March 27, 2024

To: Andrea Harbin Monahan, Colorado Water Conservation Board (CWCB)

From: The Watershed Center (formerly Lefthand Watershed Oversight Group)

RE: CWCB Watershed Restoration Grant – Adaptive Restoration & Upland Stewardship – Final Report (POGG1, PDAA, 2019-2772)

The purpose of this memo is to provide a final report on activities related to The Watershed Center's Adaptive Management and Planning project. The project timeline is 03/27/2019 – 03/27/2024 and the total project budget is currently $1,904,692 with $146,934 from the CWCB Watershed Restoration Grant.

1. Project Summary and How the Project Was Completed

Over the last five years, Adaptive Restoration and Upland Stewardship has been foundational to building regional knowledge and support for climate adapted restoration practices that increase geomorphic complexity and ecological function in transition zones of Front Range Watersheds. This project also supported establishment of the St. Vrain Forest Health Partnership, a collaborative of diverse stakeholders and community members preparing the landscape and community to receive wildland fire as a natural part of the ecosystem across the St. Vrain Watershed.

Through this project, The Watershed Center achieved two main project goals: 1. identify specific watershed restoration practices or treatments which lead to the highest functioning sites, and 2. Improve upland watershed stewardship through new partnerships, forest planning, outreach, and implementation efforts in the St. Vrain Watershed. In the sections to follow, we summarize obstacles encountered and solutions throughout the project as well as deliverables and associated accomplishments.

2. Obstacles Encountered and Solutions

Throughout this project, we faced key obstacles that changed our project approach. These obstacles and resulting solutions are described in the table below.

Obstacle Encountered	Solution
Experimental set up	We intended for many of our monitoring topics to compare data between two projects using different restoration approaches. We found that some of our original topics were not feasible during project implementation and that some topics would best be suited for the geomorphically complex site only. In order to do site-to-site comparisons, we had to incorporate monitoring design into the restoration designs. During implementation, we learned that the hard rocky soils limited our ability to establish deep ground monitoring wells and we were not able to collect water table data. Additionally, we found that some of our monitoring questions were more appropriate for testing distinct features across the geomorphically complex site. As a result, some of our monitoring only occurred across one site and others compared the two. By doing so, we were able to evaluate different climate adapted features and make recommendations for inclusion of different features.
Monitoring Methods	Across all our monitoring categories, our methods for evaluating floodplain connectivity were particularly challenging. Each monitoring year, we collected drone imagery and intended to develop Relative Elevation Models (REM) each year to evaluate connectivity changes over time. During post-processing, we discovered some REM outputs were inaccurate and not comparable to other years due to environmental variables like weather and sunlight during drone flights. As such, we had to omit some from our analysis. In response to this, we developed a protocol for standardizing drone flights with considerations for these variables that can be used by others and on our future projects.
Student Monitoring	We partnered with various CU and School of Mines classes to help collect and analyze our monitoring data. Despite the great engagement and learning opportunity, we often had to re-analyze and re-interpret our data as well as re-enter. In the future, we will continue to partner with focused researchers, but will not rely as heavily on undergraduate classes for more specialized topics. Some topics they were more helpful with included benthic macroinvertebrates and canopy cover. We do not recommend using classes to help develop new methods or collect and

	analyze more complicated datasets such as drone imagery, fisheries underwater camera monitoring, or pool sediment monitoring.
Scale of the landscape	Despite the Partnership's strong community roots and exemplary record of collaboration, engaging all relevant stakeholders and community members across the immense 625,000-acre landscape presents a challenge, especially with local fire districts which are generally resource- and time-limited. To address this challenge, the Partnership divided the landscape into sub-geographies and hosted collaborative operational meetings focused on these smaller geographic boundaries to ensure project prioritization and planning is realistic and supported by local fire districts and community members. This is a model that future collaboratives can adopt to address broad landscape scale planning.
Biomass removal	A barrier to conducting forest management in Boulder County is the difficulty of removing fuels after restoration. This is because of a combination of factors including unmerchantable timber (wood products cannot be sold here due to their quality and lack of local mills) and operability of the terrain. To address this limitation, we are taking part in working groups that discuss and move forward alternative solutions such as biochar. We believe biochar could be a viable solution, and ee recommend other collaboratives facing similar biomass removal challenges to explore alternative and innovative methods.
Implementation funding	On-the-shelf projects identified through this effort will require significant funding for implementation across the broad landscape. Acquiring sufficient implementation funding presents a challenge due to limited resources among funders. To address this challenge, the Partnership is leveraging the USFS's upcoming National Environmental Policy Act (NEPA) process which will start in the St. Vrain Watershed in the next year. Following completion of the NEPA process, USFS is expecting to receive federal funding for implementation of projects that mitigate wildfire risk, improve water quality, and increase fire resilience of ecosystems on public and private lands. Aligning the Partnership's efforts with this NEPA process helps ensure the Partnership is prepared to leverage USFS funds for implementation when they become available.

3. Deliverables and Accomplishments

In order to achieve our project goals of 1. Identify specific watershed restoration practices or treatments which lead to the highest functioning sites, and 2. Improve upland watershed stewardship through new partnerships, forest planning, outreach, and implementation efforts in the St. Vrain Watershed, key accomplishments are described for each deliverable by task in the table below.

Deliverable	Accomplishments
Task 1 – Adaptive Restoration	
Geomorphic and Ecological Responses of Climate Adapted Restoration Report (final reports)	- This Report captures all research and monitoring reports of geomorphic complexity and ecological function to support the evaluation of the hypothesis: restoration efforts incorporating a greater variety of features yield superior geomorphic and ecological advantages compared to traditionally restored sites with less complexity. Research and monitoring topics include: Diversity of Physical Features, Floodplain Connectivity, Pool Sediment Deposition, Vegetative Bench Complexity, Vegetation Canopy Complexity, Benthic Macroinvertebrates, Northern Redbelly Dace Reintroduction. - In order to engage a broader audience of both stakeholders and practitioners, the report is formatted as a highlights summary of all research and monitoring topics with associated links to technical reports and further investigation. - Research and monitoring was supported by eight different CU Boulder faculty and researchers and two undergraduate classes. - Research was shared out to a range of community, regional, and state audiences in an effort to build regional knowledge and support for climate adapted restoration practices that increase geomorphic complexity and ecological function in transition zones of Front Range Watersheds. Outreach included the High Altitude Revegetation – Society for Ecological Restoration (Rocky Mountains Chapter) conference in fall 2022, Sustaining Colorado Watersheds Conference in fall 2023, and The Watershed Center's March 2024 newsletter. - Monitoring also informed stewardship needs and resulted in 115 native plantings, 2 acres of seeding, and 5.5 acres of spot spraying noxious weeds in 2021 and 2022.

Task 2 – Upland Watershed Stewardship	
- St. Vrain Forest Health Partnership Guidelines for Projects (final report) - **Desired Conditions Visuals** - **Outreach Tool** - **Adaptive Management Map**	- Establishment of the St. Vrain Forest Health Partnership, a collaborative of more than 30 diverse stakeholder groups working with community members to collaboratively plan and implement cross-jurisdictional forest management, conduct adaptive management, integrate the best available science into management planning, and conduct meaningful community engagement. The Watershed Center is the lead coordinating entity of this Partnership. - Final report provides comprehensive guidance for forest management (stewardship) goals such as guidelines to support project managers in developing project-scale desired future conditions. This guidance is intended to be used in planning and project development across the St. Vrain Watershed. - Associated outreach included three workshops to discuss desired conditions and develop Desired Conditions Visuals and Outreach Tool followed by 16 community outreach events. Staff also participated on multiple regional planning meetings with other upland forest planning collaborative including Northern Colorado Fireshed, Boulder Fireshed, and Front Range Round Table to ensure complementary planning in the St. Vrain Watershed. - The prioritization process for identifying forest health priority areas included nine community meetings and partner meetings. Priority forest management areas are shown in the Adaptive Management Map.

4. Confirmation of Matching Commitments

Below we provide a confirmation that all matching commitments have been fulfilled.

	Funding Source	Income	Expense	Status
Task 1 – Adaptive Restoration Experiments	DOLA CDBG-DR Legacy Grant	$1,750,000.00	$1,750,000.00	Complete as of May 2020
Task 2 – Upland Watershed Stewardship	DOLA CDBG-DR Capacity Grant	$7,757.00	$7,757.00	Complete as of July 2019

5. Summary of Key Deliverables

Task 1 – Adaptive Restoration

- **Geomorphic and Ecological Responses to Climate Adapted Restoration (Final Reports)**: https://watershed.center/wp-content/uploads/2024/03/Climate-Adapted-Restoration_Final-Report.pdf

Task 2 – Upland Watershed Stewardship

- **Desired Conditions**
- **St. Vrain Forest Health Partnership Guidelines for Projects (final report):** https://watershed.center/wp-content/uploads/2024/03/SVFHP-DFC-Guidelines_Final.pdf
  - Desired Conditions Visuals: https://watershed.center/wp-content/uploads/2024/03/All.pdf
  - Outreach Tool: https://watershed.center/wp-content/uploads/2021/09/OutreachTool_V11_HighRes.pdf
  - Adaptive Management Map: https://lhwc.maps.arcgis.com/apps/webappviewer/index.html?id=1abfd13256434b8d902e53e3f6c04d3a

Studying the Geomorphic and Ecological Responses of Climate Adapted Restoration in the Foothills of Left Hand Creek, in Boulder County, Colorado

Developed by:

the Watershed Center

Acknowledgements

The Watershed Center is deeply grateful for the generosity of the **Andreas and Windhausen** families, who warmly welcomed us and our collaborators to their beautiful land. Their willingness to share their properties has been invaluable, allowing our team of engineers, scientists, construction operators, and vegetation crews to carry out restoration work. Moreover, over the past six years, we've had the privilege of hosting numerous partners, university researchers and students, youth outdoor education classes, and local land managers on this land. We extend our heartfelt thanks to the Andreas and Windhausen families for embodying true stewardship of their land and for their unwavering support throughout this endeavor.

We are grateful to the forward-thinking team that designed and constructed this project, including **Biohabitats, Left Hand Excavating, Wright Water Engineers, and GEI Consultants**. We also thank our project partners, including **Boulder County Parks and Open Space, City of Longmont, Colorado Parks and Wildlife, Left Hand Ditch Company, Left Hand Water District, St. Vrain and Left Hand Water Conservancy District**, and **Watershed Science and Design**, who all provided ideas and feedback throughout design and implementation of this project. We thank **Dr. Katie Suding, Dr. Isabel de Silva (Shewell)**, and **Dr. Katherine Lininger** of CU Boulder for their scientific contributions throughout the project, from advising design and construction, to conducting and reporting on years of ecological research.

Our partnership with CU Boulder staff, faculty and students was foundational to completing project monitoring and analysis. Special thank you to **Dr. David Harning** and students in the **Restoration Ecology and Geomorphology Classes** for their data collection and analysis of numerous ecological metrics. Thank you **Dr. Lindsay Chipman, Geoffrey House, Dr. Julia Sobczak,** and **Dr. Sean Streich** for their drone imagery, modeling, and morphological analyses.

This project was a unique opportunity to establish new populations of Colorado Tier-1 aquatic species of special concern, and it fostered a wonderful collaboration between local agencies, schools, and organizations. Special thanks to members of the **Northern Redbelly Dace Project** and **Northern Leopard Frog Headstarting Team, including Boulder County Parks and Open Space, City of Boulder, Colorado Parks and Wildlife, Ocean's First Institute,** and **St. Vrain Valley School District Innovation Center.**

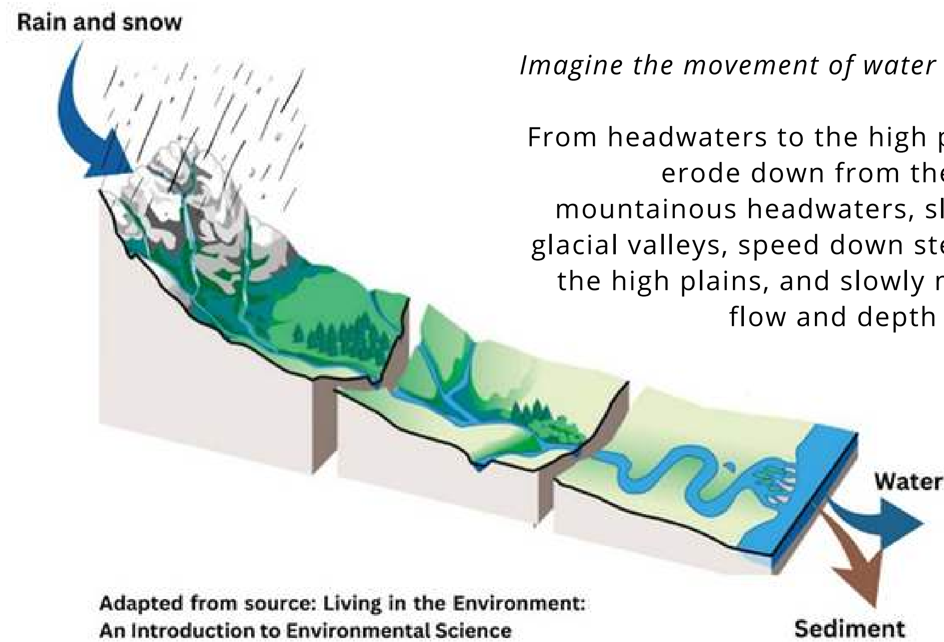
Special thanks to **Lauren Brown Studios** for the illustration of the site (shown on the front cover) and its diverse features. This illustration has been used broadly as a communication and educational tool.

All aspects of the project were funded by **Department of Local Affairs Colorado Development Block Grant** and **Colorado Water Conservation Board**. We sincerely thank these two funding entities for their investment in monitoring and learning from these important projects.






