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April 20th, 2022

Toni Boggan
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Mrs. Boggan,

This report contains Riverbank Consulting's final report for the construction and monitoring of Beaver Dam Analogs (BDAs) in Thompson Creek and the development of BDA design guidelines. Riverbank Consulting has knowledge from coursework that directly applies to these Beaver Dam Analogs. The team has completed the project with the help of The Lands Council (TLC), Spokane County Public Works, Gonzaga Faculty, and other members.

Tasks completed include construction of the BDAs, development of a monitoring plan, baseline data measurements, a literature review on design guidelines for BDAs, and the development of risk-based design guidelines for BDA designs. Construction of the 18 BDA structures in Thompson Creek was completed in October. Posts were pounded and deciduous material was woven through each structure. The monitoring plan details best management monitoring techniques for data collection for Year One following construction. Baseline data measured thus far includes three cross-sections upstream of each starter dam, a longitudinal profile of Thompson Creek, water and sediment volumes from soil probing upstream of each starter dam, and a summary of total phosphorus concentrations determined from monthly samples taken over the past year. A risk assessment matrix has also been created to help future projects determine the level of analysis required to design their BDA projects.

Due to project task changes throughout the year, the team is currently underbudget compared to the initial design fee estimate. The initial consulting fee was estimated to be $75,000. As the project progressed, certain tasks such as BDA construction, development of a QA/QC plan, and others were overestimated. The current consulting fee is now $45,000.

Thank you for reading Riverbank Consulting's final report on Beaver Dam Analogs in Thompson Creek. The team is excited to be improving the ecosystem health of the Newman Lake area. If there are any questions, please email Sarah Frisby at sfrisby@zagmail.gonzaga.edu.

Sincerely,

Hallie Stalcup	Matthew Roberts	Sarah Frisby
Project Engineer	Project Engineer	Project Engineer

IMPLEMENTATION, MONITORING, AND DESIGN OF BEAVER DAM ANALOGS

FINAL REPORT

Prepared For
The Lands Council
April 20th, 2022

Riverbank Consulting

Project Final Report

Design of Beaver Dam Analogs

CEL - ENSC 27

Presented by:

_____________________ _ _____________________

(Hallie Stalcup) (Sarah Frisby)

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(Matt Roberts)

Reviewed & Accepted By:

_____________________ ____4/20/2022_______________

Faculty Advisor Date

CENTER FOR ENGINEERING DESIGN & ENTREPRENEURSHIP

Executive Summary

Thompson Creek has been dredged for agricultural purposes, which has negatively impacted the health of the surrounding watershed. The straightened channel has enabled water to flow faster than in natural conditions, causing channel incision. This has led Thompson Creek to separate from its floodplain and transport both sediment and phosphorus into Newman Lake. Washington State Department of Ecology (DOE) put Newman Lake on the 303d list in 2007, indicating an unhealthy ecosystem due to high phosphorus loads. One main goal of this project is to reduce the total phosphorus load from Thompson Creek into Newman Lake by 42% (to less than 20 ppb) as indicated in the Total Maximum Daily Load (TMDL) Water Quality Report published in 2007. The 2020-2021 Senior Design team designed a series of Beaver Dam Analogs (BDAs) that were built in Thompson Creek in Fall of 2021. Last year's team also designed a three-year monitoring plan to evaluate the effectiveness of the BDA complex at retaining water, sediment, and phosphorus in Thompson Creek.

On September 29th, 2021, the team went to Thompson Creek with Kat Hall from TLC to locate and mark 18 BDA locations. Some dam locations were changed from last year's design due to topographic and site vegetation restrictions. Construction of the BDAs occurred on two days, October 13th and 28th. On October 13th, posts were pounded into the ground in their respective locations. On October 28th, deciduous branches were woven between the posts so the BDAs could start ponding. This day also focused on the Community Engaged Learning requirement. Members such as Gonzaga's stream restoration class, a Newman Lake community member, and Spokesman Review Newspaper reporter came to Thompson Creek. The team discussed the plans for the BDAs with a community member and listened to her thoughts on the project, which can be found in the social impact section of this report, section 4.4.3.

To ensure that the effects of the BDAs are monitored, a monitoring plan has been developed that was implemented post-construction to record effectiveness of the BDAs in retaining water and reducing sediment and phosphorus loads entering Newman Lake over the first year. Water and sediment volumes retained by the BDAs were measured and water samples were taken and tested for phosphorus concentrations upstream and downstream of the BDA complex throughout the year. Cross-sections, longitudinal surveys, and soil probing was completed this year and is to be completed annually to track the changes of the channel bed and water levels. To document baseline conditions prior to BDA installation, three cross-sections and one longitudinal profile were surveyed upstream of each starter dam. Soil probing data was collected and analyzed upstream of each starter dam and showed that current water volumes range from 261 to 706 cubic ft., and sediment volumes range from 221 to 354 cubic ft (Table 2). Over the past year, total phosphorus concentrations were measured monthly, and were found to range from a minimum of 40 ppb in June 2021 to a maximum of 58 ppb in July 2021, with an average of 46 ppb. Monitoring results will continue to be examined by future Senior Design teams led by Dr. Sue Niezgoda to measure total phosphorus loads entering Newman Lake and complete field surveys. Adaptive management is highly encouraged to increase team effectiveness such as adjusting monitoring protocols.

In addition to the BDA construction and monitoring, the team has also created a BDA risk assessment matrix to act as design guidelines for future BDA projects. This matrix breaks down the different risk factors associated with BDA implementation and organizes them into two categories: local context risks and structural failure risks. These risks were determined through the team's experience implementing the Thompson Creek BDAs, reviewing the existing literature, and doing structural analysis with the BDA Design Tool (see Section 4.3 for more detail). After visiting the site and utilizing the risk assessment matrix, any team in the future will be able to easily tell what types of design analyses will be required before implementing their project. This can help reduce risk, make BDA projects easier to approve, and streamline the site assessment process.

The team has also analyzed the sustainability and social impact of implementing the BDAs at Thompson Creek. The team has made recommendations for ways to further reduce the environmental impact of BDA implementation, however Riverbank Consulting does note that this is already a relatively low-impact technique. The team also describes what they have learned about the impacted community through interviews and the SRTC's Social Equity Mapping Tool.

Riverbank Consulting's key deliverables included BDA construction, development of a monitoring plan, and design guidelines for BDAs in any reach. Throughout the project the team remained on schedule, met required deadlines, and came out $30,000 underbudget. Riverbank Consulting could have spent more work on fieldwork items, but ultimately put in less hours than initially anticipated. The QA/QC could have been improved overall.

Finally, this report notes a few areas where the work on Thompson Creek BDAs should continue. It describes adaptive management such as sealing the BDAS, the importance of continued monitoring, as well as potential to further develop the risk assessment guidelines for publication.

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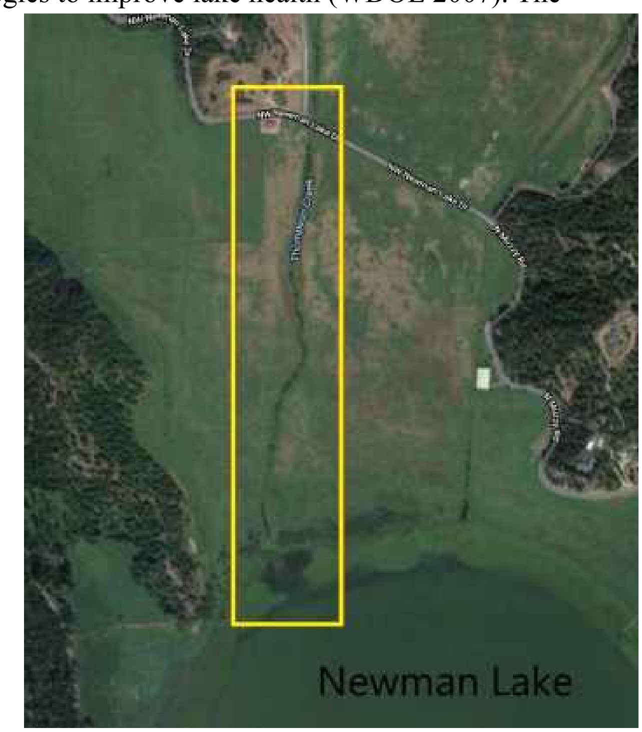
1.0 Project Description

Thompson Creek is a primary tributary to Newman Lake, located Northeast of Spokane, Washington. Figure 1 shows the location of Newman Lake within the yellow box. Thompson Creek has been straightened for agricultural purposes which has negatively affected the health of the river and downstream lake. Natural rivers have sinuosity to them. The straightening of Thompson Creek reduced channel roughness and increased the velocity of flow, resulting in bank erosion and channel incision. This resulted in Thompson Creek being disconnected from its floodplain and an increase in sediment and pollutant transport into Newman Lake. Disconnecting the creek from its floodplain allowed reed canary grass to overtake the area and limit vegetation diversity. There is very little biodiversity along Thompson Creek. An aerial image of Thompson Creek project area can be found in Figure 2.

Newman Lake was recommended for inclusion on the 303(d) list for total phosphorus by the DOE. Once Newman Lake made the 303(d) list, a TMDL study was required to identify the sources of phosphorus, set a target concentration limit, and come up with strategies to improve lake health (WDOE 2007). The report identified a total phosphorus load of 1,480 kilograms entering the lake, with 636.4 kilograms coming from Thompson Creek. The TMDL identified a goal of reducing the total phosphorus entering from Thompson Creek to 365 kilograms, reducing the total phosphorus by 42%. The TMDL reports a limit of 20 ppb for total phosphorus entering Newman Lake from Thompson Creek. In addition, the report identifies suggested improvement activities that should be completed at Thompson Creek to help restore riparian corridors to their natural state.



One solution to restore riparian corridors and reduce phosphorus loading is to construct Beaver Dam Analogs (BDAs) in Thompson Creek. BDAs are man-made beaver dams that are strategically placed to allow sediment and phosphorus to settle out. Pollutants settle out because of pooling and a reduced flow velocity in the creek. BDAs will help to reconnect Thompson Creek to its floodplain and create a healthier ecosystem.

The 2020-2021 Senior Design team designed a BDA complex as the basis for this project using a watershed assessment, reach-scale processes assessment, and hydraulic modeling (HEC-RAS). The BDA complex consists of a sequence of roughness features and BDAs as shown in Figure 3. This complex was designed to not adversely affect nearby property owners. Phase I of the plan created by last year's team will be the focus of work completed this year by Riverbank Consulting. Photos that provide examples of the different structures in the design are provided in Figures 4-7. A three-year monitoring plan was developed by last year's team and will be used for this project. The monitoring plan assesses the impacts and effectiveness of the BDAs after installation by measuring the ability to trap sediment, cause ponding, and decrease phosphorus levels entering Newman Lake.

Figure SEQ Figure * ARABIC6: Example of a Constrictor Dam (Photo Credit: Scott Shahverdian, October 20, 2017)

BDA design is fairly new so there are no set design standards. There is a large range of types of design from low-tech methods (i.e., adaptive management) to high-tech methods (i.e., computer software analysis). BDAs generally are a low-risk design to implement, especially if there is limited infrastructure nearby. However, BDAs might require a more advanced hydraulic and structural analysis to determine potential impacts if the project has a narrow floodplain, nearby infrastructure, or a FEMA mapped floodway. Building BDAs can carry a high level of associated risk for the engineer that stamps a project because of the wide variation in possible design techniques and a lack of regulations related to BDA design and construction. Riverbank Consulting has outlined a set of design analysis guidelines for future designers such as project managers, engineers, and regulators. The guidelines will assist the designer and regulator in selecting an appropriate design methodology that can help minimize risk.

2.0 Project Goals and Objectives

2.1 Project Goals

The goals of this Beaver Dam Analog (BDA) project are: 1) determine if BDAs can be an effective means of sediment and phosphorus load reduction in severely impacted downstream receiving waters, and 2) to develop BDA design guidelines for use on future BDA projects throughout other watersheds to significantly improve water quality. These goals will be met by accomplishing the objectives below.

2.2 Project Objectives

The objectives of this project include:

- **Construct BDAs in Thompson Creek**
    - Coordinate with TLC for construction.
    - BDAs installed include primary, secondary, channel spanning, and constrictor dams.
    - BDAs will trap sediment and phosphorus, reconnect the floodplain, and improve ecosystem health by increasing channel roughness and creating ponding.
- **Implement Year One of the BDA Monitoring Plan**
    - Monitoring plan was designed by the previous Senior Design team. The plan has been updated for Year One application.
    - Monitoring plan measures the effectiveness of BDAs in Thompson Creek, with effectiveness defined as the ability to create ponding, trap sediment, and decrease phosphorus levels entering Newman Lake.

    - Calibrate the existing stream gage to provide a continuous record of flow.
    - Quantify the total phosphorus load entering Newman Lake by taking consistent water samples and testing them in a laboratory.
    - Evaluate the change in sediment storage by conducting field surveys.
    - Evaluate the effect of BDAs on water storage using drone aerial imagery.
    - These results will be summarized, and recommendations will be given to TLC and Spokane County regarding BDA management in Thompson Creek.
- **Develop BDA Design Guidelines for Project Managers, Engineers, and Regulators**
    - Provide guidance for determining the applicable type of design analysis (i.e., low, medium, or high-tech) to evaluate, and thereby minimize, the risk associated with BDAs implementation. This guidance will be developed as follows:
        - Perform a literature review to find current design practices for BDAs, with the emphasis on researching design criteria, methods, and tools and level of resources used to design BDA restoration projects.
        - Identify and specify potential failure risks that come with BDAs such as flooding and structural failures.
        - Identify factors that can lead to BDA failure based on the risk associated with possible failures. Factors that will be considered include hydraulic considerations related to beaver dam viability, structural consideration, river context, and regulatory requirements (FEMA). Both 1D and 2D hydraulic modeling and the BDA Design Tool will be used to quantify hydraulic and structural failure risk factors under a variety of loadings and applications and in a variety of stream reaches with varying stream power.

3.0 Project Requirements, Constraints, and Deliverables

3.1 Sponsor Requirements

There are four main tasks required by TLC. The first task is the construction of the Beaver Dam Analogs (BDAs) in Thompson Creek followed by the second task of implementing the Year One Monitoring Plan. The third task is the development of BDA design guidelines to minimize risk and the fourth and final task is to evaluate sustainability and social impacts associated with BDAs. To meet these requirements, Riverbank Consulting has developed a schedule to make sure that the main project tasks are completed on time, while simultaneously tracking design costs and the hours worked to stay within budget. All deliverables for the project will be reported to Dr. Sue Niezgoda, the Project Advisor.

3.2 Constraints

Constraints throughout the course of the project may limit data collection, monitoring, and adaptive management of the BDAs. Riverbank Consulting is constrained to finish the project within the senior design timeframe, cost, equipment, and personnel needed to complete parts of this project. Furthermore, weather such as snowfall in the winter, and spring flooding, may limit access to the site. While Riverbank Consulting will not be working on the project in the summer, summer wildfires may pose a threat to future monitoring efforts, as well as the health of the BDAs. BDAs are also a rather new idea in the pursuit of restoring rivers and creeks, which limits the amount of research and data that exists to design BDAs.

Most of the constraints Riverbank Consulting faced were due to weather. Thompson Creek was frozen in the winter and the ice may have influenced the accuracy of phosphorus samples. After the ice melted there were very high flows that restricted Riverbank Consulting's access to get in the creek and record cross-sectional survey data in the spring.

3.3 Codes, Regulations, and Guidelines

As previously stated, Beaver Dam Analogs (BDAs) are a new concept, and there are no specific codes associated with them. There are, however, a few guidance documents such as The Beaver Design Guidebook and Low-Tech Process-Based Restoration of Riverscapes: A Design Manual, that have been released. Riverbank Consulting has reviewed and summarized these guidelines in the literature review section of this document, section 4.3.1. Riverbank Consulting also referenced monitoring plans, and other observations that previous groups have gathered to supplement the existing guidelines.

Riverbank Consulting referenced the following documents to further guide the design process of BDAs:

- Washington Department of Fish and Wildlife Water Crossing Design guidelines (WDFW 2013)
- Stream and Watershed Restoration (Roni and Beechie 2013)
- FEMA flood mapping (FEMA 2010)
- Thompson Creek Beaver Dam Analog Stream Restoration Project Final Report (Denning, Whittlesey 2021)
- BDA Monitoring Plan Development (Denning, Whittlesey 2021)
- Total Phosphorus Monitoring Program for the Thompson Creek BDA Project: QAPP (2021)
- Newman Lake Total Phosphorus TMDL Water Quality Improvement Report (2007)
- Beaver Restoration Guidebook Version 2 (2017)
- Low-Tech Process-Based Restoration of Riverscapes: Design Manual (2019)

The Low-Tech Process-Based Restoration of Riverscapes provides guidelines for implementing low-tech tools such as BDAs and post-assisted log structures (PALS) on rivers. The focus is on using simple and low-cost designs that are hand-built, use natural materials, and have low design requirements. BDAs are meant to be short-term structures that allow the system to do the work. After a BDA is installed and sediment builds up, the incised channel fills in, the bottom channel elevation rises, and the stream begins to re-establish itself and connect with the floodplain. Once this has been achieved, the BDA has done its job and remains as a structure within the stream. Riverbank Consulting installed 18 BDAs within Thompson Creek to attempt to achieve this goal.

Regulations for Thompson Creek came from the Spokane County Flood Damage Protection Ordinance (SCDPO) (Section 3.20.650). This ordinance requires that one must "obtain engineering studies from development proponents showing the impact of the proposed development on the base flood elevation…" However, this can be waived at the County Engineer's discretion if the new development's "placement of in-stream works for the sole purpose of fish habitat enhancement or stream restoration where it is readily apparent that there will be no negative impact on adjacent properties and structures". Discussions with District Staff resulted in a consensus that due to the BDAs' low profile, the proposed BDA complex would have minimal impact on large scale flood events (e.g., greater than 5-10 years). This allowed for the waiving of Section 3.20.650 of the SCDPO. As outlined by last year's senior design team, the following design requirements were followed:

- Back water from BDA complex is not to raise flood flows at the NW Newman Lake Road Bridge and roadway profile
- Flood elevations for all flow profiles will not encroach on the adjacent Newman Lake Fire Department property

There are multiple permits that were required to construct the BDAs in Thompson Creek. Kat Hall and TLC worked to acquire all permits. Riverbank Consulting interviewed Kat Hall to learn of all the necessary permits to construct BDAs in Thompson Creek. There are not as many extensive permits for

Thompson Creek when compared to a project with greater risk, such as a bridge design. One necessary permit was through the Washington Department of Fish and Wildlife, called the Hydraulic Project Approval (HPA). This permit ensures that the project is not detrimental or damaging to the stream or fish habitat. Another permit, through Army Core of Engineers. Under Section 404 of the Clean Water act, required a permit if there was any dredging or filling. Since there is no dredging or filling with the installation of beaver dam analogs, no permit required letter was received. Additionally, a joint aquatic resources project application (JARPA) permit was submitted so there was record but no permit was issued. Another permit was submitted in regard to Ecology's Clean Water Act Section 401 Certification. This certifies that a project can maintain/improve water quality standards.

Spokane County requires a Flood Plane Development permit (FPDP). There is a buffer on the edges of Newman Lake that development is not allowed in. Thompson Creek need to pass the critical areas ordinance that BDAs were not constructed within the critical buffer zone. HPA requires a landowner const form and a 10-year landowner agreement. This is proof that the landowner agrees with the specified work to be completed on their land and that the landowner will not destroy the design that was built.

A grant was submitted to the Department of Ecology for funding. This grant required a landowner agreement and a cultural resource review. The project details were sent out to all potentially affected tribes in the area, and they were given a chance to provide feedback including the Spokane, Kalispell, Colville, and Coeur d'Alene tribes. The tribes were able to request an archaeological survey if they thought the BDAs could disturb buried remains or artifacts.

3.4 Deliverables

Deliverables for Riverbank Consulting include the following:

- Construct BDAs in Thompson Creek
    - Record as-built conditions
- Develop a monitoring plan
    - Review existing monitoring plan
    - Identify new hypotheses
    - Design Year One monitoring plan
    - Develop QA/QC plan for monitoring activities
- Collect and analyze relevant data
    - Soil probe Thompson Creek for sediment and water volumes
    - Perform cross-sectional surveys
    - Perform longitudinal surveys
    - Collect water samples for phosphorus concentrations
- Review literature on BDA design methods
- Review literature on BDA risk assessment methods
- Provide guidelines for design of BDAs based on level of risk
- Complete sustainability and social impact assessment
    - Interview Dawn Matthews from Spokane County
    - Social equity mapping analysis
    - Interview Newman Lake community member(s)
- Give conclusions and recommendations for future work

4.0 Design Solutions

4.1 Construction

4.1.1 BDA Construction in Thompson Creek

To properly prepare for construction of the Beaver Dam Analogs (BDAs), Riverbank Consulting reviewed the project design from last year's team. On September 29th, 2021, the team went out to Thompson Creek with Kat Hall from TLC and staked out the BDA locations. Some locations of the dams were changed from the original design to accommodate topographic and vegetation site restrictions. Stakes were placed to locate primary, secondary, constrictor, and channel spanning dams (18 total). The color of the ribbon tied to the stake represented the type of dam to be installed. Figure 8 shows Matt, a project engineer, placing a stake. During this process, a summary of experience was recorded to meet Community Engaged Learning requirements which can be found in Section 4.4.3.

4.1.2 Construct BDAs

The construction of the dams was undertaken at the locations identified in 4.1.3 As-built Conditions by TLC, Gonzaga University Faculty and students, and a variety of other volunteers. The team helped with pounding posts on October 13th, 2021. Figure 9 shows Starter Dam 1 after post construction. There are a total of three starter dams each with three rows of posts. All other dam structures had one row of posts as shown in Figure 10. Approximately 300 posts were pounded with the help of Brian Walker from U.S. Fish and Wildlife and Kat Hall from TLC. Posts were installed by lifting a hydraulic post pounder onto a post, raising the post to a vertical position, turning on the hydraulic post pounder, and guiding the post to be drilled straight into the ground (see Figure 11). These posts were pounded into the ground approximately half the height of the post (5-6 ft). As the post pounder was very heavy and loud, hard hats with ear protection were used to protect the team.

Figure 9: Looking downstream at Starter Dam 1 after pounding posts on October 13th, 2021

Figure 11: Pounding posts in with a hydraulic post pounder on October 13th, 2021

After pounding posts was completed, the team went out on October 28th to weave materials through the posts. This is a crucial step to seal the BDAs, so that they attain their goal of creating ponding and encouraging settling out of sediment. The deciduous material was woven to the height of the floodplain within the channel. To complete Community Engaged Learning (CEL) requirements, community members were invited out to this weave day along with Gonzaga's stream restoration class taught by Dr. Sue Niezgoda. In fact, one member on the Newman Lake Property Owners Association came and supported during the construction process. She shared that the community greatly values the lake, and the water quality in the past has inhibited her ability to swim there due to algae blooms in the summer. She was excited to see how the implementation of the BDAs can improve Newman Lake.

Eli Francovich, a newspaper reporter from The Spokesman-Review, came out to the field that day and interviewed fellow students, Kat Hall, and the Senior Design Team. An article was published in The Spokesman-Review about this project (Francovich, 2021). Figure 12 shows Sarah Frisby, project engineer, in the middle of a completed BDA and Figure 13 shows a completed starter dam. The mudding and sealing of the BDAs were not completed yet due to very cold water temperatures making it uncomfortable and potentially unsafe to seal below the water line. This remains an outstanding task that will be completed by TLC in Summer 2022 when water temperatures are warmer. There is hope that the BDAs will begin to seal on their own in response to higher flows in the Spring allowing for the collection of material that can fill in the openings.

4.1.3 As-built Conditions

The completed reach with structures located can be seen in Figure 14. Note, channel spanning dams (CS) are red, constrictor dams (C) are purple, post-line wicker weave dams (PLWW) are blue, and starter dams (SD) are yellow. These locations are based on GPS coordinates taken out in the field.

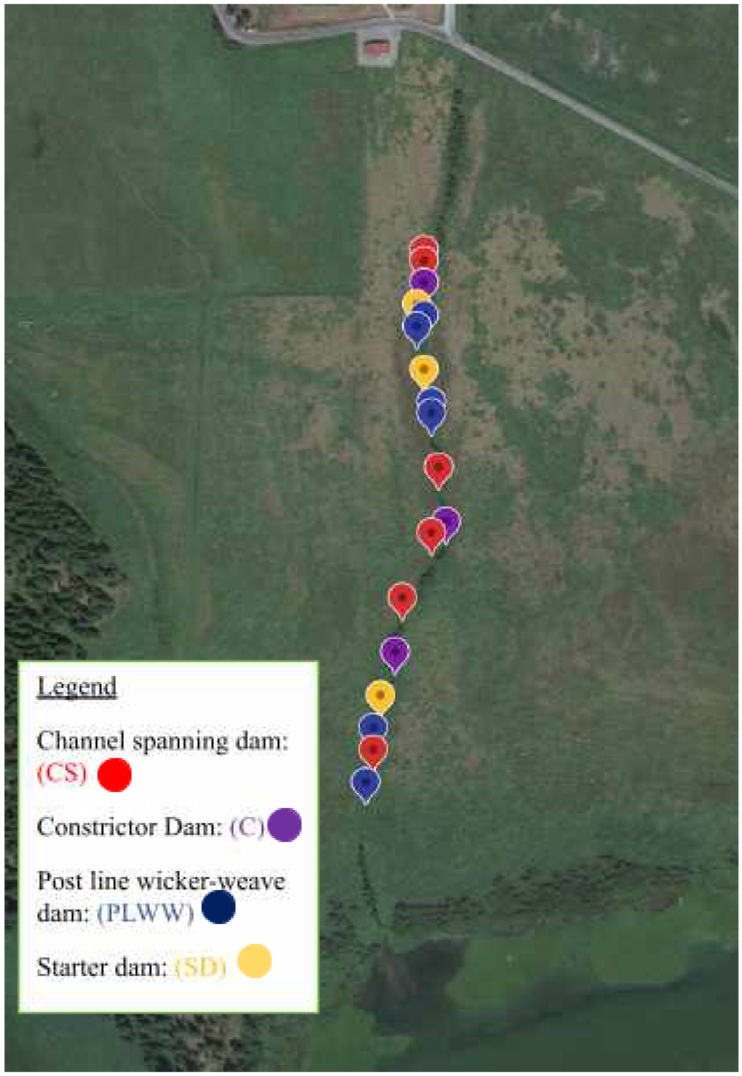


Figure 14: Final BDA Locations in Thompson Creek

A design manual on low-tech process-based restoration (LTPBR) was referenced for the design and monitoring of the BDAs in Thompson Creek. This protocol was developed by Joe Wheaton and others at Anabranch Solutions. Joe Wheaton is one of the original developers of BDAs and has created this monitoring protocol for BDAs and other low-tech restoration structures. Benefits of using this protocol include the documentation of design, implementation, and monitoring of the structures. The benefit of using this allows for field structure surveys, field geomorphic unit surveys, and remote riverscape surveys. These can capture the distribution and characteristics of habitat units and can record the digital version of the valley bottom features and how they may change through time. This protocol is applicable for repeat monitoring surveys at discrete survey events. The database also has data collection and management tools that are applicable for Thompson Creek. LTPBR has built in mapping, can export data, and is used throughout design development, implementation, field data collection, and report preparation. As emphasized in Figure 15, the report captures visual change overtime. Figure 15a shows starter dam number one when first constructed and Figure 15b shows one month after construction. The structural integrity and hydraulics around the structure can be visually seen in these reports.

Figure 15: Starter Dam #1 when A) first constructed and B) one month after construction

As-built conditions were recorded using the associated LTPBR Monitoring Protocol (Riverscapes Restoration Guide Manual). The database (FileMaker Go) is used in the field on an iPad. The monitoring protocol database contains information such as projects, reaches, complexes, and structures. These features must be added by hand and contain things such as images and helpful descriptions such as the fire house location, latitude/longitude of all BDAs, and material volumes for each BDA.

Different features captured using the protocol include:

1. Project Description – describes the overall project and location.
2. Project Area – things such as a notable riverscape feature or human infrastructure.
3. Photo Point – image of completed BDA along with latitude/longitude and description.
4. Structures – a description of all types of BDAs installed and their purpose.
5. Structure Type Descriptions – gives specific quantities of posts and deciduous branches for each structure.

Figures 16-20 show the different features captured by the team immediately after construction of the BDAs. A full as-built conditions report from the LTPBR monitoring protocol can be found by contacting Dr. Sue Niezgoda.

PROJECT OVERVIEW

PROJECT COORDINATING ENTITY
The Lands Council

PROJECT WATERSHED
Thompson Creek

TREATMENT REACHES	TREATMENT LENGTH (KM)	CONTROL REACHES	CONTROL LENGTH (KM)
1	0.70	0	0.00

TOTAL COMPLEXES	TOTAL STRUCTURES	STRUCTURE TYPES	IMPLEMENTATION PHASES
3	18	18	1

PROJECT DESCRIPTION

BDA Complex implemented to retain water, sediment, and total phosphorus in Thompson Creek and Newman Lake. Goals are to reduce total phosphorus entering Newman Lake and reconnect Thompson Creek with its floodplain.

REACHES

TYPE	REACH NAME	STREAM NAME	REACH LENGTH (KM)	FLOODPLAIN AREA (KM) CURRENT	TARGET
Treatment	Thompson Creek	Thompson Creek	0.70	1.05	3.50

STRUCTURE TYPES

TYPE NAME	MIMICS
BDA PLWW #1	Beaver Dam
BDA PLWW #2	Beaver Dam
BDA PLWW #3	Beaver Dam
BDA PLWW #4	Beaver Dam
BDA PLWW #5	Beaver Dam
BDA PLWW #6	Beaver Dam

IMPLEMENTATION PHASES

PHASE	DATE	STRUCTURES
Phase 1	Oct 20, 2021	18

THOMPSON CREEK TP BDA PROJECT

Figure 16: Project Overview Report

PROJECT AREA FEATURES

ABANDONED SIDE CHANNEL

REACH NAME
Thompson Creek
FEATURE TYPE
Riverscape Feature
FEATURE DESCRIPTION
Left floodplain channel that used to be active, we wish to reactivate with constrictor dam.

LATITUDE 47.801190
LONGITUDE -117.105600

BRIDGE CROSSING

REACH NAME
Thompson Creek
FEATURE TYPE
Human Infrastructure
FEATURE DESCRIPTION
Newman Lake Road bridge crossing with Thompson Creek.

LATITUDE 47.803590
LONGITUDE -117.105100

FIRE STATION

REACH NAME
Thompson Creek
FEATURE TYPE
Human Infrastructure
FEATURE DESCRIPTION
Fire station building edge.

LATITUDE 47.803560
LONGITUDE -117.106400

PAGE 1 OF 0 THOMPSON CREEK TP BDA PROJECT

Figure 17: Project Area Features Report Example

PHOTO POINTS

AS-BUILT BDA PLWW #3

REACH NAME
Thompson Creek

DESCRIPTION
As-built photo of BDA PLWW#4. Photo taken looking downstream from RB.

CAMERA FACING	CAMERA STANDING
Down Valley	Bank Right
LATITUDE	LONGITUDE
47.800120	-117.105623

MIN DATE	MAX DATE	REPEAT PHOTO COUNT
Nov 13, 2021	Nov 13, 2021	1

AS-BUILT BDA PLWW #4

REACH NAME
Thompson Creek

DESCRIPTION
As-built photo of BDA PLWW #4. Photo taken looking downstream from RB.

