DO BEAVER DAM ANALOGUES ACT AS PASSAGE BARRIERS TO JUVENILE COHO SALMON AND JUVENILE STEELHEAD TROUT?

By

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ABSTRACT

DO BEAVER DAM ANALOGUES ACT AS PASSAGE BARRIERS TO JUVENILE COHO SALMON (*ONCORHYNCHUS KISUTCH*) AND JUVENILE STEELHEAD TROUT (*ONCORHYNCHUS MYKISS*)?

Christopher Gregory O'Keefe

In the Pacific Northwest, the human-caused reduction of quality and quantity of freshwater rearing habitat is a limiting factor for Pacific Salmon populations. Beaver dam analogues (BDAs) increase suitable rearing habitat for juvenile salmonids and promote the restoration of critical stream processes. Installing BDAs is an increasingly popular alternative to more intensive restoration techniques, due to the relatively low cost and effort required to install BDA structures. However, widespread installation of BDAs has been slowed by regulatory agencies' concerns that BDAs may impede fish passage. Few studies have empirically assessed the extent to which BDAs impede fish passage, and no studies have elucidated physical factors (e.g., jump height, pool depth, water velocity, etc.) that affect passage. This knowledge gap in the scientific literature warrants further investigation to discern the suitability of BDAs for future restoration and/or to improve suitable fish passage conditions. Accordingly, I quantified the ability of Coho Salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) to bypass beaver dam structures by conducting field experiments on existing BDAs and controlled hatchery experiments. All barriers tested in the field had some level of successful passage, but passage was variable. Even the smallest Coho Salmon tested in the field could pass barriers of 36.5 cm. During the early, middle, and late summer experiments, the passage rates were 76%, 73%, and 21%, respectively. Low passage rates observed during the late summer were likely affected by fish behavior and natural adaptations to low-flow environmental conditions rather than just the barriers imposed by the BDAs; these factors should be considered when evaluating BDA fish passage. Passage rates changed with short-term changes in stream flow and available passageways. In general, passage of BDAs in the field was not limited when side channels or weir flow jump points were connected and accessible to fish. During the hatchery experiments, juvenile steelhead trout were able to pass the BDA-like structures that were constructed in the Humboldt State hatchery raceway. I tested jump heights of 24 cm, 34 cm, 40 cm and 44 cm, and passage rates were 76%, 55%, 45%, and 36%, respectively. When steelhead trout were smaller (~55 mm on average), jump height had a clear impact of passage success, but the passage rates were much more similar by the end of the trials when fish were larger (~82 mm on average). Given the benefits of BDAs and the leaping ability of juvenile salmonids, a jump height of about 30 cm might be a reasonable target for ensuring BDA fish passage.

ACKNOWLEDGEMENTS

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INTRODUCTION

Salmon, Beavers, and Beaver Dam Analogues

Pacific salmon are an important cultural, economic, and ecological resource and a keystone species in many ecosystems (Willson and Halupka 1995; Quinn 2005). However, over the last century, Coho Salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) distribution and abundance has significantly declined in the Pacific Northwest largely due to anthropogenic factors related to hatcheries, harvest, hydropower and habitat (Gore and Doerr 2000). State and federal salmon and steelhead recovery plans cite restoring habitat complexity as a primary objective to promote species recovery (California Department of Fish and Game 2004; National Marine Fisheries Service 2014). Resource agencies invest millions of dollars annually on stream restoration projects that focus heavily on engineered channel modifications and anchored habitat structures (Carah et al. 2014). While these projects can be beneficial for creating habitat, they are often challenging to accomplish at the watershed scale due to their high implementation costs. For salmonid populations at risk of becoming extinct, identifying cost-effective techniques is important to maximize habitat restoration effects in as many priority watersheds as possible (Carah et al. 2014). Recently, reintroducing North American beavers (*Castor canadensis*) or creating beaver dam analogues (BDAs) have become attractive alternatives to highly-engineered projects. The beaver restoration approach is substantially less expensive than other forms of restoration and has significant potential to restore critical stream and riparian habitat for Coho Salmon, steelhead, and other fish and wildlife (Pollock et al. 2004; DeVries et al. 2012).

Beavers were once abundant in North America, but populations plummeted over the last few centuries, in large part due to fur trapping. Even after this large-scale decline, landowners often trap, kill or relocate beavers because they are viewed as a nuisance (Naiman, Johnston, and Kelley 1988). Additionally, management practices such as cattle ranching and timber harvest altered the natural state of riparian zones and ultimately prevented beaver populations from rebounding (DeVries et al. 2012). The decline of beavers led to dramatic changes in the landscape and ecosystems of the West. Beaver dams alter river morphology and hydrology. Without beaver dams to trap sediment and spread water onto the flood plains, streams began to degrade and incise (Pilliod et al. 2018). In the Stillaguamish River basin in Washington state, the loss of beaver pond habitat was associated with a reduction in Coho salmon smolt production (Pollock et al. 2004).

Researchers have posited that BDAs are a cost-effective technique used to address many aspects of stream restoration (Pollock et al. 2015; Bouwes et al. 2016). BDAs enhance habitat complexity and are generally beneficial for rearing Coho Salmon and steelhead trout (Nickelson et al. 1992; Leidholt-Bruner 1992). BDAs create slow-water pond habitats that are highly productive for vegetation and provide salmonids with food and cover (Pollock, Heim, and Werner 2003). BDAs also increase the water storage in stream channels and recharge ground water (Green and Westbrook 2009) and promote floodplain connectivity and accelerate recovery of riparian vegetation (DeVries et al.

2012). Furthermore, BDAs and natural beaver ponds can significantly increase aquatic invertebrate production, especially for benthic invertebrates that prefer slow water habitats, due to an increase in captured organic materials (Pollock et al. 2015). As a result, juvenile salmonids with access to beaver pond habitats often grow at rapid rates from abundant food resources (Malison et al. 2014; Johnson-Bice et al. 2018; Kemp et al. 2012). Historically, beaver ponds were important to maintain wetted habitat during the dry-season for streams in semiarid regions that experience low streamflow conditions (Pollock, Heim, and Werner 2003). BDAs may be able to recreate many benefits of natural beaver dams. As prolonged drought conditions become increasingly prevalent due to climate change, BDAs can provide habitat refugia for endangered fish species (Johnson-Bice et al. 2018).

Beaver Dam Analogues and Fish Passage

In the western United States, the effect of beaver dams on fish movement is still highly contested. Despite the habitat benefits, regulatory agencies have been hesitant to use BDAs as a widespread habitat restoration technique in fear that they may be detrimental to survival and migration of fish under various flow conditions (Charnley 2018). Until recently, regulatory agencies have been using 15 cm jump height passage criteria designed for other in stream restoration projects (Yokel et al. 2017). In 2001, the National Marine Fisheries Service (NMFS) set a maximum hydraulic drop for juvenile salmonids to be no greater than 15 cm (0.5 ft) (National Marine Fisheries Service 2001). In 2011, NMFS suggested the maximum hydraulic drop over a weir should be no greater than 21 cm (0.7 ft) for fish between 45 to 65 mm and no greater than 30 cm (1.0 ft) for fish from 80 to 100 mm (1.0 ft) (National Marine Fisheries Service 2011). In the Fall of 2019, with information gained from field and laboratory studies, NMFS increased the maximum hydraulic drop guidelines to 1.0 ft as a general guideline (National Marine Fisheries Service 2019). In 1998, the California Department of Fish and Game (DFG) regulations suggested that jumps over 30 cm (1 ft) should be avoided (Flosi et al. 1998), and in 2004 suggested that jump heights for juveniles should not exceed 15 cm (0.5 ft) (Taylor and Love 2004).

Fish size, stage of development, species, water velocity, and water temperature all a play role in determining how high fish can jump to pass obstacles (National Engineering Handbook 2007). A lot of research has focused on understanding jumping and swimming abilities of adult salmon and steelhead, but the abilities of juvenile salmon and steelhead trout have been studied to a lesser degree. Mueller et al. (2008) examined the ability juvenile Coho Salmon that ranged in fork length from 60-135 mm to leap into an experimental culvert with 5 jump heights ranging from 0 to 32 cm and then swim through a culvert 12.2 meters in length with slopes of up to 10%. The median success rate for the five treatments were 85% for 0-cm drop, 34% for 12 cm, 20% for 20 cm, 2% for 26 cm, and 0% for 32 cm. Symons (1978) found that Coho Salmon were better able to clear jump heights of 12 cm (32% passage rate) when compared to 20 cm (17%) and 57cm jumps (7%). White et al. (2019) concluded that juvenile steelhead less than 100 mm were approximately 20% more likely to pass a 15 cm waterfall over a 30 cm waterfall, but steelhead over 100 mm were equally likely to pass either jump height and passage success averaged over 70% (White et al. 2018). They found that fish size and water temperatures were informative predictors of passage. Pollock (2019) found that 47% of tagged juvenile Coho Salmon and 42% of juvenile steelhead trout were able to leap up a 38-40 cm waterfall and concluded that both species have little difficulty crossing BDAs.

In addition to jumping over BDAs, there are two additional passageways for juvenile salmonids could use to pass obstacles: engineered fish passage side channels and subsurface orifices. Neither of these passageways have been thoroughly researched in the context of BDAs. Established criteria related to general fish passage through stream channels could be applied to assess fish passage for side channels. The California Department of Fish and Wildlife recommends a minimum water depth of at least 9-12 cm through the riffle crest for juvenile salmonids (Hass 2017). Noonan measured channel slopes that ranged from 4.2% to 14.5% and found that channel slope was negatively correlated with fish passage (Noonan, Grant, and Jackson 2012). Pollock found that juvenile Coho Salmon and steelhead trout were able to readily pass side channels that were about 8 m long with slopes up to 11% and were embedded with cobble and gravel. To my knowledge, subsurface fish passage through orifices has not been researched and it is not currently considered a valid method of volitional fish passage, as passage requirements usually pertain to jump height, and side channel slope and roughness. When describing general criteria and guidelines for upstream juvenile passage, NMFS states that juvenile Coho Salmon have adequate swimming and jumping abilities such that submerged passageways should be avoided when designing passage facilities for juvenile salmonids (National Marine Fisheries Service 2011). NMFS suggests using jump points or side channels and avoid the use of submerged ports or pipes to allow for fish passage. However, depending on the construction and materials used to build beaver dams and BDAs, structures may be permeable enough to allow juvenile fish passage through subsurface holes rather than using weir crest jumps or fish passage side channels.

Several studies have highlighted the ability of many species to pass beaver dams (Gard 1961; Snodgrass and Meffe 1998), while other studies have indicated that beaver dams can act as barriers for salmonid passage at various life stages or that passage is dependent on stream flow (Mitchell and Cunjak 2007; Collen and Gibson 2000). Some researchers have suggested that species that make their adult migration during the fall, such as Atlantic salmon, may be impeded more frequently by beaver dams due to low-flow conditions (Müller-Schwarze and Sun 2003). During their research, Müller-Schwarze and Sun (2003) only found Atlantic salmon redds above a large beaver dam (30 m long by 2 m high) during one high-flow year of the three-year study period. Another study compared two similar streams, one with beaver dams and another without, found that beaver dams limited the stream connectivity for juvenile salmon and therefore reduced the overall biomass production by as much as half (Malison, Kuzishchin, and Stanford 2016). However, a 2018 study reviewed over 150 scientific papers on the salmon-beaver relationship and found a paucity of empirical studies on the effect of beaver dams on fish movement, suggesting more research is needed (Johnson-Bice et al. 2018). Additionally, another meta-analysis from 2012 found 51 citations of beaver dams acting as a barrier to fish passage, highlighting that 22% of the studies were data-driven while 78% were speculative (Kemp et al. 2012). The authors of this analysis also advocated for more intensive research using both controlled and field-based empirical research (Kemp et al. 2012).

In 2017, the Scott River Watershed Council (SRWC) conducted a pilot study to explore if BDAs were a barrier to displaced YOY salmonids using passive integrated transponder (PIT) tags in the Scott River watershed. SRWC found that 54% of young of the year (YOY) steelhead trout and 91% of YOY Coho Salmon were able to move past a series of BDAs over the a 21-day field experiment (Pollock, Witmore, and Yokel 2019). SRWC were documented passing the BDAs by using active side channels or by making leaps of up to 40 cm (Pollock, Witmore, and Yokel 2019). SRCW assessed route preferences based on jump height and hydraulic properties. They conducted an additional experiment without displacing salmonids and they showed little motivation to move upstream. It is important to note that 2017 was an above average water year in the Scott River, which could have contributed to the high passage rate. The researchers also only assessed fish passage on the upper two BDAs and did not assess fish passage on the lowest BDA. Furthermore, in the field it is not possible to distinguish between a fish's inability to pass the BDA from a fish's behavioral decisions to seek habitat elsewhere. The limited range of field conditions, including BDA characteristics, water depth, fish presence, and fish motivation is a limitation to the field experiments. Additional concerns about fish behavior, beaver dam dimensions and other environmental factors warrant further investigation and provides cause for further field experiments and additional controlled hatchery experiments.

In order to assess the knowledge gap, I evaluated the extent to which beaver dam analogues act as a barrier to juvenile Coho Salmon and steelhead trout movement by conducting field experiments on preexisting BDAs and controlled hatchery experiments. I measured factors associated with passage such as velocity, dam permeability, water temperature, fish size and species, as few studies have examined how these factors may affect juvenile salmonid passage of beaver dams. These findings will inform future implementation efforts and address permitting concerns for BDAs.

