Adrienne McKell

November 18, 2024

CEE 6410

Linking fish habitat on the bear river

A MULTIPLE INTEGER PROBLEM

## Abstract

## The habitat for Bonneville Cutthroat Trout (BCT) in the Bear River is fragmented into multiple sections by three hydroelectric dams and the Rainbow Inlet Canal, significantly limiting connectivity and migration. This paper presents a solution using a Mixed-Integer Programming model to optimize habitat restoration by maximizing connectivity of these sections. The model evaluates options for dam removal or fish passage installation at each site to maximize habitat connectivity while considering associated costs. The goal is to provide decision-makers with a comprehensive framework to assess the ecological and environmental impacts of these barriers, aiding in determining the future of the dams and improving conditions for BCT conservation.

## Introduction

Fish passage barriers, such as hydropower dams, culverts, and diversions, significantly alter aquatic ecosystems, obstructing critical habitats and disrupting hydrological processes. In the Bear River system, these challenges are compounded by the presence of aging infrastructure, such as the Cove Dam, which was removed in 2006 following a Federal Energy Regulatory Commission (FERC) relicensing process. However, other dams in the system—Soda, Grace, and Oneida—remain in operation, with limited provisions for fish passage. This project seeks to evaluate strategies for enhancing fish passage while balancing the ecological and economic impacts of hydropower operations. Specifically, it considers whether removing or retrofitting three hydropower dams can maximize fish habitat connectivity and minimize costs to the dam operator, PacifiCore.

This research incorporates a multiple integer optimization approach, using a GAMS model to evaluate trade-offs between restoring aquatic habitat and minimizing financial losses. By integrating hydrological, economic, and ecological data, the model explores solutions that benefit both fish populations and human stakeholders.

## Background

The Bear River, home to the Bonneville Cutthroat Trout (BCT), has been significantly impacted by the development of infrastructure for irrigation, flood control, and hydroelectric generation. In 1907, the U.S. Secretary of the Interior authorized the Bear River Project, which led to the construction of three hydroelectric dams—Soda, Grace, and Oneida—and the Rainbow Inlet and Dingle (Telluride) Canals. Completed in 1927, these structures altered the natural flow of the river and fragmented its ecosystem, creating barriers that disrupt the migratory and spawning behaviors of native fish species, including the fluvial BCT. This paper focuses on addressing the ecological impacts of the Bear River Project on the BCT population.

The dams and canals have divided the river into four distinct segments, isolating BCT sub-populations and hindering their natural migration and spawning success (Hillyard, 2009). This project explores potential solutions, including dam removal or the installation of fish passage systems at each dam and the Rainbow Inlet Canal, to restore connectivity and habitat for BCT. The feasibility of these solutions will be evaluated using a model designed to inform decision-making by balancing ecological restoration with practical and financial considerations.

Notably, all three dams are over 100 years old and require significant repairs. In 2006, Cove Dam, formerly located between Grace and Oneida, was deemed beyond repair and subsequently removed. This project aims to assess a similar approach for the remaining dams, providing PacifiCore with a framework to decide whether to pursue removal or renovation with the addition of fish passage. By incorporating environmental considerations, PacifiCore may also qualify for federal and state funding opportunities, as seen in other dam removal projects, further incentivizing ecologically beneficial outcomes.

A map of the indian river

Description automatically generated

Figure Map of Bear River BCT habitat sections (Hillyard, 2009)