CAMERA FACING	CAMERA STANDING
Down Valley	Bank Right
LATITUDE	LONGITUDE
47.799976	-117.105619

MIN DATE	MAX DATE	REPEAT PHOTO COUNT
Nov 13, 2021	Nov 13, 2021	1

AS-BUILT BDA PLWW#1

REACH NAME
Thompson Creek

DESCRIPTION
As-built photo of BDA PLWW#1. Photo taken looking downstream from RB.

CAMERA FACING	CAMERA STANDING
Down Valley	Bank Right
LATITUDE	LONGITUDE
47.800857	-117.105731

MIN DATE	MAX DATE	REPEAT PHOTO COUNT
Nov 13, 2021	Nov 13, 2021	1

PAGE 1 OF 0 THOMPSON CREEK TP BDA PROJECT

Figure 18: Photo Points Report Example

STRUCTURES

CHANNEL SPANNING DAM #1: 1.1

REACH NAME	COMPLEX NAME	COUNT	DATE BUILT
Thompson Creek	BDA1	1	Oct 12, 2021

LATITUDE	LONGITUDE
47.801500	-117.105600

STRUCTURE DESCRIPTION

Channel Spanning (porous) Dam #1 - provide roughness to slow flow velocities
22 posts, 3 ft high weave - single row

CHANNEL SPANNING DAM #2: 1.2

REACH NAME	COMPLEX NAME	COUNT	DATE BUILT
Thompson Creek	BDA1	1	Oct 15, 2021

LATITUDE	LONGITUDE
47.801440	-117.105670

STRUCTURE DESCRIPTION

Channel Spanning (porous) Dam #2- to provide roughness to slow velocities
8 posts, 3ft high weave - single row

CONSTRICTOR DAM #1: 1.3

REACH NAME	COMPLEX NAME	COUNT	DATE BUILT
Thompson Creek	BDA1	1	Oct 15, 2021

LATITUDE	LONGITUDE
47.801200	-117.105700

STRUCTURE DESCRIPTION

Constrictor Dam #1- Deflector dam to force water into left bank to erode and increase sinuosity
8 posts, 3 ft high weave - single row

BDA STARTER DAM #1: 1.4

REACH NAME	COMPLEX NAME	COUNT	DATE BUILT
Thompson Creek	BDA1	1	Oct 15, 2021

LATITUDE	LONGITUDE
47.800980	-117.105770

STRUCTURE DESCRIPTION

BDA Starter Dam #1 which acts as main dam to create pond and promote sediment and TP retention
60 posts, 4 ft high weave - 3 rows

PAGE 1 OF 0 THOMPSON CREEK TP BDA PROJECT

Figure 19: Structures Report Example

STRUCTURE TYPE DESCRIPTIONS

BDA PLWW #1

STRUCTURE MIMICS	TOTAL POSTS	SEDIMENT DEPTH (IN.)
Beaver Dam	20	0

HEIGHT (FT.)	LENGTH (FT.)	WIDTH (FT.)	POST DIAM (IN.)	POST SPACING (FT. / POST)
3.0	20.0	2.0	3	3.0

MATERIAL NAME	QUANTITY
Deciduous Branch	50
Posts	18

STRUCTURE TYPE DESCRIPTION

Secondary dam to protect starter dam #1 sealed to backwater

BDA PLWW #2

STRUCTURE MIMICS	TOTAL POSTS	SEDIMENT DEPTH (IN.)
Beaver Dam	20	0

HEIGHT (FT.)	LENGTH (FT.)	WIDTH (FT.)	POST DIAM (IN.)	POST SPACING (FT. / POST)
3.5	20.0	2.0	3	3.0

MATERIAL NAME	QUANTITY
Deciduous Branch	50
Posts	18

STRUCTURE TYPE DESCRIPTION

Secondary dam to protect starter dam #1 and sealed to backwater

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Figure 20: Structures Type Descriptions Report Example

4.2 Year One Monitoring Plan Development and Application

To evaluate the overall success of the constructed BDAs, the monitoring plan developed by the 2020-2021 design team was reviewed and immediately implemented to track the progress of the structures. This monitoring plan included things such as surveys to track physical changes within Thompson Creek and collecting phosphorus samples to meet TMDL standards. The Thompson Creek BDA Project Year One Monitoring Plan is presented in the following sections and includes hypotheses, methods, and procedures on how to evaluate the changes that Thompson Creek undergoes for year one.

4.2.1 Review of Existing Monitoring Plan

Riverbank Consulting reviewed last year's team's literature review results and the final monitoring plan in order to understand what was proposed for the monitoring plan this year. Riverbank Consulting also reviewed the Thompson Creek BDA Project Total Phosphorus Quality Assurance Project Plan (QAPP) that describes the total phosphorus monitoring plan. The goal of reviewing the monitoring plan was to better understand the following key components:

- Monitoring Hypotheses
- Selected Monitoring Data Metrics
- Data Collection Methods (including personnel and equipment needed)
- Monitoring Schedule and Costs
- QA/QC for Data Collection and Analysis including QAPP for Total Phosphorus
- Results of baseline monitoring data collection

Last year's Senior Design Team developed a monitoring plan that included three hypotheses. These hypotheses are as follows:

- The implementation of BDAs in Thompson Creek will increase water storage (volume) within the landscape.
- The ponds formed by the BDAs implemented in Thompson Creek will increase sediment storage in excess of local channel storage.
- The addition of BDAs in Thompson Creek will reduce the phosphorus levels entering Newman Lake to less than 20 milligrams/Liters (mg/L) as laid out in the DOE TMDL Report.

These hypotheses gave Riverbank Consulting success in trapping a baseline for anticipated goals of the project. The monitoring plan tracks Thompson Creek's sediment, notes any increases in ponding, and assesses any decrease in phosphorus levels that are entering Newman Lake over the next two years.

4.2.2 Identify Hypotheses

Using the information provided from last year's team and Riverbank Consulting's knowledge, new hypotheses were identified to guide the Year One Monitoring Plan. The three new specific hypotheses are as follows:

- o The implementation of Beaver Dam Analog Starter Dams in Thompson Creek will increase water storage upstream of the Starter Dams in excess of initial channel storage by at least 10% after one year. Figure 21 shows an example visual of increased water storage.

Figure 21: Example of Increased Water Storage in Beaver Creek (BDA Construction on Bear Creek showing finished structure)

- The ponds formed by the BDA Starter Dams implemented in Thompson Creek will increase sediment storage upstream of the Starter Dams in excess of pre-implementation channel storage by at least 10% after one year. Figures 22 and 23 show a before and after example in Triple Creek of how sediment increases upstream of a BDA.

Figure 22: Example of Initial Sediment Level at Triple Creek (Okanogan Highlands Alliance, 2020)

Figure 23: Example of Final Sediment Level at Triple Creek (Okanogan Highlands Alliance, 2020)

o The addition of the BDA complex in Thompson Creek will reduce total phosphorus concentrations between the inlet (upstream of all BDAs) and outlet (downstream of all BDAs and entering Newman Lake) by at least 5% after one year. See Figure 24 for the initial and goal concentrations after 1 year of implementation.

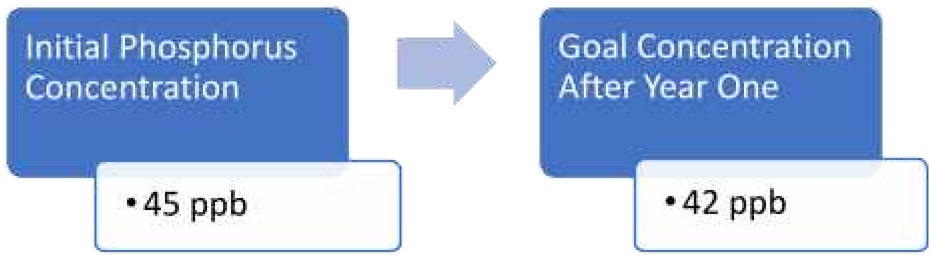


Figure 24: Initial and goal phosphorus concentrations after one year of implementation of BDAs.

4.2.3 Design Year One Monitoring Plan

After developing clear hypotheses, monitoring methods were developed each with their own description and procedure. Monitoring methods applied to test these hypotheses included Drone Aerial Imagery, Water Depth Profiling, Soil Probing, Repeat Cross-Section Surveys, Repeat Longitudinal Profile Surveys, and Total Phosphorus testing, as summarized below:

- Discharge Measurement: A new benchmark for the staff gage and flow were surveyed and measured in Thompson Creek. A tripod and level were set up on an existing benchmark in the center of the bridge deck to calibrate the tripod. Using the rod, water surface elevation readings were recorded along with the water level reading on the staff gage. This set the benchmark elevation on the staff gage which was used to record consistent water surface elevation readings.
- Aerial Imagery: A DJI Phantom 3 Standard drone was flown over Thompson Creek to capture aerial imagery of the entire study reach. Aerial imagery provided an overall view of the reach showing the extent of water in and around the BDAs. Imagery was collected in the fall and spring to compare the aerial view to see if the reach expanded. Pond areas will be measured from the images and combined with the water depth profiling and soil probing data to determine sediment and water volumes upstream of the starter dams.
- Water Depth Profiling: Profiling was performed in each upstream Starter Dam BDA Pond. The water depth was measured in one-foot intervals spaced across sections located five feet apart. When combined with the surface areas measured from aerial imagery, this shows change in water storage capacity (See Figure 2 in Appendix B).
- Soil Probing: Soil probing was performed in each Starter Dam BDA ponds. Soil depths were measured using a probing rod at the same section nodes as water depth profiling. When combined with the surface area from aerial imagery, this will provide sediment volumes retained upstream of the starter dams. An increase in trapped sediment raises the water level and helps Thompson Creek reconnect to the floodplain (See Appendix C).
- Repeat Cross-Section Surveys: Surveys were conducted at three permanent cross-sections upstream of each starter dam (See Figure 3 in Appendix B). A rod and level station were used to record elevation readings at one-foot intervals across each cross section. These repeat cross-sections measure how channel bed elevations change upstream of each Starter Dam.

- Repeat Longitudinal Profile Surveys: Surveys were conducted in the vicinity of the starter dams. The profiles started 60 feet upstream of a starter dam and ended 20 feet downstream of a starter dam, with at least one point taken on top of each starter dam (See Appendix D). Both the longitudinal and repeat cross section surveys were tied to a permanent benchmark so they could be compared over time. Longitudinal surveys document the change in channel slope over time
- Total Phosphorus (TP) Testing: TP testing was performed by collecting samples of water upstream, in the middle, and downstream in the reach. These samples were sent to Anatek Labs and the GU Chemistry Lab for a Total Phosphorus Analysis. The level of phosphorus in the stream directly impacts the health of Newman Lake and the TMDL report identified the initial concentration of phosphorus in Newman Lake to be harmful.

Table 1 below shows the schedule for the collection of these data throughout the 2021-2022 year. The full monitoring plan is found in Appendix A of this document.

Table 1. Data Collection Schedule

Activity	2020				2021												2022							
	S	O	N	D	J	F	Mar	Ap	May	Jn	Ju	Au	S	O	N	D	J	F	Mar	Ap	May	Jn	Ju	Au
	Fall			Winter			Spring			Summer			Fall			Winter			Spring			Summer		
Discharge Measurement															X					X				
Aerial Survey								X							X					X				
Water Depth Profiling															X					X				
Soil probing															X					X				
Repeat Cross-Section & Longitudinal Survey															X					X				
Total Phosphorus Testing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

4.2.5 Data Collection and Analysis

After Phase I construction was complete, the team, including Dr. Sue Niezgoda, Kat Hall, and the Senior Design Team, collected, and analyzed baseline data including water depth volumes, soil probing volumes, cross-sectional surveys, and longitudinal profile surveys. The team also analyzed baseline total phosphorous concentrations that was measured over the past year. The results of all baseline data collection activities are presented in the following sections.

4.2.5.1 QA/QC Plan for Monitoring Activities

Each monitoring method used to collect data was given a clear procedure to ensure that each was tested with little error and provided consistent data. Field data sheets were also created and included in the monitoring plan to control the way data was collected in the field. Data sheets for repeat cross-section surveys, longitudinal surveys, and soil probing can be found attached to the monitoring plan in Appendix B.1. Some methods have very specific procedures, such as total phosphorus data collection, which can be found in the *Total Phosphorus Monitoring Program for the Thompson Creek Beaver Dam Analog Restoration Project: Quality Assurance Project Plan* in Appendix B.2.

4.2.5.2 Calibration of existing Stream Gauge.

Last year's senior design team determined that that the staff gage on the NW Newman Lake Road Bridge was unreliable to evaluate flow. There was significant sediment build up on the stream gage upstream of the bridge (~1.8 ft of sediment). The team measured stream flow and depth at the stream gage and compared it to the rating curve. The streamflow measurement results found a flow if 1.8 cfs and a thalweg depth of 1.4 ft. The staff gage had a depth of 2.4 ft, correlating with a flow from the rating curve of 20 cfs. The staff gage provided inaccurate readings and could not be used to evaluate flow in Thompson Creek. It is most likely inaccurate because the channel could have widened, causing sediment to build up on the staff gage and change the cross section that was tied to the original staff gage elevation.

On September 23, 2021, Riverbank Consulting and Gonzaga University's stream restoration class visited Thompson Creek for a flow measurement lab. A new benchmark for the staff gage and flow were surveyed and measured. A tripod and level were set up on an existing benchmark in the center of the bridge deck to calibrate the tripod. Using the rod, water surface elevation readings were recorded along with the water level reading on the staff gage. This set the benchmark elevation on the staff gage which was used to record consistent water surface elevation readings. Two data points have been recorded that for the beginning of the new Thompson Creek rating curve as shown in Table 2. The rating curve plots the water surface elevation (y-axis) vs flow (x-axis).

Table 3: Rating Curve Data Points

Date	Staff Gage Reading (ft)	WSEL (ft)	Measured Flow (Q, cfs)
9-27-21	2.19	2131.65	1.1
10-25-21	2.84	2132.3	2.89

4.2.5.3 Aerial Imagery

A DJI Phantom 3 Standard drone with gimble camera was used to fly over Thompson Creek and capture aerial imagery of the entire study reach including each Starter Dam BDA and pond that is formed. Flights occurred immediately following BDA construction and again during high flows due to Spring runoff. A georeferenced orthomosaic photo for each flight was created for the entire BDA reach. The aerial images for the post-BDA construction flight are provided in Appendix D. Further analysis on these aerial images will be completed after water depth profiling and soil probing are completed in the Summer of 2022.

4.2.5.4 Water Depth Profiling and Soil Probing

After following methods outlined in the Monitoring Plan in Appendix B, the water and sediment volume in the channel upstream of each starter dam was determined from soil probing within the channel and surface water area measurements taken in the field. The water depth was probed in a 1-foot by 5-foot grid down the channel, starting 50 feet upstream of each Starter Dam. This resulted in a total water volume upstream of each starter dam. Table 3 below provides a summary of the water and sediment volumes calculated upstream of each starter dam immediately after construction of the BDAs. Following methods outlined in Butler and Malanson (1995) and Puttock et al (2018), the sediment volume trapped behind each pond will be determined from a combination of soil probing within the ponds and surface area measurements from drone imagery. The detailed tables of soil probing results for all three starter dams are provided in Appendix C. These values will be compared with future water and sediment volumes determined from water depth sampling and soil probing to identify if the BDAs are being effective and retaining water and sediment within the creek over time.

Table 4: Starter Dam Soil Probing Data Summary

	SD #1	SD #2	SD #3

Total Wetted Area (sq. ft.)	394	427	204
Volume Sediment (cu. ft.)	336.66	220.63	353.77
Water Volume (cu. ft.)	679.53	706.07	260.50

4.2.5.5 Max Water Storage Data

The max water storage volumes were collected from each of the three channel cross-sections upstream of the three starter dams. Obtaining max water volume storage values as a baseline metric allows for comparison between water depth profiling results and max storage values to establish any correlation between the two metrics. In order to calculate the max water storage for each of the three starter dams, the bank full area was first calculated using the same spreadsheet that plotted the cross-section surveys. The bank full area was obtained by setting the water surface level to top of the bank, right below the flood plain. Using the bank full area from each cross-section, the average end area method was used, which adds up the areas from each cross section and multiplies it by the length between each cross-section to obtain the final max storage volume. for each starter dam was calculated by adding up and multiplying the length between cross sections to obtain volumes. See Tables 4 and 5 for the results of this analysis.

Table 5: Bank full Area (sq ft) from Each Starter Dam Cross Section

	Bank full Area (sq. ft.)
CS 1a	74.3
CS 1b	85.4
CS 1c	70.1
CS 2a	66.8
CS 2b	40.9
CS 2c	55.3
CS 3a	32.7
CS 3b	37.3
CS 3c	31.6

Table 6: Max Water Storage Volume for Each Starter Dam

	Max water storage volume (cu. ft.)
SD 1	6894
SD 2	4890
SD 3	3048

4.2.5.6 Cross Section and Longitudinal Profile Surveys

Surveying the channel cross section and slope allowed the team to analyze the initial sediment volume, the maximum water volume, and observe how the channel cross section and slope changes with the implementation of BDAs over time. A sample cross-section and longitudinal profile surveyed at Starter

Dam #1 can be seen in Figures 25 and 26, respectively. Please note that the highest point in the longitudinal profile graph indicates the elevation taken on top of the starter dam. Appendix C of this document contains all the remaining surveyed profiles and cross-sections (one longitudinal profile and three cross-sections upstream of each starter dam). These cross-sections and profiles will be repeat surveyed over time and compared to determine the volume of sediment being retained by the starter dams.

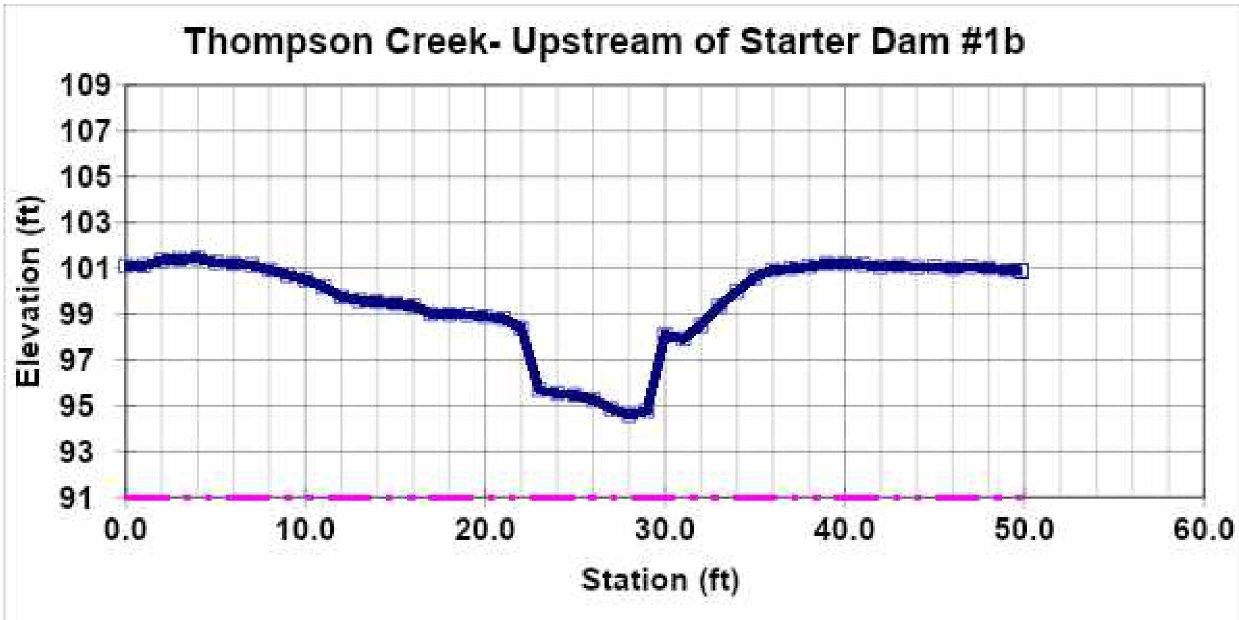


Figure 25: Surveyed ground profile for Cross Section 1B located 20 feet upstream of Starter Dam #1

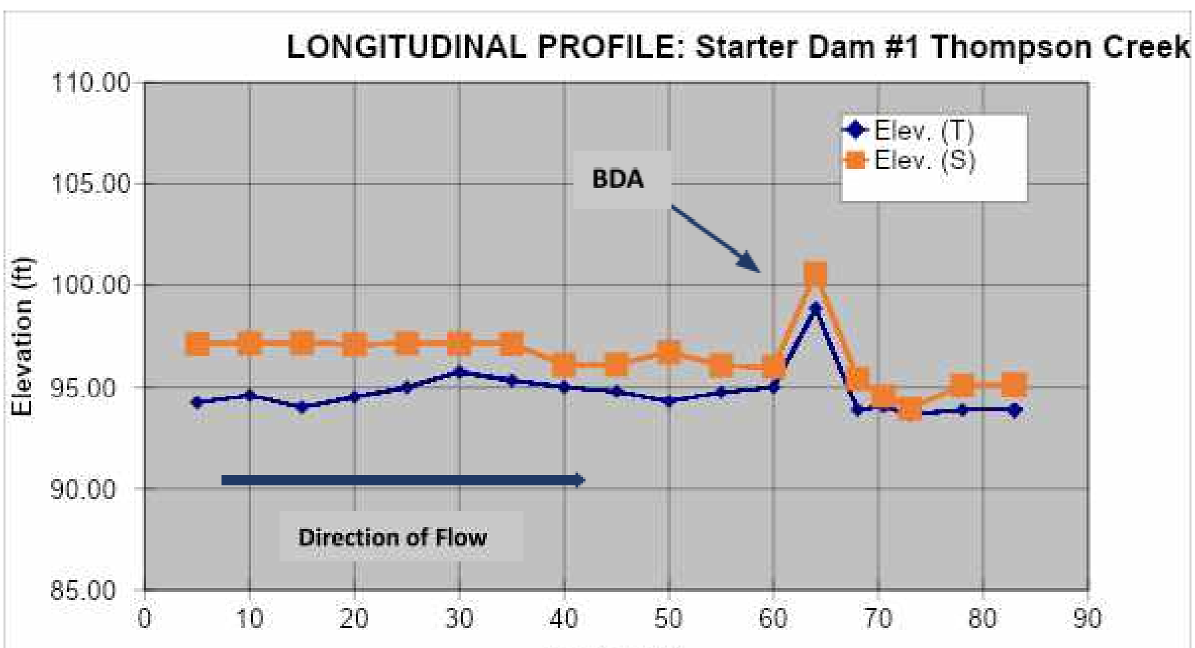


Figure 26: Surveyed longitudinal profile taken at Starter Dam #1 at Thompson Creek (November 2021).

4.2.5.7 Total Phosphorus Concentrations

To measure total phosphorus concentrations, water from the stream was collected in a clean plastic bottle. The person collecting the water made sure to hold the bottle upstream of them while collecting the water and made sure to not stir up the sediment as they entered the stream, i.e., the bottle was held underwater in the center of the channel and not too close to the streambed to avoid collecting any disturbed sediment. This water sample was then sealed in the bottle and sent to the lab for total phosphorus testing. The total phosphorous testing was performed by Anatek Labs using SM 4500-P H-and the Gonzaga Chemistry Department using Method EPA365.3 and under the direct supervision of Dr. David Cleary, Professor of Chemistry.

Prior to BDA implementation water samples were taken once a month, with one sample taken at the upstream end of the reach (upstream of NW Newman Lake Road Bridge) and the other sample taken at the downstream end of the reach (upstream of the backwater from Newman Lake). Water samples were collected and tested over several months between September 2020 and September 2021 to establish baseline total phosphorus concentrations to compare to measurements taken after BDA implementation. A few monthly samples were missed due to scheduling conflicts and poor weather conditions. The results of the monthly total phosphorus testing are provided in Figure 27 below. As seen in Figure 27, the total phosphorus concentrations in Thompson Creek generally remain between 40 to 50 parts per billion throughout the year. The TMDL identified a goal of reaching 20 ppb, represented by a red line in Figure 27. This means that the phosphorus entering Newman Lake from Thompson Creek needs to be reduced by 42% from the installation of BDAs. After BDAs were installed in October, phosphorus samples are collected on a monthly basis and taken in accordance with the protocols outlined in the QAPP (See Appendix B.2).

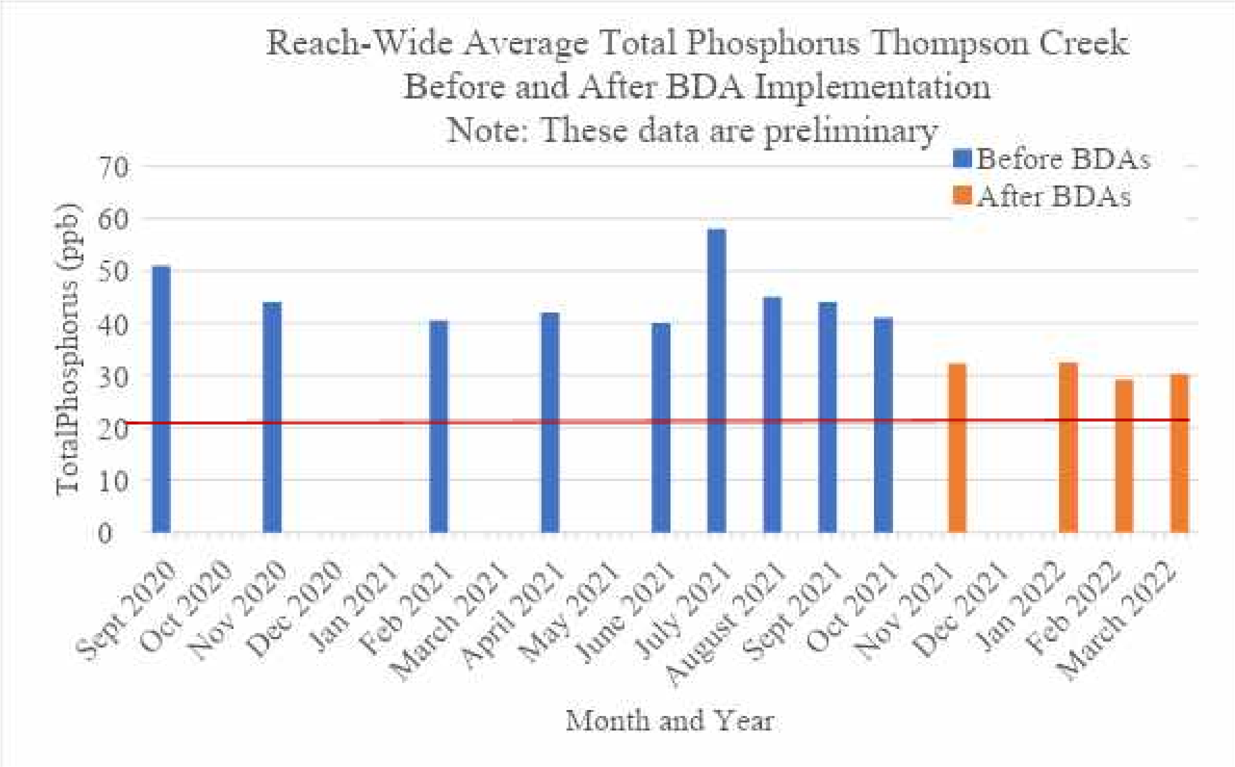


Figure 27: Preliminary Average Total Phosphorus Concentrations for Thomson Creek before and after BDA Implementation.

The data shown in Figure 27 displays the average total phosphorus levels in Thompson Creek before and after BDA implementation. The data is preliminary and represent the average monthly phosphorus concentrations in the entire BDA reach. The results will become more detailed with respect to location in the reach as more data is collected. No conclusions can be drawn yet from this data.

4.2.5.8 Monitoring Update as of March 24th, 2022

On March 24th the team headed back out to the site to collect the second set of survey data (cross-sections, soil probing, water storage volumes). Unfortunately, the water level remained rather high with the water depth seeming to be about 6 to 8 feet deep which is unsafe to try and attempt to gather in-stream data. While out at the site, water samples were still able to be collected for total phosphorus testing, while photos and observations at each of the BDAs were taken. As well, high spring runoff also caused the water table increase and rise into the surrounding floodplain as seen in Figure 28. Each starter dam (See Figure 29 through 31) is starting to show signs of providing water storage as well with a noticeable visual head difference. It is not possible to derive any conclusion about sediment storage, phosphorus concentrations, and other metrics that our group planned on gathering. This data will be collected as soon as the water level goes back down to a safe level to monitor at.

Figure 28: Drone photo of Thompson and the surrounding floodplain (3/04/2022).

Figure 29: Looking upstream of Starter Dam #1 (3/24/2022).

Figure 30: Looking upstream of Starter Dam #2 (3/24/2022).

Figure 31: Looking upstream of Starter Dam #3 (3/24/2022).

4.3 Design Guidelines for BDAs

There are not many guidelines for determining the level of analysis required before designing BDAs for a given project. The following sections will outline the existing literature, analysis, and determination of a risk assessment matrix that Riverbank Consulting created for this purpose. First, RBC reviewed literature on BDA design methods to learn what safety and risk factors are taken into consideration when implementing BDAs. Next, the team did a literature review specifically on risk assessment methods to determine how these methods can be applied to BDAs. Ultimately, a risk assessment matrix was formed to determine what level of both structural and reach scale assessments will be needed before implementing BDAs. This can help improve the safety of future projects and encourage people to implement BDAs by explaining specifically what analysis needs to be done to be confident in the BDA implementation.

4.3.1 Summary of Literature Review on BDA Design Methods

The Birch Creek BDA design was key in Riverbank Consulting's literature review as it was the basis for the design of the Thompson Creek project. Riverbank Consulting also reviewed the Beaver Restoration Guidebook and Low-Tech Process Based Restoration of Riverscapes Design Manual. A "virtual field guide" video series by the Okanogan Highlands Alliance that explains the process of implementing BDAs and provides a case study at Triple Creek was also reviewed. Two other case studies that Riverbank Consulting reviewed were the Bridge Creek BDA complex in Oregon and the Birch Creek BDAs in Utah. The team summarized the design decisions in the case studies and the considerations noted in the Beaver Restoration Guidebook and Low-Tech Process Based Restoration of Riverscapes Design Manual. Below is a concise summary of the literature that was reviewed, and some key points taken from it to help develop the risk assessment matrix:

Title: The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains

Author: Pollock et Al. 2015

Summary: This guidebook explains beaver ecology, restoration and management, types of BDAs, and risks involved in implementing BDAs.

Key Points:

- Beaver restoration projects should have a minimum timeframe of five years, as the natural processes take time for the stream to change.
- Dams should only be removed if they are causing a danger to the surrounding area or ecosystem.
- Developing a monitoring plan that is implemented before, during, and after installation is key for assessing if the restoration goals are met.
- The most common way that dams fail is through "end cut" where the side bank is eroded.
- There are few risks in implementing BDAs, but some of the risks are as follows:
    - Increased temperatures in pools (make sure to have plant vegetation that can shade/cool down the area)
    - Inadvertent flooding (place BDAs carefully when near infrastructure or other areas that cannot be flooded)

Title: Low-Tech Process-Based Restoration of Riverscapes: Design Manual

Author: Wheaton et Al. 2019

Summary: This design manual outlines 10 guiding principles to process based restoration for rivers and streams. These 10 principles are divided into two sections: Riverscape Principles (what makes a healthy river system) and Restoration Principles (what actions and designs promote recovery and resilience).