Understanding Resilient Watersheds

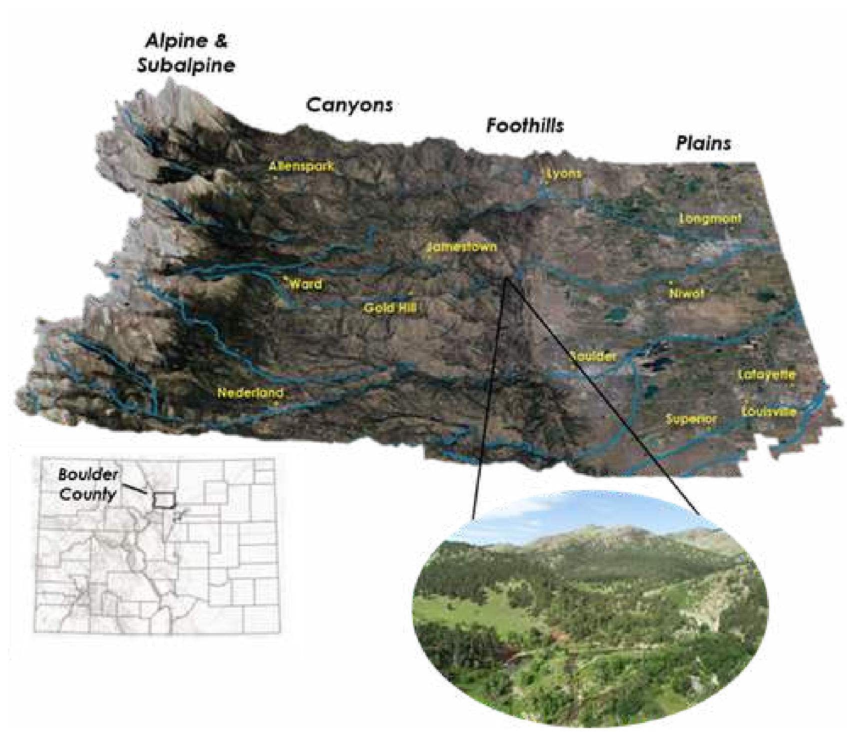


Imagine the movement of water in our Front Range streams.

From headwaters to the high plains, water and sediment erode down from the high alpine, flow through mountainous headwaters, slow and deposit along relic glacial valleys, speed down steep canyons, spill out onto the high plains, and slowly meander on, building more flow and depth with larger rivers to come.

Along this path, rivers have natural checks and balances that transport and deposit water and sediment. Notably, there are **two key depositional areas in Boulder County watersheds** that naturally have broad floodplains and geomorphic complexity:

1. **Relic glacial valleys** where the subalpine transitions to the canyons along Peak to Peak highway
2. **The foothills** where the canyons transition to the plains along Highway 93, near the City of Boulder or north along Highway 36 headed to Lyons



Landscapes with geomorphic complexity are messy, dynamic, and composed of diverse features like varied topography, multiple channels, wetlands, varied instream habitat, and broad floodplains. Combined, these features provide high biodiversity, promote natural watershed processes like sediment deposition, and help buffer impacts from disturbances like floods, drought, and wildfire. **Therefore, enhancing and protecting geomorphic complexity within transition zones can bolster watershed resilience against the effects of climate change and other ecosystem disturbances throughout the Front Range.**

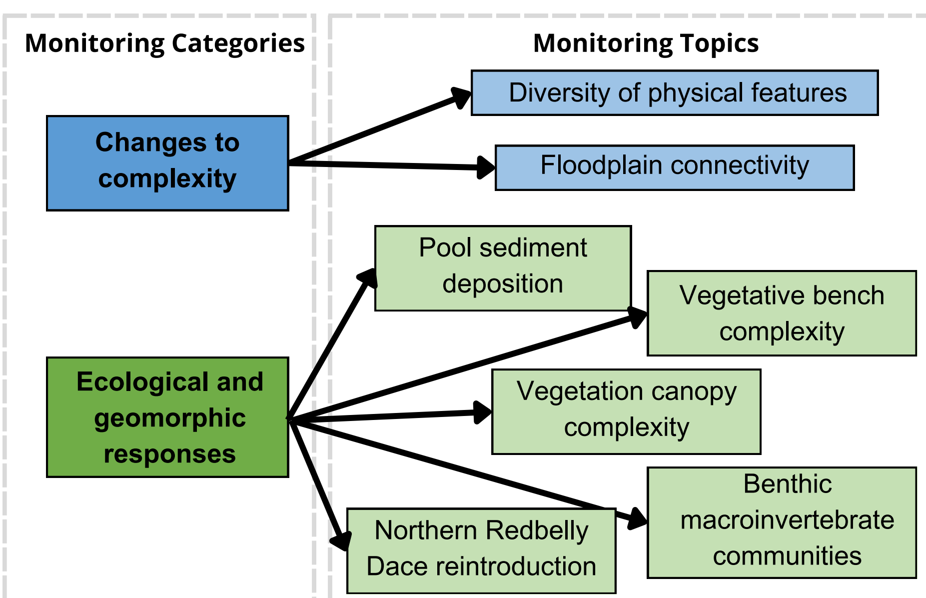
The Project and Experiment

Between 2017 and 2020, The Watershed Center and its team designed and constructed a geomorphically complex river restoration project in the canyon-plains transition zone of Left Hand Canyon (Boulder County, Colorado). This project stands out within the region for its distinctive climate adaptation features, which, in combination, deliver tangible benefits to both the local community and the environment, enhancing resilience to climate change.

In addition to creating important geomorphic complexity, the project was set up as an experiment which aimed to increase knowledge and test a hypothesis: **restoration efforts incorporating a greater variety of features yield superior geomorphic and ecological advantages compared to traditionally restored sites with less complexity.** To investigate this, we divided the project area into two distinct reaches with different restoration approaches, as outlined and described below.

Upstream Reach: geomorphically complex site with a variety of different features, including side channels, beaver mimicry structures, off channel pond, large wood, floodplain roughness.

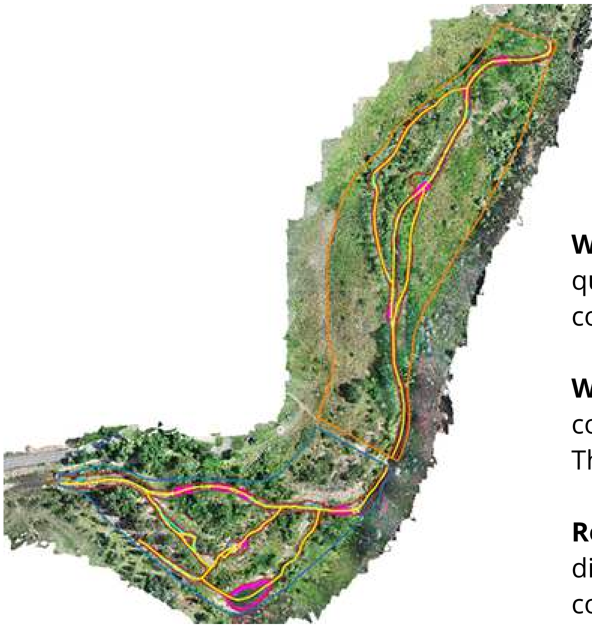
Downstream Reach: traditional restoration site with uniform floodplain grading and limited features.



This figure shows the two monitoring categories and six monitoring topics presented in this report. The team quantified changes to complexity and studied associated ecological and geomorphic responses over time and between sites. ***The following pages summarize key takeaways from each topic shown in the figure*** and share links to more in-depth technical reports.

Evaluation of Changes to Complexity

To quantify changes to complexity, we compared diversity of physical features and floodplain connectivity between the upstream geomophically complex site and the downstream traditional site, as well as changes in these features over time.



Diversity of Physical Features

Creating complexity in the foothills: Restoring a variety of physical features on a floodplain establishes a canvas for improved geomorphic and ecological processes.

What did we do? Remote sensing was used at both sites over time to quantify diversity of physical features at the upstream geomorphically complex site compared to the downstream traditional site.

What did we learn? Over time, we found more variability in feature counts at the upstream site and less variability at the downstream site. This shows the dynamic nature of more complex sites.

Recommendations for future projects: Find opportunities to maximize different restoration features in restoration and utilize remote sensing to conduct project-level evaluation across a shorter timescale.

Read the technical report here!

Floodplain Connectivity

Connecting floodplains and low-tech, novel methods: Drone methods are a flexible option for capturing high resolution changes to floodplain connectivity.

What did we do? Relative elevation models were created using drone imagery to quantify how both sites increased floodplain connection.

What did we learn? Over time, floodplain elevations at the upstream geomorphically complex site increased while the downstream traditional site did not show change. This is likely due to sediment deposition on the floodplain at the upstream site, a key project goal.

Recommendations for future projects: Drone methods, as opposed to aerial LiDAR flights, offer a relatively cheap and extremely flexible option for developing orthomosaic images, DEMs, DTMs, and REMs that can be used for measuring floodplain connectivity as well as a multitude of other metrics. We recommend these methods for project-level evaluation over a shorter timeframe is preferred.

Read the technical report here!

Drone takes off to collect static images

Ecological and Geomorphic Responses

Complexity and connectivity within ecosystems trigger both ecological and geomorphic responses. The transition zone in the foothills plays a pivotal role in our watersheds, fostering diverse habitats and biodiversity. Notably, our findings indicate that, in comparison to other zones within the Left Hand Watershed, the foothills are home to the greatest number of native vegetation species (2022 State of the Watershed). The following topics were evaluated to deepen our understanding of ecological and geomorphic processes, and advantages, at the gemorphically complex site.

Pool Sediment Deposition

Promoting sediment deposition in augmented river corridors: Beaver Mimicry Structures accumulate truckloads of sediment naturally on the floodplain and between diversion structures.

What did we find? Beaver Mimicry Structures on a side channel of the geomorphically complex site reached close to holding capacity during four years of monitoring, capturing more than 3,500 cubic yards of sediment on the floodplain.

Interestingly... Beaver Mimicry Structures captured a significant amount of sediment during a flash flood event in June 2023, up to 1,500 cubic yards.

Recommendations for future projects: Beaver Mimicry Structures and other attenuation features are effective at a project scale, but need to be implemented across a watershed to prolong their benefits. We recommend utilizing them in tributaries and other small drainages as well as on the floodplains of larger river projects in the transition zone.

Sediment stored at one Beaver Mimicry Structure in fall 2020 versus fall 2023. A flash flood, carrying high volumes of sediment, occurred in June 2023.

Read the technical report here!

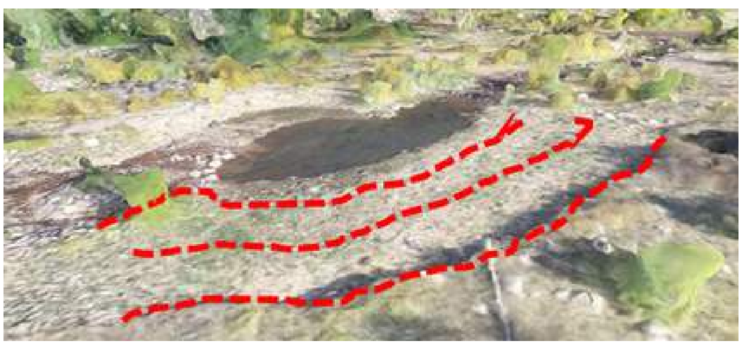
Vegetative Bench Complexity

Illuminating what drives native success: Research shows that groundwater connection is key to ward off non-native innovators and promote resilience.

What did we find? When testing different floodplain bench elevations against different plant mixes of varying functional traits (e.g., water loving or drought tolerant), soil moisture drove the degree of non-native invasion vegetation trends.

Interestingly... Since the lowland (water loving) plant mix did best in low bench heights, we expected that the functional traits or plant mixes would drive invasion trends. However, we found that these variables were not significant, and (as stated above) soil moisture was the driving factor.

Recommendations for future projects: During project design and construction, maximize lower elevation benches and groundwater connection to enhance survivability of native species and resistance against non-native invasion. Utilize mixed plant types and diversity of functional traits as a secondary strategy to enhance adaptive capacity and climate resilience.



Images showing the three bench heights with different groundwater connection used to study vegetative response.

Read the technical report here!

Vegetation Canopy Complexity

Underscoring the importance of long term monitoring: While an important measurement in years to come, vegetation responses can be delayed after restoration.

What did we find? Within two years after restoration, we did not find that restoration techniques affect canopy complexity. This is likely due to the longer time scale required for vegetation to establish after restoration.

Interestingly... Our results were likely reflective of vegetation communities present before the project was implemented.

Recommendations for future projects: Invest time and resources into identifying and protecting future project areas with existing canopy complexity rather than creating unnecessary disturbance. Implement management on pervasive non-native species such as crack willow to help native complexity establish over a longer time scale.

Read the technical report here!

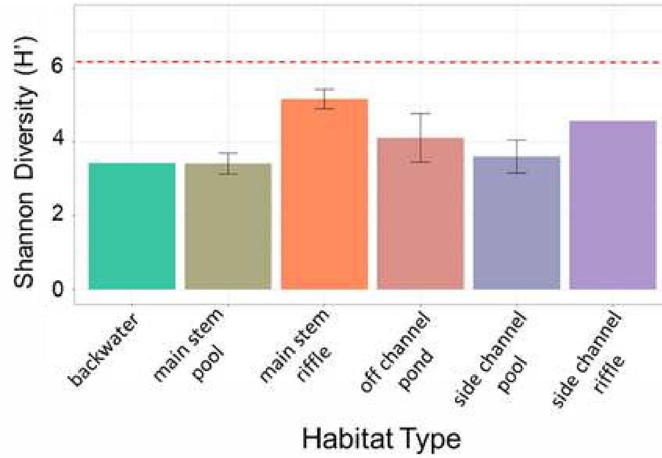
Benthic Macroinvertebrate Communities

Maximizing features and ecological resilience: Different restoration features diversify benthic macroinvertebrate communities and site-level biodiversity.