## Literature Review

### Overall Observations/contributions of 5 articles below:

1. **Holistic Habitat Management**: Alafifi and Rosenberg (2020) highlight the potential of systems models, such as the WASH model, to synergize water and vegetation management for enhancing aquatic, riparian, and wetland habitats. This approach prioritizes ecosystem-wide improvements over individual species, setting a precedent for balancing environmental and human water needs.
2. **Integrated Decision-Making**: Kraft (2017) demonstrated the effectiveness of dual-objective optimization in river barrier removal, optimizing aquatic habitat restoration while minimizing economic losses. This method provides practical insights into prioritizing environmentally harmful barriers and balancing competing water demands.
3. **Transboundary Water Management**: Sehike and Jacobson (2005) showcased the benefits of system dynamics modeling for managing complex transboundary water systems like the Bear River Basin. Their work underscores the importance of visualizing hydrologic interactions and engaging stakeholders in multiscenario analyses to manage interconnected resources effectively.
4. **Fish Passage Challenges and Innovations**: Schilt (2007) reviewed fish passage technologies and their limitations at hydropower dams. While existing methods like fish ladders and bypass systems show promise, the study emphasizes the need for ongoing innovation to address the varied responses of species to migration barriers.
5. **Insights into BCT Behavior**: Hillyard and Keeley (2009) provide valuable data on Bonneville Cutthroat Trout (BCT) spawning and migration patterns in the Bear River, identifying critical tributaries and barriers that influence their behavior. Their findings support targeted conservation strategies to improve habitat connectivity.
6. **Ecosystem Connectivity**: Kraft’s (2017) optimization model reveals that removing numerous small barriers often results in greater habitat restoration benefits compared to removing major barriers with high economic costs. This insight shifts restoration focus towards cost-effective cumulative gains.
7. **System Dynamics for Stakeholder Engagement**: Sehike and Jacobson (2005) emphasized the role of system dynamics modeling in stakeholder communication. By visualizing "what-if" scenarios, the Bear River Basin model facilitates transparent decision-making in a complex regulatory environment.
8. **Practical Tools for Conservation**: Alafifi and Rosenberg’s (2020) WASH model and the web map provide accessible tools for managers to allocate resources effectively, combining scientific data with practical operations to improve watershed habitat quality.

**Systems modeling to improve river, riparian, and wetland habitat quality and area (2020)**

Ayman H. Alafifi, David E. Rosenberg

<https://doi.org/10.1016/j.envsoft.2020.104643>

Highlights:

* A new ecological objective quantifies the suitable habitat areas of aquatic, floodplain, and wetland habitat types.
* A systems model shows when, where, and how much to allocate scarce resources to improve watershed habitat area and quality.
* Synergistic water and vegetation management can improve habitat for native fish, floodplain vegetation, and migratory birds.
* An open-access web map helps communicate opportunities to improve habitat area and quality to stakeholders.
* Requires a collective effort among researchers, manager, and stakeholders to identify habitat types, priority sites, indicator species, habitat characteristics, suitability of habitat for species, and the network of water system components.
* Model components:
  + Decision variables
    - Reservoir Releases
    - Diversion Amount
    - Planting Area
  + Maximize total watershed suitable habitat
  + Constraints
    - Urband and Agricultural Demand and Requirements
    - Plant cover balance
    - Infrastructure capacity
    - Channel toporgraphy
    - Budget
  + Took into account the different life stages that are independent from each other in flow and vegetation attributes that define their suitable habitat
* Aquatic Habitat
  + Managers can improve fish habitats in the LBR by adjusting flow regimes that influence water depth and temperature.
  + Bonneville cutthroat trout (BCT) is used as an indicator species in the cooler headwaters, while brown trout dominate warmer, lower elevation reaches.
  + An aquatic suitability index was developed for both species, based on water depth and temperature, using empirical data and stakeholder input.
* The WASH model improves suitable habitat area by recommending monthly reservoir release, storage, and floodplain planting operations

**Developing fish passage and protection at hydropower dams (2007)**

Carl R. Schilt

<http://dx.doi.org/10.1016/j.applanim.2006.09.004>

Key words: Fish passage, Fish conservation, Hydro-power Dams, Environmental impact

