Reservoir Delta Morphology and Effects on Tributary Fish Passage and Habitat—A Scoping Study

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Fish passage limitations have been identified in several reservoir deltas and rivers throughout Reclamation's Regions. In the Yakima River Basin in Washington, delta dynamics have prevented or impaired Endangered Species Act (ESA)-listed bull trout and other salmonids from migrating between the reservoirs and upstream spawning habitat. This scoping study aimed to better understand the research needs associated with reservoir delta fish passage. The main goal of the scoping study was to develop a conducting proposal to submit in June of 2021 for fiscal years 2022 through 2024. The scoping study outcomes included a literature review, an investigation of available datasets, and the conducting proposal submission.

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Acronyms and Abbreviations

CPN	Columbia-Pacific Northwest
ESA	Endangered Species Act
FY	Fiscal Year
LiDAR	Light Detection and Ranging
GIS	geographic information system
Reclamation	Bureau of Reclamation
rkm	river kilometer
TSC	Technical Service Center

Contents

Executive Summary

Fish passage limitations exist in several reservoir deltas and rivers throughout Reclamation's Regions. In the Yakima River Basin in Washington, delta dynamics can prevent or impair Endangered Species Act (ESA)-listed bull trout and other salmonids from migrating between the reservoirs and upstream spawning habitat. Specifically, sedimentation and shifting channel and thalweg locations on the reservoir delta surfaces can lead to decreased flow depths and subsurface flow. This may result in physical disconnection of the stream and reservoir, or depths too shallow for fish passage. These conditions exist at five reservoirs of focus in this study: Bumping, Cle Elum, Kachess, Keechelus, and Rimrock Reservoirs.

This scoping study aimed to better understand the research needs associated with reservoir delta fish passage. The main goal of the scoping study was to develop a conducting proposal to submit in June 2021 for fiscal years 2022 through 2024. A series of virtual workshops was held between January and June 2021 to achieve this goal: to improve understanding of the physical processes creating the reservoir deltas and to develop potential solutions to fish passage. These virtual workshops began with a virtual site visit in which local experts discussed each reservoir delta of interest. Subsequent virtual workshops focused on brainstorming and refining ideas to develop the most appropriate and achievable research questions for the conducting proposal.

The scoping study outcomes included a literature review, an investigation of available datasets, and the conducting proposal submission. The literature review focused on the physical processes associated with reservoir deltas, for which there is limited published literature due to the fact that these landforms are relatively new features on a landscape. Fish passage issues are a product of these formational processes and the characteristics and management of a given reservoir. Therefore, the conducting proposal was developed to focus on two main objectives: 1) develop a conceptual understanding of geomorphic processes of reservoir delta evolution focusing on how channel flow depth, sedimentation patterns, and inundation dynamics impact fish passage, and 2) use the conceptual model to formulate and evaluate solutions that promote sustainable fish passage across reservoir deltas. An assessment of available data was conducted during proposal development to ensure that the research goals were achievable. The conducting proposal was submitted in June 2021.

1 Introduction

1.1 Study Background

All Reclamation reservoirs are subjected to sedimentation from mainstem and lateral tributary drainages, which results in the formation of deltas. Here we term mainstem tributaries as those which flow along the reservoir valley axis and lateral tributaries as those streams that are typically of higher stream-order and are perpendicularly aligned to the reservoir valley axis. While deltas commonly exist where rivers meet natural lakes, reservoir deltas are unique in that the reservoir often exhibits an annual and seasonal fluctuation of water surface elevation as water is delivered downstream. Reservoir drawdown for downstream water supplies generally coincides with low stream inflows. This promotes reservoir delta channel drying and shallow flow depths that reduce the reservoir-tributary connectivity and are detrimental to fish passage.

The Yakima River Basin has been described by United States Fish and Wildlife Service as a "Core Area" for the threatened bull trout. Certain populations of bull trout have evolved with an adfluvial life history, meaning that these populations of bull trout historically lived in glacially-carved lakes and migrated into upstream tributaries to spawn. The Yakima River Basin reservoirs of interest, most of which were natural lakes before dam construction, (Bumping, Cle Elum, Kachess, Keechelus, and Rimrock) all have fish populations that can become disconnected from headwater spawning habitat (Figures 1 and 2). In some reservoirs, such as Kachess, two separate populations of bull trout exist and are dependent on different tributaries: the Kachess River and Box Canyon Creek. The proposed Kachess Drought Relief Pumping Plant would further decrease reservoir water levels and would be required to account for bull trout fish passage if implemented.

Reservoir-tributary disconnection and fish stranding is monitored and managed in dire passage situations. The Washington Department of Fish and Wildlife manually constructed a channel on the Box Canyon Creek delta in drier years of the last two decades. The channel, made of hay bales and visqueen plastic, is not a long-term solution and needs to be removed a few months after construction to avoid polluting the lake. In addition, these channels involve many hours of physical labor and cost ~$35,000 to $40,000 per channel. The effectiveness of these channels is not entirely known. At other reservoirs, there are no solutions beyond observing and rescuing stranded fish.