What did we find? Benthic macroinvertebrate species are specialized to different habitat types. We found community composition changed based on the habitat feature.

Interestingly... Site level diversity (all habitat types combined) was 15-77% higher than diversity at any individual habitat feature.

Recommendation for future projects: Include multiple habitat types in restoration projects for ecological diversity and resilience. Incorporating different types of features not only increases site level diversity, but it allows for refuge and population re-establishment after disturbance.



This figure shows diversity indices by habitat types (bars) and at the site level (dashed line). Larger measurements indicate a more diverse BMI community.

Read the technical report here!

Northern Redbelly Dace Reintroduction

What did we find? Using novel and non-invasive eDNA sampling methods, we were able to detect presence year after year with results that suggest naturally growing populations. Camera monitoring results suggest these fish are most active in vegetated areas and use underwater woody structures less frequently.

Interestingly... Out of five reintroduction ponds monitored with eDNA across Boulder County, this pond was one of three that had positive detections and was the only site that was monitored multiple years with positive and increasing detections. While both eDNA and camera methods can successfully detect presence, eDNA methods are more flexible but can be cost prohibitive, while camera methods must be highly standardized to environmental variables.

Recommendations for future projects: Future projects, especially ones located in the transition zone at the western extent of Northern Redbelly Dace range in Colorado, should consider reintroduction in their design if off channel ponds are present or feasible.

Camera footage of a Northern redbelly dace at a submerged woody brush bundle.

Members of the Northern Redbelly Dace project collect eDNA sample using filtration and bike pumps to pressurize!

Special note! *This pond is also home to reintroduced Northern Leopard Frogs. So far, both the Dace and Frogs are living together in harmony.*

Read the technical report here!

Complexity of Physical Features

Increased diversity of physical features and floodplain connectivity were deliberately incorporated into project design and construction. This topic describes how we quantified our project goal. All other topic summary sheets describe *ecological and geomorphic responses* that occurred as a result of increased diversity of physical features and floodplain connectivity.

Monitoring goal

The goal of this monitoring was to quantify changes and differences in complexity in both project areas. The restoration project was specifically designed and constructed to include diversity of physical features (e.g., varied topography, multiple channels, wetlands, diverse instream habitat features and broad floodplains), which can promote geomorphic complexity, in the upstream portion of the project area. We used UAS ("unmanned aircraft systems" i.e., drone)-collected images and derived data (orthomosaics and digital surface models (DSMs) or digital elevation models (DEMs), depending on availability) to quantify differences in diversity of physical features between the upstream (geomorphically restored) project area and the downstream (traditionally restored) project area by calculating six feature metrics.

A UAS (i.e., drone) takes off to collect static images that are used to develop high resolution orthomosaic images and digital elevation models.

Introduction

- A geomorphically complex landscape is composed of a diversity of physical features such as varied topography, multiple channels, wetlands, diverse instream habitat features and broad floodplains and provide aquatic, riparian, and upland habitat for generalist and specialist plant and animal species as well as encourage beneficial natural river and floodplain processes like sediment deposition to occur.
- In the event of a disturbance, species already present on the landscape are the most likely to be the first to recolonize. Thus, increasing available habitat and promoting natural river and floodplain processes before disturbances occur can offer site-level resiliency benefits.
- Geomorphic complexity can be measured by a wide range of metrics and in different ways. We used remote sensing methods to track six metrics of physical features over time in the upstream geomorphically complex restored project area and the downstream traditionally restored project area.
- In this summary sheet, we present data, takeaways, and recommendations based on our evaluation of complexity features at the upstream and downstream project areas before and after restoration and over time.

Acknowledgements

We gratefully acknowledge Dr. Sean Streich who piloted the UAS and created orthomosaic images and Geoffrey House who performed GIS analyses.

Monitoring questions

1. How did feature metrics change at each project area before and after restoration and over time?

2. How did feature metrics compare between project areas before and after restoration and over time?

Indicators and why?

The feature metrics that we examined to quantify complexity of features were:

- **Ratio of channel length to valley length** – longer river length in a given area suggests better floodplain connectivity and access to groundwater.
- **Ratio of channel area to valley area** – more channel area in a given area suggests better floodplain connectivity and access to groundwater.
- **Vegetated island counts per valley length –** islands provide riparian and aquatic habitat and instream flow complexity.
- **Ratio of wood jams/large wood to valley area –** instream wood provides aquatic habitat, sediment capture, bank stabilization, and instream flow complexity.
- **Ratio of pool area to valley area –** pools provide important habitat for overwintering fish and provide areas for sediment deposition.
- **Distribution of bench heights –** varied bench elevations provide habitat complexity for water and drought tolerant plant species alike as well as habitat and resources for other species that rely on those plants.

Location at project site

UAS flights occurred over the upstream and downstream project areas (Fig. 1). Data collection occurred in the both the geomorphically complex restored upstream project area as well as the traditionally restored downstream project area in order to compare geomorphic complexity metrics in each area.

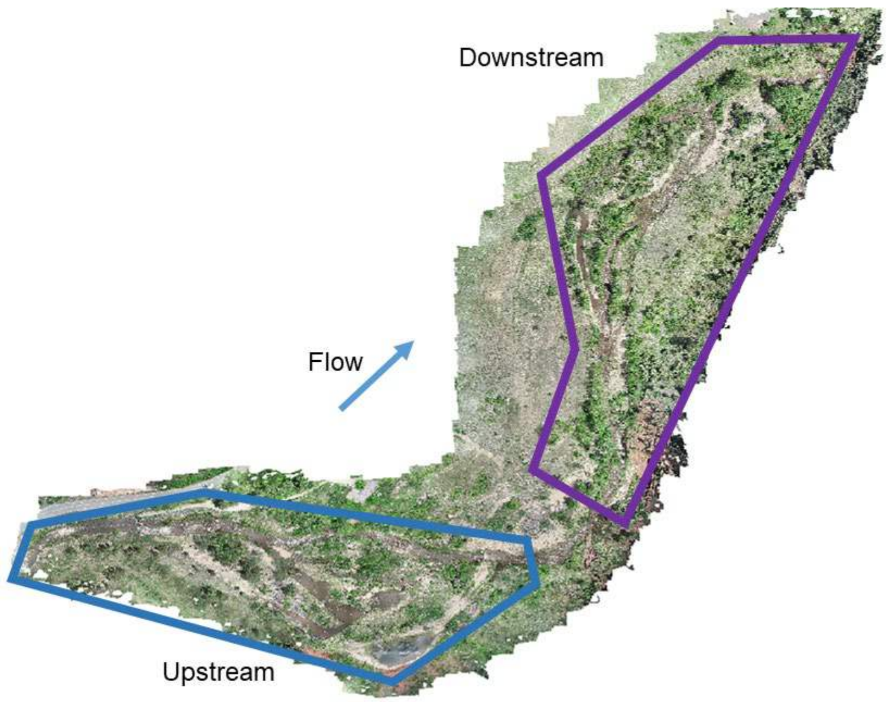


Figure 1. Aerial view of project site. The blue polygon represents the upstream project area and the purple polygon represents the downstream project area.

Methods

UAS flights occurred in fall during low flow conditions in 2019 (pre-restoration work), 2020, 2022, and 2023. Flights that took place from 2020-2023 occurred after restoration work was completed. Images from flights were processed in Agisoft Metashape to create digital surface models (DSMs), digital elevation models (DEMs), and orthomosaic images. All metrics were calculated using GIS tools in QGIS (Version 3.28.9), and all graphs were created using R (Version 3.6.3). All raster and vector layers used in the analysis used the NAD83(HARN) / Colorado North (ft US) projected coordinate system (EPSG: 2876). Raster layers from drone image collection were re-projected as needed using bilinear sampling. For a full description of GIS methods, see here.

Each metric besides bench heights were calculated for each year. Bench heights were calculated for 2020, 2022, and 2023 only, due to poor DEM quality in 2019. This resulted in 46 different metric/reach/year combinations for determination with this study. Figures 2-4 show examples from the QGIS delineations.

Figure 2. Orthomosaic image showing upstream project area (blue), downstream project area (orange), and valley line (green).

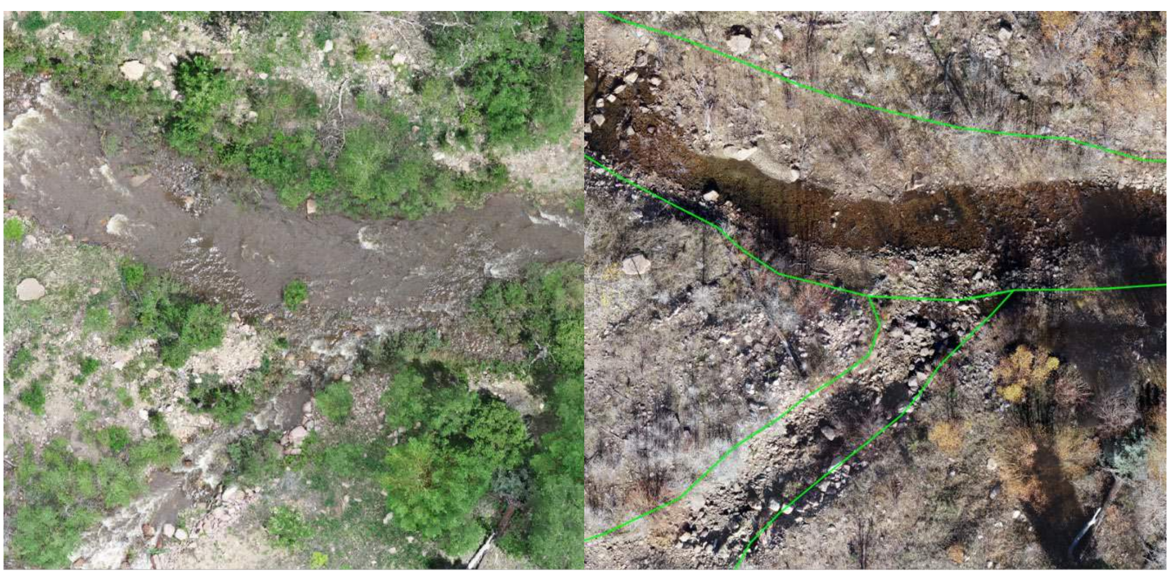


Figure 3. UAS imagery taken during high flows (left) used to delineate active stream channel during low flows (right). Green lines show the final stream channel delineation.

Figure 4. Orthomosaic image showing all delineations. Blue outline represents the upstream project area, orange outline represents the downstream project area, yellow line represents the stream channel bottom, dark red outline represents the active stream channel, pink circles represent pool area, and light blue outlines represent large wood.

Key takeaways

- As expected, our monitoring data suggests that we successfully created more complexity at the upstream project area than what is traditionally integrated into restoration.
    - In the first year after restoration, the upstream geomorphically complex project area had higher ratios of most metrics compared to the downstream traditional project area, with the exception of vegetated islands (Figs. 5-9).
    - As expected, the upstream project area had more channel length and channel area than the downstream site both before and after restoration (Fig. 8 and Fig. 9). This suggests that the upstream geomorphically complex project area has a well-connected floodplain that activates multiple channel pathways and habitat year to year.
- Notably, the upstream geomorphically complex area had more annual variation in vegetated islands, wood jams, and pool area relative to valley length and valley area metrics from 2020-2023 compared to the downstream traditionally project area (Figs. 5-7)
    - This quantifies the dynamic nature of features and how they move across the landscape over time. This could suggest that the upstream geomorphically complex project area has more dynamic river processes occurring and offers more, but varying, complexity from year to year.
    - Vegetated islands in the upstream geomorphically complex restored project area showed extreme variation relative to other metrics. This could suggest that these features are especially prone to the dynamic river processes occurring in this area.

    - As expected, pool area increased at the upstream project area after restoration and was consistently higher, with some variability, than the downstream area. Notably, the downstream project area maintained similar and less variable pool area year to year after restoration (Fig. 7).
- Bench heights are consistently distributed in the upstream project area for all years post-restoration (Fig. 10). "Hits" were detected in low relative elevation bins as well as high relative elevation bins, which indicates that there should be suitable habitat for water tolerant and drought tolerant species alike.

Recommendations for management

- When designing and constructing stream restoration projects, consider how these feature metrics can be incorporated into the project. Are channel length and area maximized, within reason, by building a multi-threaded system? Are instream features such as vegetated islands, large woody debris, and pools incorporated into the design?
- When possible, we recommend a "light-touch" approach to stream restoration. For example, when islands are already present, disturb them as little as possible. When woody debris is already present on site, use those materials for instream features.
- In geomorphically complex restored projects, be prepared to monitor the project for several years after implementation. More variability in the above described metrics is expected, but it is important to make sure over time, the area remains geomorphically complex (i.e., monitor for pools filling in, woody debris being carried downstream, etc.).