* Industrial changes, such as hydropower development, can hinder fish migration, increase predation, and negatively impact water quality and fish health.
* While measures like dam water spilling can improve fish survival, they can also lead to issues like elevated dissolved gas concentrations downstream.
* Conservation efforts now focus more on ecosystem integrity rather than just individual species, reflecting the need for holistic water-management plans.
* Fish ladders and lifts face challenges, especially for species like eels and lampreys, which struggle against strong currents and face barriers during migration.
* Turbine passage doesn't always kill fish, but survival varies by species, age, and other factors, with mortality rates for fish like juvenile shad ranging from 0-40%.Upstream migratory options:
  + Lorries
  + Ladders
  + Lifts
* Downstream migratory options:
  + Juvenile bypass system (gateway slot)
    - Impact with and descaling and other damage from screens and system hardwater
  + Spillways
    - The most benign way to pass large numbers of fish, however from the hydropower perspective the primary drawback of spill is foregone power generation represented by the spilled water
  + Sluiceways and other surface routes
    - Too few fish use these routes, it is the most cost-effective in terms of n umber of fish per bypassed water
  + Transportation
    - Water temperature and flow rates.
    - In a drought year when spill rates may be low and in-system conditions are poor transportation might be helpful
* Hydropower dams will continue to impact ecosystems, so designing and operating them with minimal ecological harm is both wise and economically beneficial. Innovations like improved turbine design and non-turbine fish passage routes show promise, but conflicts between human water needs and fish migration will persist. Efficient fish passage strategies, including surface passage, are essential, as they mimic natural waterfalls and rapids. Understanding fish behavior and sensory stimuli is key to improving passage, but success may be partial, requiring continuous evaluation and refinement of solutions.

**Distribution and Spawning Migrations of Fluvial Bonneville Cutthroat Trout in the Bear River, Idaho**

Ryan W. Hillyard, Ernest R. Keeley

Idaho Department of Fish and Game

* These dams have potentially restricted migratory behaviors of Bonneville cutthroat trout (BCT) in the Bear River, resulting in subpopulations isolated into river segments. In addition, dams may have influenced the longitudinal distribution of BCT throughout the main-stem Bear River due to alterations in river habitat (e.g. flows, temperature) (Buisson et al. 2008; Stoneman and Jones 2000). Despite the impact of past habitat alterations and the potential impact of future habitat alterations, little information is available on the movement and spawning migrations of this unique fluvial population of BCT in the Bear River.
* The primary objectives of this study include 1) identify the distribution of fluvial BCT in the Bear River in Idaho 2) use radio telemetry to identify which tributary streams are being used by fluvial BCT for spawning, and 3) use radio telemetry to identify seasonal movement of fluvial BCT in the Bear River of Idaho.
* We were unable to tag any BCT in the Riverdale or Thatcher segments. Although BCT are known to inhabit nearby tributary streams, such as Cottonwood Creek and Mink Creek, we did not sample them in adjacent mainstem habitat perhaps because of water diversions that seasonally disconnect streams.
* In the Cub River, we found three of the five implanted tags in the summer without any sign of the fish carcass. One fish was never tracked after tagging, possibly due to tag failure. The other fish remained within one km of its tagging location.
* In Nounan, five BCT spawned in two tributaries. There were 80% that spawned in Eightmile Creek and 20% that spawned in Georgetown Creek (Figure 5). In Pegram, the three BCT that spawned used the Smith Fork in Wyoming (Figure 5). In the spring of 2006, about 50% of tagged BCT migrated into spawning tributaries. In Nounan, 14 BCT spawned in two tributaries, 79% spawned in Eightmile Creek and 21% spawned in Stauffer Creek (Figure 5). In Pegram, 30 BCT spawned in two tributaries, 93% spawned in the Smith Fork and two 7% in the Thomas Fork (Figure 5). During 2005 and 2006, one fish spawned above the forest service boundary in Eightmile Creek, while the remaining fish spawned in habitat lower in the tributary.
* The nearly exclusive selection of Eightmile Creek by BCT for spawning in the Nounan segment is disconcerting. The type of diversion dams used in Eightmile Creek are primarily non-hardened structures, which are less likely to obstruct migrating fish. These structures may 26 be an important factor influencing spawning success of fluvial BCT in the Nounan segment.
* Future management and research strategies should focus on the current distribution of fluvial BCT populations. For example, during the summer of 2007, IDFG conducted a survey on fish entrainment in irrigation diversions. This project was funded by PacifiCorp in an effort to improve BCT populations within the Bear River watershed. This survey will help to identify the 29 effects of fish entrainment on BCT populations in these tributaries. In addition, a tributary monitoring program was established for 10 Bear River tributaries. This monitoring program will provide valuable population trend information, and should be expanded to the mainstem Bear River. Management Recommendations
  + 1) Establish long-term monitoring sites in each of the four river segments. 2) Prioritize management projects in tributaries and the Bear River in correlation to current distributions of fluvial BCT. 3) Implement research projects that may identify the limitations of current fluvial BCT populations from distributing throughout the four river segments.