Multiple Reclamation Regions with fish passage problems have expressed interest in this research. Within the Missouri Basin Region, bull trout also struggle with fish passage issues in Lake Sherburne and Lower Saint Mary Lake in Montana. In the Upper Colorado Basin Region, tributaries on the San Juan River and Lake Powell encounter bedrock ledges or erosion-resistant surfaces, which results in a waterfall or steep rapids that prevent fish passage. At least one tributary in the Yakima River Basin also has this issue (South Fork Tieton at Rimrock Reservoir). In the California-Great Basin Region, passage is limited across tributary deltas to larger rivers, specifically along Mill Creek in the Central Valley of California.

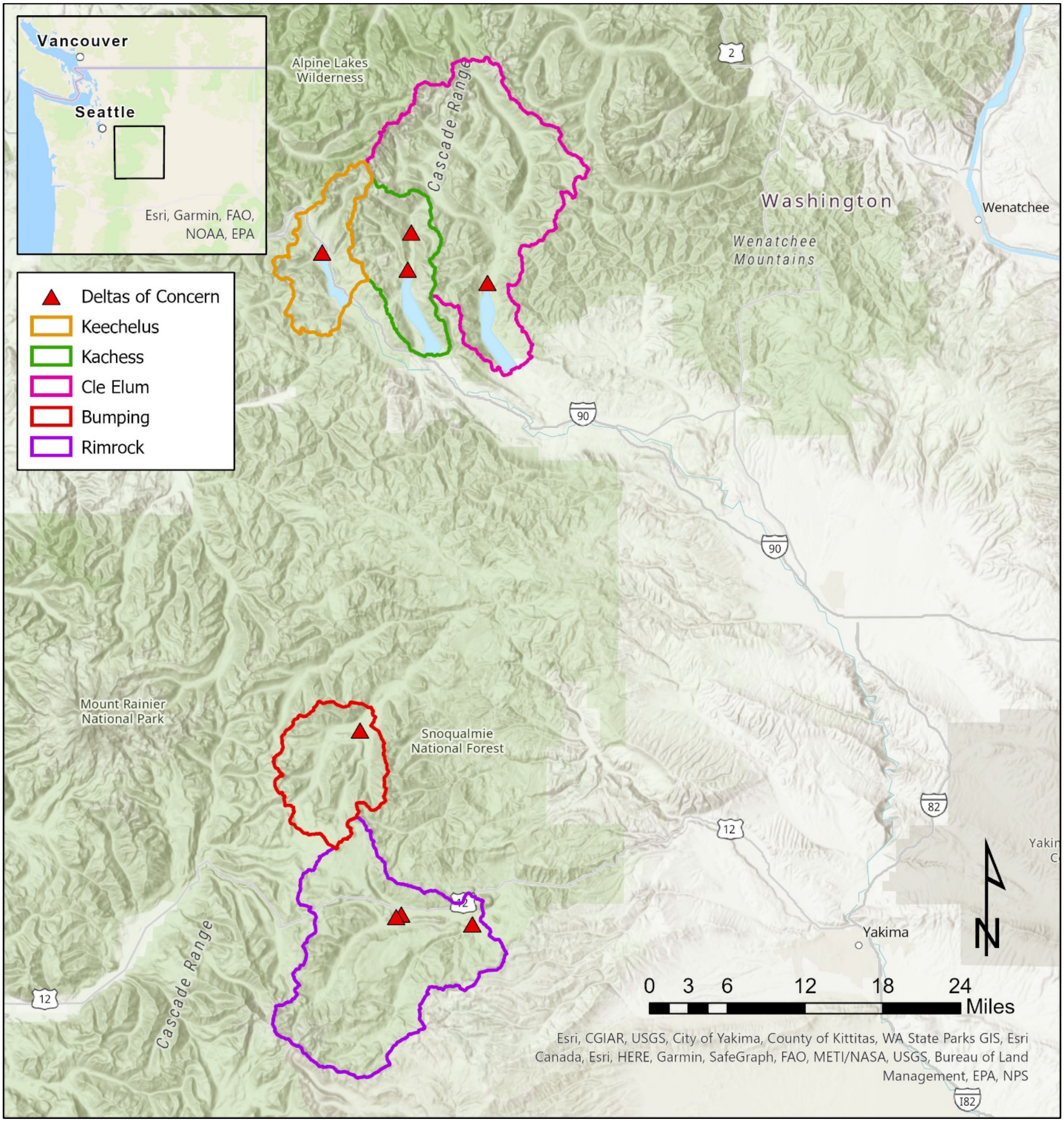

Figure 1. Yakima Basin Reservoir Deltas of interest and contributing drainage basins of interest labeled by reservoir name.

