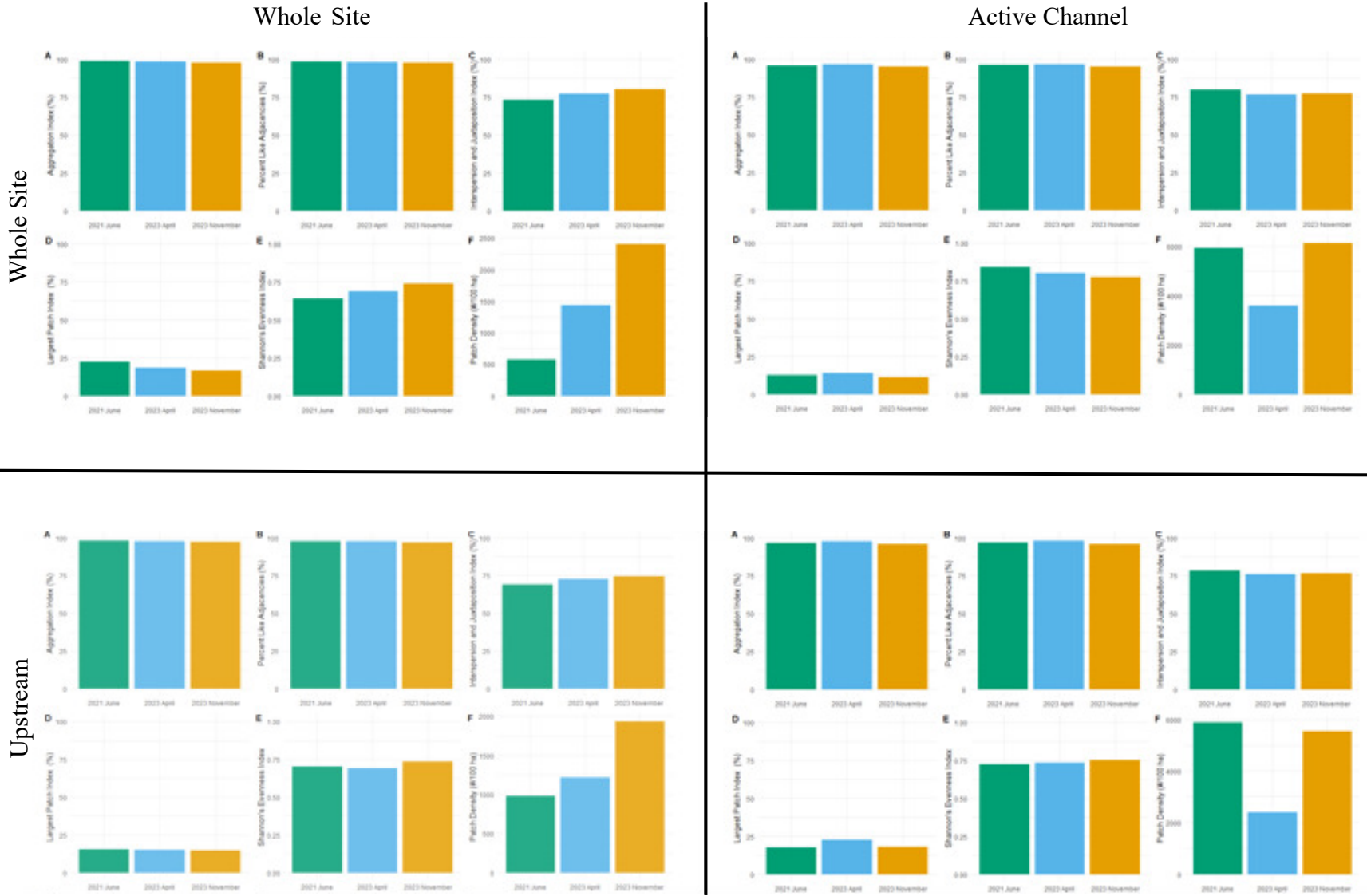






Cross Section	April – January (m ²)	April – January (m ³)
1	9.47	1.74
2	9.64	2.45
3	13.79	2.98
4	15.91	-1.12
5	1.51	-1.35
6	23.32	4.29
7	24.78	3.00
8	28.79	5.93
9	16.08	2.43
10	3.76	2.02
11	14.20	3.93
12	7.76	2.11
13	-0.85	-2.35
14	10.58	1.71
15	3.76	0.06