METHODS AND ANALYSIS

Study Site

Scott River

The Scott River is a major tributary to the Klamath River in Western Siskiyou County (Figure 1). The Scott River watershed encompasses approximately 2,105 square kilometers and the headwaters start in the Marble Mountains (Yokel et al. 2017). The two field study sites, Miners Creek and Sugar Creek, are located near the town of Etna in the upper Scott River watershed, approximately 120 km north of Weaverville and 50 km south of Yreka on Highway 3.

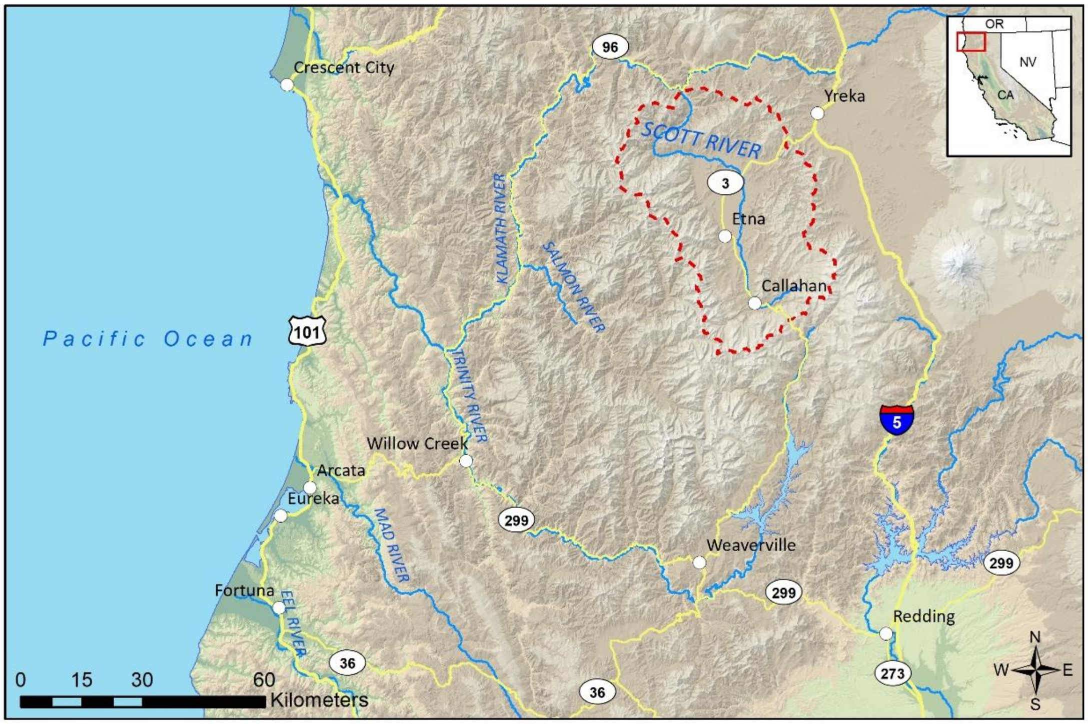

Figure 1. The Scott River watershed, highlighted by the dashed red line, is located in Northern California. The Scott River flows from south to north and empties into the Klamath River (*ESRI* (version 10.3) 2015).

The combination of the human land use activities and the natural environment make the Scott River watershed a unique environment. The major industries in the watershed include agriculture, timber, cattle, and recreation. Alfalfa is the primary crop grown in the valley and is highly dependent on irrigation (Yokel et al. 2017). The precipitation in the watershed is highly variable from year to year (Yokel et al. 2017). The valley receives approximately 56 cm of rain annually, while the surrounding mountains receive anywhere from 75-180 cm of precipitation annually (Yokel et al. 2017). Flow in the Scott River watershed is dependent on the winter snowpack. Much of the sediment in the watershed is highly permeable which promotes connectivity between surface and ground water. High sediment permeability also means that it is typical for tributaries to the Scott to flow subsurface in summer months (Yokel et al. 2017).

The Scott River watershed has been significantly altered since the early 19th century due to the decimation of the beaver populations and intensive gold mining. The Scott River Valley was originally known as Beaver Valley due to the prolific beavers that once occupied the watershed (Yokel et al. 2017). Similar to much of the West, the number of beavers in the Scott River dwindled in the early 19th century "California Fur Rush" which led to excessive trapping and soon after, the population of beavers dropped to approximately 1000 individuals in the entire state (Lundquist 2016). After the "California Fur Rush" came the gold rush, and its effects on the landscape are still evident in the upper Scott River watershed in the form of large mine tailings piles (Figure 2). The lack of beaver dams and increase of mine tailings changed the natural hydrologic connectivity between surface water and groundwater and as a result, changed the watershed from a wetted marshy valley to a single-channel intermittent stream (Yokel et al. 2017).

Figure 2. Gravel tailings extend along about 6 kilometers of the mainstem Scott River just downstream of the town of Callahan. The gravel tailings left over from the gold rush can be seen encroaching on the Scott River. (Image source: Foglia et al. 2018).

Additionally, the watershed was altered by land management practices that straightened, cleared and leveed sections of the waterways for agriculture and flood mitigation (Yokel et al. 2017). Large rip rap was placed along stream banks for stabilization and to prevent lateral stream erosion. In the early 1990's, agencies began to participate in stream restoration efforts and implement cattle fencing to help maintain riparian vegetation (Yokel et al. 2017).

Coho Salmon in the Scott River are part of the Southern Oregon Northern California Coast Evolutionarily Significant Unit (SONCC ESU) and are listed on state and federal Endangered Species Acts. The Scott River is considered to be the most important Coho Salmon stream in the Klamath Basin (Van Kirk and Naman 2008). The anthropogenic stressors on Coho Salmon in the Scott River are agricultural land development, historic mining activity, dams, water diversions, marijuana cultivation, poor logging practices, and historic overfishing (National Marine Fisheries Service 2014). Naturally occurring stressors such as drought, floods, predation, wildfires and poor water quality have increased due to anthropogenic factors and have also exacerbated the population decline of Coho salmon (California Department of Fish and Wildlife 2018). The Scott River Coho Salmon population is significantly affected by low seasonal streamflow, which is why restoration techniques, like BDAs, that increase dry-season water quantity and quality, have been implemented in the watershed (Oliver and Gallaudet 2017). One of the main reasons for the decline of Coho Salmon populations in the Scott River is due to low surface flows, especially during irrigation season (Olswang 2015). In 2015, CDFW noted that real beaver dams may have been a temporary barrier to juvenile fish during low-flow periods (Olswang 2015).

With permission from regulatory agencies, the Scott River Watershed Council (SRWC) started installing BDA structures in 2014 on tributaries to the Scott River. The BDAs were strategically placed on Sugar and Miners creeks, which are primary salmon-bearing tributaries. The SRWC found that biological and physical habitat conditions improved with the BDA structures and the overall habitat available to juvenile salmonids significantly increased (Yokel et al. 2017).

Miners Creek

Miners Creek is a small tributary to French Creek, which flows into the Scott River (Figure 3). At about 900 m above sea level, the BDA restoration site is located about 0.3 km upstream of the confluence with French Creek.

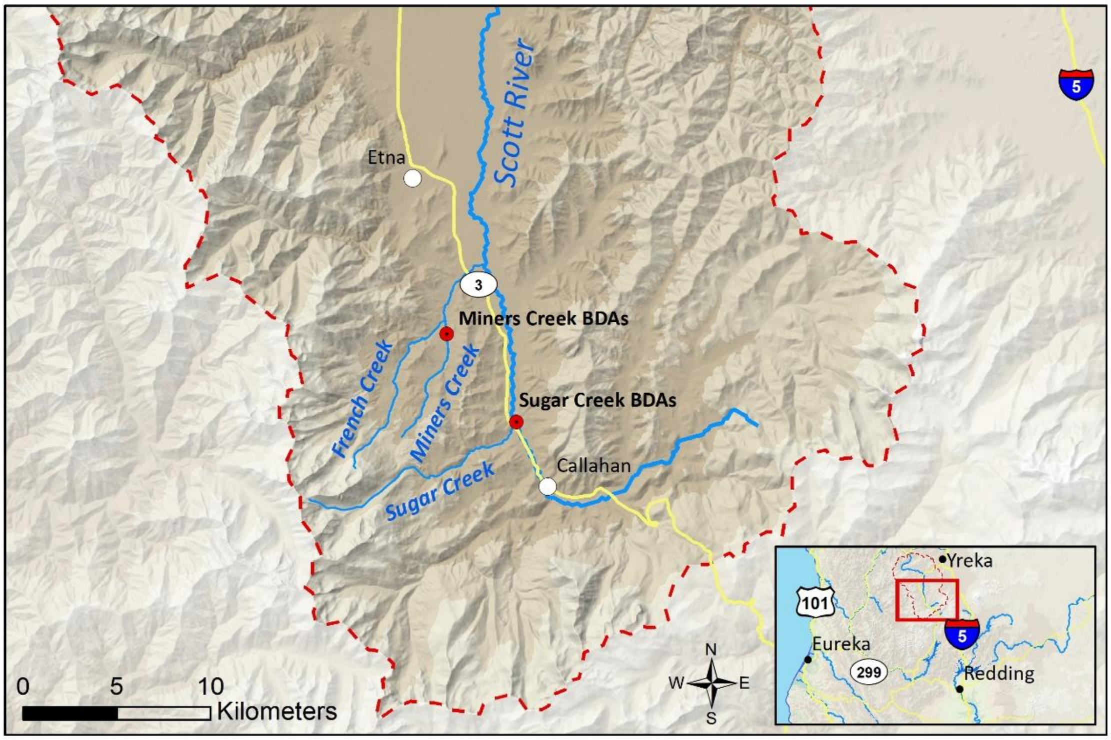

Figure 3. The BDA restoration sites on Miners Creek and Sugar Creek are in the southern portion of the Scott River watershed and are indicated on the map with the red circles. The Miners Creek site is approximately 0.3 km upstream of the confluence with French Creek. The Sugar Creek site is situated just upstream of the confluence with the mainstem Scott River and just downstream of the State Route 3 overpass bridge (*ESRI* (version 10.3) 2015).

Due to the stream having a large amount of decomposed granite, low stream flows and the preference of Coho Salmon to spawn in the creek, Miners Creek has been a challenging site for restoration. Adult spawning surveys during the winter indicate that

Coho Salmon regularly spawn in Miners Creek, despite suboptimal rearing conditions for their offspring in the summer (Yokel et al. 2017). In most years, the creek goes subsurface during the early summer months as natural flows begin to subside and the agricultural demand for water increases (Yokel et al. 2017). The SRWC started creating BDA structures in Miners Creek to try to increase water quantity and quality for rearing Coho Salmon (Yokel et al. 2017). A series of BDAs were installed in Miners Creek in the Summer of 2015 (Figure 4) and resulted in ~10 acres of slow-velocity winter rearing habitat for juvenile Coho Salmon and steelhead trout (Oliver and Gallaudet 2017). However, the site of the BDA installations has very porous alluvium and limited natural beaver activity (Yokel et al. 2017), and as a result, the BDAs drain relatively quickly, and the ponds have begun to aggrade with decomposed granite. In 2017, the SRWC was able to complete repairs to the BDAs to increase water storage, but the ponds have continued to dry in subsequent summers (Yokel, personal communication, June, 2019).

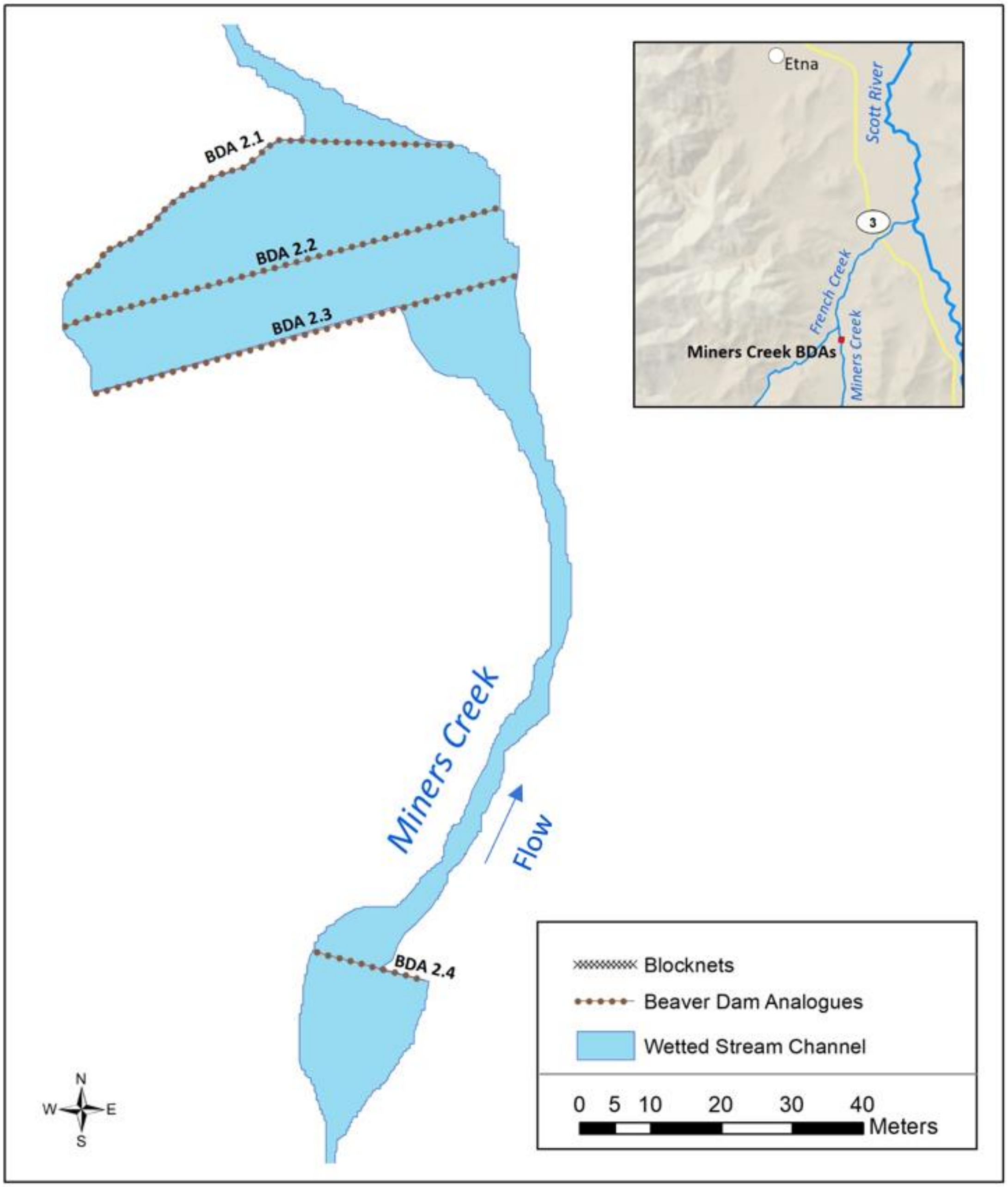

Figure 4. Map of the Miners Creek BDA restoration site where the early season passage experiments were conducted in the summer of 2019. Flow goes from the south to the north, and the confluence with the French Creek is approximately 0.3 km north of the map extent.