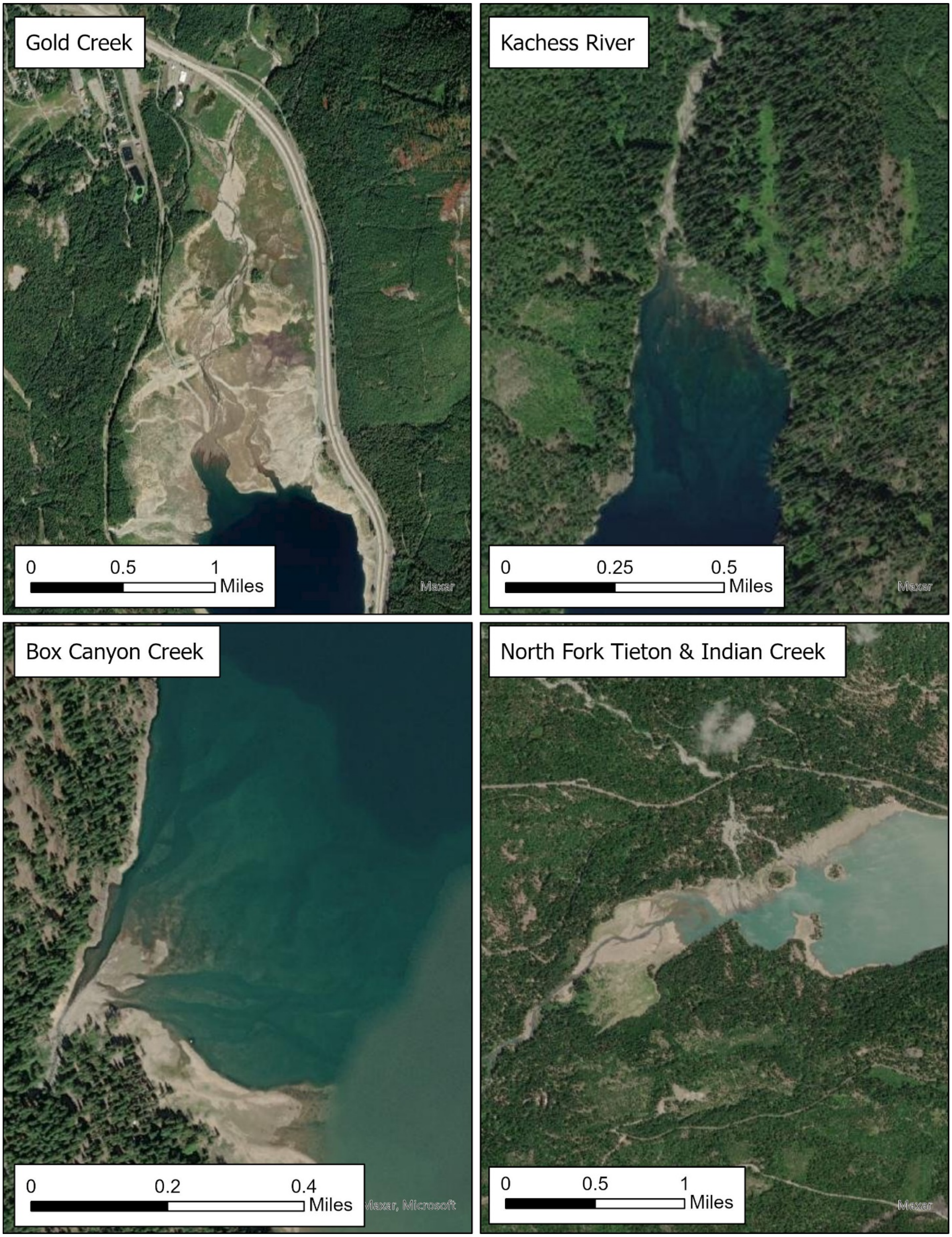

Figure 2. Examples of four reservoir deltas in the Yakima River Basin. Gold Creek enters Keechelus Reservoir, the Kachess River and Box Canyon Creek enter Kachess Lake, and the North Fork Tieton and Indian Creek enter Rimrock Reservoir.

The Columbia-Pacific Northwest (CPN) Region identified "Understanding the effects of Reservoir Delta Morphology on Tributary Fish Passage and Habitat" as one of the Regional Director Needs in the Fiscal Year (FY) 2022 call for proposals. This report details our scoping project to develop a research plan to directly address this Regional Director Need.

1.2 Previous Work

This study will build off years of experience and documentation of fish passage issues in the Yakima River Basin (Meyer, 2002 and Mizel and Anderson, 2008). The Yakima Bull Trout Working Group produced a Yakima Bull Trout Action Plan which documents knowledge about the bull trout and the best strategies to benefit bull trout populations (Reiss et al., 2012). Reclamation developed a management plan for the Yakima River Basin and also performed an assessment of Box Canyon Creek, a lateral tributary to Kachess Reservoir, to better understand potential solutions for fish passage; however, further investigation is required (Reclamation, 2016 and Reclamation, 2012). In addition, consulting groups completed assessments of two reservoir tributaries of interest in our proposed research, Gold Creek entering Kecheelus Lake and Kachess River entering Kachess Reservoir (Natural Systems Design, 2015 and Inter-Fluve, 2020).