**Kraft, Maggi, "Optimizing Barrier Removal to Restore Connectivity in Utah’s Weber Basin" (2017). All Graduate Theses and Dissertations, Spring 1920 to Summer 2023. 6885.**

[**https://digitalcommons.usu.edu/etd/6885**](https://digitalcommons.usu.edu/etd/6885)

River barriers, such as dams, culverts and diversions are important for water conveyance, but disrupt river ecosystems and hydrologic processes. River barrier removal is increasingly used to restore and improve river habitat and connectivity. Most past barrier removal projects prioritized individual barriers using score-and-rank techniques, neglecting the spatial structure and cumulative change from multiple barrier removals. Similarly, most water demand models satisfy human water uses or, only prioritize aquatic habitat, failing to include both human and environmental water use benefits. In this study, a dual objective optimization model identified in-stream barriers that impede quality-weighted aquatic habitat connectivity for Bonneville cutthroat trout. Monthly streamflow, stream temperature, channel gradient and geomorphic condition were indicators of aquatic habitat suitability. Solutions to the dual objective problem quantify and graphically present tradeoffs between quality-weighted habitat connectivity and economic water demands. The optimization model is generalizable to other watersheds, but it was applied as a case study in Utah’s Weber Basin to prioritize removal of environmentally-harmful barriers, while maintaining human water uses.

Modeled results suggest tradeoffs between economic costs of removing barriers and quality-weighted habitat gains. Removing 54 in-stream barriers increases quality-weighted habitat by about 160 km and costs approximately $10 M, after which point the cost effectiveness of removing barriers to connect river habitat slows. In other words, there is decreasing benefit of removing barriers, so that after removing the first 54 barriers, it costs more to connect more high-quality habitat. Removing reservoirs or diversions that result in large economic losses did not substantially increase habitat. This suggests that removing numerous small barriers results in greater increases in habitat for the same removal costs, without significant water scarcity losses. The set of barriers prioritized for removal varied monthly depending on limiting habitat conditions for Bonneville cutthroat trout. The common barriers removed in the model were identified to communicate the most environmentally harmful barriers to local stakeholders and inform decision-making. Additionally, limiting the budget or number of barrier removal projects resulted in a different set of barriers removed. This research helps prioritize barrier removals and future restoration decisions in the Weber Basin although the model formulation is generalizable to other watersheds. Available data and a simplified approach limit the scope of this model. The modeling approach expands current barrier removal optimization methods by explicitly including economic and environmental water uses.