Sugar Creek

The lower section of Sugar Creek empties into the Scott River through a dredged channel of mine tailings that cover the Scott River floodplain for several miles (Harter and Hines 2008). The BDA restoration site is located on Sugar Creek just upstream of the confluence with the Scott River (Figure 2) at the elevation of approximately 915 m above sea level. The streambed is made up mostly of tailings cobbles and decomposed granite. The BDA site receives subsurface flow from the mainstem Scott River through the mine tailings, which provides cool water inputs into the restoration ponds (Yokel et al. 2017).

In 2014, two primary BDA structures were created on Sugar Creek (BDA 1.0 and BDA 2.0). In 2017, an ancillary side channel structure was added onto the river-left side of BDA 1.0, in addition to two "step" BDAs just downstream of BDA 1.0 (BDA 1.1 and BDA 1.2). The focus of the 2019 passage experiment was on the lower BDAs (1.0, 1.1, and 1.2). The ancillary side channel BDA, also referred to as the wing dam, was added to promote the retention of water in the upper pond and was needed due to the formation of a river-left side channel. The two "step" BDAs were added to prevent downstream scour that could damage the structure (Yokel et al. 2017) and to enhance fish passage by creating a series of BDAs "steps" with smaller jump heights. All three BDAs in the main channel have fish passage side channels that were created to improve fish passage when water level upstream of the BDAs is sufficient to activate the side channels. During the summer 2019 low-flow conditions, only BDA 1.0 and BDA 1.2 had active fish passage side channels (Figure 5 & Figure 6). The side channels are short (3-4 m), high gradient (8-11%) channels with increased channel roughness to decrease water velocities. The only BDA with a jump point with weir flow over the top of the structure was BDA 1.1, where the jump height was approximately 38 cm.

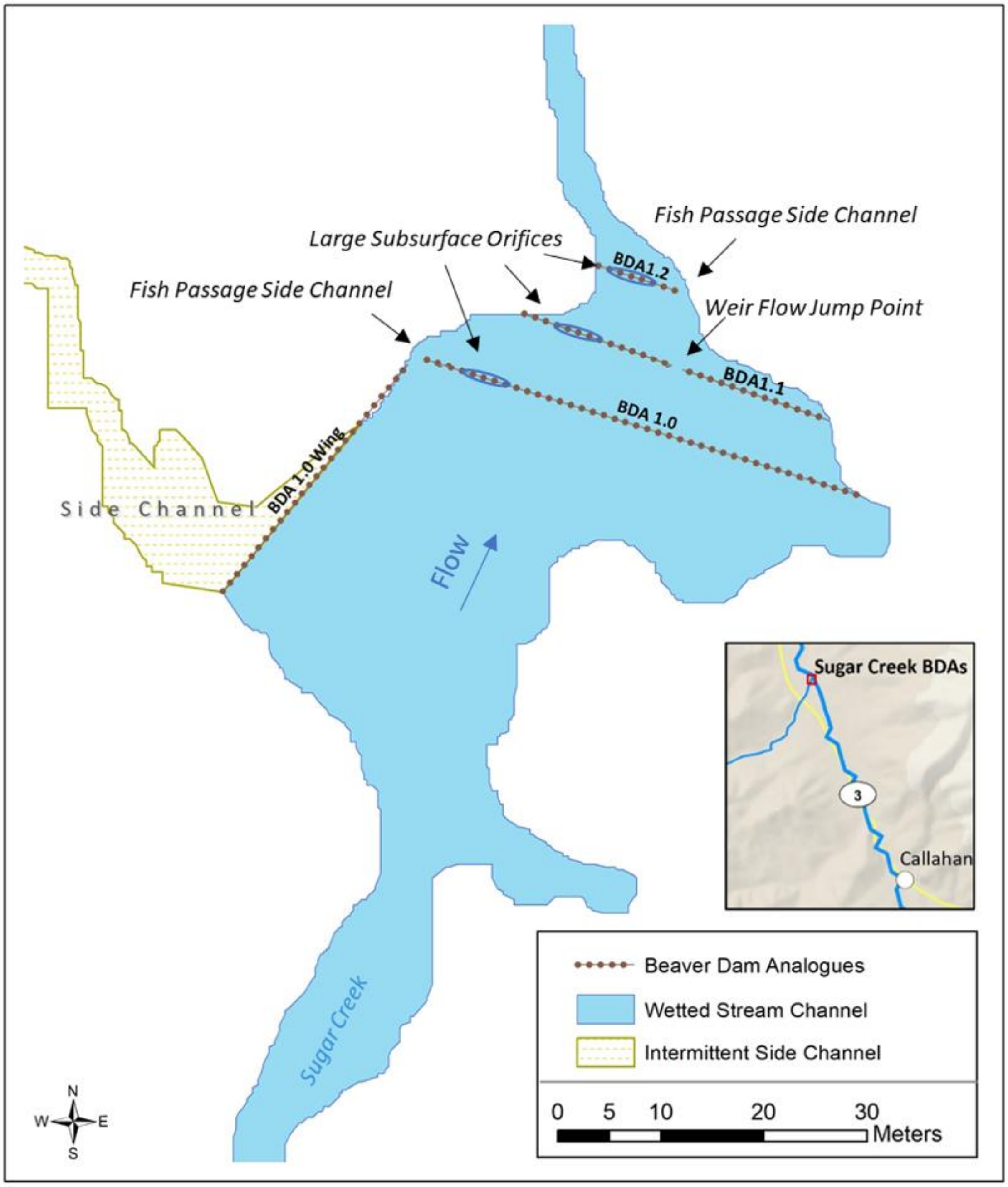

Figure 5. Map of the lower end of the Sugar Creek BDA restoration site where the passage experiments were conducted in the summer of 2019. The BDAs and the primary suspected passage pathways are identified by arrows. Flow goes from the south to the north, and the confluence with the Scott River is approximately 30 m north of the map extent.

Figure 6. Photograph (looking upstream) of the three lower Sugar Creek BDAs taken on August 9th, 2019.

All three of the BDAs installed in the main channel of Sugar Creek had large sections of subsurface flow due to orifices in the dam structures where the finer clay and straw material had washed away. The subsurface passageway length and slope varied between BDAs. On BDA 1.0, the approximate horizontal distance between the upstream hole and its downstream outflow was approximately1.2 meters and had about 0.7 meters vertically relief. BDA 1.1 featured orifices that flowed directly from the upstream pool unit to the downstream pool unit with no change in elevation. The approximate width of BDA 1.1 at the orifices was 0.4 meters and with a snorkel mask, a diver could see through BDA 1.1 into the adjacent habitat unit. The upstream to downstream width of

BDA 1.2 near the orifices was approximately 0.4 meters and the relief between the orifice inflow and outflow was approximately 0.5 meters.

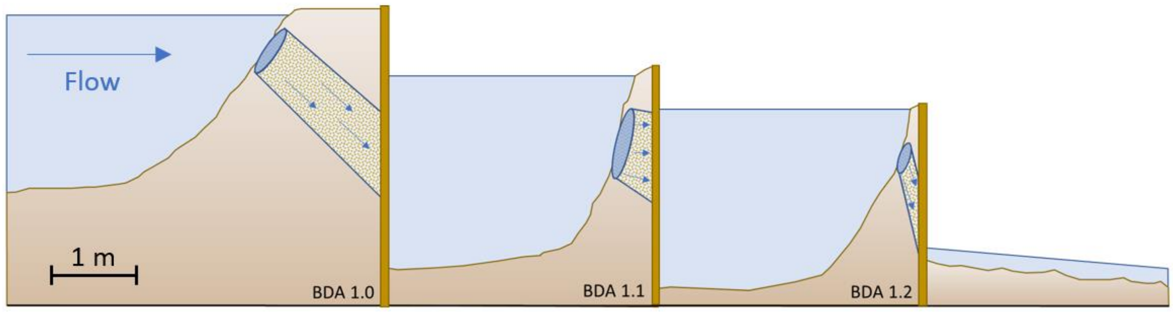

Figure 7. A cross-sectional cartoon representation of the Sugar Creek BDAs at the location of the large subsurface orifices. This diagram displays the differences in BDA widths and the variation in subsurface flow passageway slopes. The cross-sectional view is based on field measurements of the BDAs near the subsurface orifices. Note, pathways inside the BDAs are not straight, open tubes but are complex pathways filled with sticks, straw, and rocks.

The construction and materials that were near the orifices of the three BDAs varied. BDA 1.0 was much wider from upstream to downstream compared to the other two BDAs and had a mixture of decompose granite, straw, and clay near the orifices. BDA 1.1 was narrow near the orifices and had a thin wall of only sticks and straw separating the two habitat units. BDA 1.2 was also fairly narrow but had more large-cobble and clay lining the upstream wall of the BDA.

The BDAs on Sugar Creek helped to retain flow during summer low-flow months at the restoration site that previously often ran dry. Aquatic habitat, groundwater, and stream temperature conditions have also significantly improved since the addition of the BDA structures (Charnley 2018). Beavers have been very active at the Sugar Creek site, where they have been observed maintaining and modifying BDAs.

The accumulated precipitation in 2019 for the Scott River was 52.8 cm, which was slightly less than the 82 year average of 54.4 cm, but the April 1 snowpack was approximately 134% of average (Department of Water Resources 2021). In 2019, the precipitation and stream flows in Sugar Creek were about average when compared to recent water years (Figure 8).

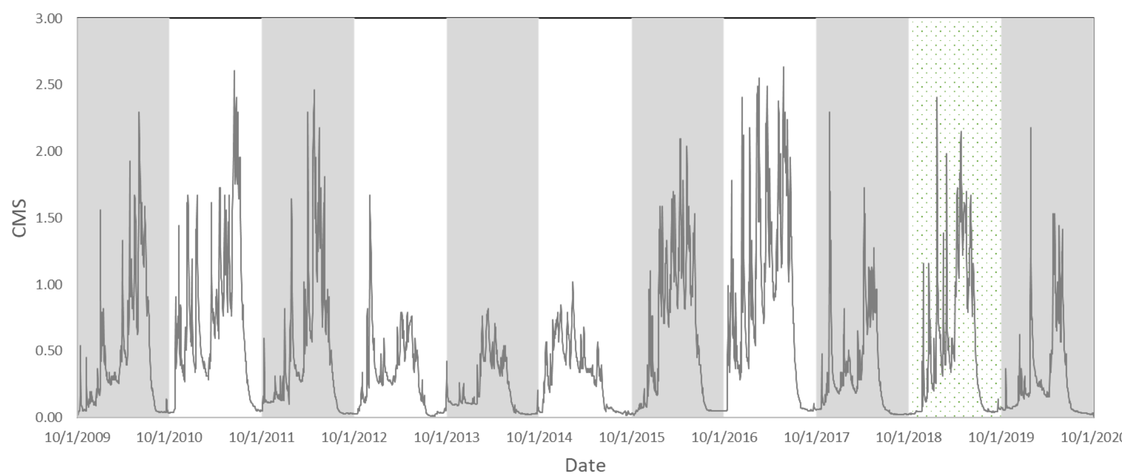

Figure 8. Eleven years of continuous stream discharge data reported in cubic meters per second from the Sugar Creek gage near Callaghan, CA (California Department of Water Resources Gage station number F25890). The area with small green dots in in background (second panel from the right) indicates the 2019 water year when I completed the field passage experiments in the Scott River watershed for this study.

The first low-flow passage experiment was completed at the tail end of the snow-melt runoff period where Sugar Creek was still dropping into baseflow conditions (Figure 9). The second Sugar Creek experiment was conducted at base flow and discharge was approximately 0.05 cubic meters per second (CMS)(Figure 9). During July through September of 2019, I also recorded flow measurements below BDA 1.1 (Figure 10).The precipitous drop in flow that occurred below the BDAs during the first experiment was probably caused by the repairing of BDA 1.0 that resulted in the upstream pond storage refilling and increasing water flow through the porous cobble tailings as the pond refilled rather than flowing down the main channel below BDA 1.0 (Figure 10).