Currently, Reclamation is researching reservoir backwater habitats in a Science and Technology project entitled, "Quantifying the Development and Dynamics of Reservoir Delta and Related Backwater Vegetation in the Context of Physical Drivers." Our proposed research focused on aquatic habitat rather than riparian habitat—but could benefit from previous investigations of vegetation growth on reservoir deltas because of the effect on channel width and stability. The aim of this project is to build off all previous work by more directly proposing research focusing on the geomorphology and sedimentation patterns of fish passage channels on delta surfaces.

1.3 Problem Statement

Reservoir deltas are dynamic hydrologic and geomorphic features. Delta sedimentation and channel hydraulics are influenced by upstream tributary inputs, reservoir water surface elevation fluctuations, and wave action. All Reclamation reservoirs include these delta systems that are formed by sediment deposits and are continuously evolving. Delta channel morphology, in combination with changes in upstream land use and reservoir operations, led to changes in and disconnection of habitat for endemic species.

Fish passage limitations were identified in several reservoir deltas and rivers throughout Reclamation's Regions. In the Yakima River Basin in Washington, delta dynamics prevented or impaired Endangered Species Act (ESA)-listed bull trout and other salmonids from migrating between the reservoirs and upstream spawning habitat. These fish passage issues include partial or complete dewatering of the delta stream channels, wide channels with insufficient flow depths for fish passage, lack of channel cover leading to increased predation, and channels flowing over bedrock ledges creating large hydraulic drops where fish are unable to jump over. In the Western United States, where climatic variability is common, these conditions are even more pronounced during dry years. Efforts are currently being made to promote fish passage on an annual basis, but the present solutions are labor intensive and unsustainable. Long-term solutions must be found to promote fish passage and the survival of local fish populations.

1.4 Study Objectives

This scoping study aimed to better understand the research needs associated with reservoir delta fish passage. The main goal of the scoping study was to develop a conducting proposal to submit in June of 2021 for fiscal years 2022 through 2024. The main study questions for the scoping proposal were identified as the following:

1) What field data, models and tools are already available to assess contributing tributary sediment budget and delta morphology within the Yakima River Basin?
2) What management decisions need to be made in the next 10 years to support fish migration and what data are needed to make those decisions?
3) What is the best approach and design for a conducting research proposal study to answer the following questions:
    a. Can we develop a tool to predict sediment transport patterns and channel morphology in reservoir delta and drawdown zones?
    b. How can we design and implement fish passage and/or channel improvement restoration projects in a dynamic reservoir delta environment?

1.5 Research Scoping Strategies

Scoping for the conducting proposal submission included virtual workshops with local experts, literature review, and documentation of potential data sources. From this information, a conducting proposal was developed that focused on unknown questions that arose during the virtual workshops.

1.5.1 Virtual Workshops

Due to the lack of travel opportunities associated with the global pandemic, people from several different agencies participated in virtual workshops to develop the conducting proposal. These workshops began with a virtual site visit with local experts describing the reservoir delta locations, previous work that was conducted at each site, and the prospects and needs regarding bull trout survival. Subsequent workshops focused on determining what questions remain unknown about these reservoir delta systems and fish biology. The main goal of these meetings was to brainstorm ideas and create a clear goal for a conducting proposal. Local expertise was vital to Reclamation's Technical Service Center (TSC) staff understanding the issues at each site and project partners provided continuing insights that made the submission of the conducting proposal possible. The conducting proposal is summarized in Section 2.3.

1.5.2 Project Partners

Several agencies participated in the virtual workshops and assisted in the development of the conducting proposal. Those agencies included:

- Reclamation's TSC
- Reclamation's CPN Regional Staff
- Yakima County Water Resources Division
- Confederated Tribes and Bands of the Yakama Nation
- Kittitas Conservation Trust
- Washington Department of Fish & Wildlife
- Yakima Basin Fish and Wildlife Recovery Board
- Consultant to Yakima Basin Joint Board

2 Scoping Study Outcomes

2.1 Literature Review

2.1.1 Physical Processes Associated with Reservoir Deltas

Reservoir deltas are important, yet understudied landforms throughout the American West. These deltas form where a river discharges into a reservoir. Reservoir deltas are relatively new features in the environment that form over short geologic time scales (decades to centuries) in response to rapid sedimentation. This literature review was conducted to describe the physical processes involved in reservoir delta formation and explore the detrimental impact of reservoir delta morphology on native fish passage.

The physical processes by which reservoir deltas form resemble river-dominated delta evolution in coastal settings, which are well accepted from coastal delta research (Giosan and Bhattacharya, 2005). However, reservoir deltas form on much shorter times scales (Volke et al., 2019). Water level fluctuations are the primary downstream boundary condition controlling reservoir delta evolution, which operate on seasonal timescales as a function of reservoir management and drought conditions. In comparison, sea level change, influences coastal delta evolution over thousands of years. Reservoir delta morphology is controlled by: (1) stream flow, (2) sediment grain size, (3) depositional patterns, (4) the timing, frequency, and duration of flooding on freshly accumulated surfaces, and (5) the age of the reservoir (Liro, 2019).