Figures

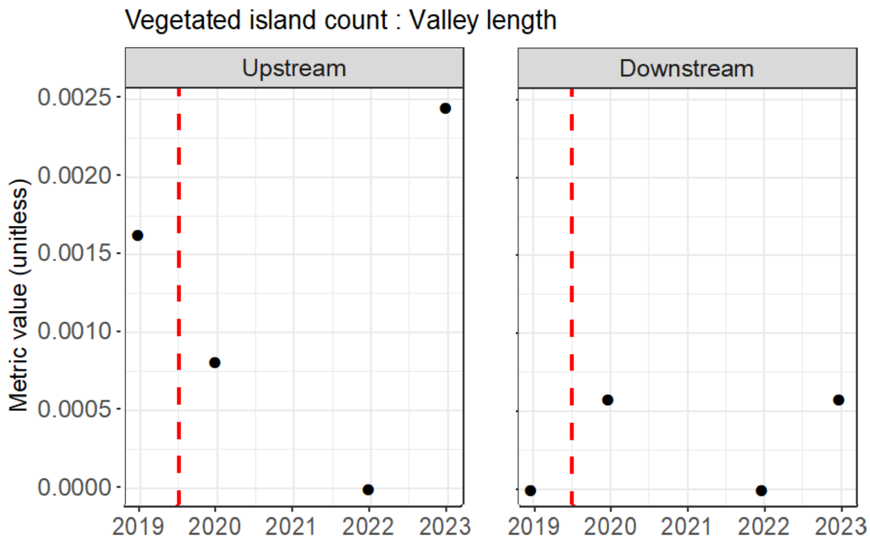


Figure 5. Vegetated island count: valley length ratio for the downstream traditionally restored project area (left) compared to the upstream geomorphically complex restored project area (right). The red vertical dashed line represents the year that restoration was completed. The x-axis represents the year that was measured and the y-axis represents the metric value.

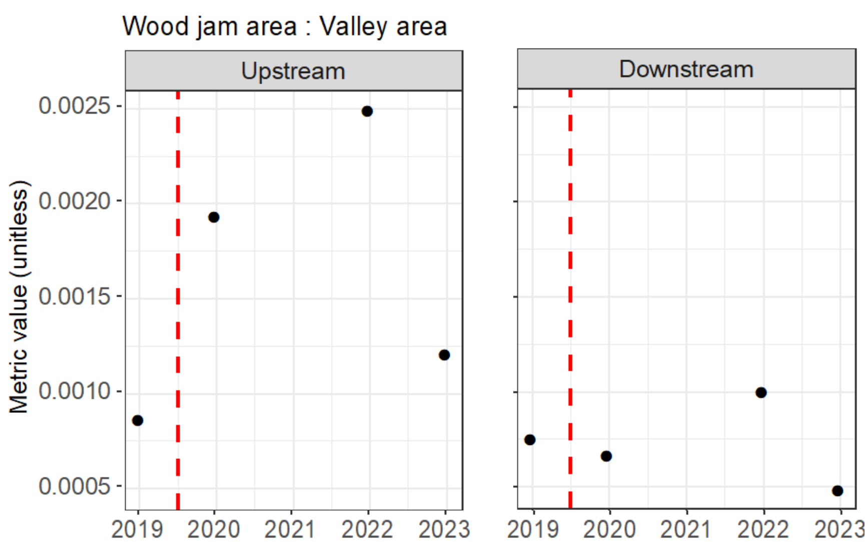


Figure 6. Wood jam area: valley area ratio for the downstream traditionally restored project area (left) compared to the upstream geomorphically complex restored project area (right). The red vertical dashed line represents the year that restoration was completed. The x-axis represents the year that was measured and the y-axis represents the metric value.

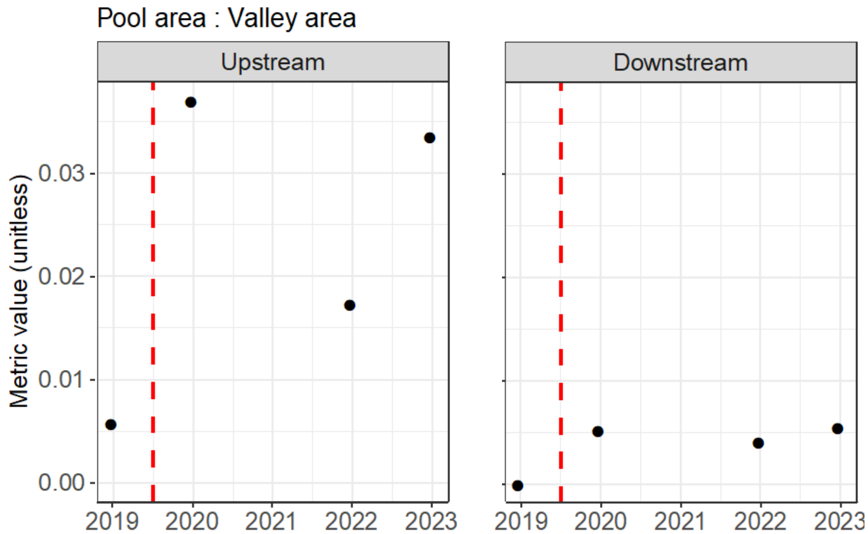


Figure 7. Pool area: valley area ratio for the downstream traditionally restored project area (left) compared to the upstream geomorphically complex restored project area (right). The red vertical dashed line represents the year that restoration was completed. The x-axis represents the year that was measured and the y-axis represents the metric value.

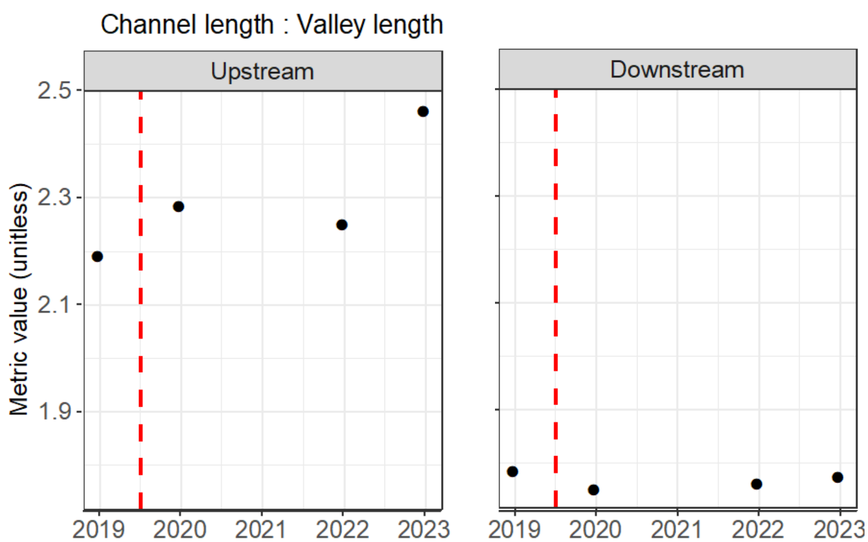


Figure 8. Channel length: valley length ratio for the downstream traditionally restored project area (left) compared to the upstream geomorphically complex restored project area (right). The red vertical dashed line represents the year that restoration was completed. The x-axis represents the year that was measured and the y-axis represents the metric value.

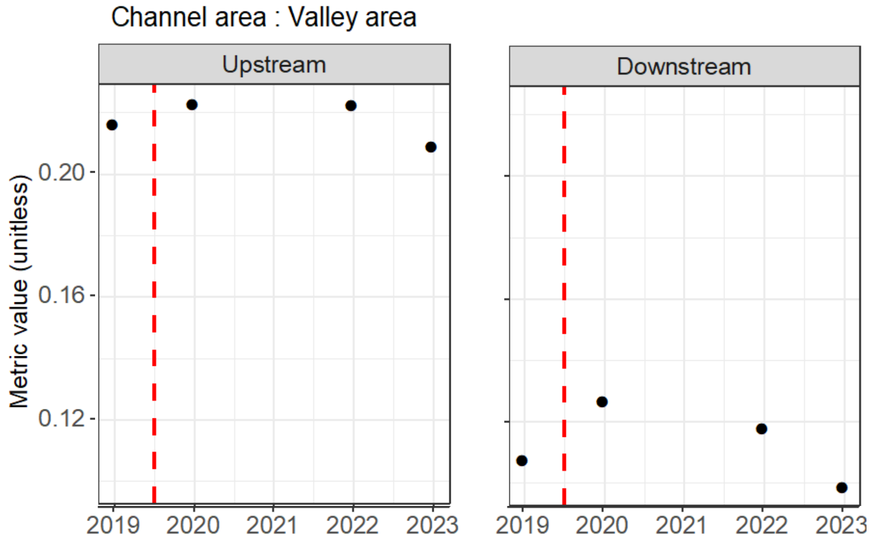


Figure 9. Channel area: valley area ratio for the downstream traditionally restored project area (left) compared to the upstream geomorphically complex restored project area (right). The red vertical dashed line represents the year that restoration was completed. The x-axis represents the year that was measured and the y-axis represents the metric value.

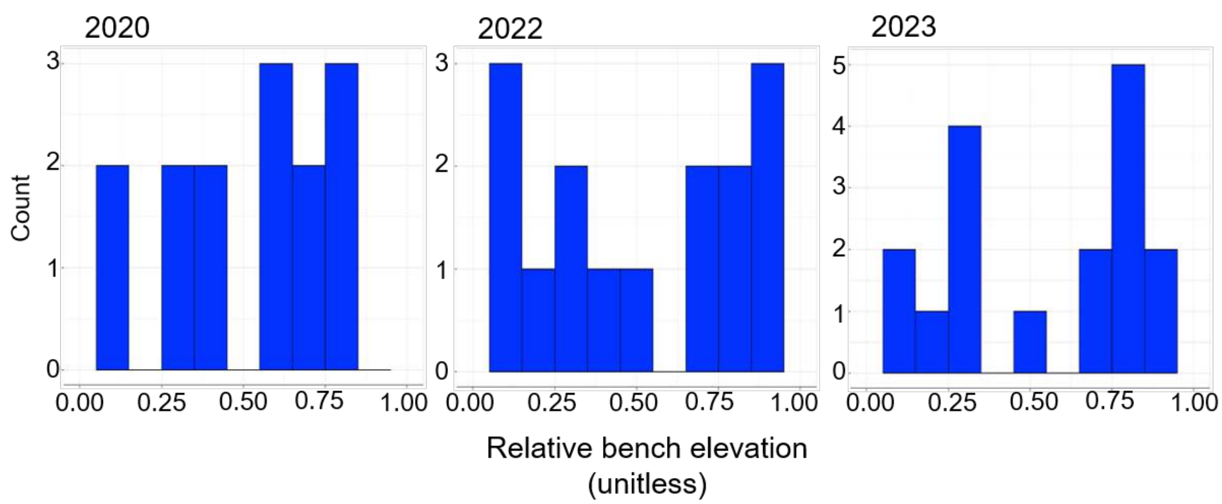


Figure 10. Histograms of post-restoration bench heights in the upstream project area from 2020-2023. The x-axis represents relative elevation to account for UAS-derived differences in absolute elevation in DEMs. The y-axis represents the number of hits for each relative elevation bin. Elevations were re-scaled within each year be relative to the uppermost (relative elevation of 1) and lowermost (relative elevation of 0) points of the valley being measured.

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Floodplain Connectivity

Increased diversity of physical features and floodplain connectivity were deliberately incorporated into project design and construction. This topic describes how we quantified our project goal. All other topic summary sheets describe *ecological and geomorphic responses* that occurred as a result of increased diversity of physical features and floodplain connectivity.

Monitoring Goal

The goal of this monitoring was to quantify changes and differences to floodplain connectivity in both project areas after restoration. This restoration project was specifically designed and constructed to increase floodplain connectivity across the project area, which can increase connection to groundwater. We used UAS ("unmanned aircraft systems" i.e., drone)-collected images and derived data (digital elevation, surface, and terrain models; DEMs, DSMs, and DTMs, respectively) to quantify differences in floodplain connectivity between the upstream (geomorphically restored) project area and the downstream (traditionally restored) project area by creating relative elevation models (REMs) and associated quantitative data.

Introduction

- Floodplain connection is important because higher flows recharge groundwater which promotes healthy riparian vegetation and supports the exchange of water, sediment, organic matter, nutrients, and organisms between the river, floodplain, and alluvial aquifer.
- A well-connected floodplain is better able to attenuate fluxes from flood conditions and post-fire runoff by allowing the river to spread out a release energy before continuing downstream.
- Relative elevation models (REMs) can be used to measure differences in floodplain elevations relative to the stream bed. A REM can be used to measure floodplain connectivity broadly, compare the observed floodplain with historical floodplains, and to identify impediments to floodplain connectivity at varying flow regimes.
- In this summary sheet, we present data, takeaways, and recommendations based on our evaluation of floodplain connectivity at the upstream and downstream project areas after restoration.

A UAS (i.e., drone) takes off to collect static images that are used to develop digital elevation models

Acknowledgements

Acknowledgements

We gratefully acknowledge Dr. Sean Streich who piloted the UAS and post-processed images and the University of Colorado Boulder Earth Lab professional graduate students, Dr. Julia Sobczak and Dr. Lindsay Chipman, who also post-processed data and developed REMs and associated data.

Monitoring questions

1. How did floodplain connectivity change at each project area over time after restoration?

2. How did floodplain connectivity differ between project areas each monitoring year and over time?

Indicator and why?

We measured the **frequency of relative elevations** standardized by monitoring area across the project over a four period. Standardizing the counts of raw elevations by monitoring area allows for comparisons of floodplain connectivity to be made across areas of different sizes and across different years where the area monitored might not be exactly the same year to year.

Location at project site

UAS flights occurred over the upstream and downstream project areas (Fig. 1). Data collection occurred in the both the geomorphically complex restored upstream project area as well as the traditionally restored downstream project area because this hypothesis examined how restoration method influenced floodplain connectivity.