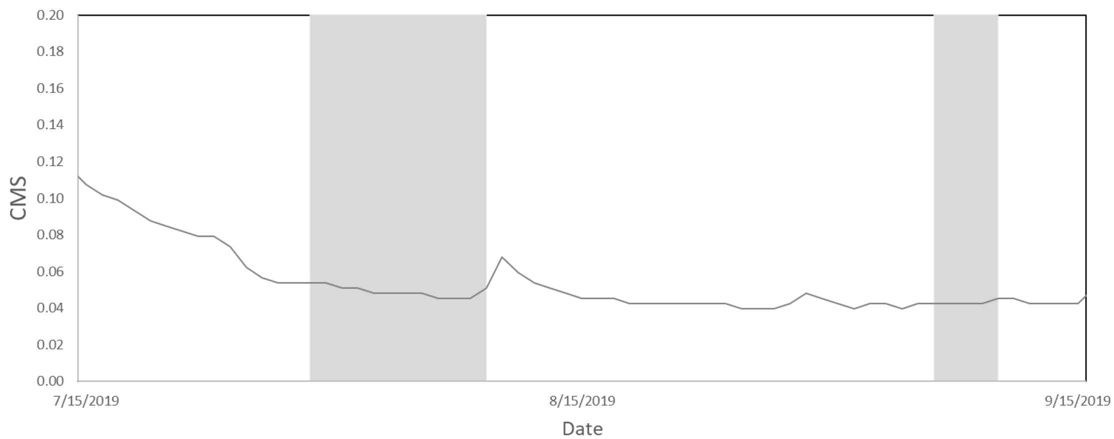

Figure 9. Continuous stream discharge data reported in cubic meters per second from the Sugar Creek gage near Callaghan, CA (California Department of Water Resources Gage station number F25890) for the summer of 2019. The shaded areas indicate the timing of the experiments that were completed on Sugar Creek. The Y-axis was adjusted in this plot to display the variation in baseflow conditions.

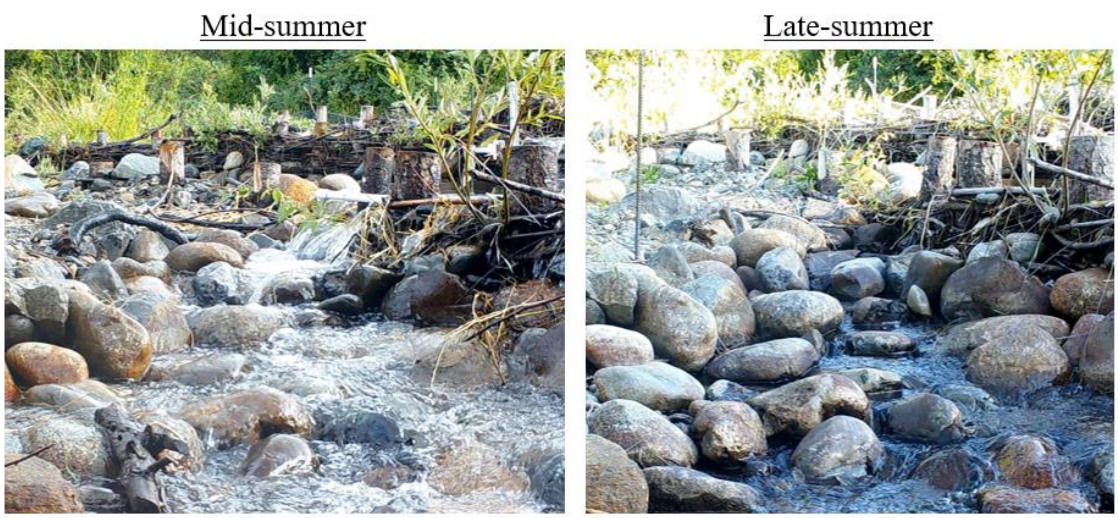

Figure 10. Downstream of BDA 1.2 looking upstream at the fish passage side channel. The flows going through the BDAs and through the side-channels were notably higher

during the mid-summer experiment (July/August) in the photo on the left compared to the late-summer experiment (September) in the photo on the right. Photo on the left was taken August 2, 2019 and the photo on the right was taken September

Field Methods

The general method for field experiments on Miners Creek and Sugar Creek followed a consistent approach. I collected juvenile fish by seining and minnow trapping, marked them with tags or fin clips, and relocated them immediately below BDAs. I placed block nets just downstream of BDAs to prevent downstream escape. Fish that intended to disperse had to attempt to pass the BDAs in an upstream manner. Subsequent recapture efforts above the BDAs, using tag antennas and in-hand capture efforts, allowed me to estimate the number of fish that crossed the structure. All fish handling was conducted using methods approved by the Humboldt State University Institutional Animal Care and Use Committee (IACUC) under protocol number 17/18.F.75-A.

I conducted three separate sets of experiments. The first set included four trials designed to assess BDA passage by small (<65 mm) Coho Salmon that were too small to mark with PIT tags (sub-taggable). This trial was completed from June 17th through June 21st, 2019 on BDAs in Miners Creek. These early summer passage experiments used caudal fin clips as marks and in-hand recaptures to evaluate passage. The second and third set of experiments were designed to evaluate fish passage during base-flow conditions with PIT tags implanted in Coho Salmon >65 mm. These summer low-flow passage experiments were completed from 07/31/2019-08/09/2019, and 09/06/2019-09/09/2019, and both trials were completed on Sugar Creek BDAs.

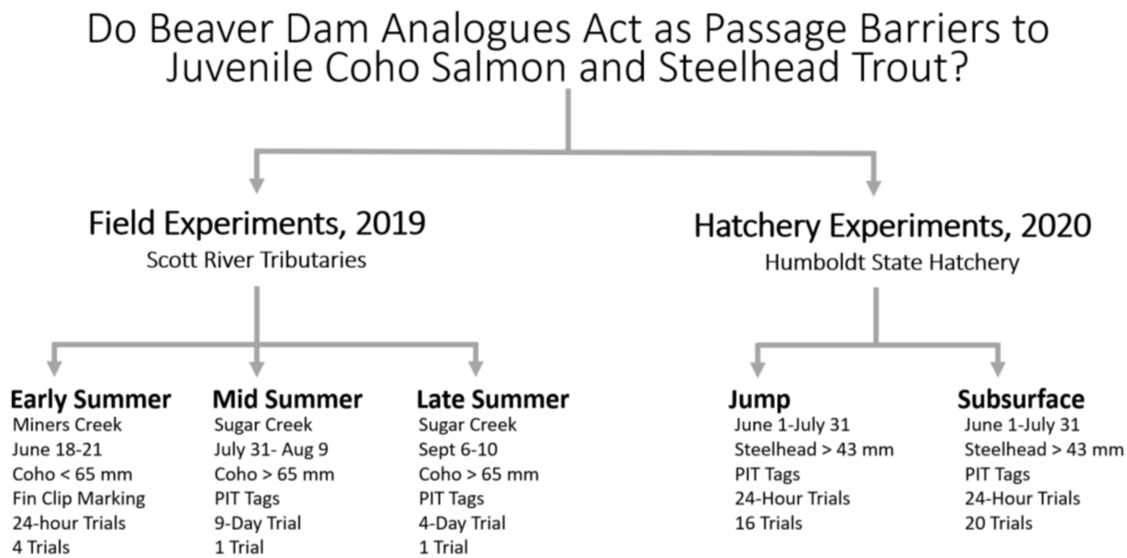

Figure 11. Tree diagram provides an overview of the field and hatchery experiments, the general timeline, and the major differences between the trials.

Flow and Temperature Measurements

Stream discharge was measured using a SonTek Flowtracker Handheld 2D Acoustic Doppler Velocimeter. An Onset HOBO Water Level Data Logger (U20L-04) was used to monitor continuous stream height on French Creek and Sugar Creek during the field experiments. For the French Creek experiment, rating curve was developed using the discrete flow measurements, and used with the stream height data to calculate continuous stream discharge.

Beach Seines

Beach seines approximately 15 meters in length and 1.5 meters high with 3 mm nylon mesh and with lead weights and float lines were used to capture juvenile salmonids

(Figure 12). Beach seines were used in areas where fish were observed rearing that have moderate to shallow depths, very low velocity and little debris or structure. Consecutive seine hauls were conducted at each sampling location. The seine was set by 2-3 crew members in a round haul fashion by fixing one end of the seine on the bank while the other end is deployed wading upstream and returning to shore in a half circle. All fish captured in the seine were kept submerged in the water until they were transferred to holding containers. Fish from each bag of each haul were placed in an aerated 5-gallon buckets prior to processing (<30 minutes). No seining occurred if water temperatures exceeded 20 C.

Figure 12. Beach seines were used to capture Coho Salmon and steelhead trout during field experiments. Photo was taken on 08/09/2019, and is looking across the channel toward the river-left bank. Field crew was seining the habitat unit between BDA 1.1 and BDA 1.2.

<u>Minnow Traps</u>

Galvanized wire mesh minnow traps (46 cm x 30 cm x 96 cm, 5 mm square mesh, 2.5 cm openings) were set out with sterilized salmon roe as bait (Figure 4). Traps were left to soak overnight on the evening proceeding the experiment (approximately 16-18 hour set time). A maximum of 20 traps at each sampling location were set next to habitat structures or locations with observed fish to maximize catch rates. Traps were also used during passage experiments and were placed above the test BDA to recapture sub-taggable (<65 mm) salmonids (Figure 13). Fish captured in the traps were transferred to aerated 5-gallon buckets for holding until processing (< 30 minutes). Minnow traps were not set if water temperatures exceeded 20 C.

Figure 13. Minnow traps were used during the early summer experiments to capture sub-taggable juvenile salmonids. Photo taken on 06/19/2019 from above Miners Creek BDA 2.4 and looking across the channel towards river-left.

Fish Processing in the Field

All captured fish were identified by species and enumerated. Non-salmonids were released. Captured salmonids were anesthetized with CO_2 using Alka-Seltzer Gold tablets (aspirin free), which was the only anesthetic approved on the SRWC permit. Once fish reached the appropriate level of anesthesia, they were measured and weighed. Salmonids used for the Miners Creek experiments were marked by applying a small lower caudal fin clip. Salmonids used for the Sugar Creek experiments with fork lengths greater than 65 mm and mass greater than 3 g were scanned for a PIT tag. Salmonids greater than 65 mm and without a tag were implanted with a pre-loaded 12 mm PIT tags using the Biomark MK25 implanter. Fish were permitted to recover in aerated buckets and were released once normal behavior was resumed. Temperature in the aerated recovery buckets was maintained within 3° C of the stream temperature using frequent water changes or re-freezable ice blocks.

Early Summer Passage Methods

From June 18-21, 2019 I conducted four passage experiments on the Miners Creek BDAs to assess early summer passage of sub-taggable juvenile Coho Salmon and steelhead trout (<65 mm). Block nets, approximately 15 m in length and 1.5 m high with 3 mm nylon mesh, were placed above and below BDA structures to keep fish confined to the study areas (Figure 14). Juvenile Coho Salmon and steelhead trout marked with a small lower caudal fin clip (Figure 15) were released below the BDAs. Due to the high rate of escape of the steelhead trout from the study area, they were omitted from the analyses for the early summer passage experiment. Fish were given one overnight period to pass the structures (~22 hours). The target sample size for each experiment was 50 Coho Salmon, but that target was not met for three of the four trials due to challenges obtaining fish. For trials one through four, sample sizes were 20, 25, 47, and 50 Coho Salmon individuals, respectively. Minnow traps were placed in the upstream habitat unit to reduce fish movement back downstream once they passed. Minnow traps were not placed in the lower habitat unit due to concerns that fish would become temporarily confined and would be less likely to pass the structure.

Figure 14. Experiment setup on Miners Creek BDA site 2.4. Block nets were set up above and below BDA structure to keep fish confined to the study area. Photo taken on 06/18/2019 from below Miners Creek BDA 2.4 and looking upstream and across towards the river-right bank.

Figure 15. Sub-taggable sized juvenile Coho Salmon with lower caudal fin clip to identify as recapture.

In 2019, when the passage experiments were conducted, there were a total of four functioning BDA structures in the lower Miners Creek watershed (Figure 16). There was no difference in water surface elevation above and below BDA 2.2, it had clear connectivity between above and below habitat units, and did not pose as a passage barrier. The remaining three BDAs (2.1, 2.3 and 2.4) did not have a side channel for fish passage, and the only visible way for fish to pass was to jump between 20 cm and 37 cm at the spill point. Experiments were conducted on the three BDAs that required fish to leap in order to pass. Experiments started by releasing juvenile Coho Salmon into the downstream habitat unit between 9 and 11 am from June 18-21, 2019.