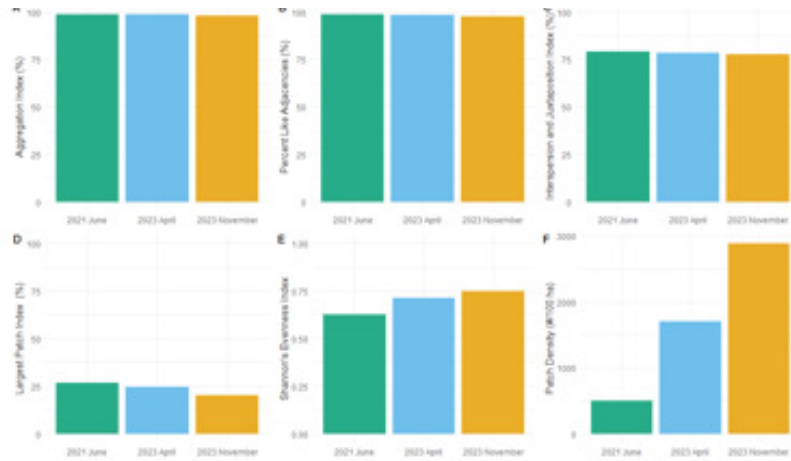
Appendix C



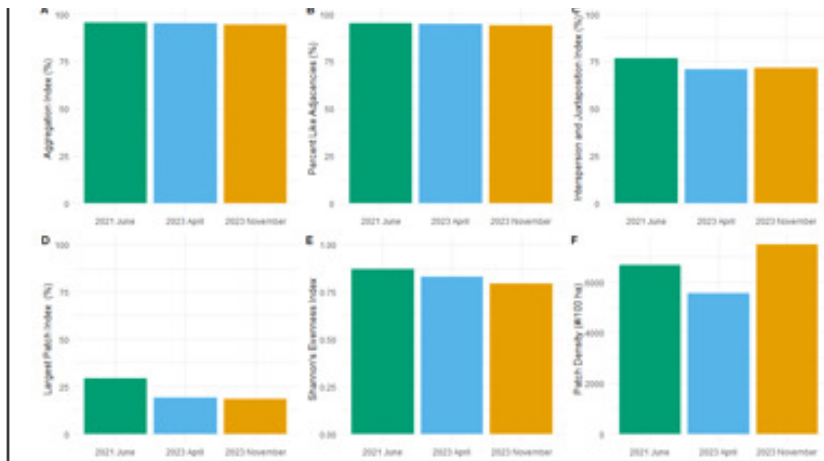
Note: Graphs within each portion go from top left to bottom right: Aggregation Index (%), Percent Like Adjacencies (%), Interspersion and Juxtapositions (%), Largest Patch Index (%), Shannon Evenness Index (%), and Patch Density (#/100 ha)

Downstream

Whole Site



Active Channel



Note: Graphs within each portion: (top left) Aggregation Index (%), Percent Like Adjacencies (%), Interspersion and Juxtapositions (%), (bottom left) Largest Patch Index (%), Shannon Evenness Index (%), and Patch Density (#/100ha)

Appendix D

Table of ELJ porosity metrics as calculated by Spreitzer et al. (2020), using a conservative correction factor of 0.5.

Metric	Month	ELJ 1	ELJ 2	ELJ 3	ELJ 4	ELJ 5	ELJ 6
V _{2.5D}	July	0.15	3.04	3.42	1.13	3.48	12.62
	October	0.05	4.00	3.38	2.08	1.53	14.76
V _{3D}	July	5.89	7.55	3.35	1.92	11.11	16.37
	October	7.30	7.84	3.22	3.16	14.58	18.7
V _{vo}	July	5.74	4.51	-0.07	0.79	7.63	3.75
	October	7.24	3.84	-0.17	1.08	13.05	3.97
PA	July	2.56	40.26	102.18	59.05	31.33	77.10
	October	0.75	51.00	105.16	65.69	10.48	78.82
PD	July	97.44	59.74	-2.18	40.95	68.67	22.90
	October	99.25	49.00	-5.16	34.31	89.52	21.18
Phi	July	98.72	79.87	48.91	70.48	84.34	61.45
	October	99.63	74.50	47.42	67.15	94.76	60.59

Appendix E

Table of values used to obtain and analyze ELJ volume metrics

2.5D	ELJ	1		2		3		4		5		6	
	Month	October	July	October	July	October	July	October	July	October	July	October	July
	Base level constant	-3.2		-3.3		0.5		-0.4		-4.6		0.3	
	Volume	7.30	5.89	7.84	7.55	3.22	3.35	3.16	1.92	14.58	11.11	18.72	16.37
	Surface	5.01	3.31	6.41	5.92	2.37	2.46	1.90	1.59	7.52	6.15	7.26	6.56
	Added Volume	7.30	5.89	7.84	7.55	3.22	3.35	3.16	1.96	4.58	1.11	8.72	6.37
	Subtracted Volume	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
3D	ELJ	1		2		3		4		5		6	
	Month	October	July	October	July	October	July	October	July	October	July	October	July
	Volume	0.05	0.15	4.00	3.04	3.38	3.42	2.08	1.13	1.53	3.48	14.76	12.62