Key Points:

- Streams need space to meander, shift position, and flood.
- Varied structures (such as BDAs) force complexity in flow regimes and build diverse, resilient habitats.
- There are three phases for planning: Collection & Analysis, Decision Support, and Application and Evaluation. As streams are highly dynamic, the plans need to shift and adjust as the river system changes.

Title: Triple Creek Virtual Field Guide to BDAs, for Restoration Practitioners

Summary: The Okanogan Highlands Alliance (OHA) has provided a "virtual field guide" video series from 2020 that shows how to implement beaver dam analogs based on their work at Triple Creek. These videos cover restoration goals, design, installation, choosing sites and materials, and results.

Author: Okanogan Highlands Alliance (2020)

Key Points:

1. Deflector dams increase sinuosity by eroding channel banks, and channel spanning dams increase roughness and can help sediment settle out and raise the water table.
2. Longer posts can be driven deeper if the substrate allows, which increases stability. They also can accommodate higher flows and last longer. However, if there is a high number of debris loading, longer posts can be a risk.
3. Shorter posts can apply less pressure to the banks and posts for areas where the goal is to see the structure easily overtopped.
4. Adding multiple BDAs in series helps improve stability and reduce scour. Gentle slopes (about 2 to 6%) are preferable to reduce shear stress on BDAs.

Title: Lessons in Beaver Based Restoration from the Bridge Creek IMW

Author: Weber et Al. 2017

Summary: This work is a conference paper from 2017 focused on a creek in the John Day Basin in Bend, Oregon. This project aimed to test assisted incision recovery and determine the benefits to fish populations and habitat. There were four treatment reaches with a total of 114 BDA reaches. This was a multi-year implementation beginning with pilot structures followed by effectiveness monitoring and structure modifications.

Key Points:

- Installing the BDAs in this creek increased the wetted area by 203% and improved the percent fish passage from 17% to 29%.
- These BDAs were concentrated upstream, with two dense clusters of BDAs downstream.

Title: Working with Beaver to Restore Salmon Habitat in the Bridge Creek Intensively Monitored Watershed: Design Rationale and Hypotheses

Author: Pollock et. Al 2012

Summary: This is a paper from 2011 by Michael M. Pollock. This team used aerial LIDAR, field survey, and a color photography survey to locate four pairs of geomorphically similar reaches within Bridge Creek. This allowed them to restore one location of each pair and leave the other one unrestored as a control. They also located sites inhabited by beavers for direct comparison to constructed BDAs.

Key Points:

- Place secondary structures immediately downstream of primary structures to avoid the gradient from dropping too low, too quickly, and to provide resilience in case an individual dam fails.
- The dams require that the incision of the area would be generally less than 1- 1.5 meters to improve stability.
- Make sure BDAs are at least 300 meters away from existing beaver colonies to avoid disturbing the beaver.
- Pound posts at least 1 meter deep wherever possible.

Title: Birch Creek Case Studies

Author: Shahveridian and Wheaton 2017, Shahveridan 2018

Summary: This is a set of two case studies (Shahveridian and Wheaton 2017, Shahveridan 2018) of the restoration of Birch Creek, a stream in Utah. This area has experienced a reduction in native woody vegetation, limited riparian community, and high summer temperatures that hinder Bonneville cutthroat trout population growth and sage grouse. A BDA project with 60 dam structures was implemented in late 2017, and this project was monitored throughout the year.

Key Points:

- BDAs work best in complexes, which are a series of 2-15 structures combining all BDA types and each with their own primary and secondary functions.
- Different complexes have different goals, such as increasing pool habitat and lateral connectivity, or increasing hydraulic diversity.
- There is a lot of uncertainty in regard to the specifics of what a stream needs, so by providing the stream with tools such as BDAs, it will naturally heal itself.
- The BDAs in Birch Creek increased groundwater storage, baseflow, peak flow attenuation, reconnected the creek with the floodplain, and slowed channel velocity.
- Results showed an increase in maximum pool length, and width and depth. The pre-restoration size was at 2,432 m^2 whereas post-restoration increased the size by 16% or 2,841 m^2.

Title: A Stream Evolution Model Integrating Habitat and Ecosystem Benefits

Author: Cluer & Thorne, 2014

Summary: The authors of this paper provide language to describe how streams adapt and change over time. This is provided through the Stream Evolution Model, a set of stages from Stage 0 to Stage 8, through which the stream change both forward and backwards through the stages.

Key Points:

- The Stream Evolution Model categorizes streams based on their levels of degradation/aggradation and widening/narrowing
- This is a helpful tool that can help describe the health of a stream, as well as the incision of the channel

4.3.2 Literature Review on Risk Assessment Methods

The sections below outline four literature reviews conducted on risk assessment methods and Riverbank Consulting's BDA design guidelines based on level of risk. A more detailed literature review can be found in Appendix F of this report.

Title: Risk-Based Method for Selecting Bridge Scour Countermeasures

Author: Peggy A. Johnson and Sue L. Niezgoda, 2004

Summary: A risk-based method for ranking, comparing, and choosing the most appropriate scour countermeasures was presented using failure modes and effects analysis and risk priority numbers. Risk was analyzed in terms of likelihood of failure, consequence of failure, and level of difficulty to detect failure. The result is a qualitative number that allows the design to assess the design element that has the most risk pre-implementation.

Key Points:

- Bridge scour can be predicted using HEC-18. Types of scour includes channel degradation, contraction scour, and local scour.
- Safety of bridge foundations can also be negatively impacted from channel widening and lateral mitigation.
- Potential failures can be very difficult to define in real-life-situations.
- For failure mode analysis, it is necessary to first define what the system failure looks like before design implementation.
- To execute a failure modes and effect analysis, the following are required: a hierarchical structure for the system illustrating all system components, failure modes of all components of the system, and an objective criterion for implementing corrective action.
- A risk priority number is established with each failure mode to get a qualitative result that suggests the nature and extent of failure.
- The risk priority number (RPN) is the product of the occurrence, consequence, and detectability ratings of a failure mode. This technique allows for a comparison between impact of various failure modes.
- Cost is not a factor in the failure modes effect and analysis.

Title: Case Study in Cost-Based Risk Assessment for Selecting a Stream Restoration Design Method for a Channel Relocation Project

Authors: Sue L. Niezgoda, Aff.ASCE; and Peggy A. Johnson, M.ASCE

Summary: A design failure modes and effects analysis is combined with a risk quantification. This analysis can be reevaluated to account for design changes and a change in ratings. This case study was based in Pennsylvania. Identifying design deficiencies of the initial design using the design failure modes and effects analysis with risk quantifications helps improves the current design.

Key Points:

- Incorporating uncertainty, consequences of failure, and costs in stream restoration projects improves the likelihood of success.
- Using the design failure modes and effects analysis helps to ensure a project will be effective when constructed. This analysis includes consequence of failure, the likelihood of a component failure, and the level of difficulty required to detect failure. Additionally, each component, possible failure modes, effects on the system, consequences, potential causes of failure, and likelihood of occurrence are identified. These are given numeric ratings from 1-10 with large values associated with high risk and low values associated with low risk.
- Risk priority numbers can be subjective if the criteria are not adequately defined. Risk is based on probability of failure and consequences.

Title: Applying Risk-Benefit Analysis to Select an Appropriate Streambank Stabilization Number

Authors: Sue L. Niezgoda, Ph.D., P.E., A.M.ASCE; and Peggy A. Johnson, Ph.D., M.ASCE

Summary: Risk is compared to benefit using risk priority numbers (RPN) and benefit priority numbers. The results are used to estimate risk and benefit quantitatively in terms of cost. This paper focuses on streambank stabilization Indiana. The goal is to apply the risk-benefit method to a design and identify the lowest risk option that gives the most return on investment.

Key Points:

- The long-term effectiveness of bank stabilization structures has been based on field observations.
- Multiple studies are available that assess the effectiveness and benefits of in-stream structures for streambank stabilization. These studies can be used to develop estimates of probability of success providing economic, environmental, and social benefits.
- There is a need for monitoring standards to better evaluate the results of in-stream structures.
- Risk is calculated using the following equation:

$$Risk = C_0 + \sum_{i=1}^{n} (P_i * C_i)$$

Where C_0 = initial component cost, including assessment, design, and construction costs; P_i = probability of failure given a measure attributable to a given failure mode, i; C_i = consequence of failure attributable to a given measure failure mode in terms of cost of repair, replacement, and damage; and n = the total number of failure modes for a given measure.

- More failure data has become available and thus an updated relationship between the likelihood of occurrence and probability was created.
- Possible benefits include economic, environmental, or social impacts. The causes of the benefit and the probability it will occur must be identified. Benefits can be detected using high-tech

materials such as LIDAR and electroshocking equipment or using low tech materials such as visual observations.

- Benefit is calculated using the following equation:

$$Benefit = \sum_{i=1}^{n_f} (P_{Bi} * B_i)$$

Where P_{Bi} = probability that a given measure function, i, will provide a given benefit; B_i = economic, environmental, and social benefits added by the given function, i; and n_f = the total number of functions provided by a given measure.

- HEC-RAS was used to analyze how stream bank stabilization would affect shear stress.
- A table that outlines the benefits from considerable to negligible should be made to identify the benefit rating. This should include economic benefits, environmental benefits, and public acceptance to get a benefit rating from 10-0.
- A table should also be made that identifies the likelihood of detection of benefit. The detection level should range from complex equipment method with a detection rating of 1 to visual inspections only with a detection rating of 10.
- A cost-benefit analysis was performed for the streambank stabilization measures within Cascade Creek. This analysis uses a benefit-to-initial-cost ratio. If the ratio is greater than one, the benefits out way the initial costs.
- The initial costs, total risk and total benefit costs are then formulated for each measure. The benefit to initial cost ratio and total benefit to total risk ratio are then calculated.
- Factors for risk are as follows:
    - Bank stabilization measure, failure mode, C, Percentage cost, O, probability of failure, component cost, consequence cost (percentage cost times component cost), expected failure cost (probability of failure times consequence cost), and risk (component cost plus expected failure cost).
- Factors for benefit are as follows:
    - Bank stabilization method, function, B, percentage cost, O, occurrence probability, component cost, value added (percentage cost times component cost), expected benefit (occurrence probability times value added), and total expected benefit (sum of expected benefit).

Title: RiverRAT: Science Base and Tools for Analyzing Stream Engineering, Management, and Restoration Proposals

Authors: Tim Beechie, NOAA Fisheries, Seattle, Washington; Janine Castro, US Fish and Wildlife Service, Portland, Oregon; Brian Cluer, NOAA Fisheries, Santa Rosa, California; George Pess, NOAA Fisheries, Seattle, Washington; Conor Shea, US Fish and Wildlife Service, Arcata, California; Peter Skidmore, Skidmore Restoration Consulting, Bozeman, MT; Colin Thorne, Professor, University of Nottingham, UK

Summary: A new resources guide named River Restoration Analysis Tool (RiverRAT) has been developed to offer a more efficient, consistent, and comprehensive review of stream management projects. The depth and scientific soundness required is addressed.

Key Points:

- Guidelines and manuals exist for the engineering and design aspects of stream management projects but there is no accepted guidance for stream management projects.
- Generally, avoiding risks in stream restoration leads to an over-design to meet the factor of safety. However, these factors of safety are often based on undesirable constraints on natural channel adjustment and evolution thus limiting long-term habitat value.
- A new screening tool, Figure 32, shows the relative review lengths that respective projects should require. This is a training aid to refine professional judgement on depth of reviews.

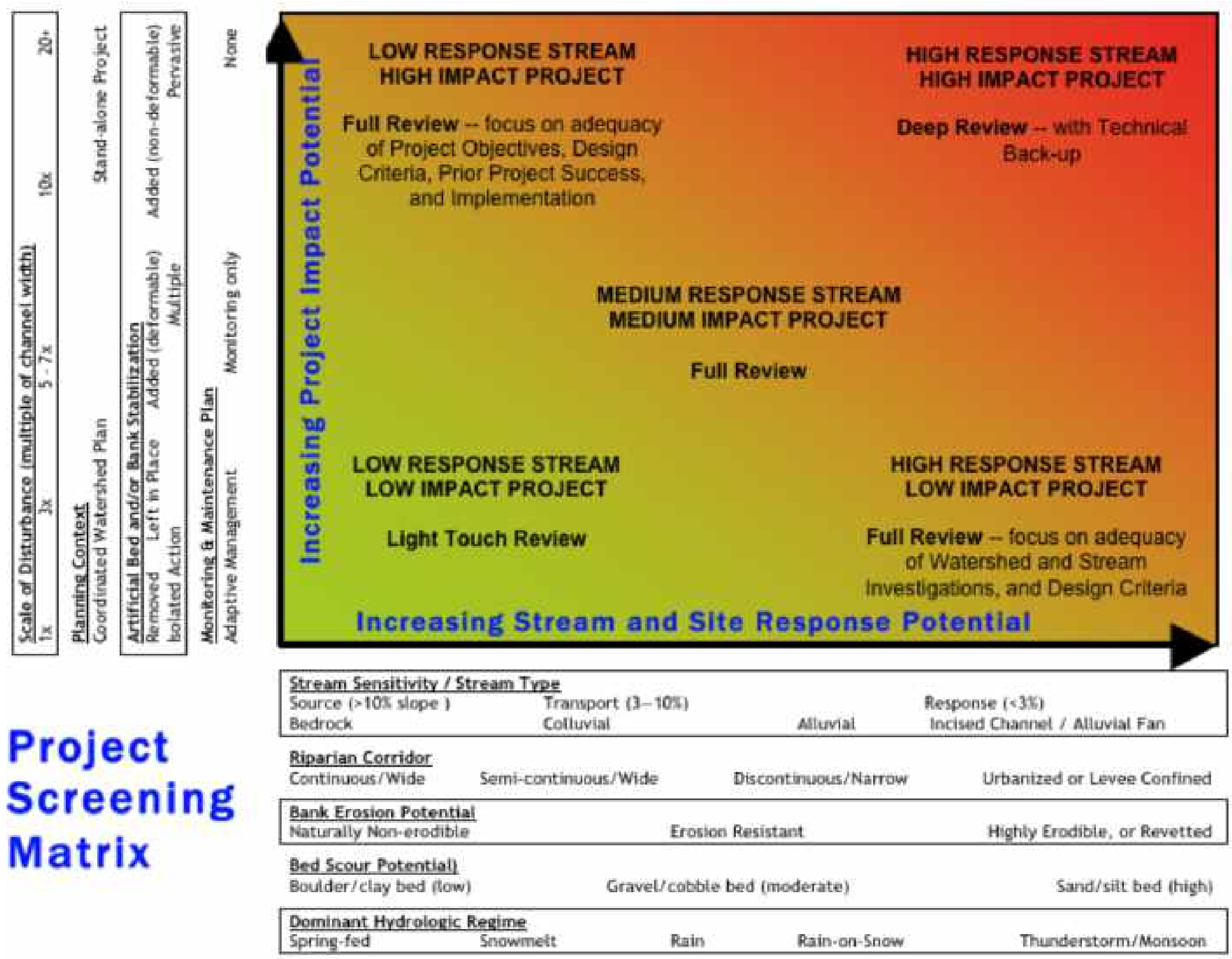


Figure 32:The Project Screening Matrix (RiverRAT)

- A checklist of design documentation is highly encouraged to promote time and resource efficiency.
- RiverRAT provides a framework that gives additional technical resources and assistance for projects of high risk.
- RiverRAT has an online database at restorationreview.com that acts a review tool for projects.

4.3.3 Development of the BDA Risk Assessment Matrix

Based on the literature reviews and from experience implementing the Thompson Creek BDAs, the team listed out the risks associated with implementing BDAs and determined that the risks can be split into two categories: structural failure and local constraints. A matrix was created by modifying the River

Restoration Analysis Tool (RiverRAT) matrix into a version that determines the level of analysis required before implementing a BDA project. See Section 4.3.4 for the completed matrix.

The y-axis outlined risks regarding local constraints/context and the x-axis outlined risks regarding structural failure. Local infrastructure included anything with human conflict potential such as existing structures (bridge, culture, roads, etc.), damage to the outlet area (boats hitting failed BDA posts), and the use of the floodplain area (agriculture vs. urban, FEMA floodway). Another consideration was how confined the valley is. Broad, flat floodplains provide space for BDAs to create ponds and spread out, whereas more confined, steep valleys will be less effective and create more stress on the dams.

The x-axis focused on risks regarding structural failure for the BDAs. The initial factors considered were the connection to the floodplain, water velocity, hydraulic radius, and soil type. The water velocity and hydraulic radius are both parts of flow and stream power, so a higher stream power is more likely to overturn the dam's posts. The connection to the floodplain also determines how much water will be directly applied to the dams compared to how much water will be spread out into the floodplain. The type of soil will affect the "grip" (skin friction to counteract uplift) and resistance to overturning for the posts.

In order to simplify the x-axis, RBC used the BDA Design Tool for two different rivers to see how stream flow and soil type impacted the Factors of Safety (FOS) for structural failure of the BDAs. Factors of Safety are the ratio of the available capacity over the amount of force applied; a FOS greater than 1.0 means that there is more capacity available than we expect to be used, so the structure is significantly less likely to fail. For example, if a structure was rated to handle 2,000 pounds of force (a 2,000 pound capacity), and it is expected to have a 1,000 pound force applied to it, then that FOS would be 2,000/1,000, or 2.0. Having a FOS of 2.0 or higher is good for BDAs, as this provides backup capacity in case there is a rare hydraulic/weather event that would provide more applied force than previously planned for.

The team was concerned with three different failure modes for the BDAs: overturning, vertical movement, and post breakage. Overturning would be caused by water or other forces tipping over the posts. The embedment into the soil (pounding the posts deep underground) resists this overturning, as the soil helps hold the posts in place. Vertical movement, on the other hand, is caused by the water's buoyant force lifting the posts up. This can be resisted by skin friction, a function of the surface area of the post interfacing with the soil to grip it in place. Post breakage is caused by impact force, which is when items like logs flow downstream and run into the dams, causing the posts to snap. Post breakage, as calculated by the BDA design tool, is independent of soil type and primarily affected by the strength of the selected posts.

The factors inputted into the model included flows, weir (BDA) height, soil type, and amount of additional post embedment beyond 50%. From the BDA Design Tool analysis, the team found that as long as the posts were at least 50% embedded, the soil type does not significantly change the FOS for any of the dams, see how the slopes of the lines do not change much Figures 33-35 below, and how all of the FOS are above 2.0.

The team did find, however, that stream flows and weir heights did make a significant impact on the safety of the BDAs. Taller dams with higher flows are at a significantly higher risk than shorter dams with lower flows. The combination of weir height and flows were then simplified to a single factor of channel incision. More incised channels have the potential for higher weirs and higher flows, whereas shallower channels that are connected to their floodplains are very low risk. This single factor of channel incision will be able to be quantified under the Stream Evolution Model, as seen in Section 4.3.4.

For more information about the BDA Design Tool analysis, see Appendix E of this report.

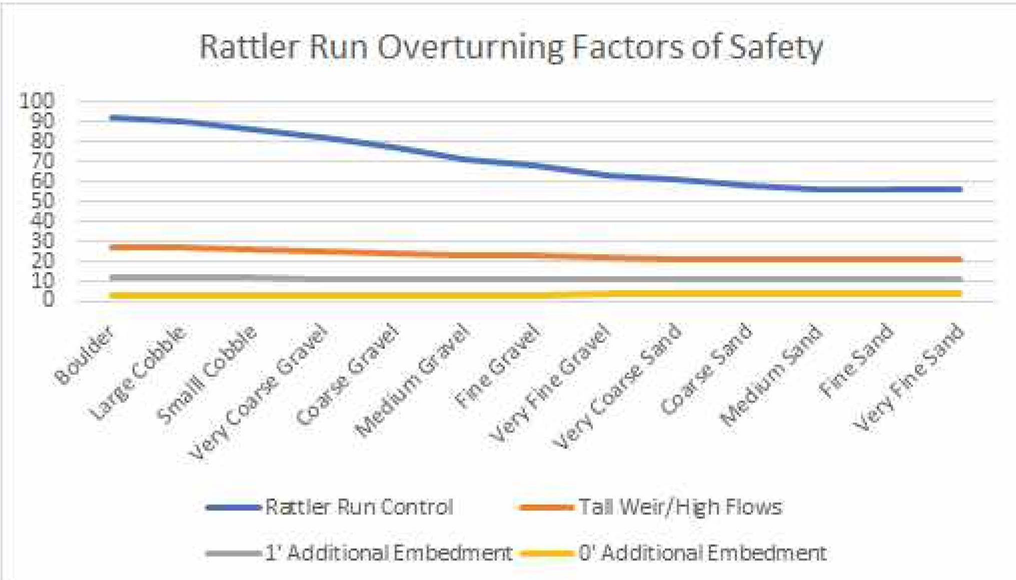


Figure 33: FOS Results for Overturning for Rattler Run Creek

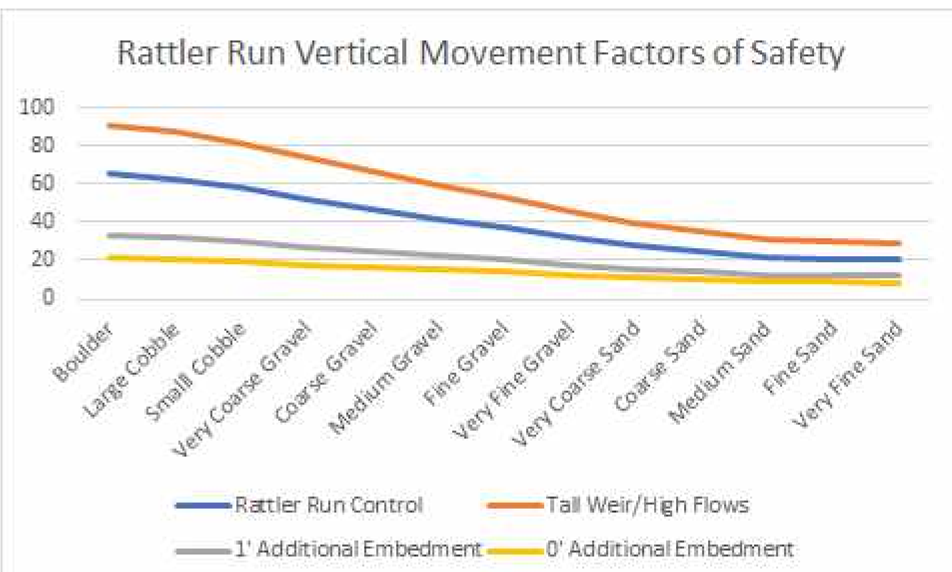


Figure 34: FOS Results for Vertical Movement for Rattler Run Creek

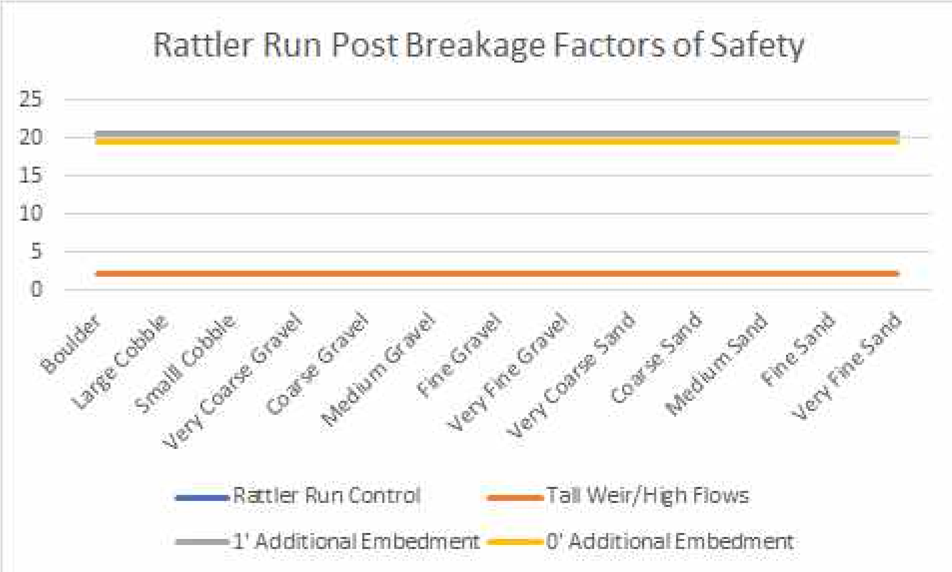


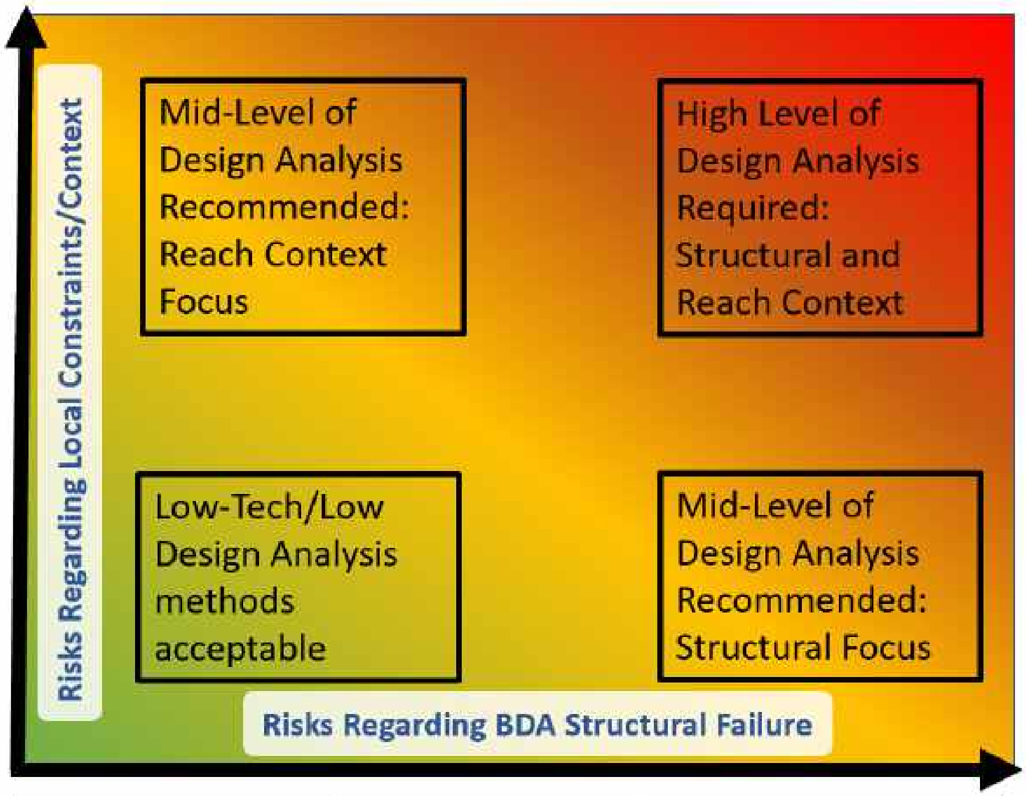
Figure 35: FOS Results for Post Breakage for Rattler Run Creek.

4.3.4 Guidelines for Design of BDAs Based on Level of Risk

Figure 36 below shows the risk assessment matrix that Riverbank Consulting created to determine the level of analysis required before implementing BDAs. A result in the upper right (red) would indicate that a high level of analysis is required before a BDA could be implemented in the area; this would be a stream that has high risk of structural failure for the dams and a high number of local constraints. Both hydraulic and structural analysis would be required to analyze the BDA impacts in this stream. A result in the lower left (green) would suggest that low-tech methods would be appropriate for the implementation of BDAs in the area, for example the stream could be away from any local constraints and have low channel incision (or stream power). The results in the lower right and upper left (orange) means that there is only one (structural or hydraulic) analysis method necessary before implementing the BDAs. This could look like a high power, incised stream in the middle of nowhere needing a structural analysis but not a hydraulic analysis, or a low power stream near some critical infrastructure that needs a hydraulic analysis but not necessarily a structural analysis.

A high level of analysis could look like creating a detailed model of the proposed BDA system in HEC-RAS under high flow conditions and determining if it could cause flooding to nearby infrastructure, and also using the BDA design tool to determine the required embedment depth, post size, and associated factors of safety. A mid-level design analysis may include doing only a HEC-RAS hydraulic analysis or a BDA design tool analysis. A low level of analysis may not require either computer-based analyses, but rather simply ensuring a 50% embedment depth and confirming that the stream is not near anything that could be impacted by floods.

Component	Analysis Required No Local Constraint Analysis Required	Local Constraints Analaysis on a Case-by-Case Basis	Local Constraints Analysis Required
Infrastructure	Minimal/abandoned infrastucture	Non-critical Infrastructure	Critical infrastructure nearby
Outlet area	Infrequently used by humans/nature reserve	Frequently used but not critical waterway	Critical waterway and/or highly populated area
FEMA Floodway	No Flood Insurance Mandatory	Orange Zone (A, AE, A1-30, AH, AR, A99)	Red Zone (V, V1-30, VE)
Wildlife	Little to no fish	Frequent fish passage (adult fish)	Spawning area/critical path for young fish
Land Use	No agriculture	Agricultural use near floodplain	Floodplain in use for agriculture, etc.
Valley confinement	Flat surrounding area	Limited room for floodplain to expand	No room for floodplain to expand



Analysis Required Based on Stream Evolution Model Stage		
No Structural Analysis Required	Structural Analysis on a Case-by-Case Basis	Structural Analysis Required
Stages 0, 1, 7, 8 (Not Incised)	Stages 4, 5, 6 (widening and/or aggrading)	Stages 2, 3, 3s (incised and degrading, or channelized/stuck in incised condition)

Figure 36: Risk Assessment Matrix, adapted from the Project Screening Matrix (RiverRAT)

For the Y-axis, Table 7 below was created to find the level of analysis required when considering the local context of the stream. For each component, a level of analysis should be determined using the table. From there, a "center of mass" of these factors should be determined and plotted on the graph. This "center of mass" allows the user to consider each of the factors provided, but also weigh them subjectively based on the perceived risks and consequences for each category.

Table 7: Y-Axis Chart for Risk Assessment Matrix

Y AXIS: Local Constraints	**Analysis Required**		
Component	Local Constraints Analysis Required	Local Constraints Analysis on a Case-by-Case Basis	No Local Constraint Analysis Required
Infrastructure	Critical infrastructure nearby, potential for significant damage and interruptions for everyday life	Infrastructure nearby, could cause temporary interruptions and damage	Minimal/abandoned infrastructure nearby, damages will not need to be fixed
Outlet area	River feeds into critical waterway and/or highly populated area	Frequently used waterway, but not dependent on having a clear area	Infrequently used by humans/nature reserve
FEMA Floodway	Red Zone (V, V1-30, VE)	Orange Zone (A, AE, A1-30, AH, AR, A99)	No Flood Insurance Mandatory
Wildlife	Spawning area/critical path for young fish	Frequent fish passage (adult fish)	Little to no fish
Land Use	Floodplain in use for agriculture, etc.	Agricultural use near floodplain	No agriculture dependent on/near floodplain
Valley confinement	No room for floodplain to expand	Limited room for floodplain to expand	Flat surrounding area

For the X axis, the BDA design tool showed that as long as the posts can be at least 50% embedded, the soil type was not a concern, but rather the incision of the channel mattered more to structural integrity. This is because more incised channels have the capacity for high flows and will need taller posts, which increase the risk of structural failure. To determine the incision of the stream, RBC is using language from the Stream Evolution Model (see Figure 37). Based on the Stream Evolution Model Stage, Table 8 below shows the level of structural analysis required for the project.