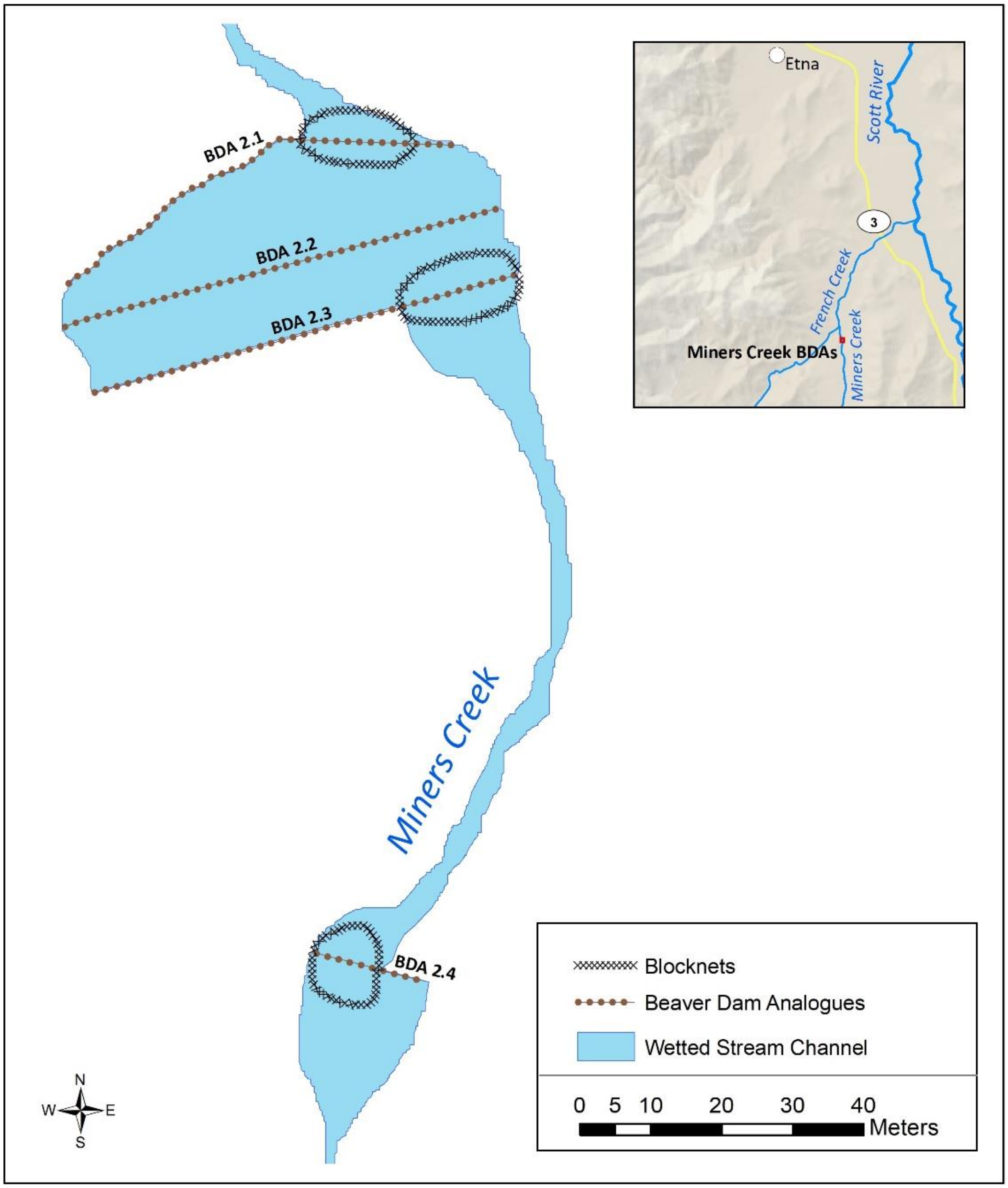

Figure 16. Map of the Miners Creek restoration site. The creek flows from south to north, and the site is situated approximated 0.3 km upstream of the confluence with French

Creek. This image depicts the BDAs and how the block nets were set up during the experiments.

At the end of the 22-hour period, a block net was placed on the upstream side of the BDA on Miners Creek to prevent further fish movement over the BDA during the recapture effort. Fish were removed from the minnow traps and placed in aerated buckets to be processed. The remainder of the fish were captured by depletion seining, involving repeated seine pulls until a minimum of three seine pulls all resulted in no captures. Recapture location (i.e., above or below BDA) was recorded along with the weight and length for each fish. Physical and environmental data were collected for each trial which included jump height, plunge pool depth, spill crest depth, spill crest width, velocity at crest, stream discharge, dam permeability, and water temperature (Table 1).

Table 1. Definitions and units of physical and environmental variables measured during the Miners Creek BDA fish passage experiments.

Variable	**Definitions**
Jump Height	Vertical distance from the water surface elevation of the lower pool to the water surface elevation of the upper pool (cm)
Plunge Pool Depth	Maximum pool depth in the vicinity of the jump location (cm)
Spill Crest Depth	Maximum water depth at the spill crest thalweg (cm)
Spill Crest Width	Wetted width of the spill crest (cm)
Velocity at Crest	Speed of the water at the spill crest thalweg (m/s)
Stream Discharge	Stream flow measured at the designated flow station (m^3/s)
Dam Permeability	Visual estimate of water seeping through vs overtopping the structure (0-33%, 33-66%, 66-100%)
Water Temperature	Water temperature in downstream habitat unit (°C) taken around 9 am

Two planned passage experiments were aborted as stream flows dropped and BDAs were clearly not passable. On 06/17/2019, an experiment was set up on Miners Creek BDA 2.3, but flow dropped precipitously throughout the morning, and as a result the experiment was not carried out (Figure 17). The same situation occurred on Miners Creek BDA 2.1 on 06/18/2019 (Figure 18). On the morning of 06/18/2019, the upstream habitat units began to reconnect and throughout the remained of the experiments, flow conditions improved significantly (Figure 19). There was no precipitation over the course of these experiments. Changes in flow were likely associated with anthropogenic influence.

Figure 17. Disconnection at Miners Creek BDA 2.3 on 06/17/2019. The photo was taken from the lower habitat unit facing upstream. Experiments were not conducted due to the clear lack of passage as a result of low stream flow. Additionally, I did not want to jeopardize fish survival by placing them in an enclosed netted area with poor water quality.

Figure 18. Disconnection at Miners Creek BDA 2.1 on 06/18/2019. The photo was taken from the below the BDA facing upstream. Experiments were not conducted due to the clear lack of passage as a result of low stream flow.

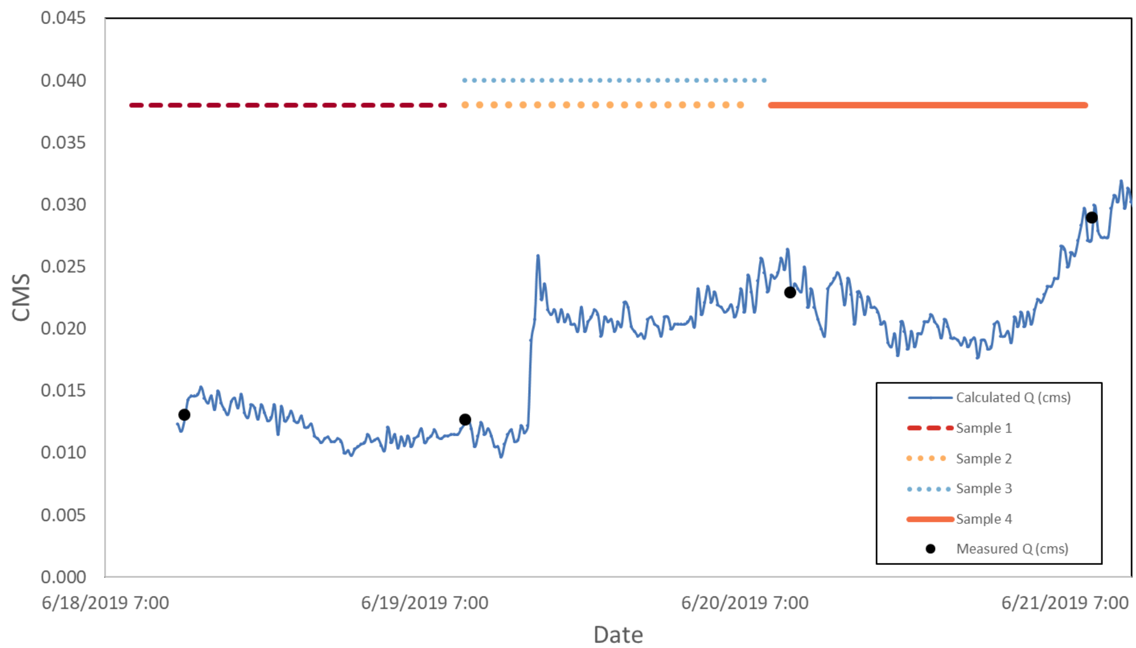

Figure 19. Stream discharge in cubic meters per second (CMS) during the Miners Creek passage experiments. The horizontal bars indicate the timing of the experiments that were completed. This figure does not include the low-flow conditions that were observed on 06/17/2019. The discharge measurement site was located at the top of the study area about 50 meters upstream of Miners Creek BDA 2.4.

Early Summer Passage Analysis

I built a random effects logistic regression model using R package lme4 (Bates et al. 2015) with fork length as the fixed effect and trial as a random effect. Fork length was standardized to improve model convergence. For this analysis, passage outcome was based only on recaptured fish since the outcome of the uncaptured fish was unknown. In summary tables, I calculated the passage rates of fish based on both the total number released and the number that were recaptured. Additional predictors of passage were not included as predictor variables due to the limited number of trials during this effort. However, I examined the environmental conditions for each trial in relation to the passage rate to generate post-hoc hypotheses based on patterns in the data.

Summer Low-Flow Passage Methods

From July 31-August 9, 2019, and again from September 6-10, 2019, I conducted experiments on Sugar Creek BDAs to assess passage of taggable juvenile Coho Salmon during summer low-flow conditions. For both experiments, juvenile Coho Salmon ≥65 mm were tagged with 12 mm PIT tags and released between the lowest BDA (1.2) and a downstream block net (Figure 20). T-posts, zip ties, and 15 m rolls of 1.25 m tall 3.1 mm square polyethylene cage netting were used to create the block nets below the lower Sugar Creek BDA (1.2). The same materials were also used to create a funnel through an antenna above the upper Sugar Creek BDA (1.0).

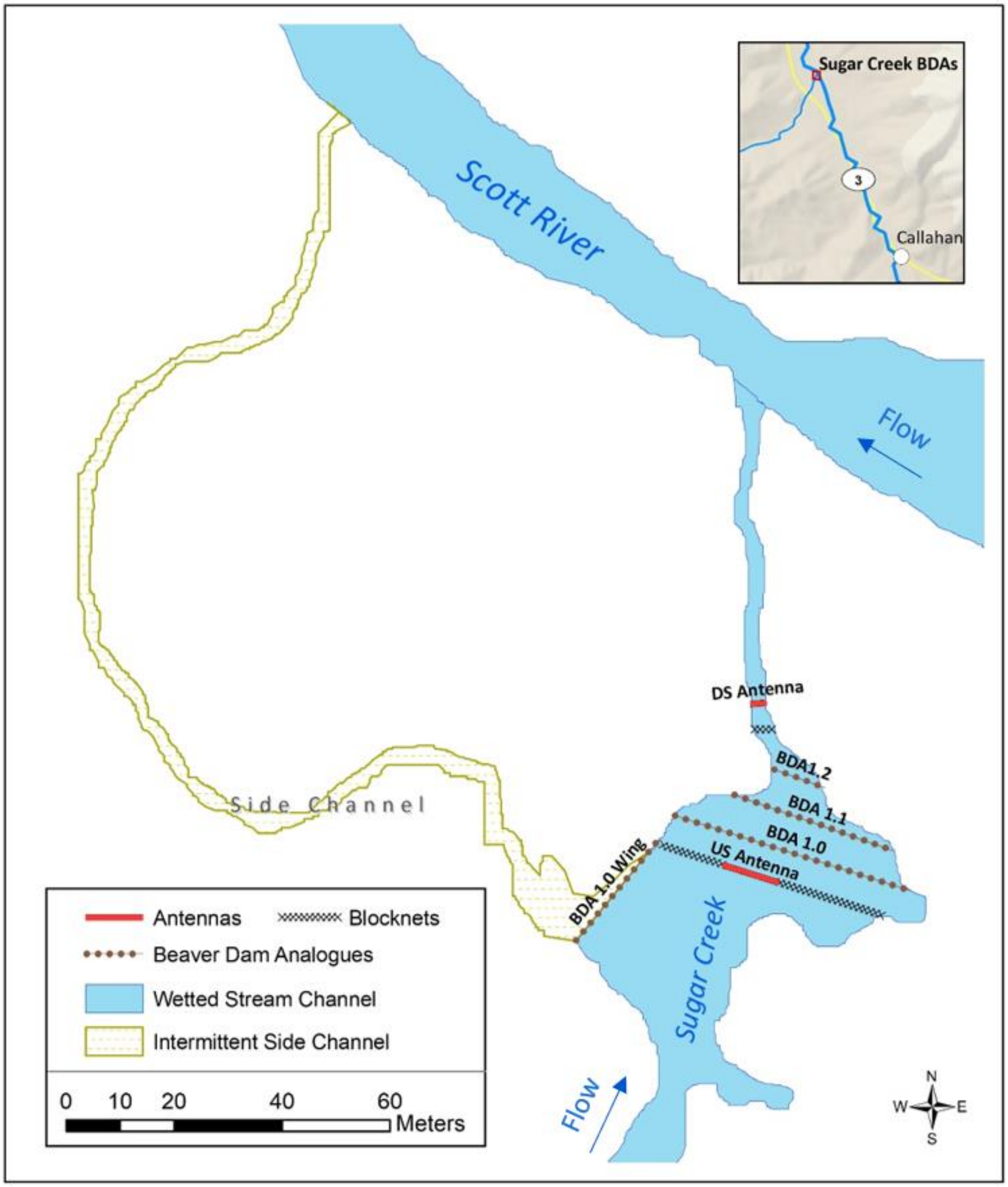

Figure 20. Map of the lower end of the Sugar Creek BDA restoration site where the passage experiments were conducted. Fish were released between BDA 1.2 and the downstream (DS) block net. The fish that passed upstream through the BDAs were funneled through an upstream (US) antenna with block nets.

Antennas and wanding surveys were used to document fish movement and passage. Two stationary 3 m x 1 m pass-through Biomark antennas were used to document fish movement above and below the BDAs (Figure 22). One antenna was placed about 5 meters below the downstream net barrier to document fish that escaped the experiment downstream. The other antenna was placed about 5 meters above BDA 1.0 and netting was used to funnel the fish through the antenna to document fish that passed the series of Sugar Creek BDAs. Paired PIT tag wanding surveys were completed throughout the experiments to collect movement data of the tagged fish between the habitat units (Figure 21). Wanding surveys were opportunistically conducted about every other day during the July-August 2019 experiment and every day during the September 2019 experiment. Each wanding survey involved one sampler working through every habitat unit a total of three times: up through the unit, back down, and once again back up; this was done to increase the probability of detection. Once the first sampler completed the survey, it was immediately followed by a second sampler with the same protocols. Single-pass shed-tag surveys were completed at the end of the experiments to identify tags that might have been shed or fish that may have died.