**System Dynamics Modeling of Transboundary Systems: The Bear River Basin Model (2005)**

Gerald Sehike, Jake Jacobson

[**https://doi-org.dist.lib.usu.edu/10.1111/j.1745-6584.2005.00065.x**](https://doi-org.dist.lib.usu.edu/10.1111/j.1745-6584.2005.00065.x)

* System dynamics is a computer-aided approach to evaluating interactions within complex systems, including natural and social sciences.
* The Idaho National Engineering and Environmental Laboratory developed a system dynamics model to evaluate large hydrological systems, specifically modeling the Bear River basin.
* System dynamics is effective in integrating surface and groundwater data and simulating their interactions within a basin.
* The model aids decision-making by visualizing hydrologic elements and constraints, allowing stakeholders to simulate and explore "what-if" scenarios.
* The Bear River basin is a complex transboundary water system shared by Idaho, Utah, and Wyoming, with unique hydrological characteristics.
* System dynamics modeling is used to address the basin’s dynamic complexity, helping manage water resources and understand cause-effect relationships across time and space.
* The modeling tool enables multiscenario analysis and better visualization, making it easier for stakeholders to understand and manage water allocation.
* Transparent communication of data and results is emphasized to ensure effective and trusted decision-making in managing transboundary water resources.
* The Bear River basin is shifting from a sparsely populated agricultural area to a more urbanized environment, increasing demand for water resources.
* Water quality issues are significant, with various pollutants impacting 52 streams and nine lakes, requiring coordinated action from Idaho, Utah, and Wyoming.
* Water allocation management is complex due to the basin's transboundary nature, with individual states operating under their laws while facing challenges in co-managing interconnected groundwater and surface water resources.
* Each state manages water quality and allocation independently, complicating overall management due to differing EPA oversight regions.
* System dynamics modeling offers real-time insights into complex systems, allowing decision-makers to explore long-term behaviors and adjust parameters without waiting for field data. In the Bear River basin, it serves as an effective decision support tool by integrating diverse data and regulations, empowering stakeholders to test management alternatives. The adaptable framework can be applied to other basins and is accessible through desktop or web-based applications, enhancing information dissemination to decision-makers.

## Contributions

The contributions of the cited studies collectively highlight advancements in river restoration, hydropower management, and aquatic ecosystem enhancement through integrated and innovative approaches. The removal of the Cove Dam on the Bear River in 2006 exemplifies a pivotal case where aging hydropower infrastructure deemed obsolete was replaced with ecologically and economically favorable solutions. This decision, tied to the renewal of the Bear River Hydroelectric Project (FERC No. 20), not only eliminated significant environmental hazards but also mandated increased minimum flow requirements and funded river restoration projects. These efforts underscore the importance of balancing energy generation with ecological sustainability and demonstrate a precedent for addressing outdated dams within a larger restoration framework.

The optimization model developed by Kraft et al. (2019) further contributes to this narrative by emphasizing the strategic prioritization of barrier removal for river restoration. Unlike traditional score-and-rank methods, this dual-objective approach incorporates both environmental and human water use benefits, maximizing habitat connectivity while minimizing economic costs associated with water scarcity. The case study in Utah's Weber Basin revealed that removing 54 instream barriers reconnects 160 kilometers of quality-weighted habitat, offering a cost-effective strategy until diminishing returns are observed. This study innovatively combines hydrological, economic, and ecological considerations, providing a replicable methodology for similar barrier removal projects.

Alafifi and Rosenberg (2020) expand these contributions by integrating systems optimization modeling to enhance aquatic, floodplain, and wetland habitats. Their participatory approach in the Lower Bear River watershed demonstrates how synergistic management of water releases, floodplain revegetation, and infrastructure can yield substantial habitat quality improvements. By aligning ecological goals with agricultural and urban water demands, their model offers a blueprint for allocating scarce resources effectively. Their findings underscore the potential of winter reservoir releases, early vegetation planting, and strategic flow adjustments to create multifaceted ecological benefits, further advancing the discourse on sustainable river basin management.

## Model Formulation

Formulation for Multi-Objective Integer Program (MIP)

s.t.

Decision Variables

Connectivity indicator for river segment *i*

: Dam removal indicator for each dam *j*

Fish passage indicator for each dam j and/or the rainbow canal

and If using a weighted sum option to combine objectives their weights will have to be decided.