Table 8: X-Axis For Risk Assessment Guidelines

	Analysis Required		
	Structural Analysis Required	Structural Analysis on a Case-by-Case Basis	No Structural Analysis Required
Stream Evolution Model Stage	Stages 2, 3, 3s (incised and degrading, or channelized/stuck in incised condition)	Stages 4, 5, 6 (widening and/or aggrading)	Stages 0, 1, 7, 8 (Not Incised)

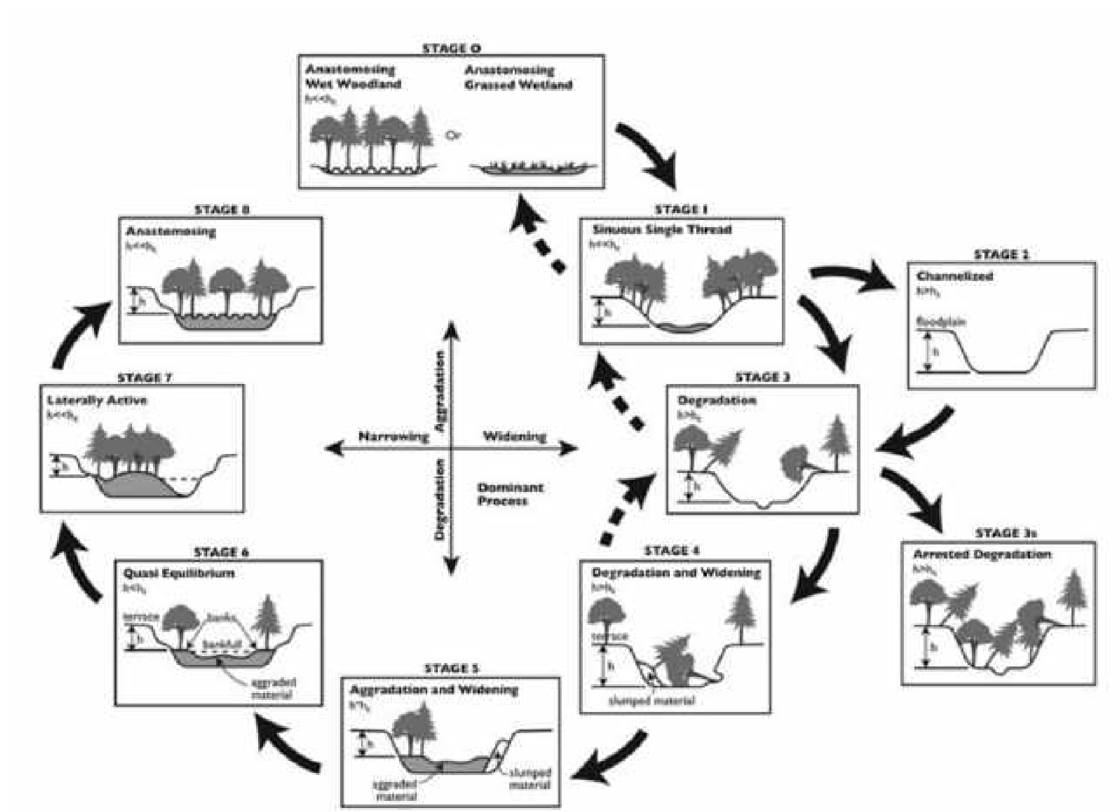


Figure 37: Stream Evolution Model (Cluer & Thorne, 2014)

Tables 6 and 7 can then be visualized on the matrix (Figure 36 above) to easily show regulators, engineers, and other people interested in BDA implementation what types of analysis are needed for their project. This can help reduce risk, streamline the site assessment processes, and also encourage people to consider sites that they may have otherwise written off due to the perceived complexity.

4.3.5 Example of BDA Design Guideline Matrix in Use

To help explain how to apply the BDA Design Guidelines, Riverbank Consulting is providing a sample analysis of Thompson Creek using the Design Guidelines Matrix.

First, the team filled out the Y-axis table as shown below in Table 9. As there is a fire station and a bridge nearby, the infrastructure posed a high risk. The outlet area was considered a medium risk, as there is a lot of activity in Newman Lake, but it is primarily recreational. The project area is not in a FEMA floodway, there are not a lot of fish in Thompson Creek, and the surrounding land is no longer used for agriculture, so those categories are all considered low risk. As the infrastructure and outlet area have a high importance to be protected, this shifts the "center of mass" in the matrix to a "Local Constraints Analysis on a Case-by-Case" rating.

Table 9: Y- Axis Example for Thompson Creek

Y AXIS: Local Constraints	**Analysis Required**		
Component	Local Constraints Analysis Required	Local Constraints Analysis on a Case-by-Case Basis	No Local Constraint Analysis Required
Infrastructure	**Critical infrastructure nearby, potential for significant damage and interruptions for everyday life**	Infrastructure nearby, could cause temporary interruptions and damage	Minimal/abandoned infrastructure nearby, damages will not need to be fixed
Outlet area	River feeds into critical waterway and/or highly populated area	**Frequently used waterway, but not dependent on having a clear area**	Infrequently used by humans/nature reserve
FEMA Floodway	Red Zone (V, V1-30, VE)	Orange Zone (A, AE, A1-30, AH, AR, A99)	**No Flood Insurance Mandatory**

Wildlife	Spawning area/critical path for young fish	Frequent fish passage (adult fish)	**Little to no fish**
Land Use	Floodplain in use for agriculture, etc.	Agricultural use near floodplain	**No agriculture dependent on/near floodplain**
Valley confinement	No room for floodplain to expand	Limited room for floodplain to expand	**Flat surrounding area**

Next, the team filled out the x-axis table, see Table 9. Riverbank Consulting classified Thompson Creek as a 3s stream as it is in arrested degradation. This is seen in the steep channel banks that haven't widened much over time, but that the channel is deeply incised. This places it in the "Structural Analysis Required" zone.

Table 10: X-Axis Example for Thompson Creek

	Analysis Required		
	Structural Analysis Required	Structural Analysis on a Case-by-Case Basis	No Structural Analysis Required
Stream Evolution Model Stage	**Stages 2, 3, 3s (incised and degrading, or channelized/stuck in incised condition)**	Stages 4, 5, 6 (widening and/or aggrading)	Stages 0, 1, 7, 8 (Not Incised)

Riverbank Consulting then plotted the x- and y-values on the graph, as seen in Figure 38. This analysis rates Thompson Creek as a project that requires a mid-to-high level of analysis before BDA implementation. These results mean that the team would recommend a hydraulic analysis focused on the safety of the bridge and fire station, as well as a BDA design tool analysis to ensure that the proper posts and embedment depths are used to reduce risk of dam failure.

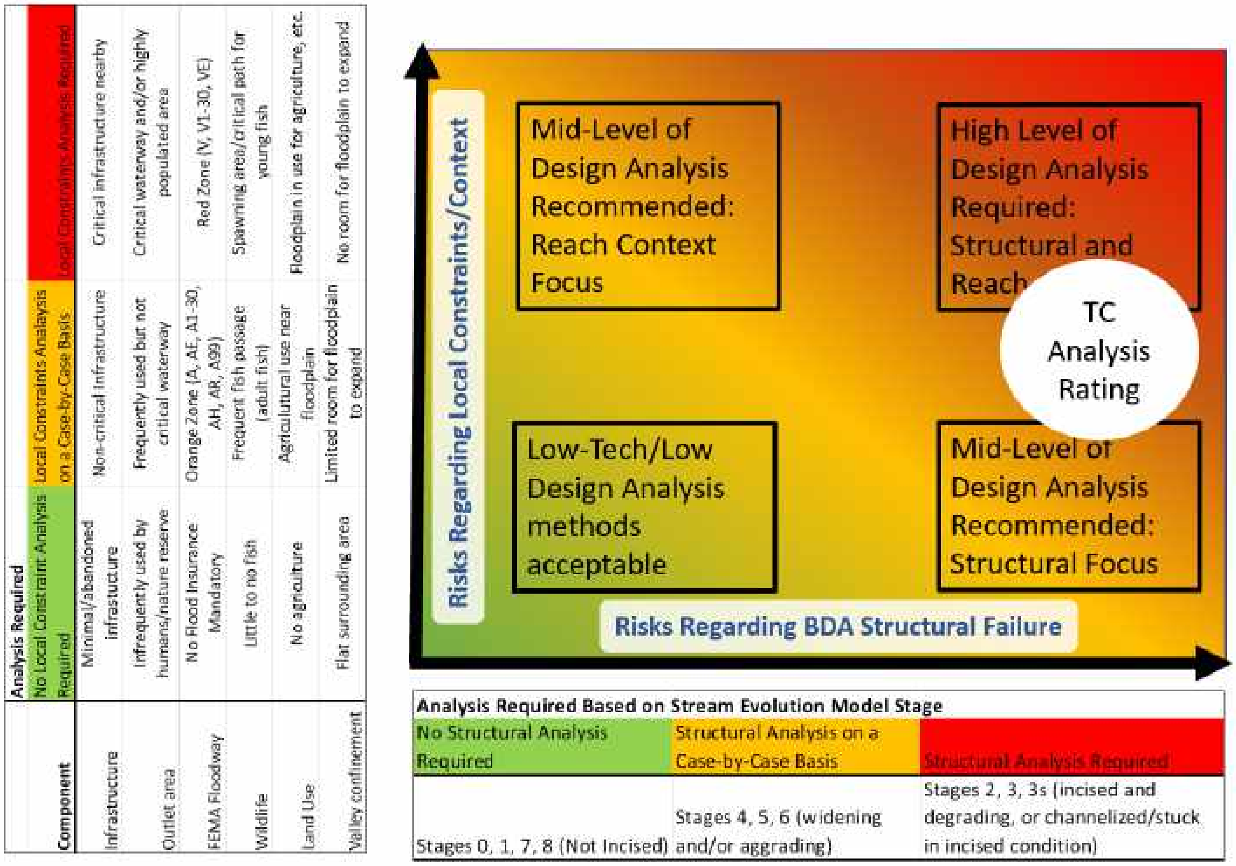


Figure 38: Risk Assessment Matrix Applied to Thompson Creek

4.4 Project Sustainability and Social Impact Assessment

4.4.1 Interview with Dawson Matthews

The team has completed three steps in assessing the social impact of the project. The first step was an interview with Dawson Matthews, a Spokane County engineer who has spent a significant amount of time working with the public in the Newman Lake area. Dawson shared that the properties on the lake have a variety of uses, as only about half of the population lives there year-round. Some homes/properties are used seasonally, primarily for recreation purposes. The community values clear communication and transparency when projects are being implemented at the lake. The community uses the lake primarily for fishing, recreation, irrigation, and some people use it for household potable water.

4.4.2 Social Equity Mapping Analysis

The second phase was a social equity assessment using the Spokane Regional Transportation Council (SRTC) Social Equity Mapping Tool. This is an online tool provided by the Spokane Regional Transit Council that shows social equity data visually through an online GIS map. Drawing from the 2000 census and the 2013-2017 average American Community Survey (ACS), this tool also shows how social equity data are changing over the past 10-15 years. This tool showed that over this time period, poverty near Newman Lake has risen from 6.8% to 16.4%. It has also shown that the senior population has increased from 7.2% to 19.4%. The number of people without health insurance coverage is 7.2 % according to the 2013-2015 average ACS, higher than the Spokane County average of 5.2%. This data supports Dawson Matthews assessment of the community and shows that there is a significant population of people who would especially benefit from improved water quality. Senior citizens, people without health insurance, and people living in poverty significantly benefit from having safe, local, outdoor recreation opportunities like Newman Lake. Using BDAs to improve the health of Newman Lake can help provide a way to improve community, increase physical activity, and improve public health at no cost to the people who live there.

4.4.3 Newman Lake Community Member Interview

The third step of the Social Impact Assessment was connecting with community members. During the weaving of the BDAs, TLC invited community members to help with the weaving. Riverbank Consulting interviewed one community member, Polly Phipps, who was highly supportive of the project. She mentioned how she enjoys swimming in Newman Lake and how it provides her with a great way to both exercise and socialize with fellow community members. She expressed that the community has a great love for the lake and all the resources it brings to the community. She was also excited about the BDA project, as algae blooms and water quality issues have prevented her from being able to swim in the past and she is excited about the BDAs improving these conditions.

4.4.4 Additional Newman Lake Community Engagement

On April 23rd, 2022, RBC will be presenting a poster to the community about the Thompson Creek BDA project at their Newman Lake cleanup day. The team's goals are to inform the community about the project, answer any questions the community may have, and take note of any concerns that the community has for future senior design teams and/or The Lands Council to address. The team will also be handing our flyers explaining what BDAs are, how they are being monitored, and what their intended impacts are.

4.4.5 Project Sustainability

The implementation of BDAs is a relatively low cost and low carbon process. All of the materials used in the dams are biodegradable and will increase nutrients in the stream at the end of their lives, further supporting the existing ecosystem. The brush weave used in this project is locally sourced from The Land's Council's other projects, and the posts are made from lodgepole pine, which is locally sourced through North Idaho Post and Pole. Locally sourcing these materials dramatically reduces the carbon emissions related to transportation, and helps the materials integrate into the existing ecosystem better.

To further improve the environmental impact, RBC has two main categories that could have been different: equipment and material sourcing. As far as the equipment goes, the primary areas of concern are the vehicles transporting the materials/equipment, and the use of the hydraulic post pounder. Using electric vehicles instead of gas vehicles wherever possible can help reduce emissions for this project, though this would require a much high level of initial investment for the project.

The most sustainable option for driving posts is by doing them manually, though most BDA projects will not have enough people/time do reasonably do so. If possible, all gas-powered equipment could use biogas, or renewable natural gas, to reduce their impact and potentially be carbon negative. If all else fails, comparison shopping for the post pounder that has the lowest emissions can help improve the sustainability while still finishing the project on time.

The sourcing of materials for BDA projects also have the opportunity to improve sustainability. Using materials that would otherwise be sent to the landfill could help reduce waste and sequester carbon. BDA builders can also use creativity in their materials based on what is locally available, such as using Christmas trees as pine weave for the dam. Another option could be using reclaimed wood from local projects as posts or filler in the dam. For any posts that are not reclaimed, ensuring proper forest management and sourcing of the wood will help ensure that the resource will still be available for years to come.

5.0 Project Management

The project manager switched from Hallie Stalcup to Matthew Roberts on 10/28/2021, when construction was complete. Once monitoring was complete, Sarah Frisby took over as project manager. Riverbank Consulting delivered the items outlined in Figure 39. The key deliverables included BDA construction, development of a monitoring plan, and design guidelines for BDAs in any reach.

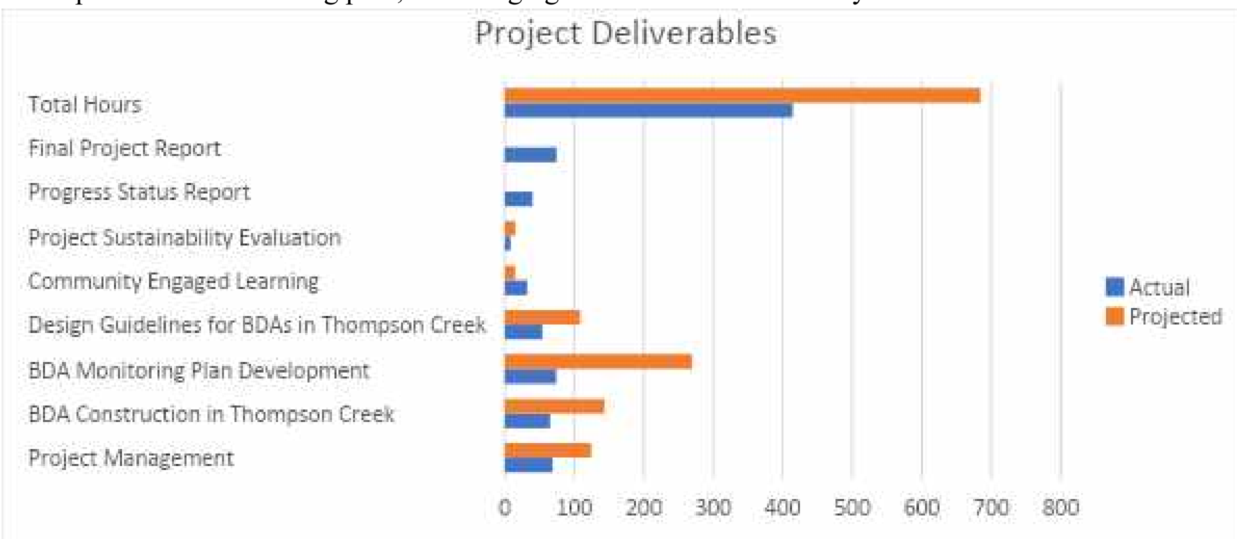


Figure 39 : Deliverables and Time to Complete

Throughout the project the team remained on schedule and met required deadlines. The deliverables that were not met were monthly phosphorus sampling and a final cross-sectional and longitudinal survey of each starter dam. Riverbank Consulting should have been more consistent about visiting Thompson Creek monthly to get water samples after the BDAs were installed. The final surveys of the starter dams were never completed because flows in Thompson Creek were too high to get in the water and measure changes. Figure 40 outlines the tasks completed this year in a Gantt chart.

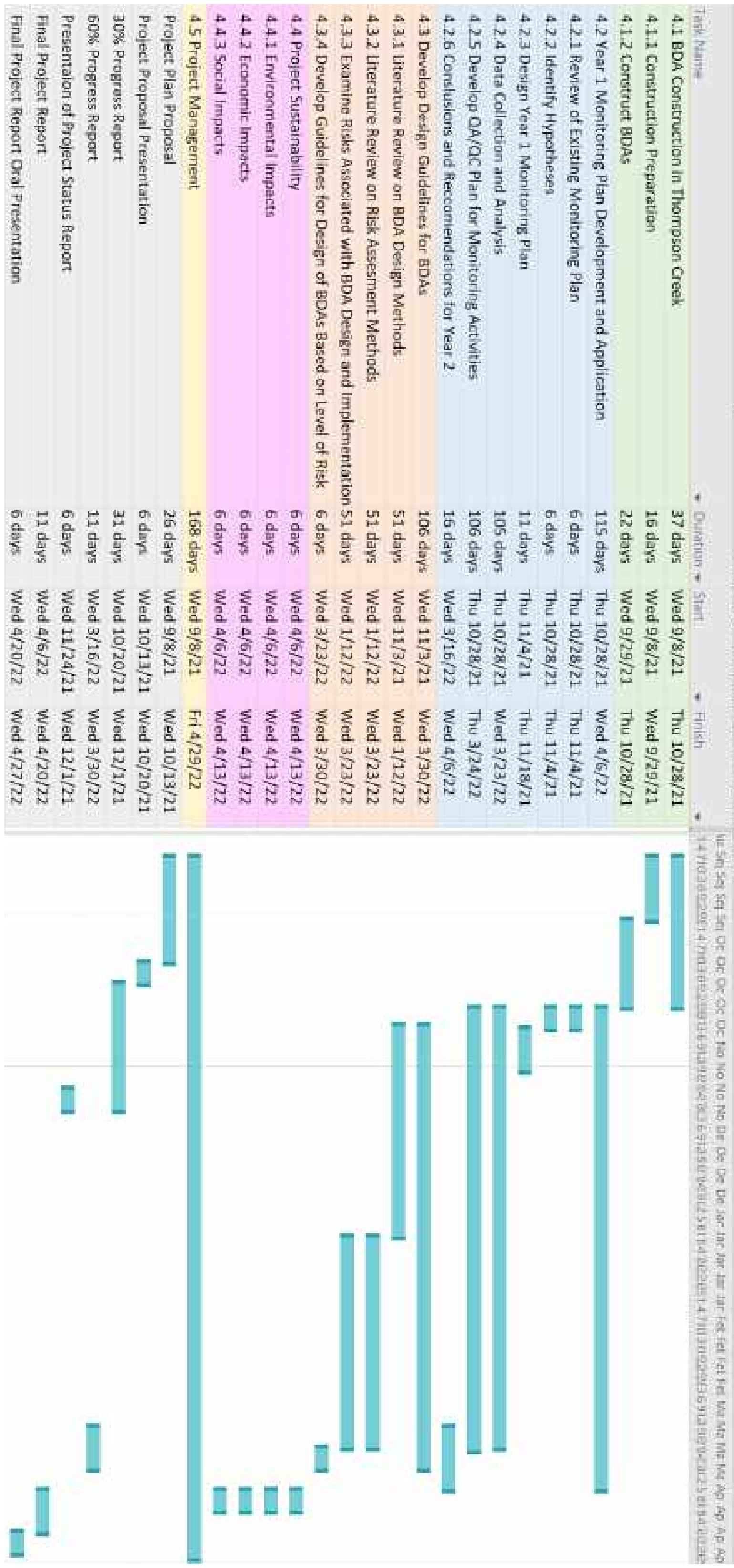


Figure 40: BDA Project Gantt Chart

Overall, Riverbank Consulting is approximately $30,000 below the predicted $75,000 budget. About 3.5 times the hours were anticipated to be worked in in the development of a monitoring plan. Additionally, construction and the design guideline were anticipated to be double the work. Riverbank Consulting did not go out in the field to collect water samples and survey as often as expected because of winter weather and high flow events that limited stream access. Two tasks were added to the deliverables including the status report and final report. A significant portion of hours (27%) were devoted to these tasks. Table 10 highlights the percent of each task's budget that was used.

Table 11: Utilized Budget

	Actual	Projected	Percent of Budget Used (%)
Project Management	$ 7,617.50	$ 13,750.00	55
BDA Construction in Thompson Creek	$ 7,205.00	$ 15,840.00	45
BDA Monitoring Plan Development	$ 8,140.00	$ 29,700.00	27
Design Guidelines for BDAs in Thompson Creek	$ 5,940.00	$ 11,990.00	50
Community Engaged Learning	$ 3,602.50	$ 1,650.00	218
Project Sustainability Evaluation	$ 935.00	$ 1,650.00	57
Progress Status Report	$ 4,400.00	$ -	N/A
Final Project Report	$ 8,195.00	$ -	N/A
Total Hours	$ 45,595.00	$ 75,350.00	61

Riverbank Consulting could have used more QA/QC on most tasks. The team fell behind on hours and the quality of the deliverables decreased because of it. Some of the lack of hours falls on a lack of communication between members of Riverbank Consulting. The lack of communication will be taken into consideration on future projects that Riverbank Consulting's engineers work on. A more detailed comparison of initial vs. actual hours spent on each task can be found in Appendix H.

6.0 Future Work

6.1 Conclusions and Recommendations for Year Two

Once the flows lower in the late summer/early fall, Riverbank Consulting recommends that the BDAs be sealed, as they were not able to be sealed in Year 1 due to cold weather. The team also recommends potentially raising up some of the dams that have sections that were lower than the spring flows.

Once more data is gathered, future senior design projects could perform a data analysis and determine if the hypotheses have been met. These results will provide more knowledge on the effectiveness of BDAs and help with future grant applications

Additionally, the Risk Assessment Guidelines should be applied to more case studies to verify its validity, and once the guidelines are confirmed and/or adjusted, an academic paper can be written to share the guidelines with other people.

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Appendix A: Thompson Creek BDA Monitoring Plan

Appendix A.1: Hypotheses

Hypotheses

1. The implementation of Beaver Dam Analog Starter Dams in Thompson Creek will increase water storage upstream of the Starter Dams in excess of pre-implementation channel storage by at least 10% after one year.
2. The ponds formed by the BDA Starter Dams implemented in Thompson Creek will increase sediment storage upstream of the Starter Dams in excess of pre-implementation channel storage by at least 10% after one year.
3. The addition of the BDA complex in Thompson Creek will reduce total phosphorus concentrations between the inlet (upstream of all BDAs) and outlet (downstream of all BDAs and entering Newman Lake) by at least 5% after one year.

Hypothesis 1: The implementation of Beaver Dam Analog Starter Dams in Thompson Creek will increase water storage upstream of the Starter Dams in excess of pre-implementation channel storage by at least 10% after one year.

Monitoring Methods

Following the procedure outlined by Puttock et al. (2015) and Puttock et al. (2016), a combination of drone aerial imagery and water depth profiling will be used to determine water storage volumes within the BDA reach.

Drone Aerial Imagery: A DJI Phantom 3 Standard drone with gimble camera will be used to fly over Thompson Creek and capture aerial imagery of the entire study reach including each Starter Dam BDA and pond that is formed. Using Agisoft Metashape software, a georeferenced orthomosaic photo of each of the three BDA Starter Dam reaches will be created. Agisoft Metashape or ArcMap 10.1 will then be used digitize the pond boundary and measure pond surface area inside the boundary from the orthomosaic photo. Figure 1 shows an illustration of a “pond” boundary digitized upstream of BDA Starter Dam #3. The result will be the wetted surface area of the ponds upstream of the BDA Starter Dams in Thompson Creek at the time of survey.

Figure 1. "Pond" boundary digitized on aerial orthophoto of BDA Starter Dam #3. In this photo, no pond has yet formed upstream of the Starter Dam, as this was taken during construction. But it illustrates how future pond boundaries will be digitized and measured for area.

Water Depth Profiling: Water depth in each upstream BDA pond, will be measured at 1 ft intervals spaced across sections that are located 5 ft apart starting at the BDA and ending at least 50 ft upstream of the BDA. The water depth will be measured each of these locations using a 10 ft long, 1–2-inch diameter plastic pipe/rod (water/soil probe) (marked with tenths of an inch increments). Figure 2 shows an illustration of sampling locations (sections and sampling points on each section) upstream of BDA Starter Dam #3. At each node (blue dot on each section in Figure 2), the probe is to be inserted into the water until the bottom of the water/soil probe gently rests on the top of sediment on the pond bottom, then the water depth on the probe is recorded. Recording depth at each node on each section will establish a water depth distribution for each BDA pond, which will then be averaged and used with wetted surface area to calculate total pond water storage volume (Buttler and Malanson 1995, Puttock et al. 2016, Puttock et al, 2018).

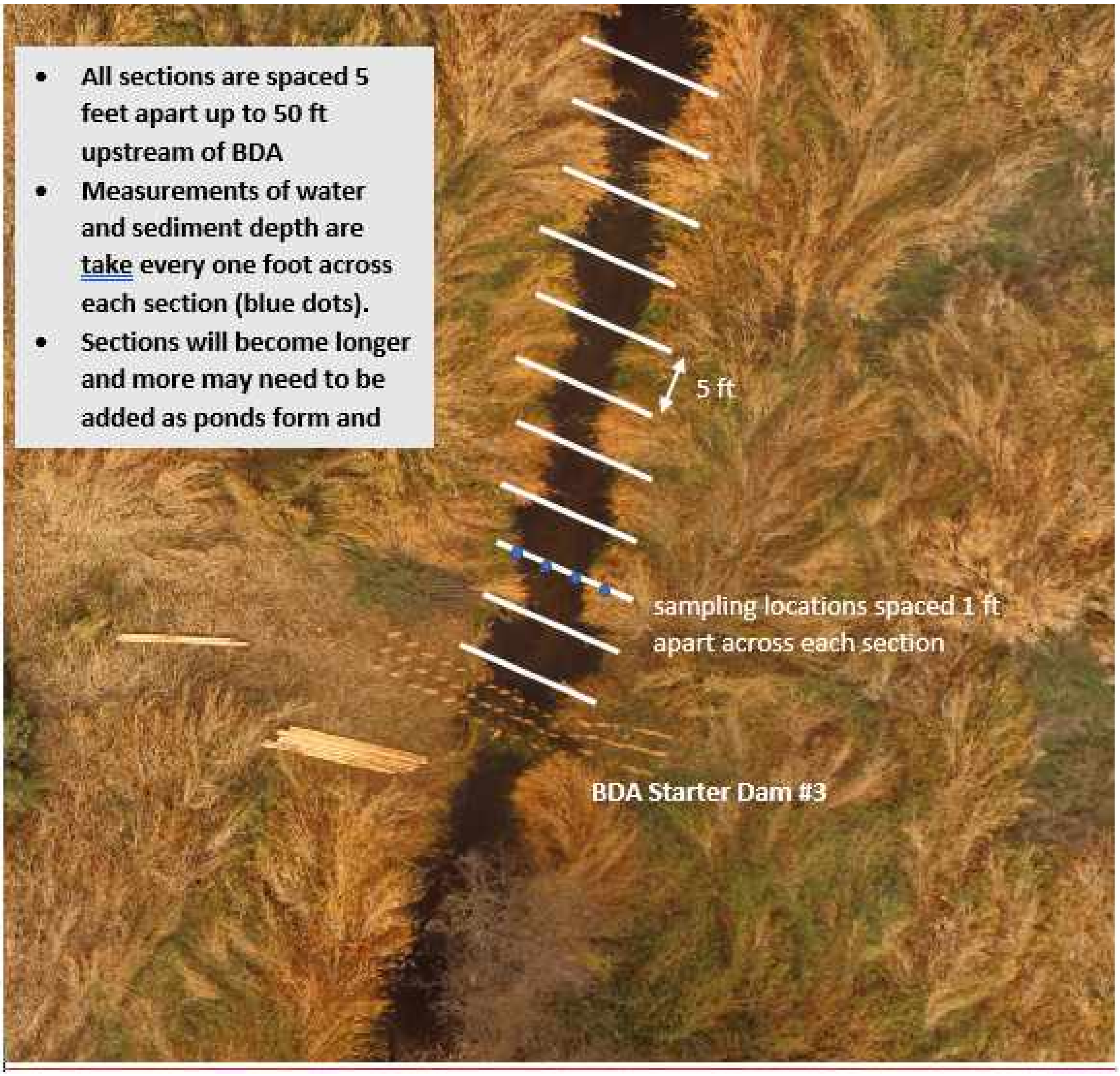


Figure 2. Subsurface profiling sampling sections and locations along sections shown upstream of BDA Starter Dam #3. Both water depth and accumulated sediment depths will be measured at each node of the grid shown. In this photo, no pond has yet formed upstream of the Starter Dam, as this was taken during construction. The number of sections and the width of each section will be adjusted to accommodate the spread of a pond that might form upstream of the Starter Dam over time.

Frequency:

- Prior to implementation of the BDA complex, existing maximum channel water storage will be calculated once from pre-established cross section surveys that were completed as part of the baseline characterization. The surveyed cross sections will be input into StreamMetrics to calculate maximum cross-sectional area in at least nine locations along the reach (3 locations upstream of each BDA Starter Dam). The maximum area in a given cross section will be defined as the cross-sectional area if water levels were at the top of bank (just about to break out into the floodplain). The average cross-sectional area upstream of each Starter Dam will be determined from the maximum area of each of the three surveyed cross sections upstream of each Starter Dam. The surveyed average maximum cross-sectional area will be multiplied by a 50 ft length (which is estimated to be the upstream most extent of future ponds) to calculate the existing (pre-BDA) maximum water storage volume within the stream channel upstream of each Starter Dam.

- After BDA implementation, water depth and drone aerial surveys will be completed once per year in the Spring (Feb-March) when seasonal reductions in vegetation cover allow for higher quality water surface images to be captured and water depths still relatively low to allow wading access into ponds prior to spring snowmelt runoff. This is also the time of year when Newman Lake water level is drawn down to its lowest level (2123.9 ft) to accommodate the upcoming spring snowmelt runoff. Thus, lake backwater influences in the downstream reach of Thompson Creek will be at a minimum and allow for easier access to BDA Starter Dam #3 located at the downstream end of the reach.