Figure 21. Wanding survey at Sugar Creek BDA restoration site, where the wand was used to detect PIT tagged Coho Salmon. Photo taken on 08/01/2019 facing downstream just upstream of Sugar Creek BDA 1.2.

Figure 22. The 3 m x 1 m Biomark antenna installed above Sugar Creek BDA 1.0 used to detect fish passage. The antennas were secured in an upright position with t-posts and ratchet straps. They were powered by 12 v batteries that were recharged with a solar panel system. Photo taken on 08/01/2019 facing upstream just upstream of Sugar Creek BDA 1.0.

Throughout the two experiments, physical and environmental data were collected including jump height, plunge pool depth, spill crest depth, spill crest width, velocity at crest, stream discharge, dam permeability, and water temperature (Table 1). Additionally, data were collected on the downstream velocity of each dam at 0.3 m intervals using a Swoffer 2100 Velocity Meter. These data were used to create a velocity profile of each BDA to be able to identify where most of the velocity was spilling over or through each dam.

Several days prior to starting the July-August 2019 experiment, the fish passage side channel around BDA 1.0 became disconnected. The start of the experiment was run with the dry side channel and no weir flow jump points to see if fish were able to pass through subsurface orifices. On the morning of August 5, 2019 (day six of the experiment), a crew of 10 SRWC employees spent a total of about 50 hours to repair the holes on BDA 1.0 to refill the upstream pool and reconnect the fish passage side channel. This was done to see if fish passage was increased by reconnecting the side channel. On August 9, 2019, fish were recaptured with beach seines, and their weight, length, and recapture location were recorded before being released where they were originally captured.

The September 2019 experiments were intended to start with the fish passage side channel connected, but due to limited staff and environmental conditions, that was not achieved. Consequently, the September experiments also started with a disconnected fish passage side channel. On September 9, 2019 (day four of the experiment), a crew of about 5 SRWC employees spent about 20 hours making repairs to BDA 1.0 and the ancillary BDA to reconnect the fish passage side channel. On September 10, 2019 the experiment was ended early due to a high number of mortalities of recently tagged Coho Salmon. Fish were recaptured with beach seines, their recapture location was documented, and they were immediately released back into the habitat where they were originally captured. Fork lengths and weights were not recorded to minimize further stress and mortality to the tagged fish.

Summer Low-Flow Passage Analysis

The Sugar Creek low-flow passage experiment dataset included PIT tag detections at two stationary PIT tag antennas, in addition to multiple active PIT tag wanding surveys. The stationary antennas detected fish that escaped the experiment downstream and fish that successfully moved upstream past all three BDAs. The wanding survey detection data provides information on where fish were located at the habitat level at a specific time, and wanding surveys were completed 1 to 3 days apart. I used R code to clean the data and to create capture histories for each fish for both trials. These final capture histories contained a series of spatial and temporal detections for each individual and were analyzed using mark-recapture methods.

I first attempted to fit a multistate-mark-recapture model using program RMark (Laake 2013), but the model had serious problems with assumption violations and it generated unrealistic parameter estimates. I then simplified the capture histories to fit the data to a Cormack-Jolly-Seber (CJS) model, but I also had issues with model assumptions and parameter estimates. There were a variety of issues with both of the mark-recapture models, but the core problem was related to fish behavior and the set-up of our detections in the different recapture locations (i.e., stationary antennas vs wanding surveys). Fish that passed one BDA tended to pass all of the BDAs; these fish were likely to be detected on the upstream stationary antenna, but were not available for detection in the wanding surveys, violating the assumption of equal capture probability. As a result, I further simplified my analysis for these experiments.

I reclassified my data so that any fish detected above any BDA as having passed that BDA and all the BDAs downstream of it, then fit a separate logistic regression model for cumulative passage of each BDA and the BDAs downstream (i.e., BDA 1.2; BDA 1.2 & 1.1; and BDA 1.2, 1.1, & 1.0). In addition, I fit a separate logistic regression model to assess passage before the fish passage side channel was reconnected. This simplified logistic regression approach does not account for capture probability, but the upstream stationary antenna (uppermost capture point) had very high detection efficiency, so likely gives a good idea of passage through the structures. Not accounting for capture probability likely leads us to slightly underestimate passage at the BDAs instead of vastly overestimating passage using the mark-recapture models. Note that the logistic regressions estimates the cumulative passage for each BDA (the probability of passing a particular BDA and all downstream BDAs). I originally back-calculated per-BDA passage rates by division, but decided not to report those results due to passage probabilities that were biased high for the upper BDAs. The back-calculated passage estimates were biased high because only fish that had already passed at least one BDA were able to attempt to pass the upper BDAs. In other words, the probability of passing the upper BDAs was contingent on fish first passing the lower BDAs and this would likely result in passage probabilities biased high for the upper BDAs given that the only fish to encounter them had already passed at least one other BDA.

I included a term to indicate whether fish were marked on the same day or during a previous field effort for the experiment completed in September due to the high observed mortality rate among tagged fish. I used AICc to determine the need for fork length in the model structure. Due to the interrelatedness of the models, I choose to include fork length in all models if it was informative in at least one model.

I summarized environmental and BDA metrics to explain patterns in fish movement. I plotted the continuous stream discharge for the flow station on Sugar Creek near Callahan (station number: F25890) for the two experiment periods. I plotted continuous stream temperature and water surface elevation for the habitat unit directly below BDA 1.0. I generated velocity profiles for each BDA at 0.3 m intervals to help visualize where and how water was flowing through or over the BDAs.

To investigate the cause of mortality during the second trial of experiments, I compared survival of previously marked and Coho Salmon marked on the same day using a chi-squared test.

Hatchery Methods

From 06/1/2019–7/24/2020, 36 controlled lab experiments were conducted at the HSU hatchery facility. The experiments followed a two-week cycle, where one week focused on a set of four different subsurface treatments and the other week focused on a set of four different jump treatments. I completed 16 jump trials and 20 subsurface trials. The weekly order of treatment type was alternated. To increase sample size for each experiment, address limited PIT tags and the limited number of fish allotted to the permit, each fish was subjected to both a jump test and a subsurface test. The same 200 fish batch was used for a two-week period with four trials per week and 50 fish per day for each trial. The trial order was also randomized within weeks. Because these experiments were different from one another, there should not have been issues with learned behavior or violations of statistical independence.

The experiments took place in one of the outdoor, covered 30 m x 1.5 m fish raceways at the HSU fish hatchery. The 5 cm slots in the side of the raceway were used to create a flashboard style dam structure. Cedar boards that measured 300 cm x 14 cm x 3.8 cm (i.e., 10 ft x 2 ft x 6 ft boards) were cut to 150 cm x 10 cm x 3.8 cm in order to fit into the 5 cm slots to create barriers and increase jump heights by 10 cm intervals. A 9 cm diameter hole was cut in the center of one flashboard to create an opening for subsurface passage tests. Recycled neoprene wader material was cut in 3.8 cm strips and attached to the lowest board to create a watertight seal at the base of the dam. Waterproof canvas material was placed on the upstream side of the dam to prevent seepage along the edges of the dam and between the boards. Net screens with 3.1 mm square holes were placed approximately 1 m above and below the flashboard dam to keep fish confined to the study area.

A water flow control ball valve located at the top of the raceway was used to control the amount of flow in the raceway and the valve handle was kept at a set position throughout the 36 experiments. The daily flow through the raceway was subject to slight changes based on the amount of water coming from the reservoir and the number of other tanks in operation in the hatchery facility. Flow measurements were taken daily at the outflow of the raceway and at the weir crest of the flashboard dam using a Swoffer 2100 Velocity Meter. Flow was calculated by multiplying the water depth and width and velocity measurements at these locations.

A Biomark HPR Plus Reader and handheld wand was used to detect fish that passed the obstacles. The handheld wand was suspended from a 5 cm by 10 cm board with rope approximately 15 cm upstream of the suspected passageway of the obstacle (spill point or subsurface orifice). The wand had a read-range of approximately 8 cm, and was positioned so that unsuccessful passage attempts were not detected by the antenna. To avoid large numbers of repeat detections of the same individual, the reader was set to detect unique tags every five minutes.

At the start of every experiment, 50 fish were released into the lower habitat unit around 11:00 AM and given one overnight period to pass the obstacle (~22 hours). Fish were recaptured the following morning at 9:00 AM using a 75 cm by 60 cm nylon mesh net. Fish recaptured above and below the obstacle were placed into separate buckets for processing. A standardized protocol to recapture fish was developed due to the difficulty of recapturing the fish in the raceway. The protocol included a minimum of 10 net pulls for each habitat unit (i.e., above & below) with the last 5 pulls producing 0 fish.

After fish were captured and processed, environmental and physical data were collected. These data included water temperature and air temperature (°C), dissolved oxygen (mg/L), flow (cms), and additional data specific to each treatment type (jump vs subsurface) described in more detail in the sections to follow.

Fish Processing in the Hatchery

I conducted controlled lab experiments in the Humboldt State Fish Hatchery located on the university campus in Arcata, California. The hatchery receives water from a reservoir positioned above the campus and uses the combination of a 190 cubic meter water storage tank and a recirculation freshwater system with internal aeration and filtration to supply the facility with habitable water. The experiments were conducted in an outdoor raceway facility, where flashboard-style dams were created to test passage.

Humboldt State University hatchery steelhead trout were used for controlled lab experiments conducted at the fish hatchery. Juvenile steelhead trout were hatched in egg incubators, raised in 1 m circular tanks, and fed approximately 5% of their body weight per day with a diet of Skretting's Complete Feed for Trout and Steelhead (52% Crude Protein, 16% Crude Fat, 3% Crude Fiber and 1.2% Phosphorus).

All steelhead were implanted with a small 8mm PIT tags using a scalpel. Fish used for hatchery experiments were tagged at least 7 days prior to trials to allow for recovery. Fish were anesthetized with MS222 when initially tagged and again when they were recaptured, measured, and weighed. Note that this is different from the anesthetic used in the field experiments as the hatchery fish handling was not limited to the methods approved in the SRWC field sampling permit. After fish completed their second experiment, they were euthanized using in a 500mg/L solution of buffered MS222 for at least 10 minutes, as described in the IACUC protocol.

Jump Experiments

Four rounds of four different jump treatments were tested throughout the duration of hatchery experiments, for a total of 16 jump trials. These treatments included a 24 cm jump, 34 cm jump, 40 cm jump and 44 cm jump (Figure 23). The 40 cm jump had woven willow added to the top 10 cm to add jump complexity at the weir crest (Figure 23). To create the jump treatments, 10 cm tall cedar boards were stacked in the raceway 5 cm concrete slots to create the desired jump height. One shorter, 112 x 5 x 3.8 cm board was secured to the top board to concentrate the flow to one side of the flashboard dam to create a jump point with a crest width of 38 cm.

Figure 23. The four jump treatments tested during the hatchery experiments included a 24 cm jump (top left), 34 cm jump (top right), 44 cm jump (bottom left), and a 40 cm jump with woven willow on the top (bottom right). The handheld antenna wand is suspended by a 5 cm by 10 cm board approximately 8 cm upstream of the weir crest. Photos were taken from 07/6/2020-07/10/2020.

Beaver dam analogues often have complex flow through small branches over the top, rather than a clean spill point. To replicate this complexity, I created a 40 cm jump where the top 10 cm was made of woven willow. The willow insert was created by welding two parallel 150 cm long rebar rods with a diameter of 1.25 cm to 2 evenly spaced perpendicular 10 cm tall rebar rods with a diameter 1.25 cm (Figure 24). Attached to each end of the willow insert was a 10 cm x 3.8 cm x 3.8 cm cedar block to allow the insert to smoothly slide into the 5 cm x 10 cm slots in the raceway. Freshly cut willow branches that were still malleable were then woven through the rebar rods in a similar density to that of BDAs observed in the field. Several 10 cm tall cedar boards were stacked in the raceway 5 cm by 10 cm concrete slots to create a jump height of 30 cm with the willow insert above the boards. A 112 x 5 x 3.8 cm board was secured to the top of the willow insert and a waterproof canvas tarp was draped over the upstream side to funnel the water over and through the willow insert with a width of 38 cm (bottom right of Figure 23).

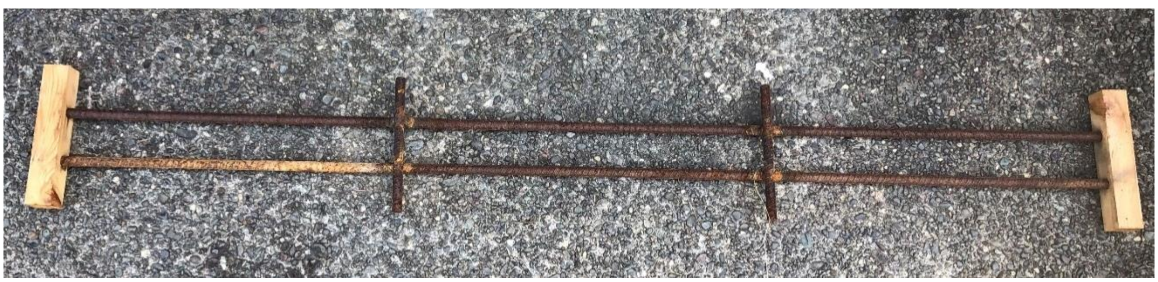

Figure 24. Willow inserts created by welding two parallel 150 cm ½ inch rebar rods to 2 evenly spaced perpendicular 10 cm ½ inch rebar rods. Two 10 cm cedar blocks attached to each end of the insert to slide into the 5 cm raceway slots.