Reservoir delta evolution begins when a fluvial current at the mouth of a river advances into a reservoir as subaqueous flow (Nichols, 2009). Bed material load and suspended load carried by the river is deposited on subaqueous levees, which aggrade to the reservoir water level and extend the front of the delta downstream as narrow ribbons of land on each side of the channel. Channel instability results from the very low delta plain gradient, causing frequent avulsions that shift the location of the mainstem and its mouth. Distributary channels prograde from the delta apex forming interdistributary bays and islands. Crevasse splays develop as distributaries funnel sediment into these basins, which gradually aggrade to the reservoir water level, providing space and ideal conditions for vegetation to establish on the delta plain (Nichols, 2009).

Olariu et al. (2012) identified several basin morphological controls on reservoir delta progradation. They observed that the Red River in Lake Texoma preferentially deposits sediment in the deepest parts of the lake following the steepest valley gradient (Olariu et al., 2012). The authors suggest that hyperpycnal plumes are responsible for this pattern of progradation in reservoir deltas (Olariu et al., 2012). Hyperpycnal plumes occur when incoming freshwater from a river is denser than the receiving basin water, causing the riverine water to sink below the basin water. It should be noted that the Red River contains high total dissolved solids and high suspended sediment concentrations during periods of high discharge, both of which contribute to the formation of hyperpycnal plumes that behave like density currents.

Olariu et al. (2012) also found that delta progradation rates mainly depend on river water discharge, which determines sediment load. Relatively high progradation rates on the Red River delta occur because of plume confinement along the old river thalweg, which restricts sediment dispersal and causes an elongated delta morphology during periods of high water and sediment discharge. This morphology contrasts with lobate-shaped deltas commonly found in coastal areas where rivers discharge into wider, more shallow basins. However, the Red River delta displayed a lobate morphology during periods of low water discharge, indicating that both morphologies can occur in the same reservoir delta depending on the magnitude of fluxes entering the system. The possibility of multiple delta formational processes occurring at different times is likely to complicate understanding of other reservoir deltas as well.

Several observations of the backwater effects from water level fluctuations on delta and fluvial morphology have been recorded, allowing for spatial zonation by physical processes and vegetation assemblages (Nichols, 2009). Liro (2019) defines the backwater fluctuation zone as a river section upstream of a reservoir that is inundated during reservoir stages higher than normal or average. Within this zone is a sequence of landforms where sediment accumulates due to the presence of the downstream reservoir and is called the delta-backwater. Shorter term flooding in this zone is controlled by fluvial processes, whereas longer term inundation is related to reservoir fluctuations. Hence, the backwater fluctuation zone is further subdivided into river- and reservoir-dominated transitional zones. The river-dominated transitional zone is where backwater effects begin to influence river flow, such that velocity is reduced, and the coarsest material is deposited. The reservoir-dominated transitional zone is positioned farther downstream and is characterized by intense sediment deposition and submerged delta front formation.

Deltas and backwater zones form most commonly where a mainstem river enters the shallow, uppermost margins of a reservoir, but also where tributaries laterally enter deeper, more stagnant portions of reservoirs. Mainstem and lateral tributary delta-backwaters both include a delta complex that progrades into the reservoir and a backwater that aggrades upstream into the antecedent river bottomland (Volke et al., 2019). In some instances, mainstem-lateral combination deltas form where a lateral tributary stream enters near the upstream end of a reservoir, causing the deltas to merge into a single complex (e.g., Elephant Butte Reservoir, NM) (Volke et al., 2019).

The location of delta-backwater processes shifts with variations in reservoir level (Volke et al., 2019). For example, existing bottomland vegetation becomes inundated as water levels rise while the exposure of depositional surfaces for colonization by new vegetation occurs during reservoir drawdown. Due to differences in landscape position and stream gradient, the length of the delta-backwater often differs between mainstem and lateral tributary backwater fluctuation zones. Delta size is also impacted by the scale of water level change in the receiving reservoir. The vertical range of the reservoir, which varies between low and high pool cycles, can dramatically alter the area of delta that is affected (Volke et al., 2015).

The physical responses of river damming were noted in several reservoir deltas on the Missouri River by Volke et al. (2019). On the White River, a tributary to the Missouri, they found that the lowermost portions of the delta-backwater (representing its delta) formed a lobe morphology with a single thread that stretched 2.3 river kilometers (rkm) into the receiving reservoir (Lake Francis Case). The delta-backwater extended upstream an additional 28.7 rkm through the White River valley due to backwater effects of the fluctuating reservoir water level. The downstream portion of the reach experienced direct effects of inundation, while the upstream portion of the reach experienced indirect effects of fluctuating reservoir stage, including increased overbank flooding as channel slope decreased and adjusted to a new base level. The Niobrara River, a tributary to the Missouri, forms a reservoir delta at Gavin's Point Reservoir. Within 20 years of Gavin's Point Dam closure in 1957, the subaerial portion of the reservoir delta nearly filled in the pre-dam channel with sediment, leaving a few narrow channels separated by sandbars. The delta continued aggrading throughout the 1990s, creating many small distributary channels separated by islands covered with herbaceous wetland vegetation (Volke et al., 2019). Continued aggradation in this delta and others could lead to avulsion of the main channel stem. Even without a drastic change such as avulsion, the continued aggradation will lead to more landform creation on the delta surface.