Equipment:

- Water/Soil Probe (10 ft long, 1–2-inch diameter thick plastic pipe)
- Waders
- Measuring Tape
- DJI Phantom 3 Standard Drone (with Pix4D Capture and Agisoft Metashape Software)
- Spreadsheet

Procedures:

Drone Aerial Imagery:

To ensure high quality images are produced that can be used to measure water surface areas, the following methods and procedures will be applied:

- To minimize shadowing, flights will be undertaken during times of the year when vegetation canopy cover is at a minimum, and flights will be completed within a few hours of mid-day.
- Three separate flights will be used to capture the full length of the study reach, with each flight focusing on the areas around each of the three BDA Starter Dams and their ponds.
- At least five ground control points will be deployed across each of the three flight paths and geolocated using differential GPS (Eos Gold Arrow RTK).
- An automatic flight will be designed using Pix4D Capture, flying a grid survey pattern with an average altitude of 100 ft.
- Flight patterns will be designed so that every part of the area of interest will be imaged in 10 or more photos.
- The camera will be triggered at distance intervals to attain 80% overlap, with the camera pointing straight down (at 90 degrees).
- Camera shutter speed should be faster than 1/800 s, ISO will be 400, aperture will be f3.5 and focus will be set to infinity. These parameters may be adjusted according to the conditions present during flight times.

Water Depth Profiling: See Hypothesis 2 Procedures

Hypothesis 2:

The ponds formed by the BDA Starter Dams implemented in Thompson Creek will increase sediment storage upstream of the Starter Dams in excess of pre-implementation channel storage by at least 10% after one year.

Monitoring Methods:

Following the procedure outlined by Butler and Malanson 1995, Puttock et al. (2015) and Puttock et al. (2016), a combination of drone aerial imagery and soil probing will be used to determine sediment storage volumes within the BDA reach. In addition, following survey methods presented by Harrelson et al. (1996), repeat cross section surveys and longitudinal profile surveys will also be used to quantify the volume of sediment accumulating in the ponds upstream of the Starter Dams.

Soil Probing: Following the methods outlined in Butler and Malanson (1995) and Puttock et al (2018), the sediment volume trapped behind each pond will be determined from a combination of soil probing within the ponds and surface area measurements from drone imagery (completed for testing Hypothesis 1). In conjunction with subsurface profiling in hypothesis 1, once water depth at a given section node is measured, the water/soil probe is to be gently pushed through the unconsolidated sediment until a compact layer of sediment is reached. The water level on the probe at that point is read and recorded as sediment depth. Similar to establishing water storage, the sediment depth at each node and the surface area determined from the drone aerial imagery for each pond will be used to calculate a trapped sediment volume behind each BDA. Sampling locations will be the same as shown in Figure 2.

Repeat Cross-Section Surveys: Three permanent cross sections will be established spaced at 10 ft intervals upstream of each BDA Starter Dam. The extent of each cross section will be marked with permanent rebar pounded into the ground, so that a tape can be strung across perpendicular to flow in the same location each time a survey is completed. Figure 3 shows the location of the cross sections upstream of BDA Starter Dam #3 (the cross sections are similarly located upstream of the other two Starter Dams). Repeat cross section surveys will be completed at these permanent cross section locations using standard surveying methods with a rod and level (see Harrelson et al 1994). station and elevation readings will be recorded at 1-foot intervals across each cross section to gain a relatively precise depiction of the channel bed elevation. A permanent elevation benchmark will be established near the cross-section locations and surveyed using differential GPS (Eos Arrow Gold) to set a consistent elevation to use for repeat surveys. The repeat cross section surveys will be tied to the permanent benchmark and compared over time to calculate the depth of sediment accumulating. The average end area method will then be applied to all three cross sections to determine the volume of sediment accumulating in the pond upstream of each Starter Dam over time.

Repeat Longitudinal Profile Surveys: Repeat longitudinal profiles will be surveyed in the vicinity of the Starter Dams. Longitudinal profile surveys will follow methods presented in Harrelson et al. (1994). The profiles will start at a distance 60 ft upstream of a Starter Dam and will end 20 ft downstream of a starter dam and will also record at least one point on top of the Starter Dam. Figure 3 shows an example longitudinal profile path for Starter Dam #3. The longitudinal profile will also be tied to the permanent benchmark. At points spaced out every 5 ft, the elevation of the existing water surface and channel bottom will be surveyed. These repeat longitudinal profile surveys will yield data such as the thalweg elevation (channel bottom) and the water surface elevation, both of which are important measurements for later analysis of channel slopes and aggradation and degradation trends at each Starter Dam location.

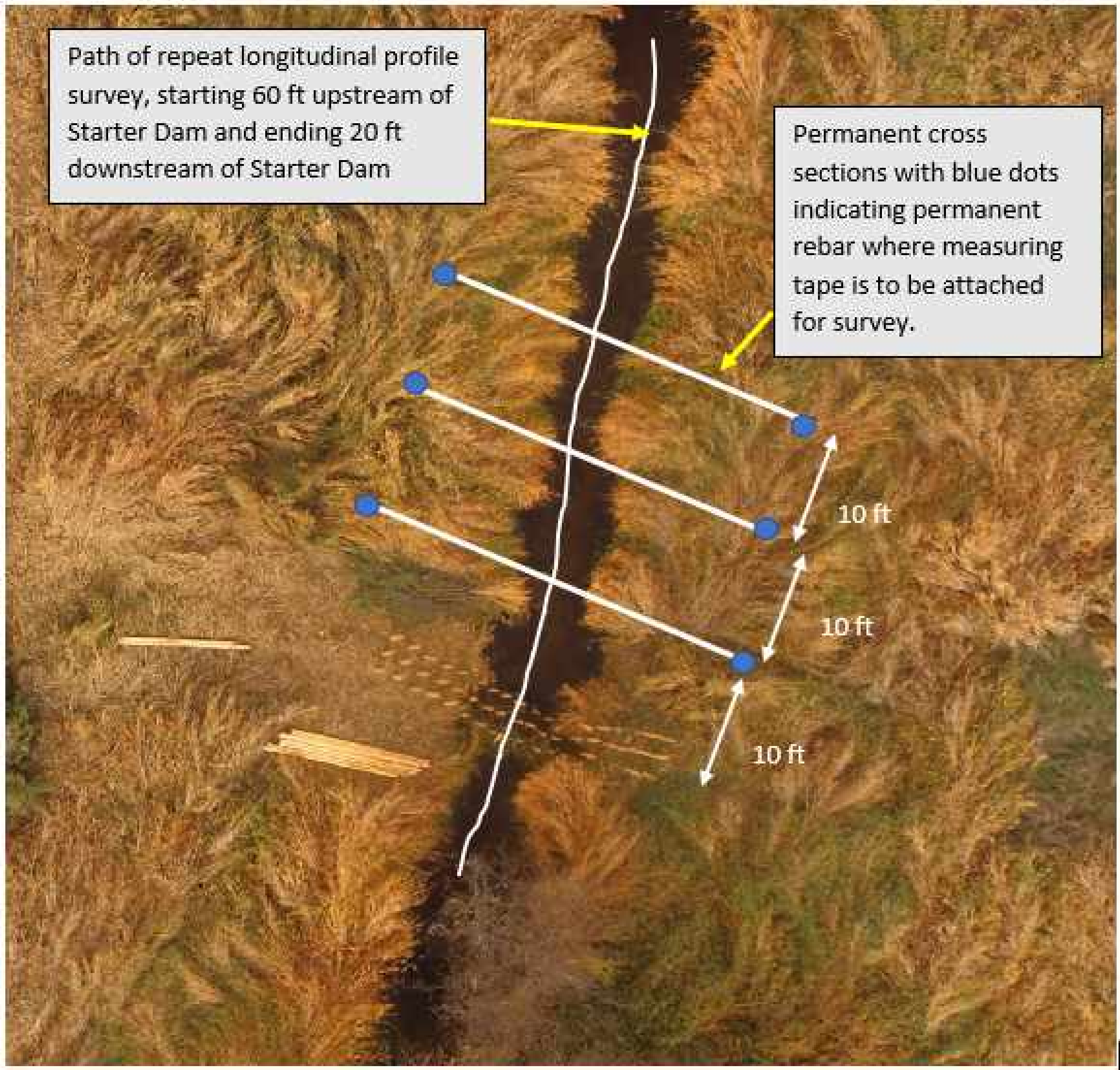


Figure 3. Permanent cross section locations upstream of BDA Starter Dam #3. Permanent cross sections will be added similarly upstream of Starter Dams #1 and #2. Figure also shows the path that will be followed for the repeat longitudinal profile surveys around all three Starter Dams.

Frequency:

Soil Probing:

- To establish baseline soil depths, soil probing will be completed upstream of each Starter Dam immediately before the completion of the BDA construction.
- After BDA implementation, soil probing and drone aerial surveys will be completed once per year in the Spring (Feb-March) when seasonal reductions in vegetation cover allow for higher quality water surface images to be captured and water depths still relatively low to allow wading access into ponds prior to spring snowmelt runoff. This is also the time of year when Newman Lake water level is drawn down to its lowest level (2123.9 ft) to accommodate the upcoming spring snowmelt runoff.

Thus, lake backwater influences in the downstream reach of Thompson Creek will be at a minimum and allow for easier access to BDA Starter Dam #3 located at the downstream end of the reach.

Repeat Cross Section and Longitudinal Profile Surveys:

- The permanent cross section locations will be established prior to the completion of the Starter Dam construction. These cross sections will also be surveyed once prior to the completion of construction to establish baseline channel bed elevations and cross-sectional areas. In addition, the longitudinal profiles should also be surveyed once prior to the completion of the construction of the Starter Dams to establish baseline slopes along the reaches in the vicinity of the Starter Dams.
- After BDA implementation, all cross sections and longitudinal profiles will be surveyed once per year either in the Summer (depending on available resources) or in the early Fall (October) when water levels are low enough to safely access the channel. Due to summer low flows, it is expected that even a Fall survey will still allow for the capture of channel changes that occurred during the previous spring runoff event.

Equipment:

- Water/Soil Probe (10 ft long, 1–2-inch diameter thick plastic pipe) Waders
- Measuring Tapes
- DJI Phantom 3 Standard Drone (Pix4D Capture and Agisoft Metshape software)
- Rebar for Cross Section Bank Pins
- Surveying Rods
- Levels
- Tripods
- Rebar
- Flagging tape

Procedure: **Water Depth Profiling and Soil Probing (for Hypotheses 1 and 2):**

- Setup first section and begin data collection on the left bank closest to the BDA Starter Dam.
- Insert the water/sediment probe until it rests gently on the top of the sediment at the bottom of the pond. Read the water level on the measurement scale on the probe and record this as water depth WD1-1 (Section 1 – water depth 1).
- Keeping rod in same location, push the probe down as far as you can or until you hit a consolidated layer. Record this new water level value from the scale on the probe as sediment depth SD1-1 (Section 1 – sediment depth 1).
- Move to the right a distance of one foot and record values for WD1-2 and SD1-2.
- Once the right bank is reached in section 1, move upstream a distance of five feet and repeat the measurement process across section 2. Repeat this entire process until you have reached the upstream extent of the pond.
- Average the WD values over the area.
- Average the SD values over the area.
- Multiply the average water depths and average sediment depths by the surface area measured from orthophoto to find both the water and sediment volume being stored behind the BDA Starter Dam.
- Repeat Steps for all BDA Starter Dams.

Repeat Cross-Section Surveys:

- At each starter dam location establish permanent benchmark to use as the consistent elevation datum for the surveys.
- Install one rebar on each side of the channel (pound into ground to a depth of 3ft) such that when a tape is strung between each rebar it is orientated perpendicular to flow. Extend the cross-section rebar an extra 10 feet beyond where the Starter Dam ends. Tie a piece of bright flagging tape around each rebar to identify each bank pin location. .
  Attach the zero end of a measuring tape to the left rebar (left as you look downstream) and run it across the channel to attach to the right rebar. Record the tape length from rebar to rebar. Be sure to read the tenths side of the tape.
- Set up the level to determine initial elevation from benchmark. Place the rod on the established benchmark and using the level record the benchmark rod reading as your backsight.
- Starting at the left bank rebar, begin surveying by recording the station reading (in tenths) from the tape and the elevation reading from the rod and level. Take station and elevation readings at one-foot intervals across the cross section until you reach the right bank rebar. Make sure to take a reading at the left edge and right edge of water and label these points. Record all survey data in the cross-section survey data sheet.
- Repeat the process for all cross sections at all Starter Dams.

Repeat Longitudinal Profile Surveys:

- Set up the level and determine initial elevation from on the benchmark. Place the rod on the established benchmark and using the level record the benchmark rod reading as your backsight.
- Beginning at 60 ft upstream of a Starter Dam, stretch the measuring tape down the centerline length of the channel trying to have it lay in the thalweg (deepest part of the channel).
- Starting at station 0, and taking notes in the longitudinal profile data sheet, measure and record the station (read from the measuring tape), water surface elevation (read directly from the rod as water depth), and channel elevation (read from the rod and level combination).
- Repeat the entire procedure downstream at 5-foot intervals along the tape. End the survey 20 ft downstream of the Starter Dam.
- Repeat the process at all Starter Dams.

Hypothesis 3: The addition of the BDA complex in Thompson Creek will reduce total phosphorus concentrations between the inlet (upstream of all BDAs) and outlet (downstream of all BDAs and entering Newman Lake) by at least 5% after one year.

References:

Butler, D. R., Malanson, G. P. (1995). “Sedimentation rates and patterns in beaver ponds in a mountain environment”.

Harrelson, Cheryl C; Rawlins, C. L.; Potyondy, John P. (1994). Stream Channel Reference Sites: An Illustrated Guide to Field Technique. Gen. Tech. Rep. RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest, and Range Experiment Station. 61 p.

Puttock, A., Cunliffe, A. M., Anderson, K., Brazier, R.E. (2015). “Aerial Photography collected with multirotor drone reveals impact of Eurasian beaver reintroduction ecosystem structure.” NRC Research Press 123-130.

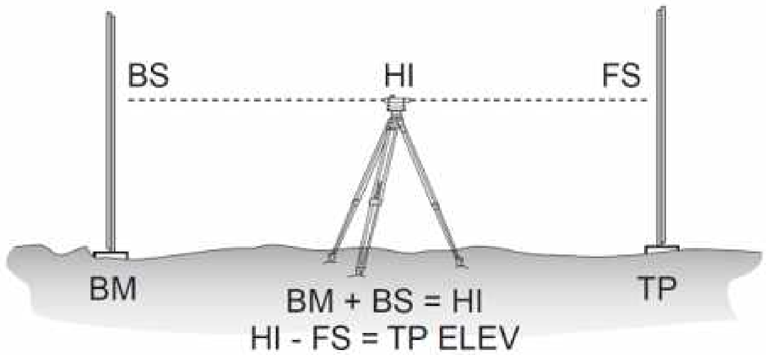
Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M., and Brazier, R. E. (2016). “Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands.” Science of The Total Environment, 576, 430–443.

Puttock, A., Graham, H. A., Carless, D., and Brazier, R. E. (2018). “Sediment and nutrient storage in a beaver engineered wetland.” Earth Surface Processes and Landforms, 43(11), 2358–2370.

Appendix A.2: Data Sheets

Field Data Collection Sheet

Differential Leveling Field Data Sheet – Xsec1



1. Take a backsight (BS) on benchmark (BM)
2. Move rod (do not move instrument) and take a foresight (FS) on the rod
3. Move instrument, do not move rod.
4. Take a backsight on rod
5. Move rod (do not move instrument) and take a foresight
6. Repeat until instrument is in suitable location for surveying entirety of cross section

	Point	Rod Reading (ft)
	BS on BM	
	FS	
TP 1	BS	
	FS	
TP 2	BS	
	FS	
TP 3	BS	
	FS	
TP 4	BS	
	FS	Begin survey

Channel Cross Section Field Form

Reach Name			Date:	
Starter Dam ID			Team:	
Cross section ID			Survey tape length (ft)	

Point	Station (ft)	Rod reading (ft)	Notes	Point	Station (ft)	Rod reading (ft)	Notes
1				31			
2				32			
3				33			
4				34			
5				35			
6				36			
7				37			
8				38			
9				39			
10				40			
11				41			
12				42			
13				43			
14				44			
15				45			
16				46			
17				47			
18				48			
19				49			
20				50			
21				51			
22				52			
23				53			
24				54			
25				55			
26				56			
27				57			
28				58			
29				59			
30				60			

Notes:

- Take a rod reading every 1 ft along the profile.
- Place the rod on the ground surface (not on top of reed canary grass)
- Gently sway the rod back and forth to ensure the rod is level when the reading is taken.
- Make note of any specific channel features that might influence the channel slope (BDA location, large boulder, in-stream wood, etc.)

Longitudinal Profile field form				
Reach Name		**Date:**		
Starter Dam ID		**Team:**		
Survey Tape length				
Station (ft)	**Rod Reading (ft)**	**Water Depth (ft)**	**Channel Bottom (ft)**	**Notes**

Notes:

- Take a rod reading every 5 ft along the profile.
- Make note of any specific channel features that might influence the channel slope (BDA location, large boulder, in-stream wood, etc.)

Soil Probing Data Sheet

BDA ____

In a grid above each BDA, take the difference in Water Surface Elevation before probing and after to determine soil depth at five locations equally spaced in the cross section and along the stream above the BDA.

1. Input water elevation with apparatus resting on top of soil
2. Input water elevation with apparatus pushed through soil layer

X length __________ft

BDA

1______ 2______	1______ 2______	1______ 2______	1______ 2______	1______ 2______
1______ 2______	1______ 2______	1______ 2______	1______ 2______	1______ 2______
1______ 2______	1______ 2______	1______ 2______	1______ 2______	1______ 2______
1______ 2______	1______ 2______	1______ 2______	1______ 2______	1______ 2______
1______ 2______	1______ 2______	1______ 2______	1______ 2______	1______ 2______

Stream Flow

Y Length
__________ ft

Appendix B: Data Tables

Water Depth Profiling and Soil Probing Data Tables

Starter Dam #1

Length	5	5	5	5	5	5	5	5	5	5	3	53		
Width	2.7	2.5	2.6	3.2	0.6	3.1	0.6	1	1.2	1.9	2.5	BDA		Average Water Depth (ft)
1	2.7	2.3	2.2	2	0.5	0.8	0.6	0.9	1.2	0.9	1.9	BDA	Average Depth (ft)	1.455
Depth (ft)	0	0.2	0.4	1.2	0.1	2.3	0	0.1	0	1	0.6	BDA	0.536	
	3.1	2.7	2.7	2.5	2.9	3.8	2.8	2.7	3.1	3.3	2.1	BDA		
1	2.5	2.05	2.2	2.3	2.8	3.2	2.7	1.7	1.9	1.7	2	BDA		2.277
Depth (ft)	0.8	0.65	0.5	0.2	0.1	0.6	0.1	1	1.2	1.6	0.1	BDA	0.605	
	2.6	2.65	2.8	2.5	4.3	4.1	3.4	3	3.5	2.9	3.6	BDA		
1	2.3	1.9	2.2	2.3	2.5	3.1	2.9	2.3	2.7	1.75	3	BDA		2.450
Depth (ft)	0.3	0.75	0.6	0.3	1.8	1	0.5	0.7	0.8	1.15	0.6	BDA	0.764	
	2.5	2.2	2.5	2.8	2.9	3.9	3.4	3.1	3.45	2.9	3.55	BDA		
1	2.2	1.8	2.3	2.1	1.8	3	2.75	2.5	3.2	2	1.25	BDA		2.264
Depth (ft)	0.3	0.4	0.2	0.3	1.1	0.9	0.05	0.6	0.25	0.9	2.3	BDA	0.755	
	4	2.4	2.4	3.3	1.4	3.2	3.8	3.1	3.4	2.6	3.5	BDA		
1	2	1.5	2	1.9	1	2.9	2.4	2.8	3.25	2.2	2.4	BDA		2.234
Depth (ft)	2	0.9	0.4	1.4	0.4	0.3	1.4	0.3	0.15	0.4	1.1	BDA	0.796	
	2.95	1.35	3	3.4	5	3.2	2.6	3.35	1.25	2.8	0.6	BDA		
1	1.35	1.35	1.7	1.7		3	2.1	2.8	1.1	2.5	0.5	BDA		1.830
Depth (ft)	1.8	0	1.3	1.7		0.2	0.5	0.55	0.15	0.3	0.1	BDA	0.640	
	6	0.6	3	0.5		3.65	3.5	3.5	4	3.6	0.7	BDA		
1		0.3	1.3	0.4		2.1	1.4	3	1.5	2.5	0.5	BDA		1.444
Depth (ft)		0.3	1.7	0.1		1.55	2.1	0.5	2.5	1.1	0.2	BDA	1.117	
		7	7	7		7	1.6	2.9	2.4	7	0.7	BDA		
1							0.6	2.5	0.8		0.5	BDA		1.100
Depth (ft)							1	0.4	1.6		0.2	BDA	0.800	
							0.9	2.5	2.35		8	BDA		
1							0.3	1.5	1			BDA		0.933
Depth (ft)							0.6	1	1.35			BDA	0.983	
							9	2.85	9			BDA		
1								1.3				BDA		1.300
Depth (ft)								1.55				BDA	1.550	
								10				BDA		
Area	30	35	35	35	25	35	45	50	45	35	24	394	0.854	1.725
												Total Wetted Area (sq.ft.)	Average Depth (ft)	Average Water Depth (ft)
													Starter Dam #1 - Pre-BDA	Starter Dam #1 - Pre-BDA November
													Volume Sediment (cu.ft.)	Water Volume (cu. ft.)
													336.46	679.53

Starter Dam #2

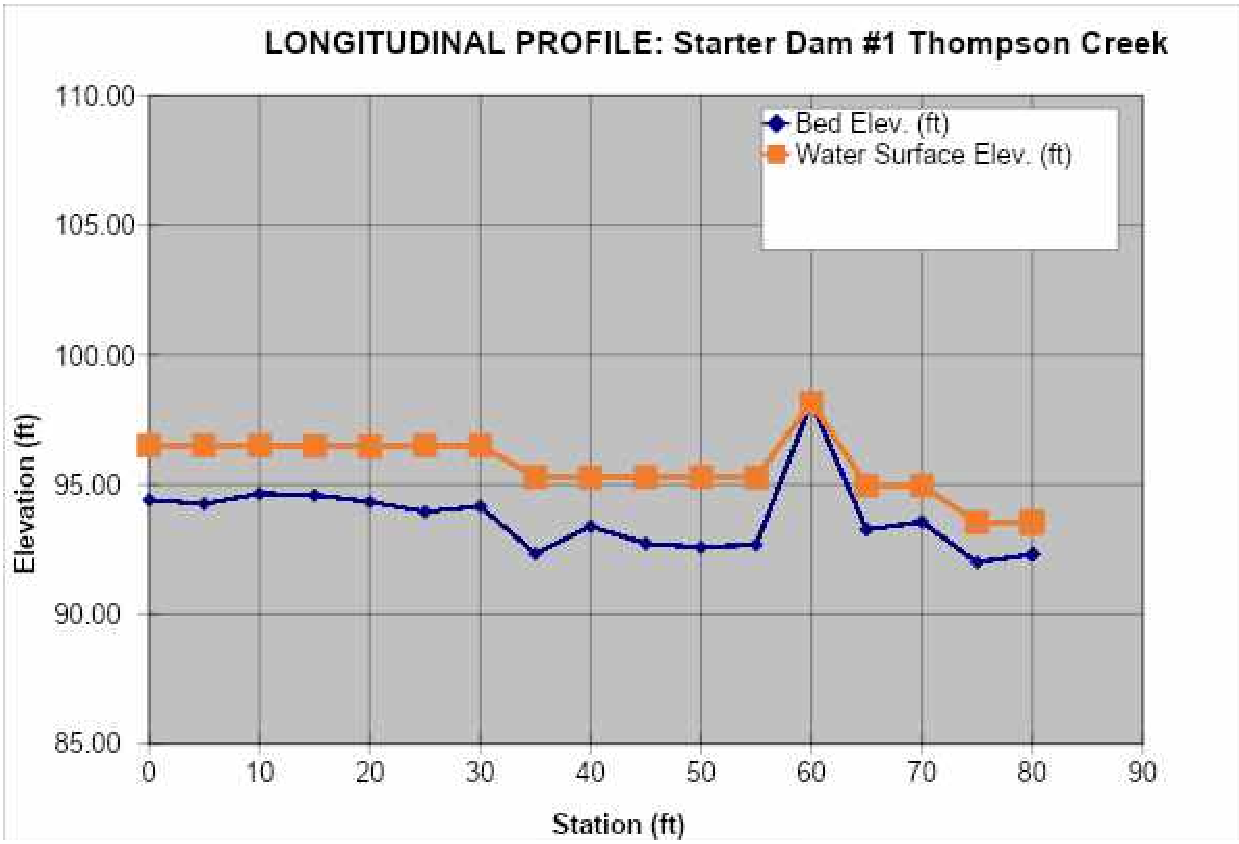
Length	5	5	5	5	5	5	5	8	5	3	51		
Width	2.9	2.5	2.6	2	1.6	2.5	1.7	1.8	1.4	0.4	BDA		Average Water Depth (ft)
1	0.9	1.5	2.3	1.7	1.5	2	1	1	0.8	0.3	BDA	Average Depth (ft)	1.3
Depth (ft)	2	1	0.3	0.3	0.1	0.5	0.7	0.8	0.6	0.1	BDA	0.640	
	3.4	3.5	2.7	2.6	1.6	2.1	0.9	3.2	1.7	1.5	BDA		
1	3.2	2.2	2.4	1.9	1.6	1.8	0.8	3	1	0.6	BDA		1.85
Depth (ft)	0.2	1.3	0.3	0.7	0	0.3	0.1	0.2	0.7	0.9	BDA	0.470	
	3.3	3.6	2.7	2.2	1.8	1.8	1.5	3.4	2	2.3	BDA		
1	2.8	3	2.3	1.9	1.65	1.7	0.65	3.35	1.9	2.05	BDA		2.13
Depth (ft)	0.5	0.6	0.4	0.3	0.15	0.1	0.85	0.05	0.1	0.25	BDA	0.330	
	3.3	3.6	2.5	2.2	1.9	1.8	1.9	3.5	3.2	2.3	BDA		
1	2.8	3.25	2.3	1.9	1.7	1.6	1.1	3.2	2.2	2.2	BDA		2.225
Depth (ft)	0.5	0.35	0.2	0.3	0.2	0.2	0.8	0.3	1	0.1	BDA	0.395	
	3.5	3.8	3.5	3	2.1	1.7	1.5	3.3	2.9	2.3	BDA		
1	2.9	3.5	2.3	1.65	1.8	1.5	1.4	3.1	2.4	2.2	BDA		2.275
Depth (ft)	0.6	0.3	1.2	1.35	0.3	0.2	0.1	0.2	0.5	0.1	BDA	0.485	
	3.5	3.7	3.1	1.7	2.2	1.6	2	3.2	2.9	2.5	BDA		
1	2.8	3.5	1.9	1.5	2.05	1.4	1.4	3	2.4	2	BDA		2.195
Depth (ft)	0.7	0.2	1.2	0.2	0.15	0.2	0.6	0.2	0.5	0.5	BDA	0.445	
	3	3.7	2.8	1.6	2.3	1.6	1.7	3	2.9	2	BDA		
1	1.4	3.2	1.8	1.3	2.1	1.2	1.4	1.9	2.2	1.85	BDA		1.835
Depth (ft)	1.6	0.5	1	0.3	0.2	0.4	0.3	1.1	0.7	0.15	BDA	0.625	
	0.7	3	3	2.1	2.1	7	7	0.6	3	1.55	BDA		
1	0.6	0.5	1	0.6	2			0.1	2.3	1.4	BDA		1.0625
Depth (ft)	0.1	2.5	2	1.5	0.1			0.5	0.7	0.15	BDA	0.944	
	8	8	8	8	2.1			8	3	0.9	BDA		
1					1.7				2.3	0.7	BDA		1.567
Depth (ft)					0.4				0.7	0.2	BDA	0.433	
					1				2.5	0.7	BDA		
1					0.5				1.8	0.7	BDA		1.15
Depth (ft)					0.5				0.7	0	BDA	0.400	
1					10				10	1.1	BDA		
										0.6	BDA		0.6
										0.5			
										11			
Area	40	40	40	40	50	35	35	64	50	33	427	0.517	1.654
											Total Wetted Area (sq.ft.)	Average Depth (ft)	**Average Water Depth (ft)**
												Starter Dam #2 - Pre-BDA	**Starter Dam #2 - Pre-BDA November**
												Volume Sediment (cu.ft.)	**Water Volume (cu. ft.)**
												220.63	**706.07**