After fish were recaptured and processed, environmental and physical data, in addition to data specific to the jump experiments were collected. This additional data included jump height, plunge pool depth, spill crest depth, spill crest width, and velocity at crest. The description of these variables is the same used in the Miners Creek experiments (Table 1).

Subsurface Experiments

Several combinations of conditions that might affect subsurface passage rates, including passageway length, depth, material, slope, velocity, and flow were explored during the subsurface experiments. The same flashboard style dam used for the jump experiments was also used for the subsurface experiments with slight modifications. One board from the jump experiments was replaced with a larger, 300 cm x 14 cm x 3.8 cm cedar board (i.e., 2 ft x 6 ft board). A hole was drilled through the face of the board large enough to fit a PVC pipe with an 8.9 cm outer diameter (Figure 25). An overtopping spill point was maintained to calculate flow through the pipe (description later in methods); however, a block net was placed at the weir crest to prevent passage by jumping (Figure 26).

Figure 25. Cedar board (300 cm x 14 cm x 3.8 cm) with hole drilled through the face to fit a 8.9 cm outer diameter PVC pipe.

Figure 26. Subsurface passage experiment setup with the handheld antenna wand suspended by a 5 cm x 10 cm board (A), the blocknet placed at the jump point to prevent fish passage by jumping (B), and the 8.9 cm PVC pipe secured through the cedar board hole. Photo taken on 07/15/2020.

A combination of two slope treatments (10% and 14%) and two internal material treatments (branches and twigs) were the original variables examined. After the first four subsurface trials with these treatments had passage success rates of 0%, it was clear that other variables needed to be considered. The subsequent treatments also examined the effect of a shorter pipe, no material inside the pipe, and the depth of the pipe in the upstream pool.

Two different materials placed inside the pipe were tested. Twigs (< 1 cm in diameter) and branches (> 1 cm in diameter) were stuffed inside the PCV pipe perpendicular to the stream flow; similar to how they would be oriented in a BDA (Figure 27). To keep the material secured inside the pipe, one end was fitted with two 10 cm long bolts and several zip ties in a crisscross pattern (Figure 28). To fix the location of the pipe inside the cedar board, a 3 cm long PVC O-ring was created to be able to fit around the pipe. The pipe was fixed inside the cedar board with the O-ring that was secured in place by a small stainless-steel screw and the bolts at the end of the pipe (Figure 28). In addition, a square 30 cm x 30 cm waterproof canvas skirt with a hole just large enough to fit around the pipe was placed between the O-ring and the cedar board to seal any gaps between the wood and the pipe.

Figure 27. Twigs less than 1 cm in diameter (left) and branches greater than 1 cm in diameter (right) were stuffed inside the 7.6 inner diameter PCV pipes. Material was

placed in the pipes perpendicular to the stream flow; similar to how they would be oriented in a BDA.

Figure 28. Upstream end of the PVC pipe fixed in place by a PVC O-ring and stainless-steel screw with waterproof canvas skirt (left). Overhead view of the pipe fixed inside the cedar board with the top being upstream and the bottom being downstream(middle). Downstream end of the pipe with screws, bolts and zip ties to secure the material inside the pipe (right).

Conditions related to the pipe length, slope and depth were modified to examine their effect on passage. Two different pipe lengths were examined. A pipe length of 60 cm was originally chosen because it was the average width of the BDAs measured at Sugar Creek. Later, after several trials with low passage success rates, a shorter, 25 cm pipe length was used. To adjust the slope of the pipe, three different boards had holes drilled through the faces at different angles with 0%, 10% and 14% slopes. To adjust the depth of the pipe below the upstream water surface elevation, the number of boards placed above the pipe was altered. The three depths examined were 57 cm, 28 cm, and 17 cm.

After fish were recaptured and processed, environmental and physical data including water temperature, dissolved oxygen, air temperature, and raceway flow were collected, in addition to data specific to the subsurface experiments. These additional data included passageway length, depth, material, slope, velocity, and flow (Table 2). Flow through the pipe was estimated by taking the total flow through the raceway measured at the raceway outflow weir and subtracting it from the flow spilling over the weir crest on the flashboard dam.

Table 2. Description of the passageway covariates sampled specific to the subsurface experiments.

Variable	**Definitions**
Length	The length of the pipe from end to end (cm)
Depth	The vertical distance between the submerged upstream pipe inflow and the upstream water surface elevation (cm)
Material	The categorical type of material inside the pipe. Branches (> 1 cm in diameter), twigs (< 1 cm in diameter), or no material
Slope	The percent slope calculated by dividing the vertical rise of the pipe by the horizontal run of the pipe times 100 (%)
Velocity	Speed of the water measured at the downstream pipe outflow (m/s)
Flow	Volume of water flowing through the pipe per second. This was measured by subtracting the total flow through the raceway from the flow spilling over the top of the weir crest (m^3/s)

Hatchery Analysis

To determine the effect of specific covariates and experimental treatments on fish passage success, I built mixed-effects logistic regression models in R using package lme4 (Bates et al. 2015). Fork length was standardized to improve model convergence and to avoid issues with multicollinearity. Continuous variables were assessed for linearity using visual locally weighted smoothing (LOESS) plots. When linearity was violated, I fit models with polynomial terms and compared model fit using AIC. I used model averaging to calculate the OR estimates for models that fell within two delta AIC scores. For these data, the response variable of passage was based only on fish that were recaptured during each of the trials' corresponding recapture effort, as it was possible for fish to move freely when the structure was rebuilt between trials. I intended on modeling the subsurface experiment data, but after the experiments were completed, it was clear that there would not be any additional knowledge gained from statistical inference due to the limited number of successful passes during the subsurface trials.

As part of the experimental design, a random intercept based on sample number was included in the model to control for random sample-to-sample variation for both the jump and subsurface models. For the jump experiments, I modeled trial type (jump height and the presence of woven willing branches), morning water temperature, and fish fork length as fixed effects.

RESULTS

Early Summer Passage

Juvenile Coho Salmon were observed successfully passing the BDAs during all four of the early season trial experiments in June 2019. Across all trials, 76% of the recaptured Coho Salmon were above the BDAs at the end of the trials. Over-night passage rates for the four trials ranged from 53% to 94% (Table 3). However, about 50% of the Coho Salmon released for the early season trials were not recaptured. It was later discovered that the block nets had several rips in the netting that were large enough to allow for juvenile Coho Salmon to escape from the study area.

Table 3. Summarized data from the Miners Creek passage experiments. The columns indicate the four trials and the rows indicate the data collected for each trial. The average and standard deviations for Coho Salmon fork lengths are reported for each trial.

Trial	1	2	3	4
BDA Site	Miners 2.4	Miners 2.3	Miners 2.4	Miners 2.1
Start Date	06/18/2019	06/19/2019	06/19/2019	06/20/2019
Physical Parameters				
Jump Height	36.5 cm	20 cm	33 cm	20 cm
Plunge Pool Depth	23.5 cm	19.5 cm	26.5 cm	12.5 cm
Permeability Estimate	0-33%	33-66%	0-33%	33-66%
Water Temperature	12.8 C°	10.9 C°	10.9 C°	10 C°
Spill Crest Depth	3 cm	3 cm	7.5 cm	4.5 cm
Spill Crest Width	205 cm	170 cm	205 cm	200 cm
Velocity at Crest	0.518 m/s	0.137 m/s	0.612 m/s	0.307 m/s
Stream Flow	0.013 cms	0.023 cms	0.023 cms	0.028 cms
Passage				
Total Released	20	25	47	50
Recaptured Above	6	9	23	15
Recaptured Below	2	8	6	1
Not Recaptured	12	8	18	34
Percent of Recaptured Fish Caught Above BDA	75%	53%	79%	94%
Percent of Released Fish Caught Above BDA	30%	36%	49%	30%
Fish Size				
Fork Length (Avg ± SD)	58.5 ± 3.4 mm	58.7 ± 5.0 mm	55.3 ± 4.1 mm	55.2 ± 6.1 mm

The BDA with the greatest jump height was Miners 2.4, where I conducted two trials at two different stream flows (Table 3). The higher stream flow slightly decreased the jump height from 36.5 cm to 33 cm. The trials at this site were repeated due to the low flows (0.013 cms) during the first trial and the limited number of recaptured Coho Salmon (8 recaptures). Passage rates were fairly consistent between the two trials on

Miners 2.4 and ranged from 75% to 79%. The trials at the other 2 BDA sites, Miners 2.3 and Miners 2.1, were only conducted once at fairly comparable flows and jump heights were both 200 mm. However, the percent of recaptured fish that were caught above the BDAs were considerably different, where Miners 2.1 had the highest passage rate of 94%, while Miners 2.3 had the lowest passage rate of 53%. These data suggest that passage rate may not be a simple function of jump height. The two noticeable differences between these sites were the difference in the spill crest depths and the velocity at the spill crest (Table 3). The mean fork lengths were comparable among the four trials, however, some of the trials had a larger variation in the distribution of fork lengths (Table 3). There is no clear signal of fork length affecting passage between the four different trials (Figure 29 and Figure 30).

Due to the limitations of working with small fish and the methods used during these trials, passage rates recorded may be an underestimate of the actual passage rates. During hatchery experiments conducted the following summer, fish were observed repeatedly moving between upstream and downstream habitat units and I suspect wild fish exhibit this same behavior. If they were moving repeatedly, fish that successfully passed the BDA could have moved back downstream so their recapture location was below the BDA; these fish would not be included in the passage rates reported here.

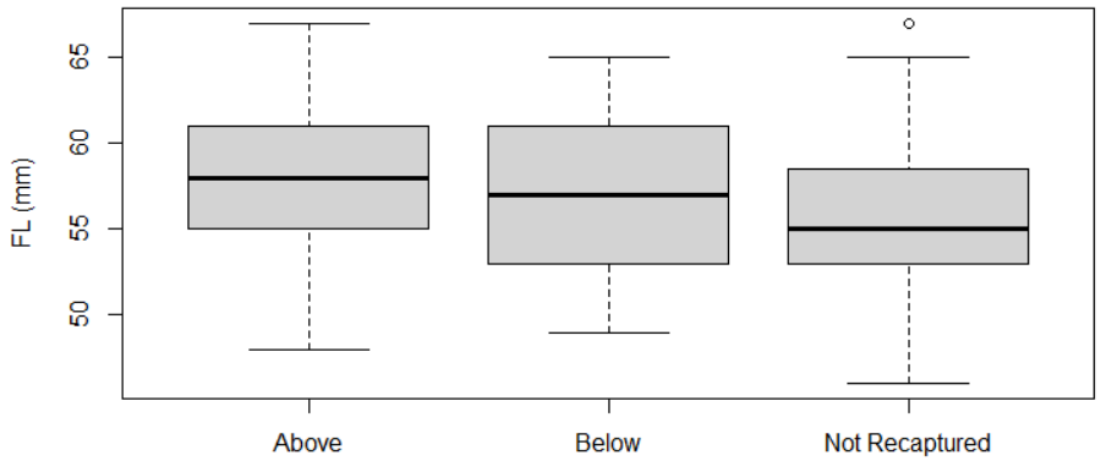

Figure 29. Box plot displays the distribution of fork lengths for fish captured above and below the Miners Creek BDAs and fish that were not recaptured. Trials for the Miners Creek experiments were completed from 06/18/2019-6/20/2019.

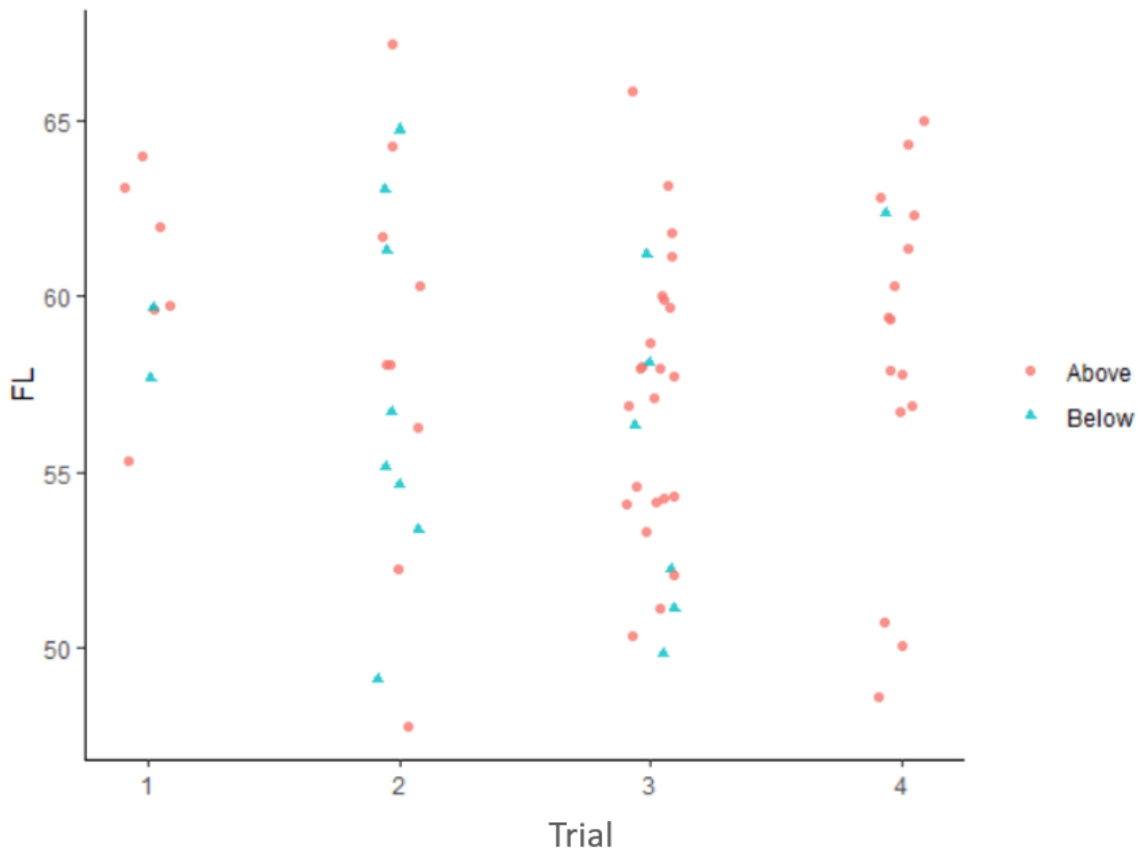

Figure 30. A spread of the fork lengths plotted for each of the four trials for the Miners Creek experiments from 06/18/2019-6/20/2019. Trials 1 and 3 were conducted on BDA 2.4, while trial 2 and trial 4 were completed on BDA 2.3 and BDA 2.1, respectively. Each point represents one individual fish and the points for trial were jittered to visualize overlapping points. The color of the dots indicates the recapture location of each fish.