Other common channel and floodplain responses to downstream damming discussed by Volke et al. (2019) include: the width and depth of the active channel generally decreased and the floodplain aggraded to a similar degree as the thalweg; at some channel cross-sections, prominent natural levees formed next to the active channel, representing a highly depositional environment with very little erosion or channel movement during the post-dam period; aggradation rates were greatest in the period immediately following dam closure and at the most downstream cross sections, with rates decreasing upstream; and a sediment plug led to the flattening of the stream gradient across the White River delta-backwater. This sediment wedge was thickest in the lowermost 13 rkm of the White River where channel slope flattened to near 0.00 m/km. In turn, the wedge reduced upstream flow velocity, decreased width and depth of the active channel, and increased the frequency of overbank flows delivering sediment, water, and coarse woody debris to the floodplain. Sediment plugs may also develop in tributaries to Yakima River Basin reservoirs albeit at a different scale.

2.1.2 Implications of Reservoir Delta Physical Processes on Yakima River Basin Reservoirs

Past investigations of reservoir deltas have often focused on systems of much greater hydrologic contributing area than reservoirs of the Yakima River Basin. However, many of the same processes are likely to exist. The delta backwater fluctuation zone introduced by Liro (2019) has been observed at Yakima Basin reservoirs where a common problem is coarse sediment deposited at upstream locations. At lower flows, the channel becomes shallow as water is diverted into smaller flow paths or goes subsurface, which renders fish passage non-existent. Volke et al. (2019) also observed that reservoir deltas from nearby tributaries can end up merging to create larger delta features with multiple tributary inputs. It is possible that the North Fork Tieton and Indian Creek dynamics impact each other as depicted in Figure 2. While some processes are likely to translate across all deltas, there may also be unique conditions at Yakima River Basin reservoirs. The literature is on reservoir deltas is lacking; therefore, our proposed research on reservoir deltas in different regions will be beneficial to overall scientific understanding of the physical processes and biological implications of these landforms. In comparison to past reservoir deltas of focus, many of the reservoirs in the Yakima River Basin were deep, glacial lakes before dams were constructed. We expect that further geomorphic investigation of the Yakima River Basin reservoir deltas will be beneficial to the broad literature on these landforms as well as improving our understanding of mitigation strategies for the endemic fish of the Yakima River.

2.2 Data Investigation and Availability

Two data sources were determined to be important for proposed geomorphic research in the conducting proposal. Light Detection and Ranging (LiDAR) surveys and historical aerial imagery would be used to detect topographic and vegetation change, respectively. LiDAR is available at all reservoir deltas of interest for the proposed study and can be downloaded from the Washington State Department of Natural Resources' LiDAR Portal (https://lidarportal.dnr.wa.gov/). The years of available LiDAR for all locations is documented in Table 1. Aerial imagery exists across a large number of years at times of both full reservoir pool and lower water surface elevations, which will be important for understanding vegetation growth and channel patterning.

The hydrology of each basin is also important for the proposed research topics discussed below. Upstream hydrology will be important for defining flood events and sediment supply. Flood hydrology statistical estimates are available for all upstream rivers that contribute to each of the reservoirs of interest through the United States Geological Survey's StreamStats portal (https://streamstats.usgs.gov/ss/). While no long-term stream gauging records exist upstream of the reservoirs, regional experts will help provide expertise on time series flows. Reservoir pool information which is also critical to reservoir delta dynamics can be found for all Yakima Basin reservoirs through Reclamation's Yakima Project Hydromet System (https://www.usbr.gov/pn/hydromet/yakima/index.html). In addition, project partners can provide information about the hydrology and sediment transport characteristics of many of the reservoir tributaries of interest.