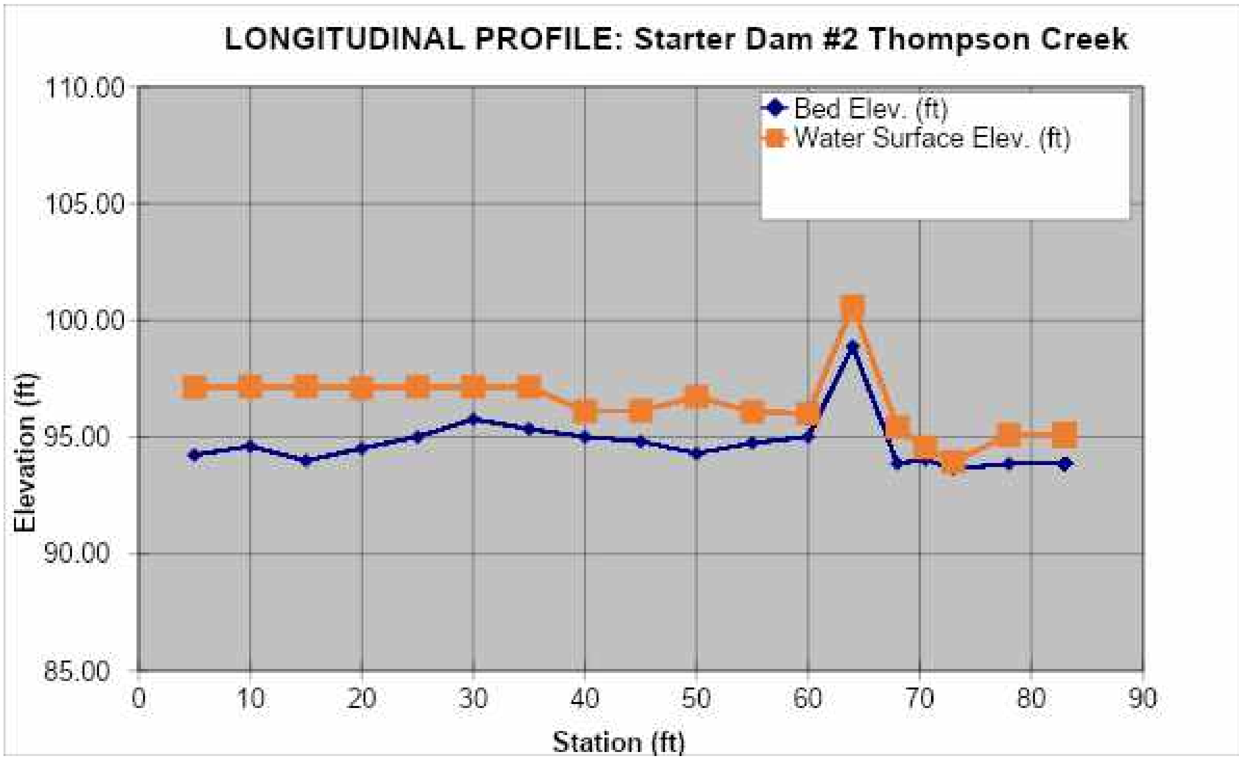
Starter Dam #3

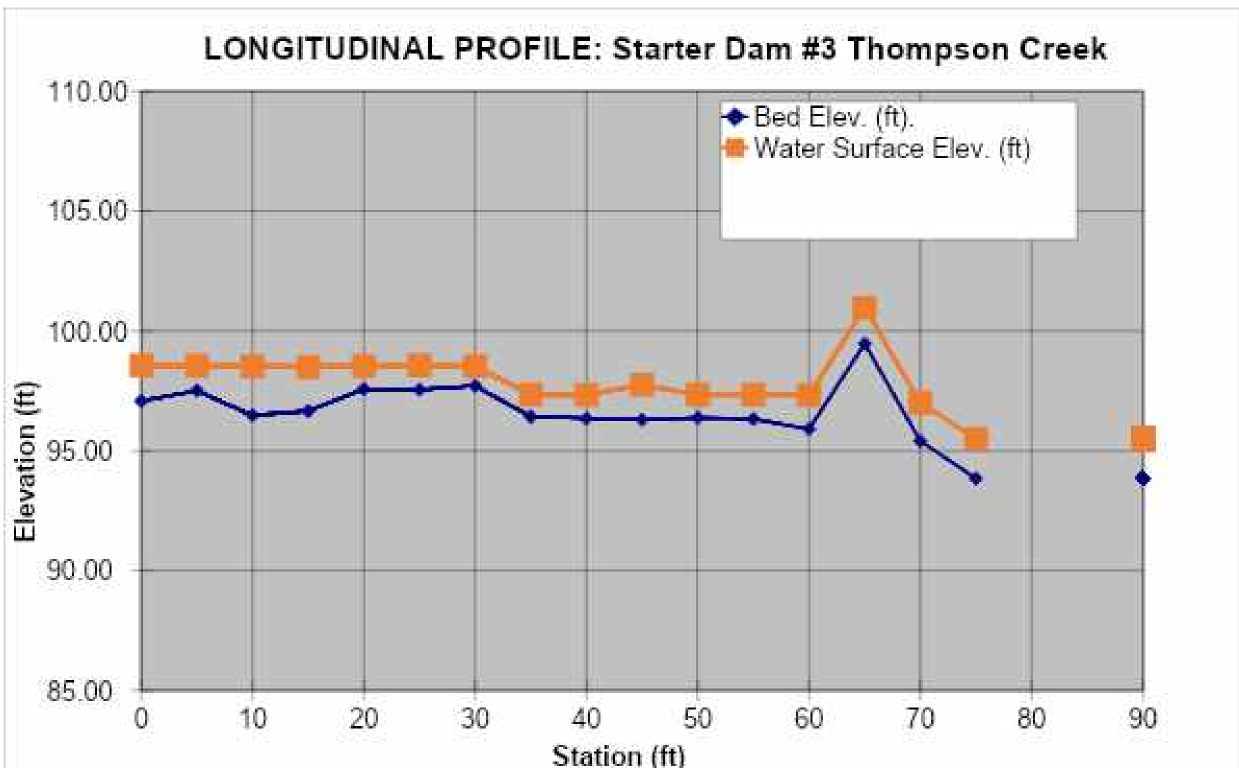
Length	10	5	5	5	1	26		
Width	4.3	4.7	3.9	3	2.75	BDA		Average Water Depth (ft)
1	1.3	2.3	1.3	1.05	1	BDA	Average Sediment Depth (ft)	1.39
Depth (ft)	3	2.4	2.6	1.95	1.75	BDA	2.340	
	3.6	3.3	3.8	3	3.4	BDA		
1	1.4	1.4	1.4	1.2	1.9	BDA		1.46
Depth (ft)	2.2	1.9	2.4	1.8	1.5	BDA	1.960	
	2.1	3.5	3.3	3.9	3.3	BDA		
1	1.8	1.3	2.1	1.6	1.8	BDA		1.72
Depth (ft)	0.3	2.2	1.2	2.3	1.5	BDA	1.500	
	1.6	3.9	2.3	3.3	2.05	BDA		
1	1.2	1.1	1.8	1.5	1.85	BDA		1.49
Depth (ft)	0.4	2.8	0.5	1.8	0.2	BDA	1.140	
	1.5	3.7	3.35	2.8	1.7	BDA		
1	0.9	1	1.2	1.1	1.6	BDA		1.16
Depth (ft)	0.6	2.7	2.15	1.7	0.1	BDA	1.450	
	4.1	3.3	3.3	2.9	1.6	BDA		
1	0.8	0.9	1.1	1	1.5	BDA		1.06
Depth (ft)	3.3	2.4	2.2	1.9	0.1	BDA	1.980	
	3.9	6	3.4	1.7	1.5	BDA		
1	0.8		1.15	1	1.4	BDA		1.0875
Depth (ft)	3.1		2.25	0.7	0.1	BDA	1.538	
	3.5		3.6	3	1.4	BDA		
1	0.7		1.1	1	1.3	BDA		1.025
Depth (ft)	2.8		2.5	2	0.1	BDA	1.850	
	8		8	3.1	2.8	BDA		
1				0.9	1.3	BDA		1.1
Depth (ft)				2.2	1.5	BDA	1.850	
				9	9	BDA		
Area	80	30	40	45	9	204	1.734	**1.277**
						Total Wetted Area (sq.ft.)	Average Sediment Depth (ft)	**Average Water Depth (ft)**
							Starter Dam #3 - Pre-BDA	Starter Dam #3 - Pre-BDA November
							Volume Sediment (cu.ft.)	Water Volume (cu. ft.)
							353.77	260.50

Appendix C: Profile Graphs

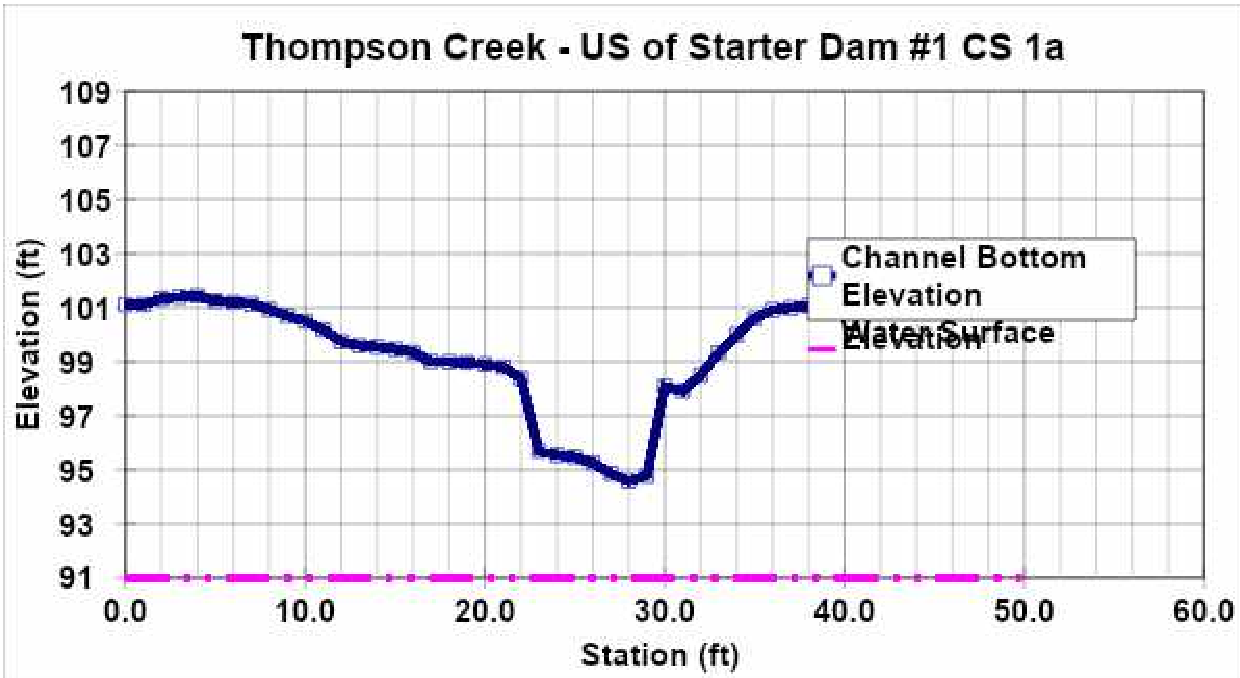
Longitudinal Profile Graphs

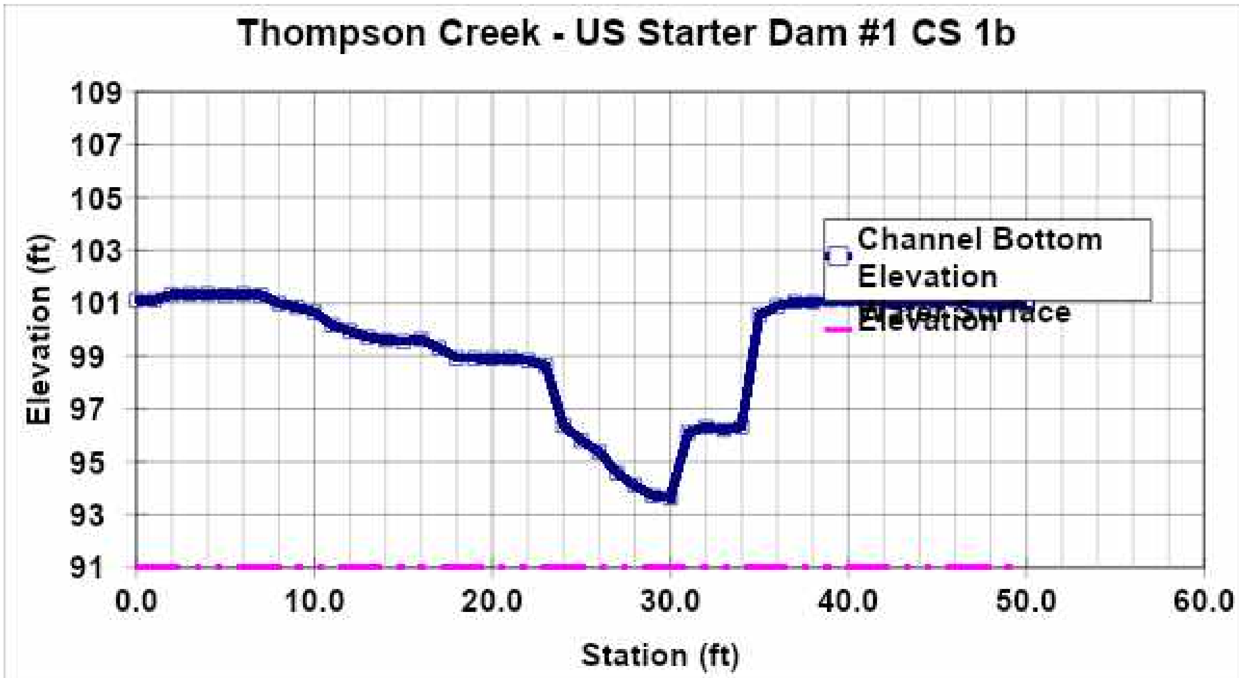


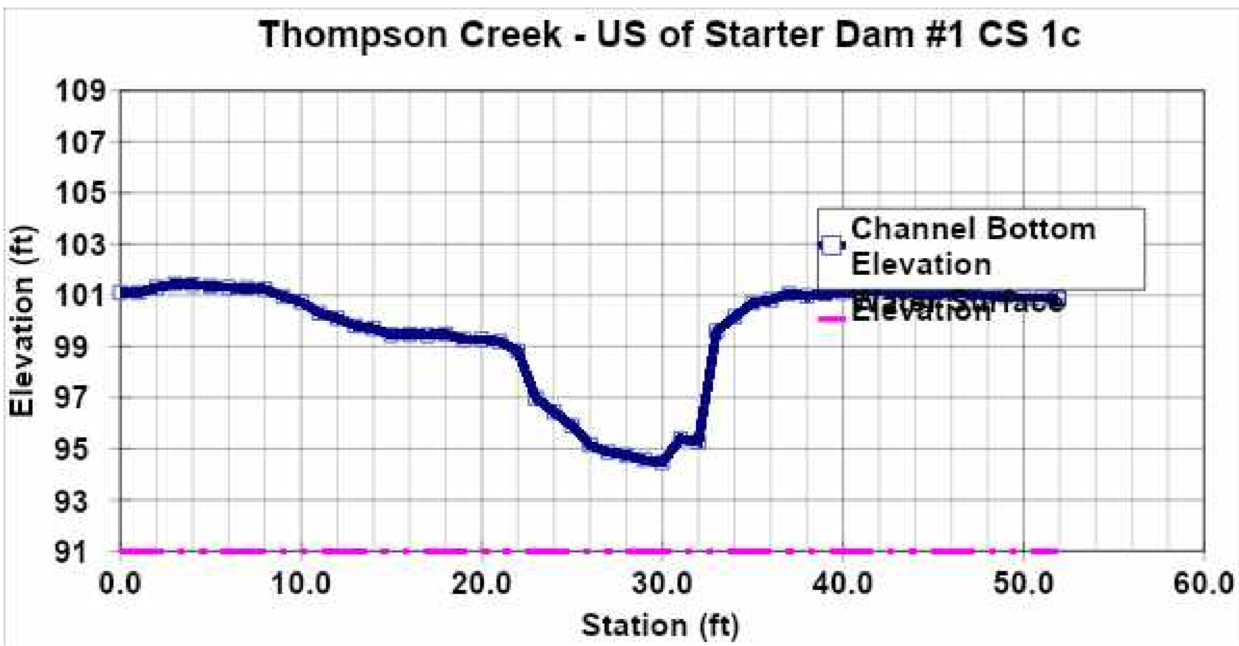

LONGITUDINAL PROFILE: Starter Dam #2 Thompson Creek
Bed Elev. (ft)
Water Surface Elev. (ft)
Elevation (ft)
110.00
105.00
100.00
95.00
90.00
85.00
0
10
20
30
40
50
60
70
80
90
Station (ft)

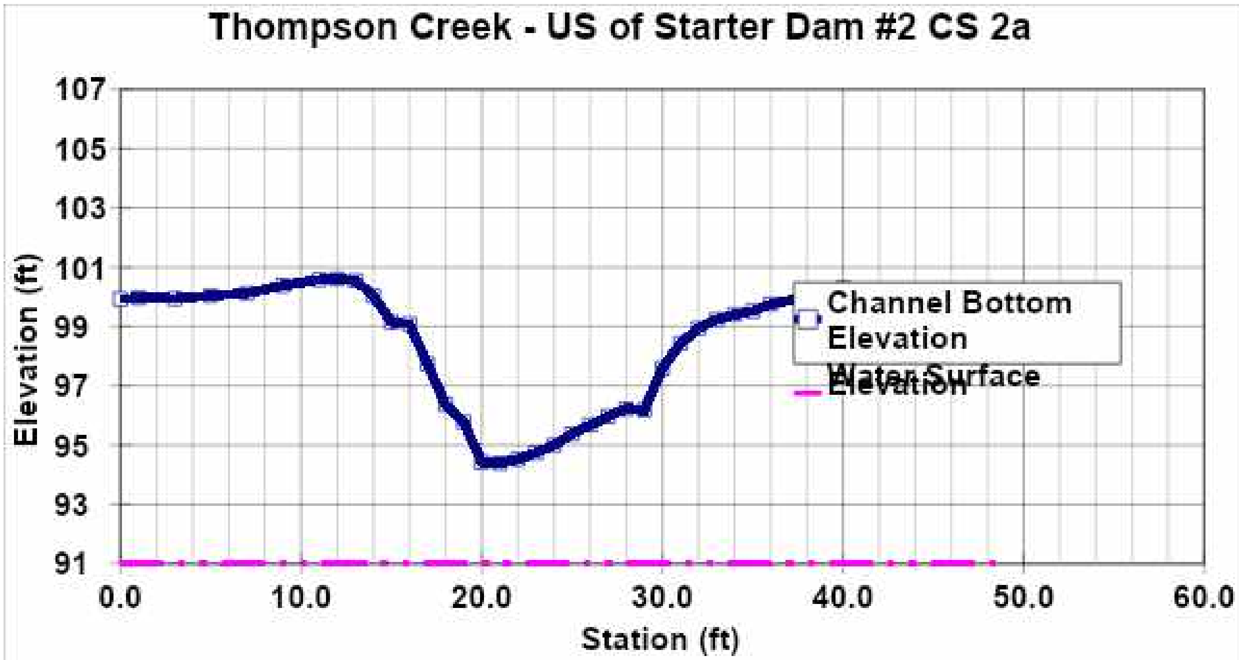

LONGITUDINAL PROFILE: Starter Dam #3 Thompson Creek
Bed Elev. (ft).
Water Surface Elev. (ft)
Elevation (ft)
110.00
105.00
100.00
95.00
90.00
85.00
0
10
20
30
40
50
60
70
80
90
Station (ft)

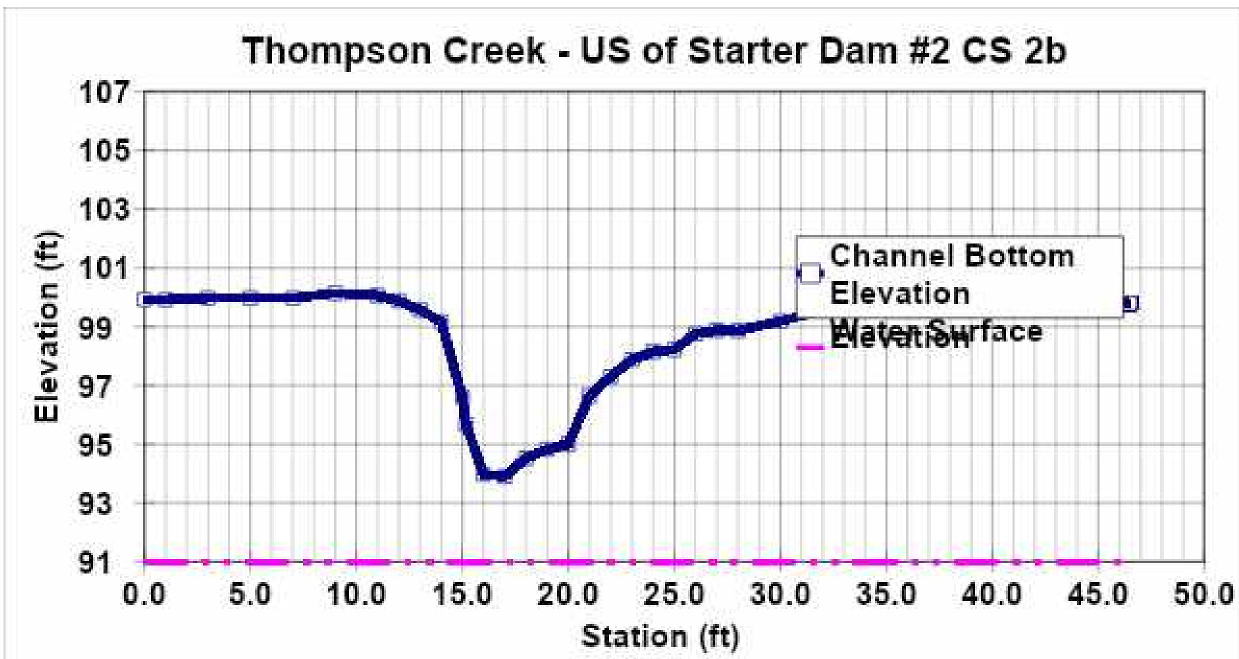
Channel Cross-Section Graphs

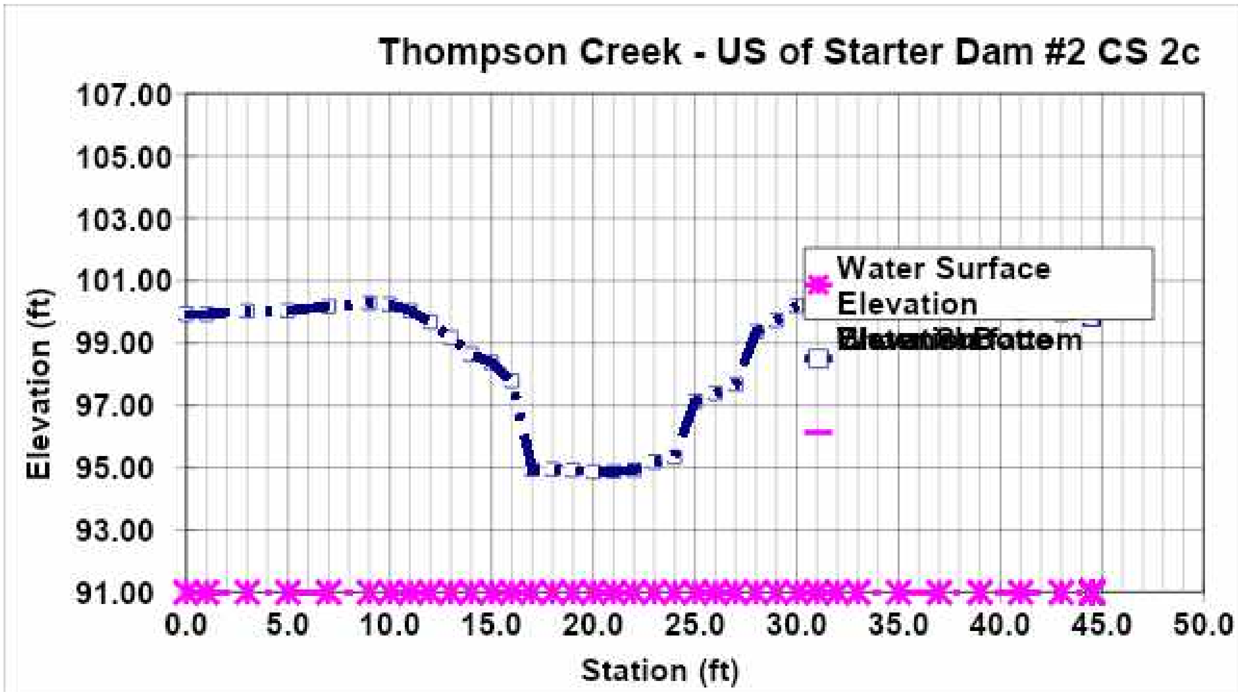



Thompson Creek - US Starter Dam #1 CS 1b
109
107
105
103
101
99
97
95
93
91
Elevation (ft)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Station (ft)
Channel Bottom Elevation
Water Surface Elevation

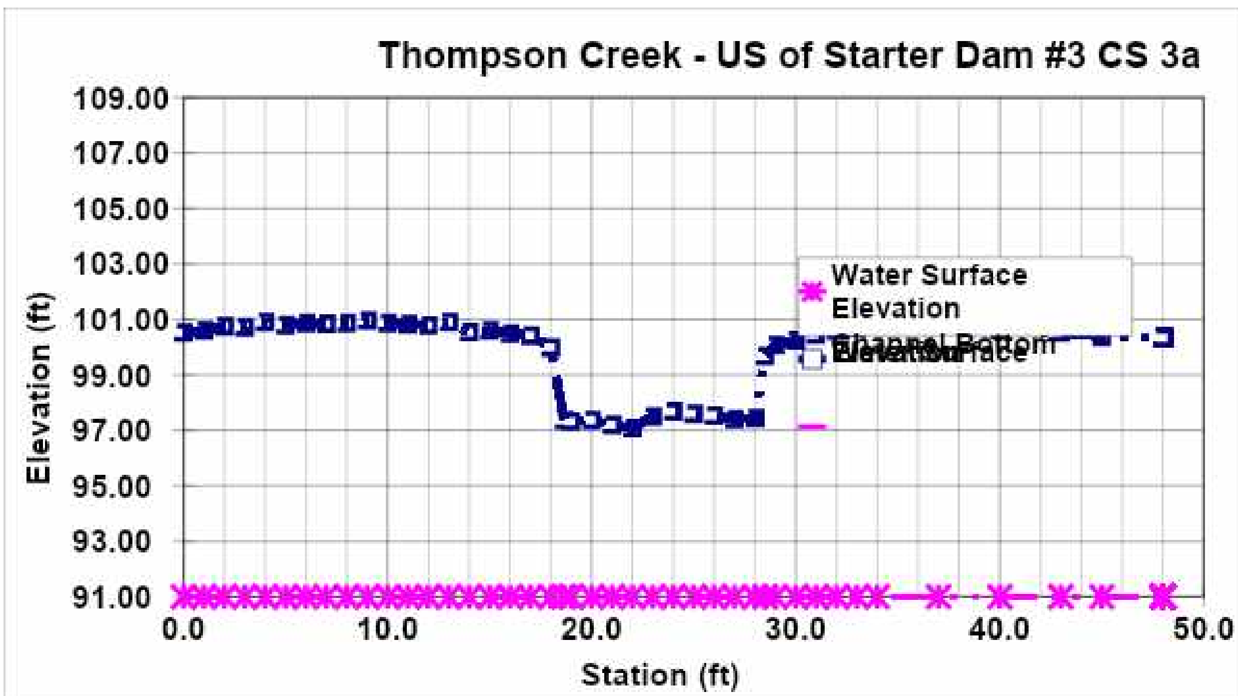

Thompson Creek - US of Starter Dam #1 CS 1c
109
107
105
103
101
99
97
95
93
91
Elevation (ft)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Station (ft)
Channel Bottom Elevation
Water Surface Elevation


Thompson Creek - US of Starter Dam #2 CS 2a
107
105
103
101
99
97
95
93
91
Elevation (ft)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Station (ft)
Channel Bottom Elevation
Water Surface Elevation

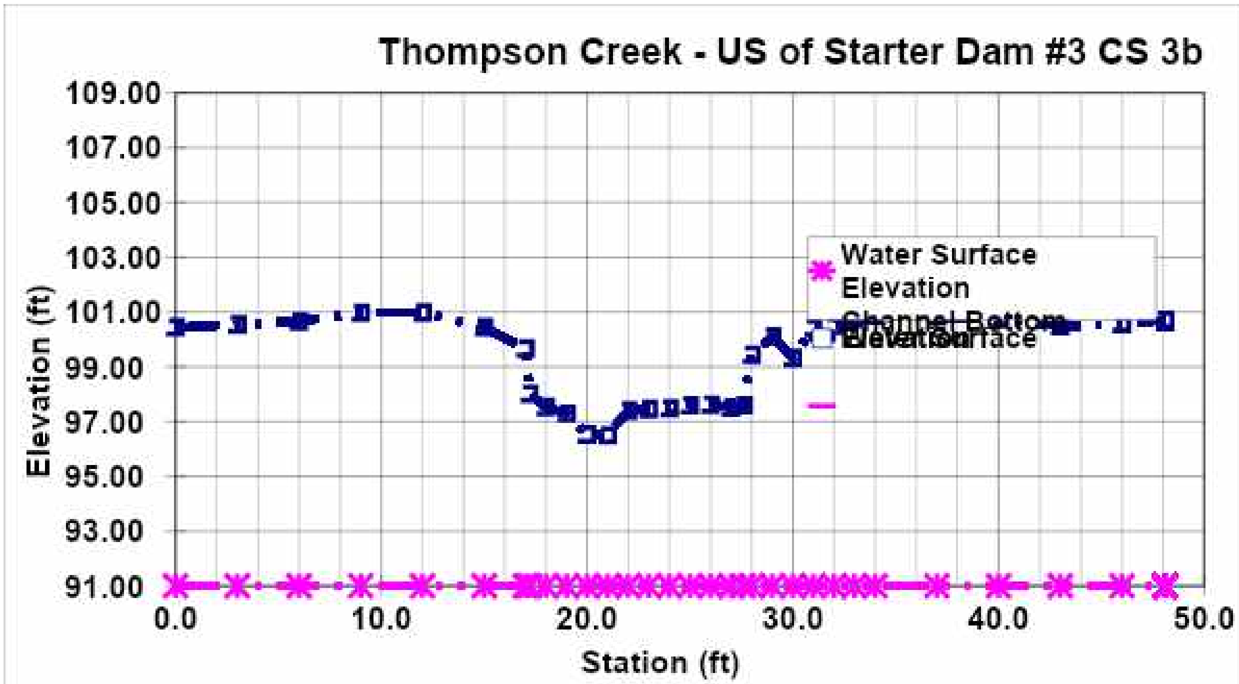

Thompson Creek - US of Starter Dam #2 CS 2b
107
105
103
101
99
97
95
93
91
Elevation (ft)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Station (ft)
Channel Bottom Elevation
Water Surface Elevation

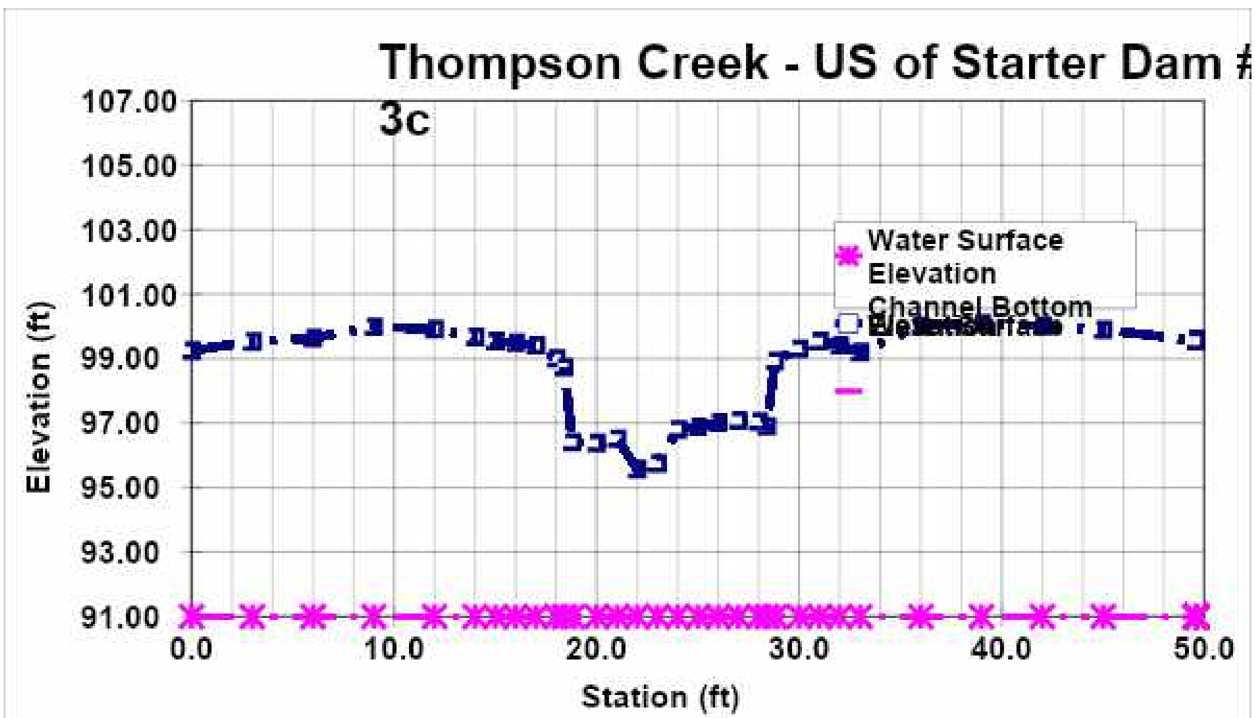


Thompson Creek - US of Starter Dam #2 CS 2c
107.00
105.00
103.00
101.00
99.00
97.00
95.00
93.00
91.00
Elevation (ft)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Station (ft)
Water Surface Elevation



Thompson Creek - US of Starter Dam #3 CS 3a
109.00
107.00
105.00
103.00
101.00
99.00
97.00
95.00
93.00
91.00
Elevation (ft)
0.0
10.0
20.0
30.0
40.0
50.0
Station (ft)
Water Surface Elevation