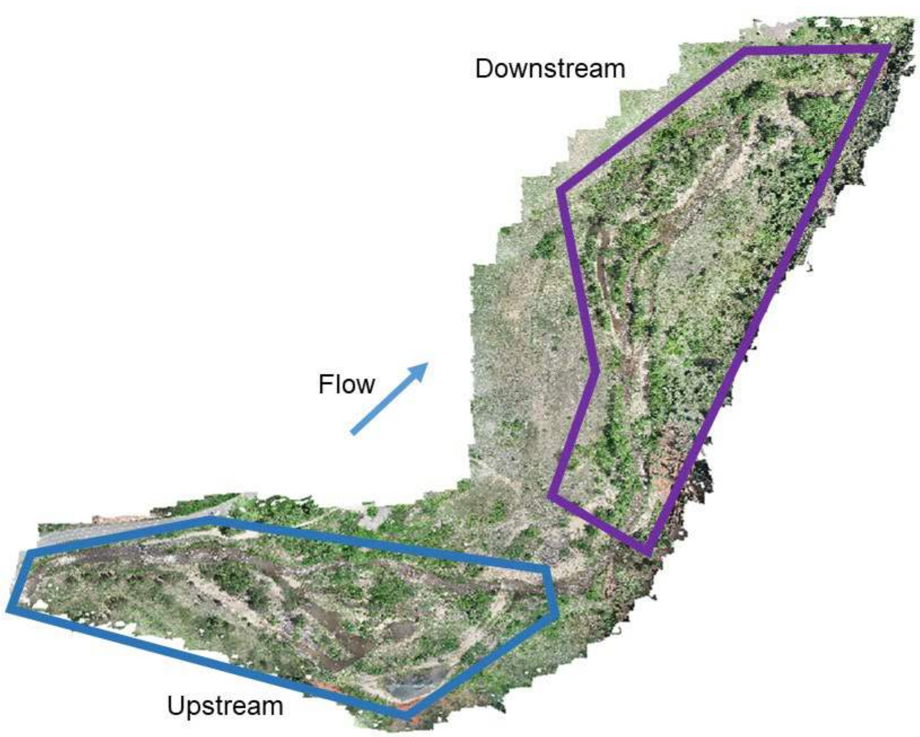

Figure 1. Aerial view of project site. The blue polygon represents the upstream project area and the purple polygon represents the downstream project area.

Methods

Methods selection

Measuring floodplain connectivity is frequently done using LiDAR data. A plane or UAS ("unmanned aircraft systems" i.e., drone) is usually mounted with a LiDAR sensor. As the aircraft flies over a study area, lasers are sent from the sensor to the ground where they bounce back and return to the sensor. Differences in the amount of time it takes the laser to return to the sensor helps create a three dimensional model of the study area, which can then be used to examine floodplain connectivity. Using LiDAR data is usually cost-prohibitive, and practitioners do not have much power over determining at what spatial and temporal scale flights will occur.

Relatively affordable UAS can be purchased with a standard camera already mounted. The UAS can be flown over a study area in a grid pattern, capturing photographs along the way. Images can then be stitched together using Structure for Motion (SfM) methods to create orthomosaic images and elevation models. While UAS and SfM struggles with "seeing through" dense tree canopy, it provides extremely high resolution (e.g., less than 1 meter) point clouds and other data products. UAS and SfM are relatively cheap compared to LiDAR and are easy and flexible to use whenever the practitioner wants.

LiDAR data and UAS data can each be used to generate point clouds and elevation models.

Data collection and analysis

Static images were collected by flying a DJI Phantom 4 UAS over the downstream and upstream project areas in a grid pattern. Orange buckets lids were placed on the ground throughout the site to be used as ground control points (GCPs). Data collection occurred during low flow conditions in the fall of 2019, 2020, 2022, and 2023. The flight pattern was chosen to cover the full extent of the stream channel and its floodplain with sufficient overlap and resolution to create a REM.

Agisoft Metashape was used to stitch images together using SfM methods. Images with a quality below 0.7 were removed. Image stitching was done by manually identifying GCPs and then aligning images. After the orthomosaic model was completed, we panned through the model and manually deleted any erroneous points. A high quality dense point cloud was generated from the model followed by a digital elevation model (DEM). A digital terrain model (DTM, i.e., a DEM with vegetation removed) was created by classifying known ground points. The DEM, DTM, and orthomosaic were exported for use in creating the REM.

We created REMs using the Colorado Water Conservation Board (CWCB) REM Generator Tool, which is a publicly available plugin for ArcMap. We followed the workflow in the guidance document. Instead of using the 'Create Cross Sections' feature, we drew the cross sections by hand, perpendicular to the valley line, then ran the 'Process Cross Sections', 'Create Bounding Polygon', and 'Create REM' tools to create the REM. We also delineated the stream channel by hand using the drone imagery and DTM.

After obtaining the REM, we classified the data in ArcMap using the 'Symbology' tab into defined intervals of 0.3 m (1 foot), ranging from the lowest elevation up to a maximum 6 m, classes containing elevations higher than 6 m were lumped into the last bin. The bins represent changes in elevation relative to the stream channel. To compare the upstream and downstream areas of interest (AOI), we created shapefiles representing the upstream and downstream AOIs and clipped the full REM to each. We then used the Spatial Analyst 'Reclassify' tool to reclassify the clipped REMs with the same schema (defined intervals of 0.3 m) and used 'Unique Values' to display the raster by assigning a color to each value. Histograms that show the frequency of each relative height value and line graphs that compare the percent total of each frequency between the upstream and downstream AOIs were then created.

Final REMs from 2019 and 2022 were significantly different than those from 2020 and 2023 and did not make geomorphic sense. Therefore, we only used data from 2020 and 2023 for our analysis and takeaways. Notes on why 2019 and 2022 data were inaccurate are described in more detail in recommendations for management section below.

Key Takeaways

- Project implementation improved floodplain connection immediately post-restoration.
  - For both project areas, the majority of relative floodplain elevation counts and proportions were between zero and three meters in 2020 (Fig. 2 and Fig. 4).
- Over time, deposition at the upstream geomorphically complex site drove a shift in relative floodplain elevations.
  - Between 2020 and 2023, there were more counts of relative elevations above three feet compared to immediately post-restoration at the upstream geomorphically complex project area (Fig. 2 and Fig. 3). This is likely due to sediment accumulation from 2020 to 2023, while the downstream traditionally restored project area did not appear to have any long-term sediment storage effects.
  - When raw counts are standardized as a percentage of total project area, the downstream project area shows little change in elevation from 2020 to 2023 (Fig. 4). This is expected because sediment is expected to be transported through this reach.
  - When raw counts are standardized as a percentage of total project area, the upstream project area shows a shift in peak relative elevation counts at 1.5-1.8 meters in 2020 to a peak in relative elevation at 2.1-2.4 meters in 2023 (Fig. 4). The upstream project area was designed to capture sediment, so a small shift in relative elevations was expected. Notably, the secondary stream channel that flows through a series of three beaver mimicry structures that showed sediment accumulation from 2020 to 2023.

Recommendations for management

- UAS and SfM methods, as opposed to aerial LiDAR flights, offer a relatively cheap and extremely flexible option for developing orthomosaic images, DEMs, DTMs, and REMs that can be used for measuring floodplain connectivity as well as a multitude of other metrics (e.g., vegetation structure, canopy heterogeneity, etc.). Floodplain connectivity has implications for sediment capture as well as groundwater connection, so incorporating a low cost and flexible workflow like this one could be useful for land and resource managers. Low cost and flexibility of use means that a practitioner could theoretically use this workflow pre- and post-project (as was done here) or pre- and post-flood or at whatever spatial or temporal scale was necessary without being constrained by availability of public LiDAR data. Additionally, UAS-captured images are extremely high resolution, which creates far denser point clouds used for analyses than LiDAR-derived point clouds, for detailed final products.

- When using relatively complicated methods such as these (e.g., UAS data collection in the field across multiple years, multiple post-processing steps across multiple software), we stress the importance of adhering to a consistent workflow from UAS flight parameters to UAS flight time of the year (due to differences in sun position and shading effects) to post-processing of UAS images and final analyses.
    - In addition to collecting data in 2020 and 2023, data was also collected in 2019 and 2022. Final REMs from 2019 and 2022 were significantly different than those from 2020 and 2023 and did not make geomorphic sense. We were unable to reconcile those differences, and thus, we do not present those results here. Factors that likely influenced poor results in 2019 and 2022 include:
        - Different UAS pilots using slightly different UAS and camera settings (e.g., altitude, speed, camera tilt, photo overlap, flight pattern, number of total captured images, etc.).
        - Differences in photo quality due to slightly different weather conditions and shadow effects.
        - Slight differences in parameters used in post-processing of UAS images (e.g., which images were filtered out due to being deemed "poor quality") and differences in parameters chosen to develop DEMs, DTM, and REMs.
    - REMs from 2020 and 2023 were likely most similar and, crucially, geomorphically accurate, due to the above factors being minimized as much as possible.

Figures

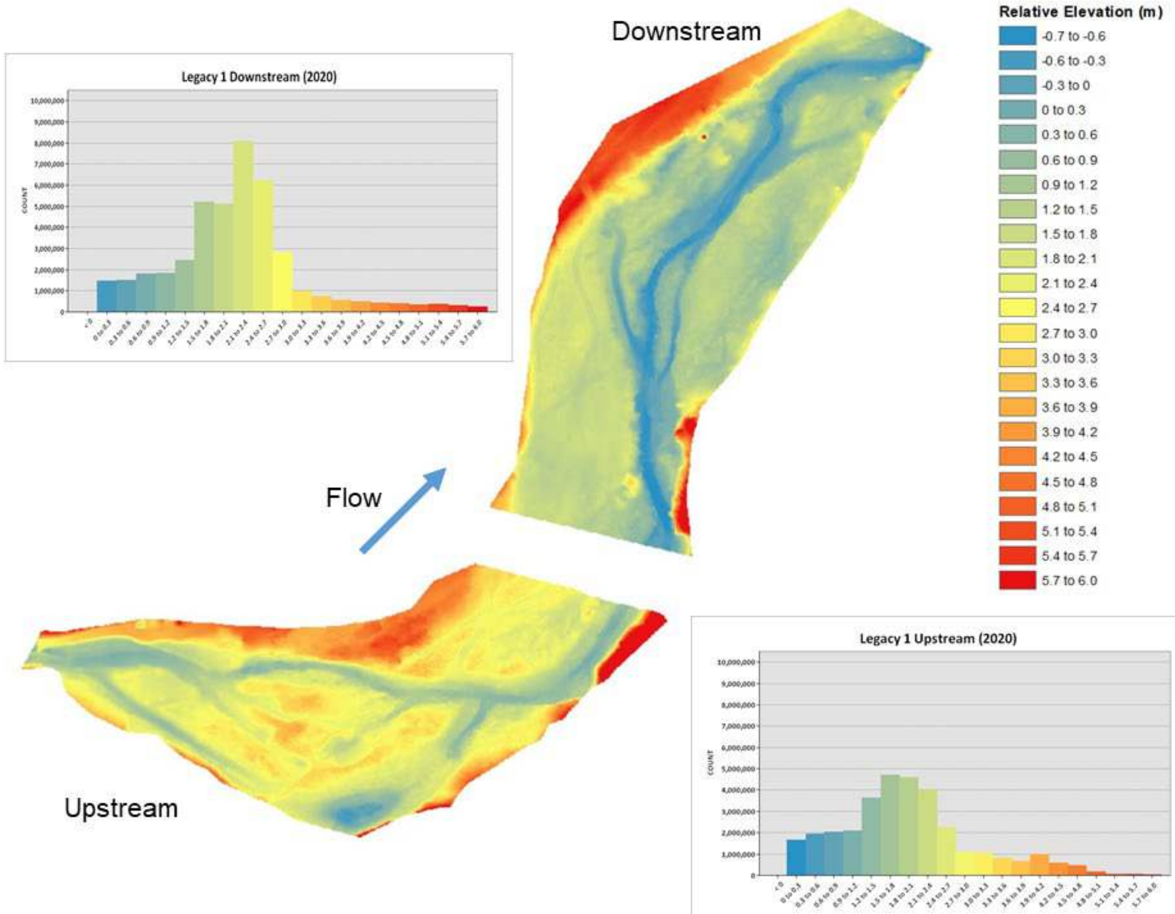

Figure 2. Relative elevation model (REM) and associated histograms for upstream and downstream project areas for 2020. Cooler colors represent areas at lower elevations relative to the stream channel and warmer colors represent areas at higher elevations relative to the stream channel. Histograms represent raw count data for various elevation bins. Note that because they are raw counts, there are more points in the downstream project area because the downstream area is larger than the upstream project area.