Table 1. Summary of reservoir tributaries of interest, reservoir characteristics, and data availability.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Stream Name	Kachess River	Box Canyon Creek	Gold Creek	Deep Creek	Indian Creek	South Fork Tieton	North Fork Tieton	Cle Elum River
Dam Name	Kachess Dam	Kachess Dam	Keechelus Dam	Bumping Lake Dam	Tieton Dam	Tieton Dam	Tieton Dam	Cle Elum Dam
Reservoir Name	Kachess Lake	Kachess Lake	Keechelus Lake	Bumping Lake	Rimrock Reservoir	Rimrock Reservoir	Rimrock Reservoir	Cle Elum Lake
Date of Dam Closure	1912	1912	1917	1910	1925	1925	1925	1933
Dam Hydraulic Height (ft)	57	57	71	36	196	196	196	124
Reservoir Drainage Area (sq mi)	63	63	54	68	187	187	187	260
Reservoir Stage Data	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Stream Discharge Data	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated
Historical Aerial Imagery	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
LiDAR Data Years	2000, 2018	2000, 2014	2000, 2014	2000, 2014, 2018	2000, 2017, 2018	2000, 2018	2000, 2018	2000, 2014, 2018

2.3 Conducting Proposal Submission

The conclusion of the scoping proposal was the submission of a conducting proposal entitled "Investigating the physical processes that impact reservoir delta fish passage and evaluating potential solutions," submitted to S&T in June of 2021 for fiscal year 2022 through 2024 funding.

2.3.1 Proposed Research Objectives

We propose two main research objectives to address fish passage problems on reservoir deltas: 1) develop a conceptual understanding of geomorphic processes of reservoir delta evolution focusing on how channel flow depth, sedimentation patterns, and inundation dynamics impact fish passage, and 2) use the conceptual model to formulate and evaluate solutions that promote sustainable fish passage across reservoir deltas. Two types of delta stream channels important to fish passage have been identified and will be a focus of the research: mainstem alluvial streams that enter the reservoir at the upstream extent, and lateral tributaries that are smaller and likely have steeper entry slopes.

To address the first objective, we propose to test multiple hypotheses. First, we hypothesize that mainstem alluvial deltas are growing at a faster rate than lateral tributary deltas due to differences in hydrology and sediment supply, and this is likely to have a larger impact on fish passage. To test this hypothesis, we will quantify delta growth from the time of dam construction to contemporary conditions. Second, we hypothesize that establishment of woody vegetation on reservoir deltas is directly related to delta growth, inundation of delta surfaces by fluctuating reservoir water surface elevations, and channel stability. To test this hypothesis, we will compare a time series analysis of reservoir water surface elevations to the growth of woody vegetation based on aerial imagery and compare channel dimensionality in vegetated versus unvegetated delta locations.

To address our second objective, we will evaluate several solutions that we hypothesize will sustainably promote fish passage along reservoir delta channels for fish populations in the Yakima River basin and other Reclamation Regions. Potential solutions will include channel excavation, channel narrowing with wood or rock, limiting downstream delta growth, construction of delta islands and channels, reduced delta channel seepage, different reservoir pool management strategies, or a combination of these solutions. To evaluate these solutions, we will conduct a literature review, data analysis, and numerical hydraulic and sediment transport modeling based on information regarding delta conditions learned in the first research phase. Results will inform understanding of which solutions result in more favorable fish passage channels over time.

2.3.2 Proposed Research Questions

How do reservoir deltas affect fish passage compared to natural lakes and streams, and how can fish passage be improved by considering modifications to delta channel width and depth, promoting woody vegetation along stream banks, preventing downstream growth of delta surfaces, and managing the seasonal and annual fluctuations in reservoir pool water surface?

We hypothesize that unique geomorphic processes in reservoir delta environments cause fish passage issues that are more severe than natural lakes and streams. Fluctuating water surface levels in reservoirs are often not timed with fish life cycle histories and natural flow hydrographs. Further, the reservoir water surface influences delta sedimentation and woody vegetation growth, which may cause wider and shallower channels. Fish need a channel with sufficient flow depth, longitudinal slope, substrate, and cover to migrate from reservoirs to upstream reaches.

We also hypothesize that fish passage in reservoir delta environments can be improved by considering a range of solutions from physical modifications of delta channels, control of delta sedimentation and growth, and management of reservoir pool water surface elevations over time.

This research proposes a two-step approach that first investigates the root cause (i.e., the physical processes) of fish passage limitations in reservoir delta channels. Secondly, a better understanding of the physical processes will be used to develop and evaluate solutions with the goal of improving fish passage through reservoir deltas.

2.3.3 Proposed Research Steps

The first phase of the study will focus on data collection, data processing, and conceptual understanding of geomorphic processes at reservoir tributary deltas at the five Reclamation reservoirs of interest (Bumping, Cle Elum, Kachess, Kecheelus, and Rimrock). An early site visit will aid in understanding of topographic and inundation analyses. Descriptions of first year tasks are provided below.

- Data and Imagery Collection and Processing: Pre-dam topography exists for at least three of the five reservoirs proposed in this study. Project partners will help to retrieve available datasets and literature for each reservoir. Aerial imagery and pre-dam contours will be georeferenced using ESRI's ArcPro geographic information system (GIS) to properly align the dataset. Existing publicly available light detection and ranging (LiDAR) and Reclamation-surveyed bathymetric data will be retrieved as well.
- Topographic surface creation and sedimentation analysis: ArcPro will be used to digitize elevation contours of pre-dam surveys. Contemporary above water LiDAR and below water bathymetric surveys will be combined as needed. Elevation differences will be used to analyze sedimentation volumes at reservoir tributary deltas from historical to contemporary time periods. Cross-sectional and longitudinal form of deltas will be assessed and channel dimensions across datasets will be quantified.
- Reservoir pool inundation analysis: A time-series of reservoir water surface elevations will be assembled from existing data. Water surface elevations will then be compared to reservoir delta elevations. A python-script (computer code) will be developed to calculate inundation frequency and annual inundation and drying patterns.
- Vegetation and channel dimensionality and inundation relationships: In this GIS-based task, woody vegetation and channel boundaries will be digitized on reservoir tributary deltas. Relationships between channel width, woody vegetation, and inundation will be assessed.