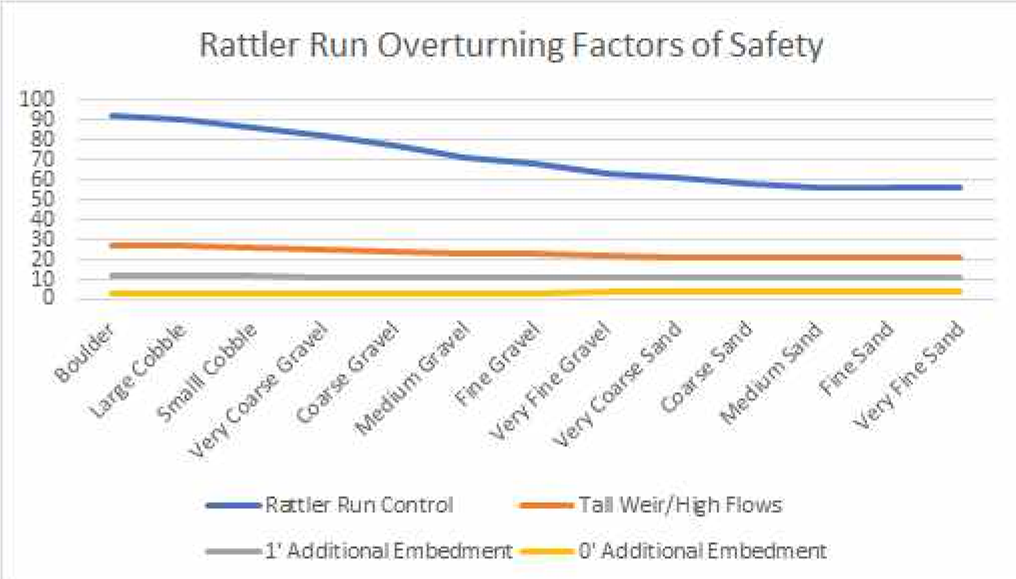

Thompson Creek - US of Starter Dam #3 CS 3b
Elevation (ft)
Station (ft)
Water Surface Elevation
Channel Bottom Elevation

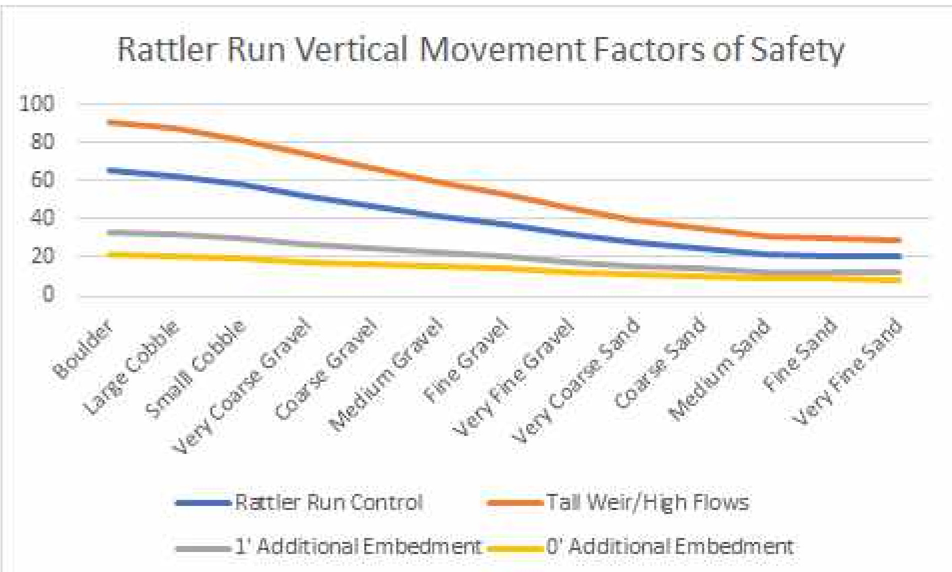

Thompson Creek - US of Starter Dam #
3c
Elevation (ft)
Station (ft)
Water Surface Elevation
Channel Bottom

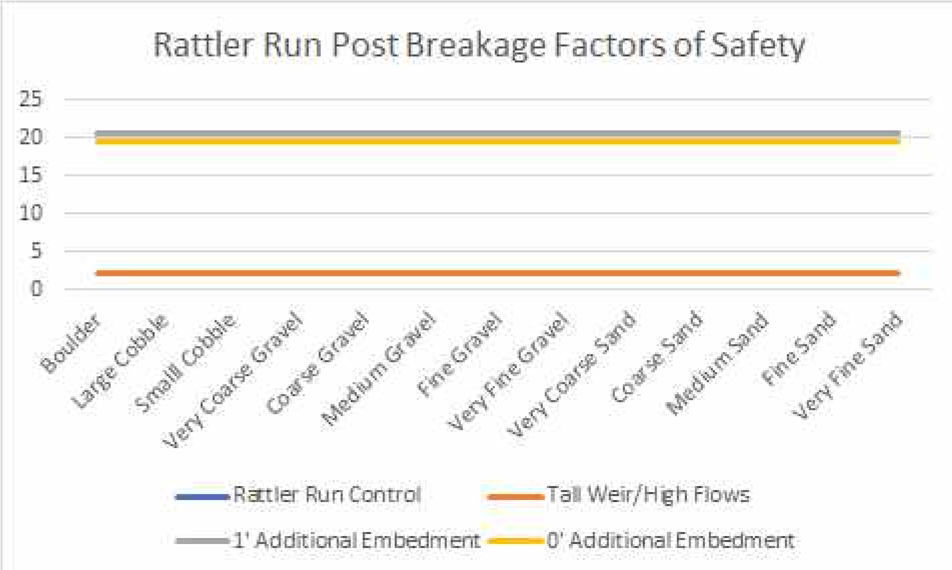
Appendix D: Drone Aerial Images

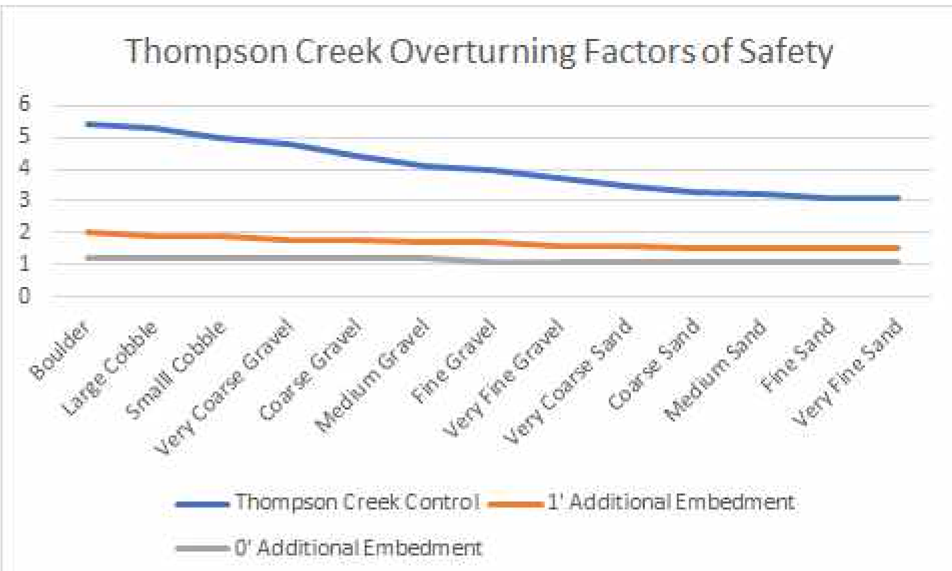
Appendix E: Factors of Safety Calculations

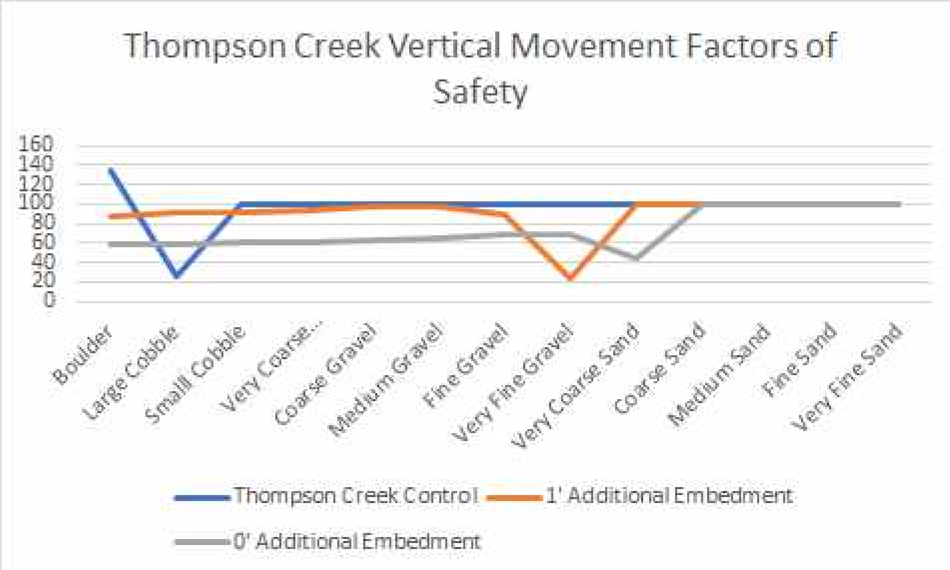
Below are the graphs of all of the FOS calculations used in the BDA design tool. A table of the variables inputted is also provided.

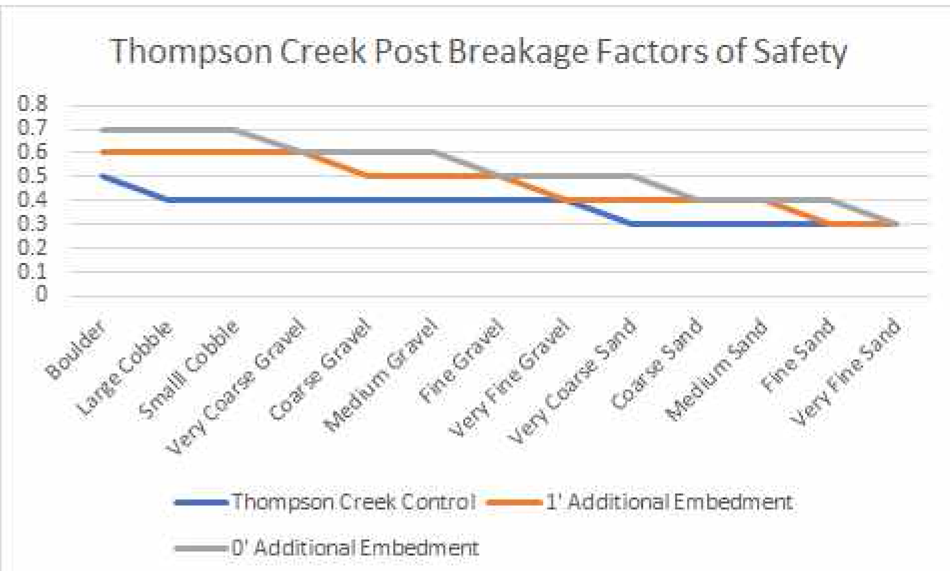

Rattler Run Overturning Factors of Safety
100
90
80
70
60
50
40
30
20
10
0
Boulder
Large Cobble
Small Cobble
Very Coarse Gravel
Coarse Gravel
Medium Gravel
Fine Gravel
Very Fine Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Rattler Run Control
Tall Weir/High Flows
1' Additional Embedment
0' Additional Embedment


Rattler Run Vertical Movement Factors of Safety
100
80
60
40
20
0
Boulder
Large Cobble
Small Cobble
Very Coarse Gravel
Coarse Gravel
Medium Gravel
Fine Gravel
Very Fine Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Rattler Run Control
Tall Weir/High Flows
1' Additional Embedment
0' Additional Embedment


Rattler Run Post Breakage Factors of Safety
25
20
15
10
5
0
Boulder
Large Cobble
Small Cobble
Very Coarse Gravel
Coarse Gravel
Medium Gravel
Fine Gravel
Very Fine Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Rattler Run Control
Tall Weir/High Flows
1' Additional Embedment
0' Additional Embedment


Thompson Creek Overturning Factors of Safety
6
5
4
3
2
1
0
Boulder
Large Cobble
Small Cobble
Very Coarse Gravel
Coarse Gravel
Medium Gravel
Fine Gravel
Very Fine Gravel
Very Coarse Sand
Coarse Sand
Medium Sand
Fine Sand
Very Fine Sand
Thompson Creek Control
1' Additional Embedment
0' Additional Embedment





Parameters Used for BDA Design Tool:

Values	Rattler Run Control	Thompson Creek Control	Rattler Run Tall Weir/High Flows	Rattler Run 1' Additional Embedment	Thompson Creek 1' Additional Embedment	Rattler Run 0' Additional Embedment	Thompson Creek 0' Additional Embedment
Design flow (CFS)	20	100	80	20	100	20	100
Weir (BDA) heights	2	4	4	2	4	2	4
Additional Embedment	4	4	4	1	1	0	0

Appendix F: Full Literature Review on Risk Assessment Methods

The Birch Creek BDA design was key in Riverbank Consulting's literature review as it was the basis for the design of the Thompson Creek project. Riverbank Consulting also reviewed the Beaver Restoration Guidebook and Low-Tech Process Based Restoration of Riverscapes Design Manual. A "virtual field guide" video series by the Okanogan Highlands Alliance that explains the process of implementing BDAs and provides a case study at Triple Creek was also reviewed. Two other case studies that Riverbank Consulting reviewed were the Bridge Creek BDA complex in Oregon and the Birch Creek BDAs in Utah. The team summarized the design decisions in the case studies and the considerations noted in the Beaver Restoration Guidebook and Low-Tech Process Based Restoration of Riverscapes Design Manual. Below is a concise summary of the literature that was reviewed, and some key points taken from it to help develop the risk assessment matrix:

Title: The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains

Author: Pollock et Al. 2015

Summary: This guidebook explains beaver ecology, restoration and management, types of BDAs, and risks involved in implementing BDAs.

Key Points:

- Beaver restoration projects should have a minimum timeframe of five years, as the natural processes take time for the stream to change.
- Dams should only be removed if they are causing a danger to the surrounding area or ecosystem.
- Developing a monitoring plan that is implemented before, during, and after installation is key for assessing if the restoration goals are met.
- The most common way that dams fail is through "end cut" where the side bank is eroded.
- There are few risks in implementing BDAs, but some of the risks are as follows:
    - Increased temperatures in pools (make sure to have plant vegetation that can shade/cool down the area)
    - Inadvertent flooding (place BDAs carefully when near infrastructure or other areas that cannot be flooded)

Title: Low-Tech Process-Based Restoration of Riverscapes: Design Manual

Author: Wheaton et Al. 2019

Summary: This design manual outlines 10 guiding principles to process based restoration for rivers and streams. These 10 principles are divided into two sections: Riverscape Principles (what makes a healthy river system) and Restoration Principles (what actions and designs promote recovery and resilience).

Key Points:

- Streams need space to meander, shift position, and flood.
- Varied structures (such as BDAs) force complexity in flow regimes and build diverse, resilient habitats.
- There are three phases for planning: Collection & Analysis, Decision Support, and Application and Evaluation. As streams are highly dynamic, the plans need to shift and adjust as the river system changes.

Title: Triple Creek Virtual Field Guide to BDAs, for Restoration Practitioners

Summary: The Okanogan Highlands Alliance (OHA) has provided a "virtual field guide" video series from 2020 that shows how to implement beaver dam analogs based on their work at Triple Creek. These videos cover restoration goals, design, installation, choosing sites and materials, and results.

Author: Okanogan Highlands Alliance (2020)

Key Points:

5. Deflector dams increase sinuosity by eroding channel banks, and channel spanning dams increase roughness and can help sediment settle out and raise the water table.
6. Longer posts can be driven deeper if the substrate allows, which increases stability. They also can accommodate higher flows and last longer. However, if there is a high number of debris loading, longer posts can be a risk.
7. Shorter posts can apply less pressure to the banks and posts for areas where the goal is to see the structure easily overtopped.
8. Adding multiple BDAs in series helps improve stability and reduce scour. Gentle slopes (about 2 to 6%) are preferable to reduce shear stress on BDAs.

Title: Lessons in Beaver Based Restoration from the Bridge Creek IMW

Author: Weber et Al. 2017

Summary: This work is a conference paper from 2017 focused on a creek in the John Day Basin in Bend, Oregon. This project aimed to test assisted incision recovery and determine the benefits to fish populations and habitat. There were four treatment reaches with a total of 114 BDA reaches. This was a multi-year implementation beginning with pilot structures followed by effectiveness monitoring and structure modifications.

Key Points:

- Installing the BDAs in this creek increased the wetted area by 203% and improved the percent fish passage from 17% to 29%.
- These BDAs were concentrated upstream, with two dense clusters of BDAs downstream.

Title: Working with Beaver to Restore Salmon Habitat in the Bridge Creek Intensively Monitored Watershed: Design Rationale and Hypotheses

Author: Pollock et. Al 2012

Summary: This is a paper from 2011 by Michael M. Pollock. This team used aerial LIDAR, field survey, and a color photography survey to locate four pairs of geomorphically similar reaches within Bridge Creek. This allowed them to restore one location of each pair and leave the other one unrestored as a control. They also located sites inhabited by beavers for direct comparison to constructed BDAs.

Key Points:

- Place secondary structures immediately downstream of primary structures to avoid the gradient from dropping too low, too quickly, and to provide resilience in case an individual dam fails.
- The dams require that the incision of the area would be generally less than 1- 1.5 meters to improve stability.
- Make sure BDAs are at least 300 meters away from existing beaver colonies to avoid disturbing the beaver.
- Pound posts at least 1 meter deep wherever possible.

Title: Birch Creek Case Studies

Author: Shahveridian and Wheaton 2017, Shahveridan 2018

Summary: This is a set of two case studies (Shahveridian and Wheaton 2017, Shahveridan 2018) of the restoration of Birch Creek, a stream in Utah. This area has experienced a reduction in native woody vegetation, limited riparian community, and high summer temperatures that hinder Bonneville cutthroat trout population growth and sage grouse. A BDA project with 60 dam structures was implemented in late 2017, and this project was monitored throughout the year.

Key Points:

- BDAs work best in complexes, which are a series of 2-15 structures combining all BDA types and each with their own primary and secondary functions.
- Different complexes have different goals, such as increasing pool habitat and lateral connectivity, or increasing hydraulic diversity.
- There is a lot of uncertainty in regard to the specifics of what a stream needs, so by providing the stream with tools such as BDAs, it will naturally heal itself.
- The BDAs in Birch Creek increased groundwater storage, baseflow, peak flow attenuation, reconnected the creek with the floodplain, and slowed channel velocity.
- Results showed an increase in maximum pool length, and width and depth. The pre-restoration size was at 2,432 m^2 whereas post-restoration increased the size by 16% or 2,841 m^2.

Title: A Stream Evolution Model Integrating Habitat and Ecosystem Benefits

Author: Cluer & Thorne, 2014

Summary: The authors of this paper provide language to describe how streams adapt and change over time. This is provided through the Stream Evolution Model, a set of stages from Stage 0 to Stage 8, through which the stream change both forward and backwards through the stages.

Key Points:

- The Stream Evolution Model categorizes streams based on their levels of degradation/aggradation and widening/narrowing
- This is a helpful tool that can help describe the health of a stream, as well as the incision of the channel

4.3.2 Literature Review on Risk Assessment Methods

The sections below outline four literature reviews conducted on risk assessment methods and Riverbank Consulting's BDA design guidelines based on level of risk.

Title: Risk-Based Method for Selecting Bridge Scour Countermeasures

Author: Peggy A. Johnson and Sue L. Niezgoda, 2004

Summary: A risk-based method for ranking, comparing, and choosing the most appropriate scour countermeasures was presented using failure modes and effects analysis and risk priority numbers. Risk was analyzed in terms of likelihood of failure, consequence of failure, and level of difficulty to detect failure. The result is a qualitative number that allows the design to assess the design element that has the most risk pre-implementation.

Key Points:

- Bridge scour can be predicted using HEC-18. Types of scour includes channel degradation, contraction scour, and local scour.
- Safety of bridge foundations can also be negatively impacted from channel widening and lateral mitigation.
- Potential failures can be very difficult to define in real-life-situations.
- For failure mode analysis, it is necessary to first define what the system failure looks like before design implementation.
- To execute a failure modes and effect analysis, the following are required: a hierarchical structure for the system illustrating all system components, failure modes of all components of the system, and an objective criterion for implementing corrective action.
- A risk priority number is established with each failure mode to get a qualitative result that suggests the nature and extent of failure.
- The risk priority number (RPN) is the product of the occurrence, consequence, and detectability ratings of a failure mode. This technique allows for a comparison between impact of various failure modes.
- Cost is not a factor in the failure modes effect and analysis.
- Tables 3 and 4 show how to create a failure modes effect and analysis table.

Table 6. Example of Failure Modes Effect and Analysis for Bridge Scour (Johnson and Niezgoda, 2004)

Countermeasure	Failure modes	Effects on other components	Effects on whole system	Detection methods	Compensating provisions
Riprap	Slide down bank slope	Slide into and disrupt function of vanes, etc.	Contracts flow	Slumping of rock at bank toe; unprotected upper bank	Reduce bank slope; use more angular or smaller rock; use granular filter rather than geotextile fabric
	Displaced downstream (rock undersized)	None	Local erosion	Rock moved downstream from original location	Increase rock size; increase rock gradation
	Erosion beneath (improper filter)	Sediment input buries other vanes, etc.	Downstream deposition, clogging of waterway opening	Scalloping of upper bank; bank cutting; vacant spaces beneath and between rocks	Use gravel or fabric filter beneath
Rock vanes, w-weirs, bendway weirs	Burial by incoming sediment	None or minimal	Minimal	Measure has a lower profile; vegetation growth	Reorient or reposition measure; decrease Q_r*
	Rapid lateral migration away from vane	None or minml	May cause property or infrastructure damage	Bank retreat at bank pins; proximity to structures and/or survey marker	Armor opposite bank; construct vanes on opposite bank upstream to direct flow toward vane
	Erosion of opposite bank	Erosion around other measures	May erode at pier or opposite abutment	Bank retreat at bank pins; raw banks; undercutting of bank	Reorient or reposition measure
	Ineffective angles	Minimal, nearby measures may be less effective	Minimal, may cause design to be less effective	Scoured pool position incorrect; scour around bank-side of vane	Rebtient or reposition measure
	Displacement	Nearby measures may be less effective	May not be effective in concentrating flow away from bank	Rock moved downstream from original location	Increase rock size; use gravel filter to prevent undermining
Submerged vanes	Burial by incoming sediment	None or minimal	Minimal	Measure has a lower profile; vegetation growth	Reorient or reposition measure; decrease Q_r*
	Rapid lateral migration away from vane	None or minimal	May cause property or infrastructure damage	Bank retreat at bank pins; proximity to structures and/or survey marker	Armor opposite bank; construct vanes on opposite bank upstream to direct flow toward vane
	Erosion of opposite bank	Erosion around other measures	May erode at pier or opposite abutment	Bank retreat at bank pins; raw banks; undercutting of bank	Reorient or reposition measure
	Ineffective angles	Minimal, nearby measures may be less effective	Minimal, may cause design to be less effective	Scoured pool position incorrect; scour around bank-side of vane	Reorient or reposition measure
	Displacement	Nearby measures may be less effective	Will not be able to redirect flow away from bank and abutment	Vane moved downstream from original location	Use deeper foundation/rebar; make sure footing material is adequate

Countermeasure	Failure modes	Effects on other components	Effects on whole system	Detection methods	Compensating provisions
Riprap	Slide down bank slope	Slide into and disrupt function of vanes, etc.	Contracts flow	Slumping of rock at bank toe; unprotected upper bank	Reduce bank slope; use more angular or smaller rock; use granular filter rather than geotextile fabric
	Displaced downstream (rock undersized)	None	Local erosion	Rock moved downstream from original location	Increase rock size; increase rock gradation
	Erosion beneath (improper filter)	Sediment input buries other vanes, etc.	Downstream deposition, clogging of waterway opening	Scalloping of upper bank; bank cutting; vacant spaces beneath and between rocks	Use gravel or fabric filter beneath
Rock vanes, w-weirs, bendway weirs	Burial by incoming sediment	None or minimal	Minimal	Measure has a lower profile; vegetation growth	Reorient or reposition measure; decrease Q_s*
	Rapid lateral migration away from vane	None or mimml	May cause property or infrastructure damage	Bank retreat at bank pins; proximity to structures and/or survey marker	Armor opposite bank; construct vanes on opposite bank upstream to direct flow toward vane
	Erosion of opposite bank	Erosion around other measures	May erode at pier or opposite abutment	Bank retreat at bank pins; raw banks; undercutting of bank	Reorient or reposition measure
	Ineffective angles	Minimal, nearby measures may be less effective	Minimal, may cause design to be less effective	Scoured pool position incorrect; scour around bank-side of vane	Rehrient or reposition measure
	Displacement	Nearby measures may be less effective	May not be effective in concentrating flow away from bank	Rock moved downstream from original location	Increase rock size; use gravel filter to prevent undermining
Submerged vanes	Burial by incoming sediment	None or minimal	Minimal	Measure has a lower profile; vegetation growth	Reorient or reposition measure; decrease Q_s*
	Rapid lateral migration away from vane	None or minimal	May cause property or infrastructure damage	Bank retreat at bank pins; proximity to structures and/or survey marker	Armor opposite bank; construct vanes on opposite bank upstream to direct flow toward vane
	Erosion of opposite bank	Erosion around other measures	May erode at pier or opposite abutment	Bank retreat at bank pins; raw banks; undercutting of bank	Reorient or reposition measure
	Ineffective angles	Minimal, nearby measures may be less effective	Minimal, may cause design to be less effective	Scoured pool position incorrect; scour around bank-side of vane	Reorient or reposition measure
	Displacement	Nearby measures may be less effective	Will not be able to redirect flow away from bank and abutment	Vane moved downstream from original location	Use deeper foundation/rebar; make sure footing material is adequate

Table 7. Continued Example of Failure Modes Effect and Analysis for Bridge Scour (Johnson and Niezgoda, 2004)

Grout bags	Displaced downstream (rock undersized)	None	Local erosion	Rock moved downstream from original location	Increase rock size; increase rock gradation
	Erosion beneath (improper filter)	Sediment input buries other vanes, etc.	Downstream deposition, clogging of waterway opening	Scalloping of upper bank; bank cutting; vacant spaces beneath and between rocks	Use gravel or fabric filter beneath
Check dam	End-around erosion	Nearby measures may be less effective	Widening of channel; redirection of high shear stresses	Local scour along mid- to upper bank at dam edge	Plant woody vegetation at bank edge; add vanes upstream to direct flow to center of dam
	Undermining	Other measures may be destroyed	May permit headcut to proceed to bridge	Underwater inspection; in situ methods; exposed footers	Riprap toe; construct ramped or sloped toe
Channel realignment	Channel migration	Burial of other measures; undermining of other measures	Loss of property	Bank retreat at bank pins proximity to structures and/or survey marker	Install vanes on migrating side armor banks
	Excessive deposition d/s of bridge	Minimal	Loss of conveyance at bridge, increased flooding	Bar formation narrowing of channel	Install vanes and/or cross vanes; narrow and/or straighten channel

Note: Q_s =sediment discharge (load entering restoration reach). Q_s can be decreased at either the watershed or reach level, depending on the source of the material. At the watershed level, steps must be taken to decrease sediment input into stream. At reach level, steps must be taken upstream of the project reach to reduce bank widening and/or bed degradation.

Grout bags	Displaced downstream (rock undersized)	None	Local erosion	Rock moved downstream from original location	Increase rock size; increase rock gradation
	Erosion beneath (improper filter)	Sediment input buries other vanes, etc.	Downstream deposition, clogging of waterway opening	Scalloping of upper bank; bank cutting; vacant spaces beneath and between rocks	Use gravel or fabric filter beneath
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Note: Q_s =sediment discharge (load entering restoration reach). Q_s can be decreased at either the watershed or reach level, depending on the source of the material. At the watershed level, steps must be taken to decrease sediment input into stream. At reach level, steps must be taken upstream of the project reach to reduce bank widening and/or bed degradation.

- For the given example of bridge scour, Table 7 describes to occurrence likelihood. The numbers ranged from 1-10 but can be changed based on project needs.

Table 8. Example of Occurrence Likelihood (Johnson and Niezgoda, 2004)

Occurrence likelihood	Rating
Impossible or has never occurred previously; well tested; known to be effective treatment; low maintenance	2
Remotely possible; similar events may have occurred previously; tested at many sites; moderately effective; low maintenance	4
Possible; has previously occurred rarely; tested at several sites; appears to be effective treatment; moderate maintenance	6
Probable; has previously occurred occasionally; not systematically tested; effectiveness not well documented; high maintenance	8
Reasonably probable; has previously occurred frequently; never been tested in the field; effectiveness unknown; high maintenance	10

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Reasonably probable; has previously occurred frequently; never been tested in the field; effectiveness unknown; high maintenance	10

- The detection rating is described in Table 9 and was based on the level of difficulty to detect failures.

Table 9. Example of Detection Methods (Johnson and Niezgoda, 2004)

Detection methods	Rating
Simple visual from field inspection	1
Simple analysis from photo record, bank pins	4
Cross sectional or longitudinal surveys; sediment sampling	7
Scour chains, pressure transducers, on other in-situ installations required	10

Detection methods	Rating
Simple visual from field inspection	1
Simple analysis from photo record, bank pins	4
Cross sectional or longitudinal surveys; sediment sampling	7
Scour chains, pressure transducers, on other in-situ installations required	10

- The overall RPNs for a meandering channel and poor alignment as correlating to bridge scour was calculated as follows in Table 10. The RPN is the multiplication of consequence rating, occurrence rating, and detection rating for each failure mode.

Table 10. Example to Calculate Risk Priority Number (Johnson and Niezgoda, 2004)

Component	Failure mode	Consequence rating	Occurrence rating	Detection rating	Risk priority number
Channel realignment	Channel migration	10	8	7	560
	Excessive deposition d/s of bridge	7	4	1	28
Riprap	Slide down slope	4	6	1	24
	Displaced downstream (rock undersized)	8	8	4	256
	Erosion beneath (improper filter)	4	6	7	168
Vanes and cross vanes	Burial by incoming sediment	4	6	1	24
	Rapid lateral migration away from vane	7	4	4	112
	Erosion of opposite bank	7	8	4	224
	Ineffective angles	7	6	10	420
	Displacement	4	8	4	128
Submerged vanes	Burial by incoming sediment	4	6	1	24
	Rapid lateral migration away from vane	7	4	4	112
	Erosion of opposite bank	7	4	4	112
	Ineffective angles	7	4	10	280
	Displacement	10	4	4	160

Component	Failure mode	Consequence rating	Occurrence rating	Detection rating	Risk priority number
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	Displacement	10	4	4	160

- Each type of failure mode is to be analyzed similar to Table 10. These results enable the designer to pay more attention to parts of the design that are prone to failure and take action.

Title: Case Study in Cost-Based Risk Assessment for Selecting a Stream Restoration Design Method for a Channel Relocation Project

Authors: Sue L. Niezgoda, Aff.ASCE; and Peggy A. Johnson, M.ASCE

Summary: A design failure modes and effects analysis is combined with a risk quantification. This analysis can be reevaluated to account for design changes and a change in ratings. This case study was based in Pennsylvania. Identifying design deficiencies of the initial design using the design failure modes and effects analysis with risk quantifications helps improves the current design.