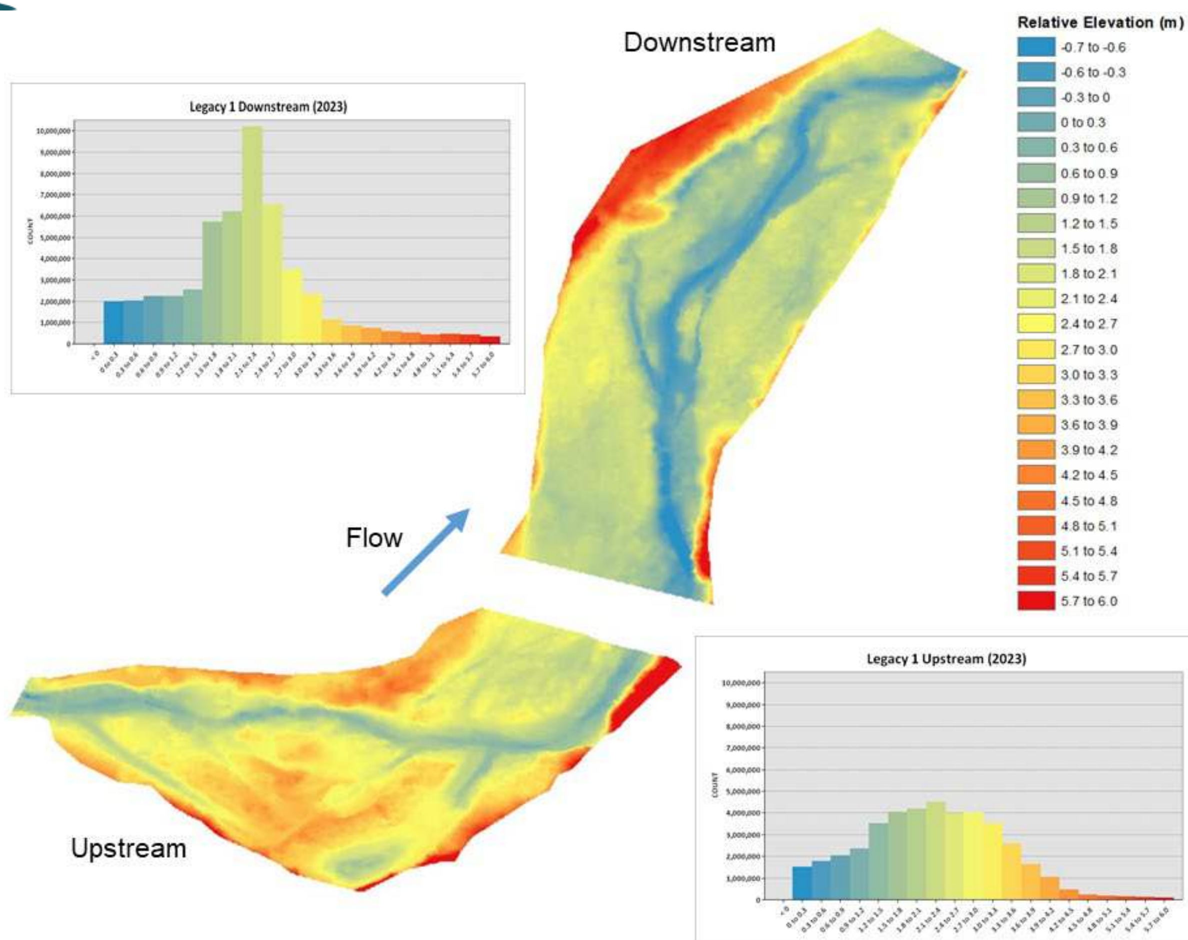

Figure 3. Relative elevation model (REM) and associated histograms for upstream and downstream project areas for 2023. Cooler colors represent areas at lower elevations relative to the stream channel and warmer colors represent areas at higher elevations relative to the stream channel. Histograms represent raw count data for various elevation bins. Note that because they are raw counts, there are more points in the downstream project area because the downstream area is larger than the upstream project area.

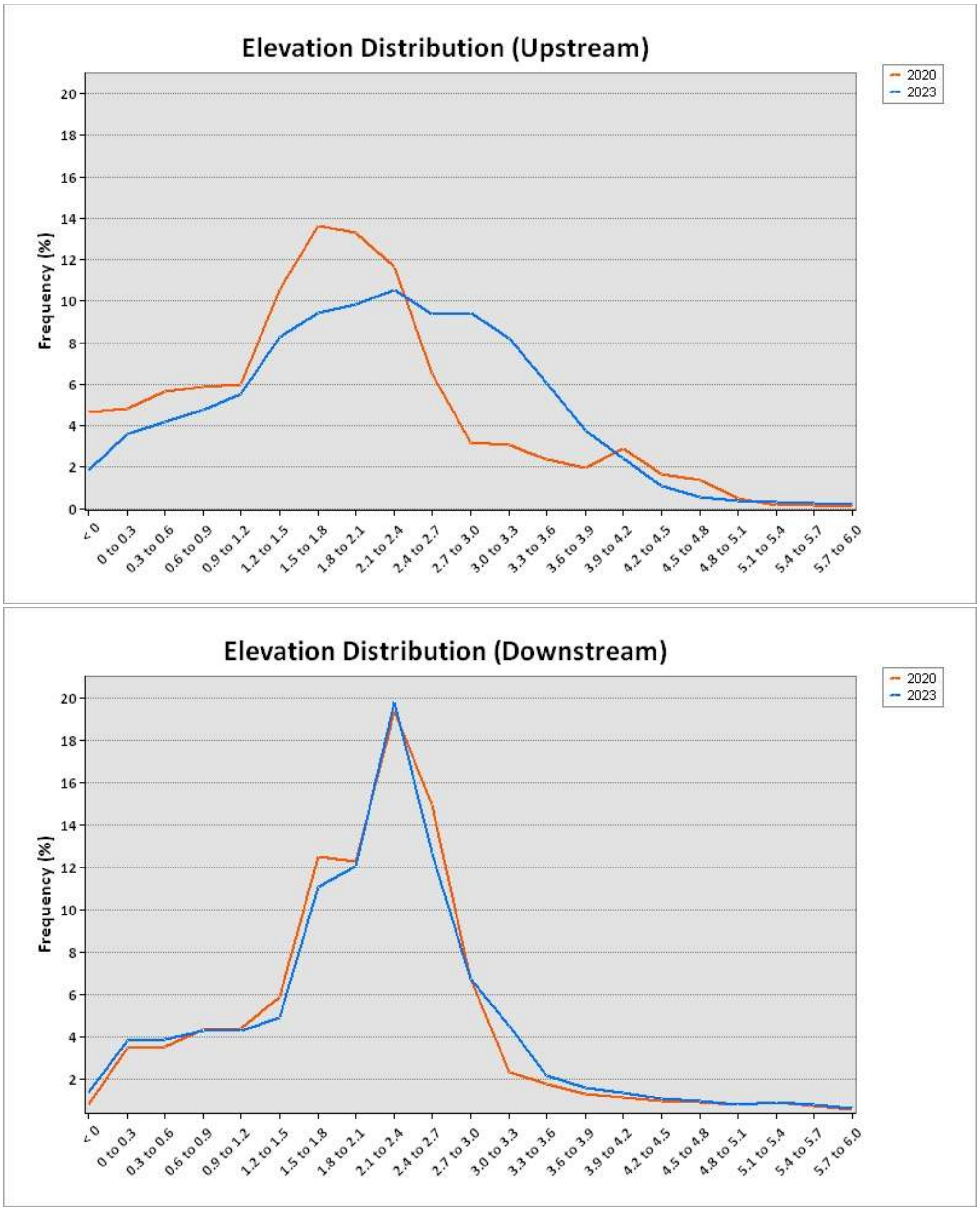

Figure 4. Comparison of frequency of counts for various elevation bins standardized as a percentage of the project area for downstream (top) and upstream (bottom) project areas in 2020 and 2023. The orange line represents the 2020 distribution and the blue line represents the 2023 distribution.

Pool Sediment Deposition

Pool sediment deposition responses described below were a *geomorphic response* to deliberately increased diversity of physical features and floodplain connectivity implemented during project design and construction.

Introduction

- Sediment transport and deposition is a natural watershed process that occurs throughout the seasons. In a typical water year, finer sediment is highly mobile during peak runoff (May-July) and settles out during low flows. In flood events, finer and larger sized sediment can be mobilized quickly and heavy loads will deposit out in depositional areas with broad floodplains.
- Fine sediment is a concern to water resource managers and the ecology of ecosystems alike.
    - Water resources managers use diversion structures to divert water from natural rivers to agricultural and municipal water users in different areas. The Front Range of Colorado depends on efficient water infrastructure to accomplish these needs. Too much fine sediment accumulation can make water delivery difficult and costly.
    - Some benthic macroinvertebrates and fish use the interstitial space between and underneath rocks in the streambed for habitat. Too much fine sediment can fill the interstitial space between rocks, which takes up valuable habitat. Fish depend on benthic macroinvertebrates as a food source, so impacts to benthic macroinvertebrate communities can have cascading effects throughout the ecosystem.
- Restoration practices use a variety of approaches to promote sediment deposition.
    - Most commonly, projects will incorporate instream pools. These are also depositional channel features that can also promote sediment deposition and high quality habitat.
    - Another restoration feature is called a beaver mimicry structures (BMS). These features are made of woody material and are typically installed in smaller streams like headwaters or side channels. They help deposit out sediment and slow flows as well as create high quality wetland habitat.
- In the upstream geomorphically complex area, we constructed a series of three BMSs on a side channel to promote floodplain sediment deposition as well as multiple in-stream pools.
- In this summary sheet, we present data, takeaways, and recommendations based on our evaluation of sediment capture in BMSs and traditional mainstem pools in the years after restoration.

A BMS during low flow conditions in fall 2021. Note the layer of fine sediment.

Acknowledgements

We gratefully acknowledge Dr. Katherine Lininger, Dr. David Harning, and students of the University of Colorado Boulder Geomorphology Class that helped collect and analyze these data.

Monitoring questions

1. How much sediment do BMSs accumulate in the first four years after restoration?

2. Do BMS features at the geomorphically complex project area catch more fine sediment than a traditional instream pool, relative to respective sizes?

Indicators and why?

- **Sediment storage (ft^3)** represents the raw volume of estimated sediment in a BMS or traditional pool. Sediment storage was calculated by measuring water and sediment depths at points along transects through a BMS or traditional pool. Depths are then extrapolated to the entire BMS or traditional pool by averaging known depths along cross sections and multiplying by widths of cross sections and length of the entire BMS or traditional pool. This value is important to water managers and ecologists because it represents actual amounts of sediment that is not flowing downstream.
- **V*** is a proportion of sediment volume to total residual pool volume. It was calculated by dividing the volume of estimated sediment by the estimated residual pool depth volume (esdimated sediment volume plus estimated sediment volume). The values are scale of 0 to 1 with higher values indicating that storage is nearing capacity. This standardized value provides a method for comparing BMSs and traditional pools of varying sizes.

Location at project site

Sediment sampling occurred in the upstream project area and downstream project area (Fig. 1). Sampling occurred in both the geomorphically complex restored upstream project area as well as the traditionally restored downstream project area because this hypothesis specifically examined how geomorphic complexity, specifically BMSs, influenced sediment capture and storage.

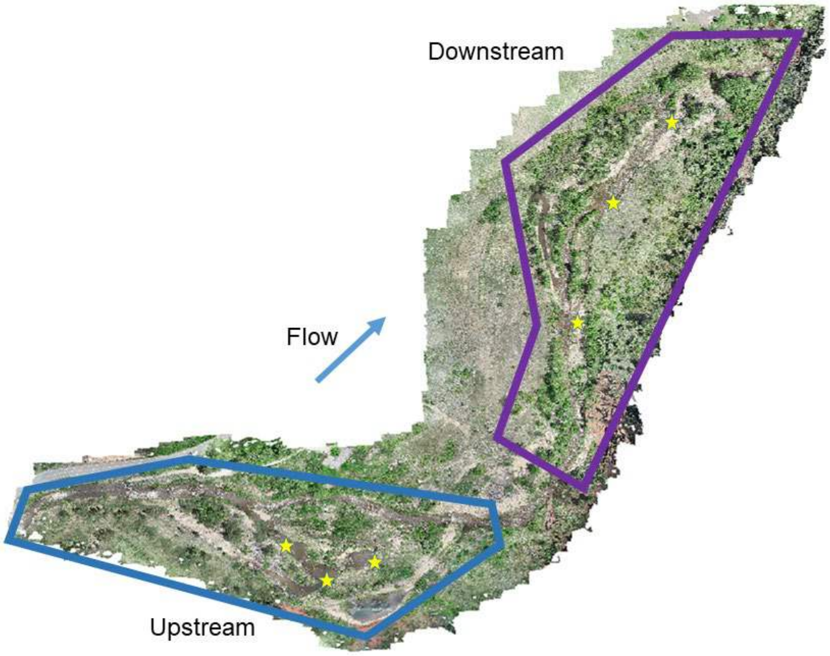

Figure 1. Aerial view of project site. The blue polygon represents the upstream project area and the purple polygon represents the downstream project area. Yellow stars represent approximate locations of sediment sampling at BMSs (upstream only) and natural pools (downstream only).

Methods

Sediment sampling occurred at three BMSs in the geomorphically complex upstream project area and three restored pools at the traditional downstream project area (Fig. 1) in the fall of 2020, 2021, 2022, and 2023 during low flow conditions. Once at a BMS/pool, a measuring tape was used to measure the distance along the longest distance parallel to flow to gather pool length. Pool lengths were divided into four or more cross sections based on complexity. Another measuring tape was used to measure cross sections perpendicular to the pool length. Along each cross section, four or more equally spaced depth measurements were recorded using a metal sediment probe based on complexity. The probe was inserted into the water/sediment until it reached the hard bottom. Depths of sediment and water were then recorded. In instances where the BMS/pool was dry, the water level was estimated at a residual pool height and delineated by keeping the measuring tape taut to simulate a water depth. All distances and starting points were chosen using a random number generator.

Volumes of sediment and water were estimated using methods from Lisle and Hilton and Lisle (1993). Calculations were performed in Microsoft Excel.

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Top left: Example of dry pool set up, where we estimated residual pool water depth and held tapes taut to simulate water depth.

Top right: A student measures water and sediment depth along one of the perpendicular measuring tapes.

Bottom left: A student uses the sediment probe to measure sediment depth.

Bottom right: The same process used in BMSs is used in a natural pool in the downstream project area.

Photo taken of the BMS structures and backwater during a June 2023 flash flood in Left Hand Watershed. This event occurred between 2022 and 2023 sampling years.