The second phase of the study will then focus on solution development and evaluation and research documentation.

- Modeling of sedimentation processes will be conducted for both mainstem and lateral tributary types. The following hypothesized solutions will be analyzed using a numerical hydraulic and sediment transport model (e.g. Sedimentation and River Hydraulics One- or Two-Dimensional – SRH-1D or 2D):
  - Installation of timber pilings along existing stream channels
  - Excavation of channels with channel banks reinforced by timber pilings, constructed, log jams, or stone
  - Limit downstream growth of the delta through dredging
  - Construction channels and high island areas for vegetative growth
  - Test different management strategies for the reservoir pool drawdown timing
  - Implement a combination of the above strategies

- Model parameterization: Topographic surfaces will be created for each of the fish passage solutions. Model inputs such as the upstream water and sediment supply, sediment sizes, and bed roughness will be parameterized based on field-collected and existing data. A site visit prior to model creation will be conducted to retrieve any necessary data that does not exist. Tributary hydrology will be partitioned based on previous return-period flow analysis. Downstream reservoir water surface elevations will be set based on Reclamation dam management data and input from Columbia-Cascades Area Office water managers.

- Model Runs: Modeling will be conducted based on delta morphology characteristics quantified in the first year of the study. Modeling will be conducted over a time series to better understand how high discharge events deposit sediments on the delta surface and the subsequent distribution of flows after the larger storm events.

- Model Analysis: With different management strategies implemented, a comparison of solution longevity will be assessed with a focus on retention of fish passage.

2.3.4 Potential Research Benefits and Impacts of Conducting Proposal

The solution development and evaluation portion of this research can immediately aid in the understanding of how long certain solutions will persist on reservoir delta surfaces. Therefore, the research could immediately support management at five Reclamation reservoirs. This research will also immediately provide more quantified understanding of reservoir delta morphology and reservoir sedimentation. For example, how much higher is the delta surface now than the channel bed at dam construction, or approximately what volume of sediment has been deposited at these reservoir deltas over time? These are important questions we need to answer to better quantify reservoir sedimentation. By using previously collected data resources at these reservoir locations, the proposed analysis provides substantial benefit at a low relative-cost.

Ultimately, it is the goal of this research to help improve fish passage at Reclamation reservoirs, so a future benefit would be the increased abundance of threatened or endangered fish (e.g., bull trout and other salmonids) in Reclamation reservoirs and upstream channels. Beyond fish abundance, the results from this study may indicate at what water surface elevations vegetation can be introduced to narrow channels to more natural widths. Inundation time series analysis may provide insights into reservoir management under a changing climate as well. Reservoir pool filling and related delta inundation timing may be changing. This could have important implications for sediment transport if high flow sediment transport events enter reservoirs at different average water levels than in previous years. Another implication of climate-induced changes in inundation patterns would be on vegetation growth. For example, if the water levels are rising earlier in the year due to warmer spring temperatures and early spring snowmelt, delta surfaces will be inundated earlier in the year. In conjunction, if downstream users need water earlier due to warmer temperatures and an earlier snowmelt peak, reservoir drawdown may need to occur earlier, and deltas may dry earlier. We hope our inundation analysis may answer some of these questions and be applied more broadly to regional reservoirs. Failure to develop effective fish passage solutions for ESA-listed species may compromise Reclamation's continued operation of these systems. Finally, wildfire is also likely to impact reservoir deltas in the future through increased sediment supplies. Increased sediment supplies may lead to fish passage issues and lack of tributary-reservoir connectivity. This research could provide answers for those types of situations as well.

Because this research will focus on fish passage and delta channel longevity, there are likely to be many reservoirs beyond those identified here with similar fish passage issues. Multiple sites have already been identified within four of the five Reclamation Regions. Impacts of the research may include more efficient and applicable reservoir delta channel design and maintenance. Results of the analysis might also show that a slight change in management of reservoirs could help to retain fish passage and reservoir-tributary connectivity over longer periods of time. The results would not need only apply to fish passage. Water delivery to reservoirs through a connected surface channel may also be of interest and sedimentation of reservoirs is an increasingly important management topic. For example, Reclamation and its partners spend hundreds of thousands of dollars annually to maintain surface water connection between the Rio Grande channel and Elephant Butte Reservoir in New Mexico. In short, this research is likely to add to knowledge that will reduce impacts to fish and reduce water delivery interruptions.

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