Key Points:

- Incorporating uncertainty, consequences of failure, and costs in stream restoration projects improves the likelihood of success.
- Using the design failure modes and effects analysis helps to ensure a project will be effective when constructed. This analysis includes consequence of failure, the likelihood of a component failure, and the level of difficulty required to detect failure. Additionally, each component, possible failure modes, effects on the system, consequences, potential causes of failure, and likelihood of occurrence are identified. These are given numeric ratings from 1-10 with large values associated with high risk and low values associated with low risk.
- Risk priority numbers can be subjective if the criteria are not adequately defined. Risk is based on probability of failure and consequences.
- Tables 11 and 12 describe the cost risk analysis that was conducted for Oliver Run Relocation example.

Table 11. Cost-Severity Table Developed for Oliver Run Relocation Example (Niezgoda and Johnson, 2007)

Consequence category	Consequence rating	Failure cost percentage relative to project replacement costs (%)	Failure cost of component ($2004) (% × replacement cost)
Critical (extreme)	10	100	$55,000
High	8	75–100	$41,250–$55,000
Moderate	6	50–75	$27,500–$41,250
Low	4	25–50	$13,750–$27,500
Negligible	2	0–25	<$13,750

Consequence category	Consequence rating	Failure cost percentage relative to project replacement costs (%)	Failure cost of component ($2004) (% × replacement cost)
Critical (extreme)	10	100	$55,000
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Negligible	2	0–25	<$13,750

Table 12. Total Risk Calculated for Each Design of the Oliver Run Relocation Example (Niezgoda and Johnson, 2007)

Design alternative	Average initial costs ($2004)	Monitoring costs ($2004)	Expected cost project component failure ($2004)	Total risk ($2004)
1—Allowable shear stress	78,177	6,254	234,100	318,531
2—Sediment transport analysis	90,789	7,263	54,347	152,399
3—Alluvial channel modeling	87,639	7,011	24,100	118,750

Design alternative	Average initial costs ($2004)	Monitoring costs ($2004)	Expected cost project component failure ($2004)	Total risk ($2004)
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- Steps in a design failure modes and effects analysis include:

1.) Select and apply a design method

2.) Develop consequence, occurrence, and detection rating tables
3.) Review the design to identify each component
4.) Brainstorm potential failure modes for each component
5.) List potential effects of failure on individual components and the system as a whole
6.) Assign consequence, occurrence, and detection ratings
7.) Calculate the RPN
8.) Develop an action plan by examining new design methods or detection methods
9.) Take action by implementing a new design method or additional detection methods, and
10.) Reevaluate the potential failures once improvements are made and adjust RPN values.

- Tables from this paper have been adapted in “Applying Risk-Benefit Analysis to Select an Appropriate Streambank Stabilization Number” and can be found there.

Title: Applying Risk-Benefit Analysis to Select an Appropriate Streambank Stabilization Number

Authors: Sue L. Niezgoda, Ph.D., P.E., A.M.ASCE; and Peggy A. Johnson, Ph.D., M.ASCE

Summary: Risk is compared to benefit using risk priority numbers (RPN) and benefit priority numbers. The results are used to estimate risk and benefit quantitatively in terms of cost. This paper focuses on streambank stabilization Indiana. The goal is to apply the risk-benefit method to a design and identify the lowest risk option that gives the most return on investment.

Key Points:

- The long-term effectiveness of bank stabilization structures has been based on field observations.
- Multiple studies are available that assess the effectiveness and benefits of in-stream structures for streambank stabilization. These studies can be used to develop estimates of probability of success providing economic, environmental, and social benefits.
- There is a need for monitoring standards to better evaluate the results of in-stream structures.
- Risk is calculated using the following equation:

$$Risk = C_0 + \sum_{i=1}^{n} (P_i * C_i)$$

Where C_0 = initial component cost, including assessment, design, and construction costs; P_i = probability of failure given a measure attributable to a given failure mode, i; C_i = consequence of failure attributable to a given measure failure mode in terms of cost of repair, replacement, and damage; and n = the total number of failure modes for a given measure.

- More failure data has become available and thus an updated relationship between the likelihood of occurrence and probability was created. The updated numbers can be found in Table 13.

Table 13. Likelihood of Occurrence - Probability Relationship for Estimating the Probability of Failure or the Probability of Benefit (Niezgoda and Johnson, 2012)

Occurrence likelihood	Occurrence rating (O)	Probability
Almost certainly probable; could be expected to occur more than once during project life	10	0.75–1
Probable; could easily be incurred and has generally occurred in similar projects	8	0.5–0.75
Possible; incurred in a minority of similar projects	6	0.25–0.5
Remotely possible; hasn't occurred in similar projects, but could	4	0.1–0.25
Almost impossible; has occurred only in extreme circumstances	2	< 0.1

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Remotely possible; hasn't occurred in similar projects, but could	4	0.1–0.25
Almost impossible; has occurred only in extreme circumstances	2	< 0.1

- Possible benefits include economic, environmental, or social impacts. The causes of the benefit and the probability it will occur must be identified. Benefits can be detected using high-tech materials such as LIDAR and electroshocking equipment or using low tech materials such as visual observations.
- Benefit is calculated using the following equation:

$$Benefit = \sum_{i=1}^{n_f} (P_{Bi} * B_i)$$

Where P_{Bi} = probability that a given measure function, i, will provide a given benefit; B_i = economic, environmental, and social benefits added by the given function, i; and n_f = the total number of functions provided by a given measure.

- Table 11 illustrates the associated cost percentage relative to measure replacement costs based on the consequence or benefit rating. These ratios should be considered on a case-by-case basis based on available data and judgement.

Table 14. Severity/Value Added - Percentage Cost Relationship for Estimating the Cost of Failure or the Value Added by a Given Benefit (Niezgoda and Johnson, 2012)

Consequence category	Consequence (C) or Benefit (B) Rating	Cost percentage relative to measure replacement costs (percentage)
Critical (Extreme)	10	100
High	8	75-100
Moderate	6	50-75
Low	4	25-50
Negligible	2	0-25

Consequence category	Consequence (C) or Benefit (B) Rating	Cost percentage relative to measure replacement costs (percentage)
Critical (Extreme)	10	100
High	8	75-100
Moderate	6	50-75
Low	4	25-50
Negligible	2	0-25

- HEC-RAS was used to analyze how stream bank stabilization would affect shear stress.
- Table 14 displays an example of a basic setup for a FMEA. The RPN was calculated as the product of consequences, occurrences, and detectability.

Table 15. Risk Analysis for Stabilization Measures in Cascades Creek (Niezgoda and Johnson, 2012)

Bank stabilization measure (1)	Potential failure mode(s) (2)	Potential effect(s) of failure on components (3)	Potential effect(s) of failure on whole system (4)	C[a] (5)	Potential cause(s)/ mechanism(s) of failure (6)	O[a] (7)	Failure detection criteria (8)	D[a] (9)	RPN[b] (10)
Imbricated rip-rap *(hard armoring)*	Excessive scouring above or behind structure (flanking)	Clog downstream infrastructure	Downstream deposition, clogging of waterway opening	6	Design of bank stabilization measures not sufficient	10	Bank scalloping; bank cutting; vacant spaces beneath and between rocks	1	60
	Structure displacement or sliding	Slide into and disrupt function of other measures	Bank erosion; lateral movement; infrastructure impact; sediment input	8	Improper sizing of rock that composes structure, improper anchoring into bedrock foundation	6	Rock movement downstream from original location, Wall pulling away from bank	4	192
Vegetated gabion baskets *(bioengineering technique)*	Excessive scouring above or behind structure (flanking)	Clog downstream infrastructure	Bank erosion; lateral movement; infrastructure impact; sediment input	6	End not keyed properly into bank with angular rock bolsters on all sides	10	Slumping of baskets; Unprotected upper bank;	4	240
	Structure displacement or sliding	Slide into and disrupt function of other measures	Bank erosion; lateral movement; infrastructure impact; sediment input	8	Improper anchoring into bedrock foundation	6	Baskets pulling away from bank, flanking behind structure	4	192
	Vegetation grows too large for baskets- burst baskets	Rock from inside gabions can clog downstream infrastructure	May cause structural collapse and bank instability	6	Vegetation not maintained; improper vegetation used	2	Large woody vegetation visible cause swelling of baskets; Breaking of baskets	4	48
	Corrosion and/or structural damage from debris or ice	Rock from inside gabions can clog downstream infrastructure	May cause structural collapse and bank instability	8	Structure not protected from heavy sediment and debris loads which can lead to corrosion	10	Visible scarring of wire mesh; Holes in baskets; Vegetation and stone removal; Structure slumping	4	320
Live log crib walls *(bioengineering technique)*	Mass wasting	Slide into and disrupt function of other measures, destruction of fish habitat, etc.	Bank erosion; lateral movement; infrastructure impact; sediment input	10	Used on too high a bank; surcharge in excess on top of bank, high flows undercut portions of structure	4	Slumping of structure; Unprotected upper bank;	4	160
	Excessive scouring above or behind structure (flanking)	Slide into and disrupt function of other measures, destruction of fish habitat, etc.	Bank erosion; lateral movement; infrastructure impact; sediment input	6	Structure not keyed into bank with angular rock bolsters on all sides; rock bolsters not designed for allowable velocities	10	Bank retreat at edges of rolls; Raw or scalloped banks;	4	240
	Structure sliding	Disrupt function of other measures, destruction of fish habitat, etc.	Bank erosion; lateral movement; infrastructure impact; sediment input	8	Improper anchoring of wall into bank or bedrock foundation	6	Wall collapse	4	192
	Structural damage from debris, ice, or rot	Minimal, nearby measures may be less effective	May not be effective in concentrating flow away from bank	4	Structure not protected from heavy sediment and debris loads	10	Visible scarring of logs; Cracked logs; vegetation removal; structure slumping	4	160

Bank stabilization measure (1)	Potential failure mode(s) (2)	Potential effect(s) of failure on components (3)	Potential effect(s) of failure on whole system (4)	C[a] (5)	Potential cause(s)/ mechanism(s) of failure (6)	O[a] (7)	Failure detection criteria (8)	D[a] (9)	RPN[b] (10)
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	Structural damage from debris, ice, or rot	Minimal, nearby measures may be less effective	May not be effective in concentrating flow away from bank	4	Structure not protected from heavy sediment and debris loads	10	Visible scarring of logs; Cracked logs; vegetation removal; structure slumping	4	160

- Table 15 is like Table 14 but identifies the benefits rather than the risks of each bank stabilization measure. As before, the BPN was calculated by multiplying the benefit, occurrence, and detectability.

Table 16. Benefits Analysis for Stabilization Measures in Cascades Creek (Niezgoda and Johnson, 2012)

Bank stabilization measure (1)	Physical and biological function (2)	Potential local benefit (3)	Potential system-wide benefit (4)	B[a] (5)	Potential cause(s) of benefits (6)	O[a] (7)	Benefit detection methods (8)	D[a] (9)	BPN[b] (10)
Imbricated rip-rap *(Hard armoring)*	Armor and protect surface	Enhanced bank stabilization	Reduction in sediment and improvement in water quality	4	Flow deflection, bank toe protection	10	Channel geometry surveys, turbidity and water quality sampling	4	160
	Enhance in-stream habitat	Provide hiding and cover areas for fish	Cooler temperatures and improved fish passage	6	Gaps in structure during construction; scour of finer sediments around structure	4	Visual surveys, temperature readings	7	168
Vegetated gabion baskets *(bioengineering technique)*	Armor and protect surface	Enhanced bed and bank stabilization	Reduction in sediment and improvement in water quality	4	Flow deflection, bank toe protection, increased roughness and lower near-bank velocities	10	Channel geometry surveys, turbidity and water quality sampling	4	160
	Enhance riparian habitat	Enhance bank stabilization; provide shade, filter sediments; aesthetic screening of gabion structure	Reduction in stream temperature; Reduction in microbes, nutrients, and pesticides; provide; overhead cover and hiding places for fish	8	Establishment of a riparian buffer	6	Vegetation counts (survival rates), water quality sampling, macroinvertebrate sampling	4	192
	Enhance in-stream habitat	Provide hiding and cover areas for fish	Cooler temperatures and improved fish passage	6	Gaps in structure during settling; scour of finer sediments around structure	4	Visual surveys, temperature readings	7	168
Concrete retaining wall *(hard armoring)*	Armor and protect surface	Enhanced bank stabilization	Reduction in sediment and improvement in water quality	4	Flow deflection, bank toe protection	10	Channel geometry surveys, turbidity and water quality sampling	4	160
Live log crib walls *(bioengineering technique)*	Armor and protect surface	Enhanced bed and bank stabilization	Reduction in sediment and improvement in water quality	4	Flow deflection, bank toe protection, increased roughness and lower near-bank velocities	10	Channel geometry surveys, turbidity and water quality sampling	4	160
	Enhance in-stream habitat	Provide overhead cover, refuge areas; holding areas	Cooler temperatures and improved fish passage	6	Gaps in logs structure; scour of fine sediment around structure; vegetation growth	4	Visual surveys, temperature readings	7	168
	Enhance riparian habitat	Enhance bank stabilization; provide shade, filter sediments;	Reduction in stream temperature; Reduction in particulate wastes and sediment attached microbes, nutrients, and pesticides	8	Establishment of a riparian buffer	10	Vegetation counts (survival rates), water quality sampling, macroinvertebrate sampling	4	320

Bank stabilization measure (1)	Physical and biological function (2)	Potential local benefit (3)	Potential system-wide benefit (4)	B[a] (5)	Potential cause(s) of benefits (6)	O[a] (7)	Benefit detection methods (8)	D[a] (9)	BPN[b] (10)
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- A table that outlines the benefits from considerable to negligible should be made to identify the benefit rating. This should include economic benefits, environmental benefits, and public acceptance to get a benefit rating from 10-0.
- A table should also be made that identifies the likelihood of detection of benefit. The detection level should range from complex equipment method with a detection rating of 1 to visual inspections only with a detection rating of 10.
- A cost-benefit analysis was performed for the streambank stabilization measures within Cascade Creek. This analysis uses a benefit-to-initial-cost ratio. If the ratio is greater than one, the benefits out way the initial costs.
- Factors for risk are as follows:
  - Bank stabilization measure, failure mode, C, Percentage cost, O, probability of failure, component cost, consequence cost (percentage cost times component cost), expected failure cost (probability of failure times consequence cost), and risk (component cost plus expected failure cost).
- Factors for benefit are as follows:
  - Bank stabilization method, function, B, percentage cost, O, occurrence probability, component cost, value added (percentage cost times component cost), expected benefit (occurrence probability times value added), and total expected benefit (sum of expected benefit).
- The initial costs, total risk and total benefit costs are then formulated for each measure. The benefit to initial cost ratio and total benefit to total risk ratio are then calculated.

Title: RiverRAT: Science Base and Tools for Analyzing Stream Engineering, Management, and Restoration Proposals

Authors: Tim Beechie, NOAA Fisheries, Seattle, Washington; Janine Castro, US Fish and Wildlife Service, Portland, Oregon; Brian Cluer, NOAA Fisheries, Santa Rosa, California; George Pess, NOAA Fisheries, Seattle, Washington; Conor Shea, US Fish and Wildlife Service, Arcata, California; Peter Skidmore, Skidmore Restoration Consulting, Bozeman, MT; Colin Thorne, Professor, University of Nottingham, UK

Summary: A new resources guide named River Restoration Analysis Tool (RiverRAT) has been developed to offer a more efficient, consistent, and comprehensive review of stream management projects. The depth and scientific soundness required is addressed.

Key Points:

- Guidelines and manuals exist for the engineering and design aspects of stream management projects but there is no accepted guidance for stream management projects.
- Generally, avoiding risks in stream restoration leads to an over-design to meet the factor of safety. However, these factors of safety are often based on undesirable constraints on natural channel adjustment and evolution thus limiting long-term habitat value.
- A new screening tool, Figure 32, shows the relative review lengths that respective projects should require. This is a training aid to refine professional judgement on depth of reviews.

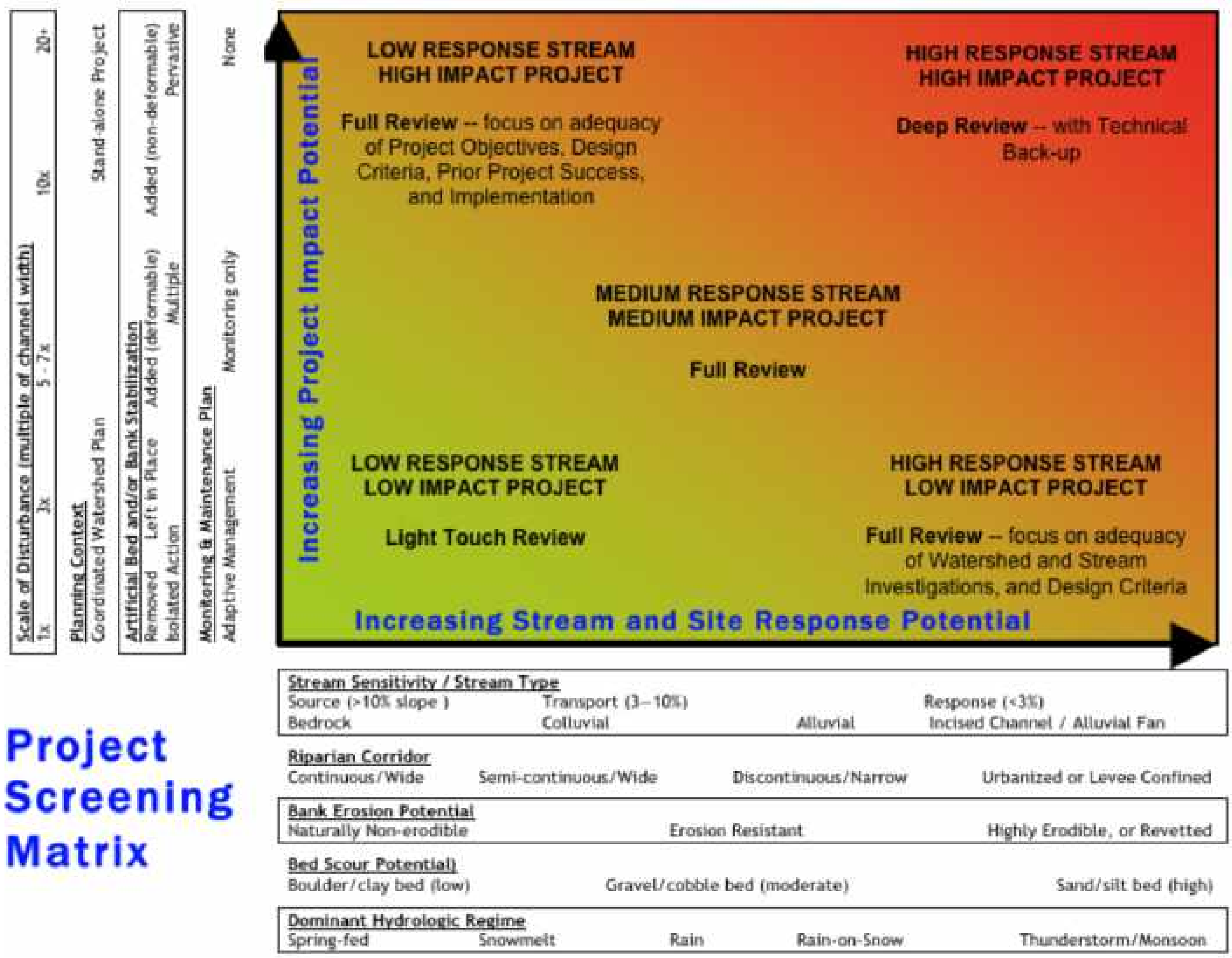

Figure 32. The Project Screening Matrix (RiverRAT)

- Table 16 outlines Figure 32 without the visuals.

Table 17. Selection of Treatment Based on Project Impact Potential and Stream Response Potential (RiverRAT)

Impact & Response Potential	Level of Review	Indicated Treatment
Low Response Stream Low Impact Project	Light	• Only light review needed • Light touch okay for RiverRAT evaluation
Low Response Stream High Impact Project	Full	• Full review needed • Particular attention paid to adequacy of: • Project objectives; • Project elements that pose greatest threats; • Design criteria; • Evidence of prior success with similar projects • Implementation plan • Since stream risk is low, responses to action may be limited to project and adjacent reaches • Lighter touch okay for evaluating wider watershed and stream channel contexts and implications of proposed work
Medium Response Stream Medium Impact Project	Full	• Full review needed • Careful application of RiverRAT recommended
High Response Stream Low Impact Project	Full	• Full review needed • Particular attention paid to adequacy of: • Watershed and stream investigations; • Design criteria related to preventing project impacts on greater fluvial system; • Plans for post-project monitoring and adaptive management to limit unforeseen impacts within project reach
High Response Stream High Impact Project	Deep	• Full extensive review needed • Proposals may be complicated or groundbreaking, requiring backup from subject specialists to deal with challenging technical aspects • Reviewers should not hesitate to seek assistance where necessary

- A checklist of design documentation as found in Figure 33 is highly encouraged to promote time and resource efficiency. The given checklist is just an example of possible things to include.

DESIGN DOCUMENTATION

	Y	N	NA	***Design team***
57	☐	☐	☐	Name and titles of firms and individuals responsible for design.
58	☐	☐	☐	List of project elements that have been designed by a licensed Professional Engineer.
	Y	**N**	**NA**	***Hydrologic analysis***
59	☐	☐	☐	Description of historic, ongoing, or anticipated impacts to basin hydrologic regime.
60	☐	☐	☐	Summary of hydrologic analyses conducted, including data sources and period of record.
61	☐	☐	☐	List design discharge (Q) and return interval (RI) for each design element.
	Y	**N**	**NA**	***Sediment transport and dynamics analysis***
62	☐	☐	☐	Description of previous or anticipated impacts to basin or reach sediment supply.
63	☐	☐	☐	Summary of sediment supply and transport analyses conducted, including data sources.
64	☐	☐	☐	Describe sediment size gradation used in streambed design.
	Y	**N**	**NA**	***Hydraulic analysis***
65	☐	☐	☐	Summary of hydraulic modeling or analyses conducted and data source.
66	☐	☐	☐	Inundation map for design and flood flows before and after implementation.
	Y	**N**	**NA**	***Vegetation design***
67	☐	☐	☐	Species list, materials sources, and plant form.
68	☐	☐	☐	Planting plan map (distribution and density by species) and irrigation plan.
	Y	**N**	**NA**	***Soils and geotechnical analysis***
69	☐	☐	☐	Summary of geotechnical analyses including stratigraphy and grain size of materials.
70	☐	☐	☐	Groundwater elevation, flow direction and seasonality within floodplain and banks.

Figure 33. Example of Details in the Checklist (RiverRAT)

- RiverRAT provides a framework in Figure 34 that gives additional technical resources and assistance for projects of high risk.

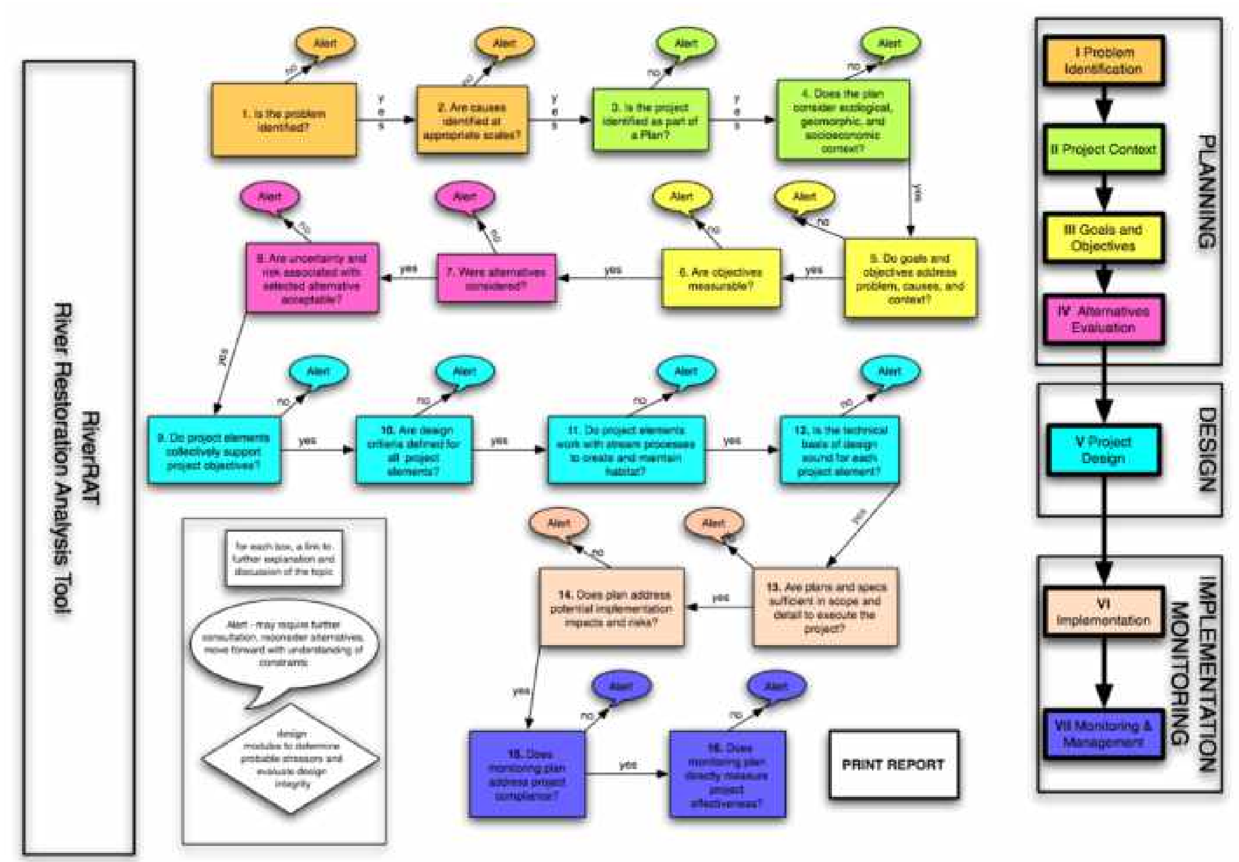

Figure 34. The RiverRAT framework (RiverRAT)

- RiverRAT has an online database at restorationreview.com that acts a review tool for projects.

Appendix G: Monitoring Plan Flyer

THOMPSON CREEK BDA MONITORING PLAN FLYER

Thompson Creek is a channel that feeds into Newman Lake. Due to agricultural use around the creek, the channel has become incised, meaning its bed depth has lowered, and the channel has become disconnected from its floodplain. Channel Incision has led to a higher stream velocity, causing the creek to transport high sediment loads into Newman Lake

HYPOTHESIS 1

The implementation of Beaver Dam Analog Starter Dams in Thompson Creek will increase water storage upstream of the Starter Dams in excess of pre-implementation channel storage by at least 10% after one year.

HYPOTHESIS 2

The ponds formed by the BDA Starter Dams implemented in Thompson Creek will increase sediment storage upstream of the Starter Dams in excess of pre-implementation channel storage by at least 10% after one year.

HYPOTHESIS 3

The addition of the BDA complex in Thompson Creek will reduce total phosphorus concentrations between the inlet (upstream of all BDAs) and outlet (downstream of all BDAs and entering Newman Lake) by at least 5% after one year.

THOMPSON CREEK BDA MONITORING PLAN METHODS AND DATA

METHODS: HYPOTHESIS 1

- **Drone Aerial Imagery:** Capture aerial imagery of the entire study reach
- **Water Depth Profiling:** Water depth upstream of each BDA will be measured in 1ft spaced across sections 5ft apart

METHODS: HYPOTHESIS 2

-**Repeat Cross-Section Surveys:** Three permanent cross sections will be established at 10 ft intervals.
- **Repeat Longitudinal Profile Surveys:** Profiles will start 60 feet upstream of a Starter Dam and will end 20 feet downstream.
- **Soil probing:** Sediment volume trapped behind dams

METHODS: HYPOTHESIS 3

- Total Phosphorus Collection: Water samples will be collected and sent to Anatek Labs

STATUS UPDATE FROM THE END OF MARCH

Photo of Starter Dam #1 looking upstream
(3/24/2022)

Prior to the site visit on March 24th, the team was hoping that the water level would have dropped to safe level in order to survey the creek. Unfortunately, the water level remained quite high due to spring runoff, which only allowed us to take some photos and gather water samples. These photos show that the dams are beginning to create some storage as there is some head difference before and after each starter dam

Photo of Starter Dam #2 looking upstream
(3/24/2022)

Appendix H: Detailed Tasks and Hours

Projected Design Fee Cost and Hours

Task	Project Manager: Hallie Stalcup	Project Engineer : Matt Roberts	Project Engineer : Sarah Frisby
Project Management	45	40	40
BDA Construction in Thompson Creek	48	48	48
BDA Construction in Thompson Creek	25	25	25
Construction Preparation	5	5	5
Construct BDAs	18	18	18
BDA Monitoring Plan Development	89	92	89
Year 1 Monitoring Plan Development and Application	16	16	16
Review of Existing Monitoring Plan	3	3	3
Identify Hypothesis	12	15	10
Design Year 1 Monitoring Plan	13	13	15
Develop QA/QC Plan for Monitoring Activities	20	20	20
Conclusions and Recommendations for Year 2	25	25	25
Design Guidelines for BDAs in Thompson Creek	37	37	35
Develop Design Guidelines for BDAs	5	5	5
Literature Review on BDA Design Methods	5	5	5
Literature Review on Risk Assessment Methods	10	10	10
Examine Risks Associated with BDA Design and Implementation	10	10	15
Develop Guidelines for Design of BDAs Based on Level of Risk	7	7	7
Community Engaged Learning	5	5	5
Project Sustainability Evaluation	5	5	5
Total Hours	229	227	229
Rate ($/hr)	125	110	110
Design Fee	$28,625.00	$24,970.00	$25,190.00
Travel Expenses (500 mi x $0.50/mi)	$250.00		
Total Consulting Fee	$79,035.00		

Final Design Fee Cost and Hours

Task	Project Engineer : Hallie Stalcup	Project Engineer : Matt Roberts	Project Engineer : Sarah Frisby

Project Management	23.25	23	23
BDA Construction in Thompson Creek	26.5	20	19
Construction Preparation	16.5	10	9
Construct BDAs	10	10	10
BDA Monitoring Plan Development	13.75	50.25	10
Year 1 Monitoring Plan Development and Application	0	12	0
Review of Existing Monitoring Plan	0	3	2
Identify Hypothesis	1.25	5	0
Data Collection & Analysis	8.5	6.25	8
Design Year 1 Monitoring Plan	0	15	0
Develop QA/QC Plan for Monitoring Activities	0	3	0
Conclusions and Recommendations for Year 2	4	0	0
Design Guidelines for BDAs in Thompson Creek	16.25	6	31.75
Develop Design Guidelines for BDAs		4	18.75
Literature Review on BDA Design Methods	4	2	6
Literature Review on Risk Assessment Methods	7.25	0	3
Examine Risks Associated with BDA Design and Implementation	3	0	6
Develop Guidelines for Design of BDAs Based on Level of Risk	2	0	2
Community Engaged Learning	14.75	6.5	11.5
Project Sustainability Evaluation	1.5	1	6
Progress Status Report	13.25	12.5	14.25
Final Project Report	31	22	21.5
Total Hours	140.25	135.25	139
Rate ($/hr)	110	110	110
Design Fee	$15,427.50	$14,877.50	$15,290.00
Travel Expenses (500 mi x $0.50/mi)	$250.00		
Total Consulting Fee	$45,845.00		