Key takeaways

- BMSs have the potential to store a large amount of sediment, but they are near holding capacity by year four. Even with their benefits of sediment storage, BMSs can be prone to filling up and could require maintenance such as dredging.
    - By 2023, there was almost 3,500 yds^3 (10,500 ft^3) of sediment stored in BMSs (Fig. 2). However, by year four post restoration, all three BMS structures were at 80% sediment catchment potential (Fig. 3).
    - BMS1 (the most upstream BMS) had consistently higher V* values than BMS2 (downstream of BMS1) and BMS3 (downstream of BMS1 and BMS2) from 2020-2022 (Fig. 2), which was expected because BMS1 provided the first opportunity for sediment to settle out of the water column. With the majority of sediment settling in BMS1, this allowed BMS2 and BMS3 to remain only just over 25% full from 2020-2022. However, with BMS1 close to 100% capacity in 2022, 2023 high flows were directed into BMS2 and BMS3.
- BMSs and traditional pools function differently and their V* values reflect this.
    - BMS are designed to promote sediment deposition on the floodplain and were expected to accumulate over time. This is reflected in both sediment volume and V* data, with increasing sediment and holding capacity over time (Figs. 2 and 3)

  - While they are not designed to be permanent in natural settings and may shift in space and size over time, traditional pools in mainstem channels typically are designed to maintain deeper water depths over time through seasonal springtime sediment scour and low flow deposition. Notice how their V* holding capacity were similar for the first three years (2020-2022), with the exception of Pool3 (Fig. 3).
- Notably, there was a flash flood in Left Hand Watershed that resulted in higher flows and sediment at the geomorphically complex site in June 2023. We were excited to capture the impacts in fall 2023, and our data shows that the BMS and traditional pools functioned differently during this event.
  - The BMSs behaved as attenuation features on the floodplain during flash flood conditions. The sediment volumes and V* at the BMSs both dramatically increased between 2022 and 2023, up to 4,600 ft^3 was captured (Figs. 2 and 3). This highlights how impactful BMS features can be at attenuating fluxes in flood events.
  - Alternatively, sediment in the traditional pools was scoured our during the flash flood event. The V* values at the traditional pools all decreased between 2022 and 2023 (Fig. 3).

Recommendations for management

- When possible and where feasible, we recommend incorporating large BMSs into river restoration project designs. Their functionality and capacity to store sediment is far greater than what traditional pools are capable of storing. Further, BMSs can store sediment over longer periods of time while traditional pools will experience natural flushing processes. Incorporating these features above critical water infrastructure can provide multi-purpose benefits, helping water managers more efficiently deliver water to constituents as well as providing ecological benefits to downstream benthic macroinvertebrate and fish communities.
- The benefits of BMS features at a single project are temporary as they accumulate sediment and these features and project types need to be implemented at a watershed scale. While project benefits are clear, the cumulative benefits of hundreds to thousands of BMS and other catchment features in smaller tributary streams and throughout transition zones can sustain both project and watershed scale benefits for longer. It is uncertain what will happen in the BMSs and surrounding floodplain into the future.
- Measuring sediment depth in BMSs was nuanced, given they were dry when monitoring occurred in the fall of each year. We recommend having a plan for measuring sediment depth in the case that BMSs are dry.

Figures

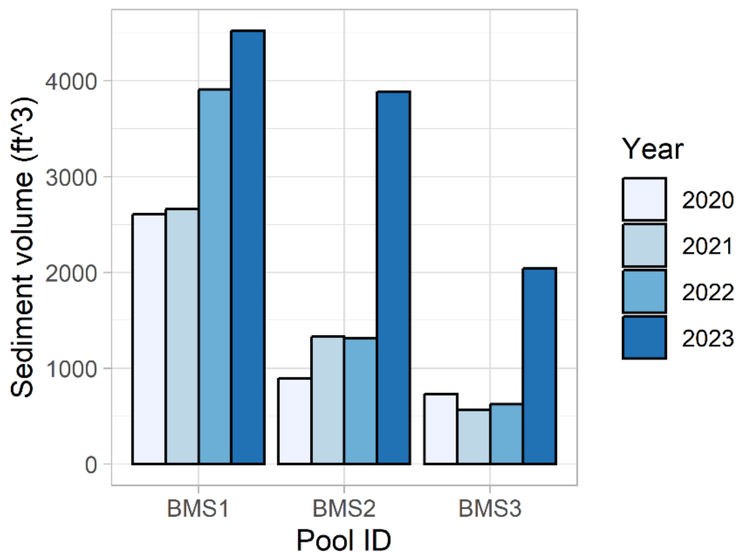

Figure 2. Sediment volume (ft^3) across four years in BMSs located in the geomorphically complex restored upstream project area. The x-axis represents the pool ID (oriented upstream to downstream), and the y-axis represents the sediment volume amount. Colors represent year of sampling.

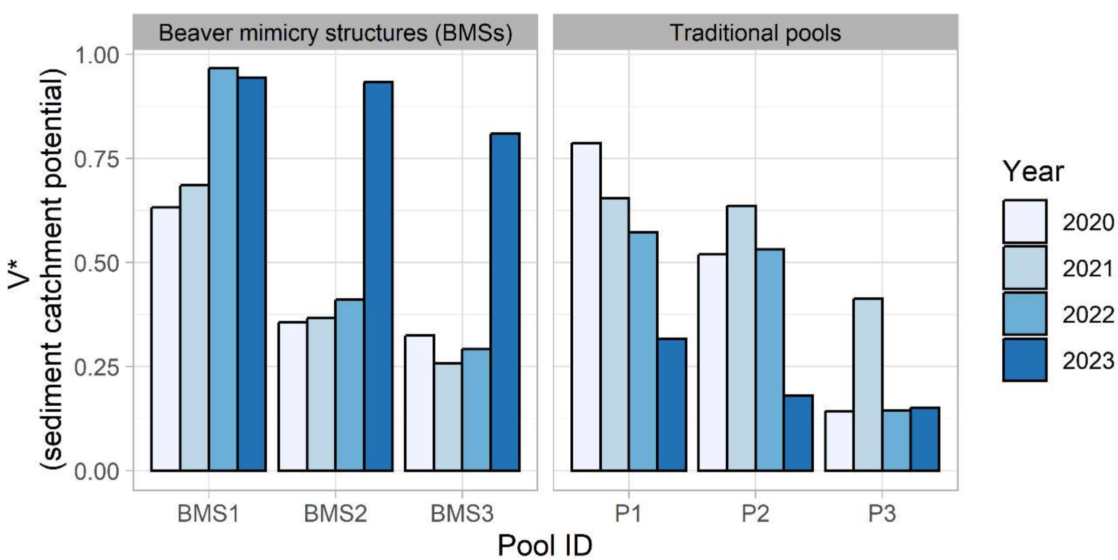

Figure 3. V*, which represents the catchment potential of a BMS/pool, across four years in the geomorphically complex restored upstream project area and the traditionally restored project area. BMSs were located in the upstream project area and traditional pools were located in the downstream project area. The x-axis represents the pool ID (oriented upstream to downstream), and the y-axis represents the V* value, which is on a scale of 0 to 1. Colors represent year of sampling. Higher V* values indicate that the BMS/pool has limited volume remaining to catch and store sediment while lower values indicate that the BMS/pool has more capacity to catch and store future sediment.

Vegetated Bench Complexity

Riparian vegetation responses described below were an *ecological response* to deliberately increased geomorphic complexity and floodplain connectivity implemented during project design and construction.

Introduction

- Plant functional traits (i.e., leaf, stem, and root characteristics) affect ecosystem functioning and also allow species to respond differently to environmental pressures. Planting a native functionally diverse plant palette (mixture of species) is one approach that is thought to be beneficial for limiting invasion by non-native species and also for maintaining ecosystem functions (e.g., biomass production) despite environmental changes.
- The hydrologic setting that plant palettes are planted in is a key consideration in the semi-arid Front Range of Colorado, both in terms of present-day survival of plantings, and for ecosystem trajectories with future environmental change.
- In this summary sheet, we present data, takeaways, and recommendations based on Dr. Isabel de Silva (Shewell) doctoral research of vegetated native cover, non-native cover, and biomass responses to the interactions of different plant mixes and functional traits planted at different floodplain bench elevations. Dr. de Silva (Shewell)'s full dissertation found here.

Acknowledgements

We gratefully acknowledge Dr. Isabel de Silva (Shewell) who collected and analyzed these data.

Research question

1. Do treatments aimed at promoting functional diversity confer stability in productivity and help keep invasion low?

Hypotheses

1. In dry conditions (slow growth strategies typical), upland riparian species accumulate the highest relative biomass, while under wet conditions (fast growth strategies typical), lower riparian species accumulate the highest relative biomass.
2. Increased functional diversity afforded by mixed community treatments buffers productivity across water availability gradients, with lower variability in both biomass and greenness as a function of variability in water availability compared to lowland and upland riparian community types.
3. Invasion will best be explained by water availability, with higher invasion in drier conditions. Regardless, mixed upland-lower riparian seed treatments, regardless of water availability, will confer the most invasion resistant restoration strategy.

Photo of the geomorphically complex site, with ephemeral channels and beaver mimicry structures.

Indicators and why?

- **Total, native, and non-native species cover** were measured in plots at varying elevations (i.e., connection to ground water) after plots were seeded with seed mixes of varying functional traits. These metrics are useful to examine because they provide a snapshot of plant establishment success or failure under different conditions. Plant cover is desirable after restoration for bank stabilization and erosion control. However, invasion by non-natives is always a concern due to the short-term disturbance restoration causes.
- **Variability in biomass**, which was measured using NDVI (i.e., a greenness metric), was another metric that captured success of plant establishment. Using seed mixes that include high functional diversity allow for more species to be successful under broad and narrow environmental conditions, whereas seed mixes with low functional diversity might only be successful under ideal conditions. Variability in biomass captures that success across all plots.

Location at project site

Riparian vegetation monitoring occurred in the upstream project area (Fig. 1). Monitoring only occurred in the geomorphically complex restored upstream project area because this hypothesis specifically examined how varying bench heights, which were only constructed in the upstream project area, influenced riparian vegetation establishment.

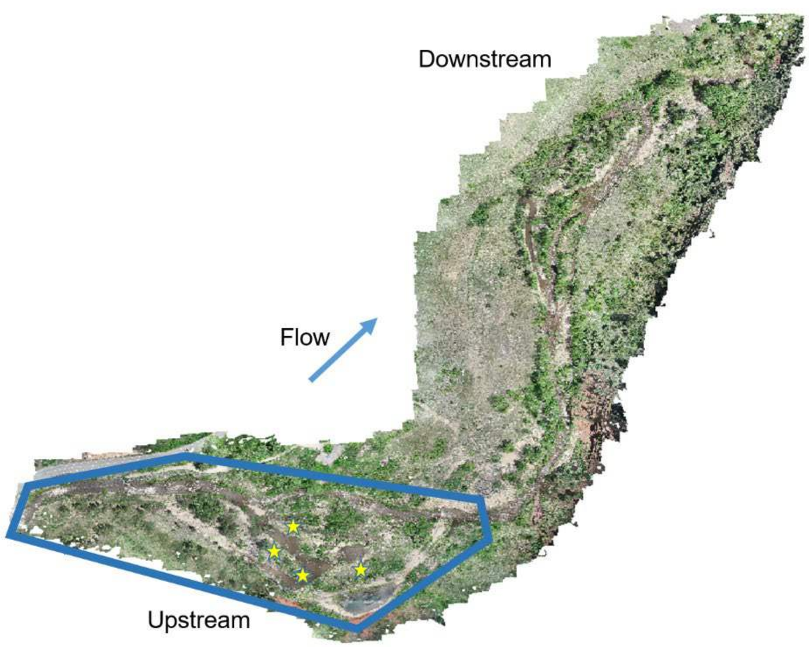

Figure 1. Aerial view of project site. The blue polygon represents the upstream project area. The yellow stars represent approximate locations of riparian vegetation monitoring within upstream project area.

Methods

During the construction of the project, bench elevation relative to the stream was experimentally varied to create lower elevation, middle elevation, and upper elevation benches (Fig. 2A and Fig. 2B). Manipulation of bench heights successfully created a gradient of wetter soil moisture (lower elevation benches) to drier soil moisture (upper elevation benches). Nine plots, each 12m x 2m, were established on each bench for a total of 27 plots. Each plot included tree, shrub, and herb plantings, soil moisture monitoring locations, and LAI and NDVI monitoring locations (Fig. 3). On each bench, three plant community types were planted: lowland riparian community, upland riparian community, and co-mixed lowland-upland riparian community (Fig. 2C). Plant communities were developed from regional native species lists developed in 2017 from the NRCS Emergency Watershed Protection Program, administered through CWCB for all flood recovery projects across the region.

Planting occurred during fall 2019, and plots were monitored for three years during 2020-2022 to determine which treatments had the highest native cover/lowest invasion and lowest variability in biomass production. In total, the planted area was 324 m^2 and included 1,377 planted individuals.

Linear mixed effects models were used to analyze data in R (version 4.1.2). Full methods details in Dr. de Silva (Shewell)'s full dissertation found here.

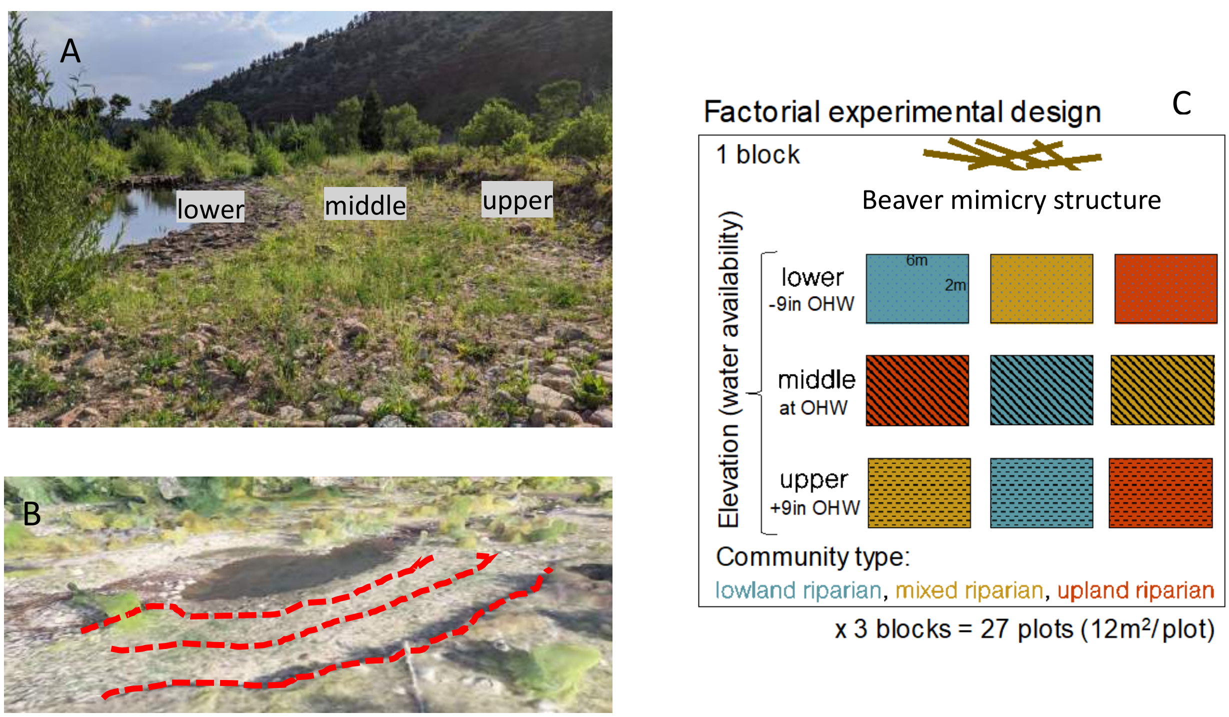

Figure 2. (A) Image showing lower, middle, and elevation benches adjacent to a beaver mimicry structure (BMS). (B) 3D mesh model created from drone imagery showing lower, middle, and elevation benches. Dashed red lines denote the approximate locations of benches boundaries. (C) Schematic diagram of methods. Lowland, mixed riparian, and upland riparian communities were planted on each elevation bench. Figures adapted from Dr. de Silva (Shewell)'s full dissertation found here.