Constraints (MIP)

1. Connectivity Constraint for Each Segment *i*
2. Mutal Exclusivity Constraint for Each Dam *j*
3. Budget Constraint
4. Minimum Connectivity Requirement
   1. is a target value for river connectivity (e.g. minimum length or percentage of river segments connected)

## Major Findings

In 2009, PacifiCore funded a study to investigate the distribution and spawning migration patterns of fluvial Bonneville Cutthroat Trout (BCT) in the Bear River. The study revealed several significant findings. Within the four areas surveyed, no BCT were captured in the Riverdale and Thatcher segments, both of which are downstream of Grace Dam. In the Pegram segment, the highest catch rates occurred near the Idaho-Wyoming border, while in the Nounan segment, BCT were concentrated at the confluence of Eightmile Creek, between Alexander Reservoir and Georgetown Creek. Two critical spawning tributaries were identified: Eightmile Creek and Smiths Fork River, though BCT migrations were limited above the forest service boundary. Notably, several tributaries in the Nounan and Pegram segments showed no evidence of BCT spawning, potentially due to diversion dams and altered flows. Temperature was a critical factor influencing migration, with higher summer water temperatures concentrating fish near cooler tributaries. Alarmingly, over 65% of tagged fish died in the Bear River, with 50% mortality among tagged fish during the study.

Information regarding the storage capacity, dam height, type, and power generation capacity of each dam on the Bear River was found on the PacifiCore website. This data provides essential context for understanding the infrastructure's operational constraints and impacts on river flows. Additionally, documents related to the Bear River Hydroelectric Project (FERC No. 20) outlined agreements made during the proposed removal of Cove Dam. These documents included budget estimates for necessary repairs if the dam were not removed, general steps for removal, benefits to PacifiCore from dam removal, and a timeline covering proposal, permitting, design, and construction phases. Efforts to locate the total cost of the Cove Dam removal are ongoing.

Real-time flow data for the Bear River at each dam has also been identified and is instrumental for evaluating how dam operations influence water availability and fish habitat. This data aids in understanding the temporal variability of flows and their implications for both hydropower operations and ecological conditions in the river system.

## Steps to Completion

To complete the project, I need to identify 1-3 viable fish passage options for the dams and the Rainbow Inlet Canal, along with their associated costs. Additionally, I must determine whether fish pass through Mud Lake between Bear Lake and Soda Dam. Estimating dam removal costs is another key step, requiring reliable sources to provide accurate data. Once these inputs are gathered, I will develop the GAMS model to optimize fish passage solutions while balancing costs and connectivity. The final step will be compiling the findings and analysis into a comprehensive report.

## Anticipated Challenges

One major challenge is managing time effectively to ensure I can gather all the necessary information to create a viable model with realistic solutions. I also need to determine how confident I should be in my cost estimates and how much expertise I need to develop to feel assured in their accuracy. Another concern is the possibility of missing important constraints that could affect the model’s validity. Additionally, formulating the model itself will be a significant challenge, particularly in ensuring it functions correctly and produces reliable results.

## Conclusion

The ongoing research on fish passage optimization in the Bear River system underscores the complex interplay between ecological sustainability and economic feasibility. By leveraging a systems-based optimization model, this project addresses critical questions about how best to manage aging hydropower infrastructure while enhancing fish habitat connectivity. Initial findings suggest that strategic interventions, such as targeted barrier removals or retrofits, have the potential to create solutions that align ecological goals with stakeholder priorities.

As the project progresses, it will provide actionable insights into balancing hydropower generation with ecosystem restoration, offering a framework that could guide similar efforts in other river systems. The anticipated outcomes will contribute to the broader understanding of how integrated modeling approaches can support sustainable water resource management. By addressing both ecological and economic considerations, this research has the potential to create long-term benefits for the Bear River system's aquatic life and the communities it serves.