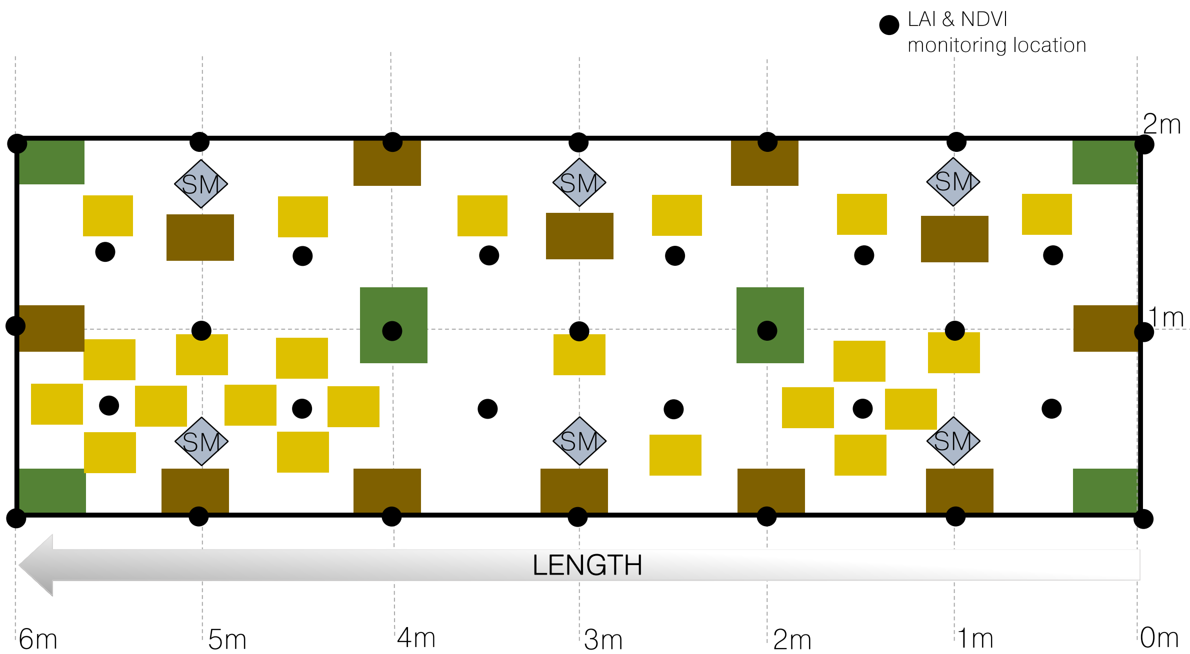

Figure 3. Schematic diagram of planting layout and soil moisture, LAI, and NDVI monitoring locations of each plot. Figure from Dr. de Silva (Shewell)'s full dissertation found here.

Key takeaways

- **Native cover**
  - Native cover was highest in the lower elevation benches planted with a lowland palette (Fig. 4).
- **Variability in biomass**
  - When monitoring biomass via a greenness metric (NDVI), variability in productivity was reduced with higher levels of functional diversity, based on leaf and stem traits (Fig. 5).
- **Invasion**
  - Instead of functional diversity/planting palettes driving invasion trends, we found that soil moisture was the most important factor affecting the degree of invasion, with higher invasion in drier conditions (Fig. 6).
- **Best surviving woody species and their traits**
  - In wet conditions, coyote willow (*Salix exigua*), peachleaf willow (*Salix amygdaloides*), and blue-stem willow (*Salix irrorata*) had the highest survivorship, and generally had notably low stem densities, consistent with a fast, acquisitive growth strategy.
  - In dry conditions, snowberry (*Symphoricarpos occidentalis*), skunkbush (*Rhus trilobata*), narrowleaf cottonwood (*Populus angustifolia)* had the highest survivorship, and

generally had greater nitrogen use efficiencies, consistent with a slow, conservative growth strategy.

- More details provided in Dr. de Silva (Shewell)'s full dissertation found here.

Recommendations for management

- During project design and construction, incorporate lower elevation benches to maximize connection to ground water to enhance survivability of native species and resistance against non-native invasion.
- Perform focused weed control in dry areas – at middle and upper bench heights – in the early years following planting for future projects.
- Continue utilizing a mixed palette approach with an underlying diversity of functional strategies to enhance adaptive capacity in the face of future environmental change and variability.
- Continue monitoring to elucidate long-term trends.
- More details provided in Dr. de Silva (Shewell)'s full dissertation found here.

Figures

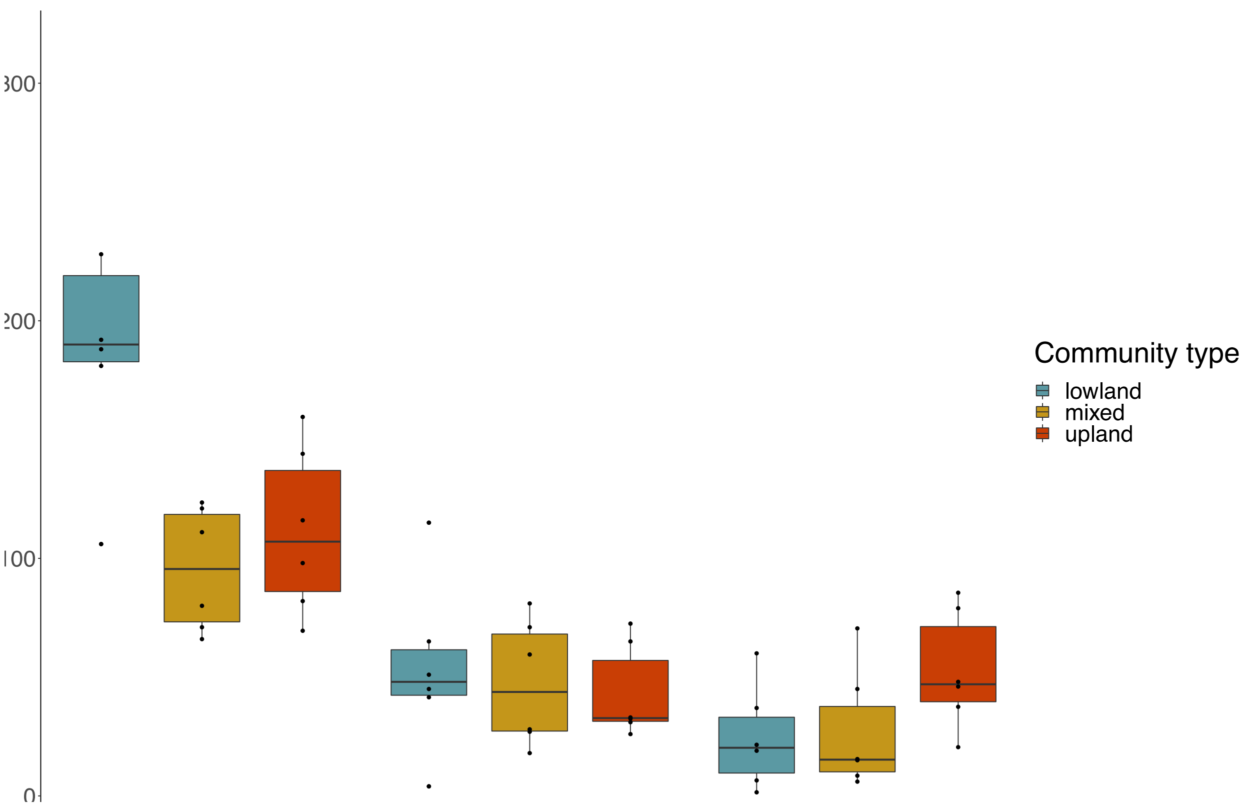

Figure 4. Percent planted native community cover across community type (x-axes, colors) and elevation treatments (panels). Treatments with the same letters do not significantly differ from each other (Tukey's HSD test, $p > 0.05$). Asterisks denote significance where '***'indicates p=0.001, '**'indicates p=0.01, and '*'indicates p=0.05. Total cover of a plot could exceed 100% due to overlapping plant canopies. A linear mixed effects model indicated that there was significantly higher cover of the lowland community treatment in the lower elevations, but not significantly higher cover of the upland community in the upper elevations. Additionally, elevation alone was the strongest predictor of total planted community

cover, with significantly higher planted cover in lower elevations compared to both middle and upper elevations. Figure from Dr. de Silva (Shewell)'s full dissertation found here.

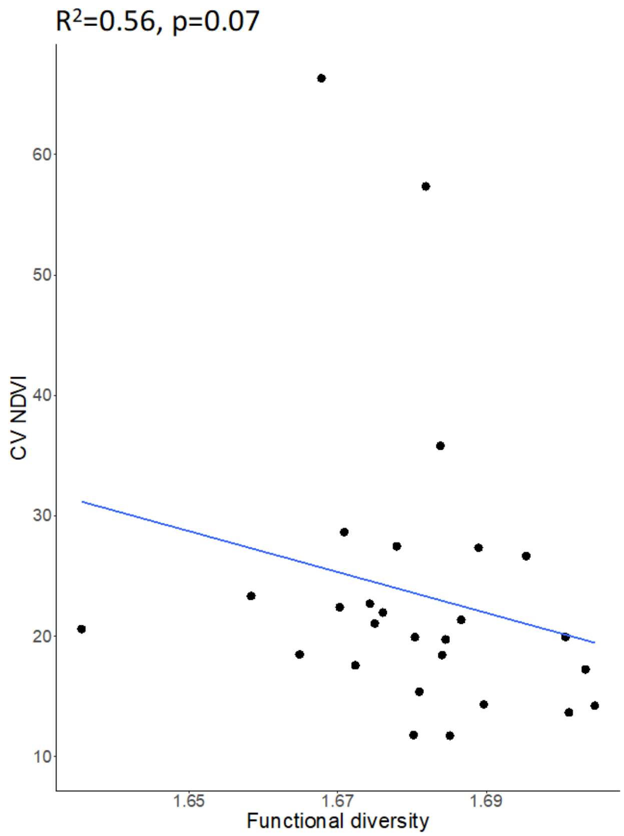

Figure 5. Coefficient of variation (variability) of NDVI (greenness) across native species Shannon functional diversity (x-axis). A linear mixed effects model indicated that there was marginally lower variability in NDVI at high levels of functional diversity. Figure from Dr. de Silva (Shewell)'s full dissertation found here.

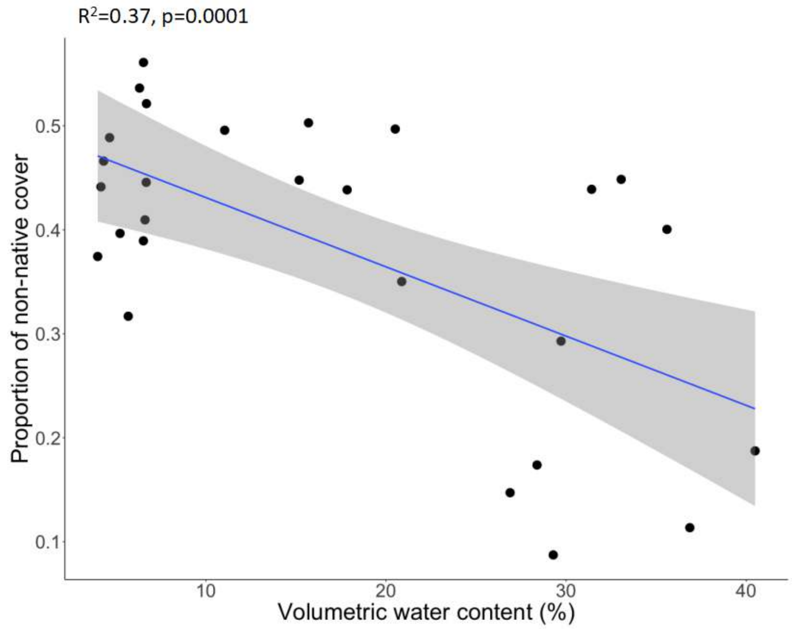

Figure 6. Proportion of non-native cover across soil volumetric water content, averaged across both years of sampling per plot (points). A linear mixed effects model indicated that soil volumetric water content was the sole best predictor of invasion, and inclusion of species diversity or functional diversity (based on traits) did not improve the model. Figure from Dr. de Silva (Shewell)'s full dissertation found here.