The random effects logistic regression model with fork length as the fixed effect and trial as a random effect generated a parameter estimate for fork length indicating no effect of fork length on passage rate (0.29, $p = 0.33$). The intercept had a coefficient value of 1.21 and was significant at the 0.05 level ($p = 0.007$). The trial random effect had a variance of 0.39 and a standard deviation of 0.62.

Low-Flow Passage

Juvenile Coho Salmon were observed successfully passing all three of the Sugar Creek BDAs during both summer low-flow passage trials completed from 07/31/2019-08/09/2019. During the first trial that lasted nine days, a majority of the 272 Coho Salmon (~73%) were able to pass all of the BDAs (Figure 31). The second trial was limited to four days from 09/06/2010-09/10/2019 due to observed Coho Salmon mortalities in the study area. The known mortalities were removed from the following data summaries and analyses. The suspected cause of mortality was tagging injury. A total of 120 fish (~44%) were tagged by the SRWC during a population estimate sampling effort a few weeks before (~08/25/2019) and the remainder of the sample, 154 (~56%) fish, were tagged on the same day that the trials began on 09/06/2019. Both September 2019 cohorts of tagged fish were accounted for in the data summaries and analyses. During the abbreviated second trial, only 26 of the 274 Coho Salmon (~10%) were able to pass all three BDAs (Figure 32). However, 25 of the 120 of the fish that were previously tagged were able to pass the BDAs during the abbreviated trial (~21%). For comparison, on day four of the first trial, 75 (~28%) of the released Coho Salmon had passed all three of the BDAs.

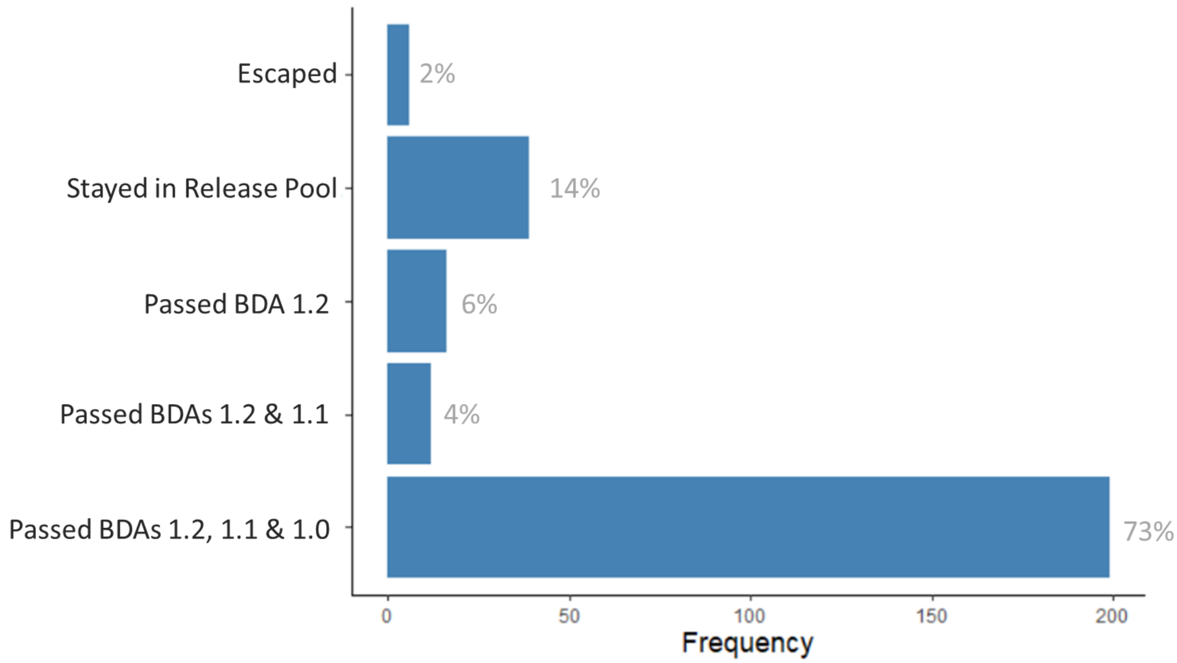

Figure 31. Frequency of the greatest state reached for tagged fish during the first BDA juvenile Coho Salmon passage experiment on Sugar Creek from 07/31/2019-08/09/2019.

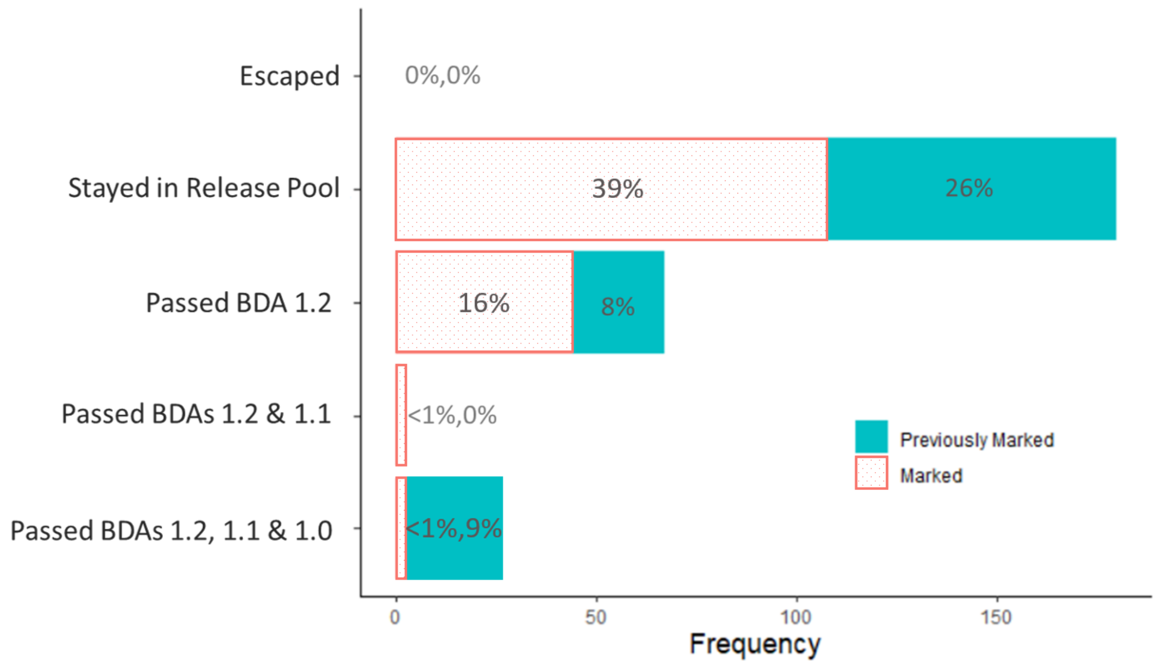

Figure 32. Frequency of the greatest state reached for tagged fish during the second BDA juvenile Coho Salmon passage experiment on Sugar Creek from 09/06/2019-09/10/2019. The bars on the left colored red were fish that were marked on the same day of the release and the bars on the right colored turquoise were fish that were marked on a previous, unrelated sampling effort.

During the initial six days of the first trial (07/31/2019-08/05/2019), the upper BDA (1.0) was very permeable and was not retaining enough water to activate the fish passage side channel or to create a weir flow for fish to be able to jump. In all, 81 fish (30%) made it past BDA 1.0 during the first six days and would have had to swim through subsurface orifices in the BDA. The distance between the downstream and upstream habitat units where I suspected passage was approximately 1.2 m, suggesting that juvenile Coho Salmon swam at least that distance through an orifice the dam to in order successfully make it to the upper habitat unit. The velocity on the downstream side of BDA 1.0 ranged from 0.003 to 0.05 meters per second during that period of time (Figure 33).

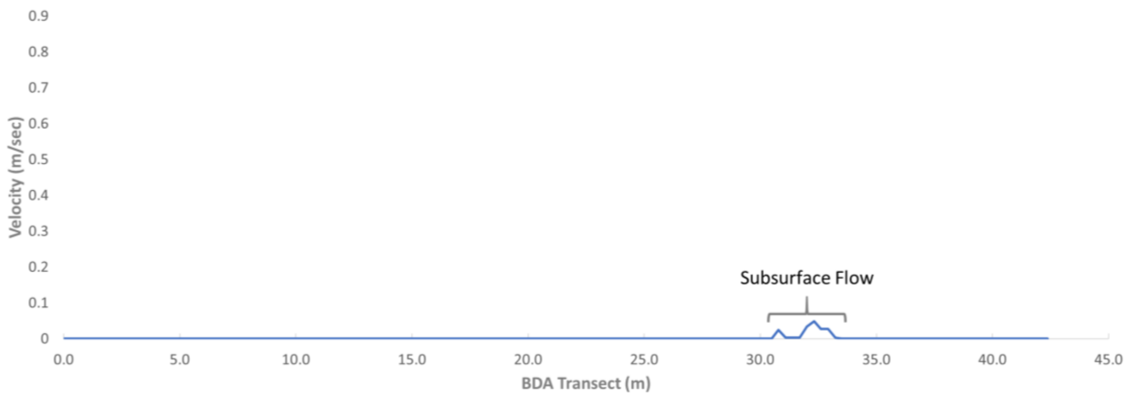

Figure 33. Velocity profile of Sugar Creek BDA 1.0 on 08/02/2019 where maximum velocity measurements were recorded on the downstream side of the BDA at 0.3-meter intervals.

On day six of the trial (8/5/2019), the subsurface orifices on BDA 1.0 were patched in order to reconnect the fish passage side channel. The side channel on BDA 1.0 had a length of approximately 3.4 m and a slope of 7.7%. When the side channel reconnected, velocities at the head of the side channel ranged from 0.2 to 0.7 meters per second (Figure 34). Prior to reconnecting the side channel, during a snorkel survey, I had observed well over 100 juvenile Coho Salmon staged in a close proximity to one another all near the outflow of the subsurface passageway (Figure 35).

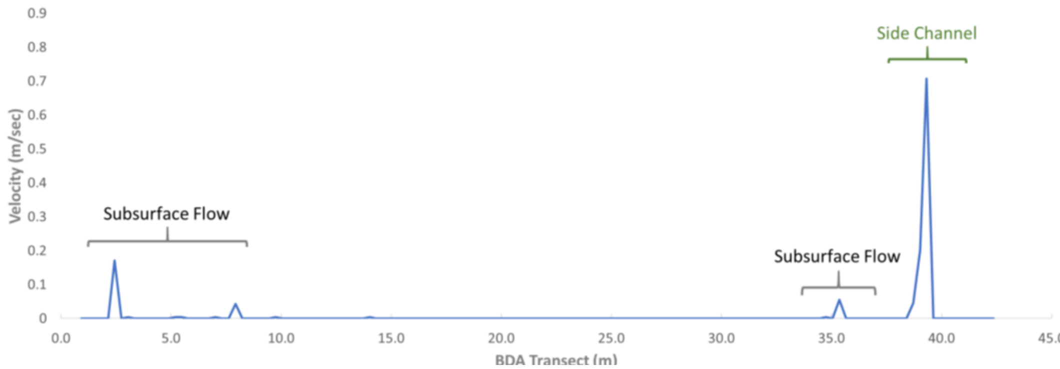

Figure 34. Velocity profile of Sugar Creek BDA 1.0 on 08/07/2019, where maximum velocity measurements were recorded on the downstream side of the BDA at 0.3-meter intervals. Additional subsurface flow locations were activated when the water surface level increased.

Figure 35. Juvenile Coho Salmon clustered below BDA 1.0 on 08/04/2019 prior to the fish passage side channel was reconnected. Over 100 Coho Salmon were observed lined up near the subsurface passageway. All of the fish were not captured in this photo.

Immediately after the reconnection of the side channel, a spike in the fish passage rate was observed (Figure 36), where 45 individuals (17%) passed the BDA by the end of the repair day and 118 (43%) passed in the last four days of the experiment. However, during the BDA repair period, the habitat unit below BDA 1.0 increased in temperature and decreased in water surface elevation. This was due to limited streamflow to the downstream habitat unit while the upstream pond was refilling. It took approximately five hours for the BDA fish-passage side channel to reconnect. As a result, in the habitat unit below BDA 1.0, the daily maximum water temperature was approximately 2 °C warmer (Figure 37) than the previous day, and the water surface elevation dropped from about 0.8 m to about 0.4 m when compared to the previous day (Figure 38). These degrading habitat conditions paired with the connection of the side channel may have triggered fish to move.

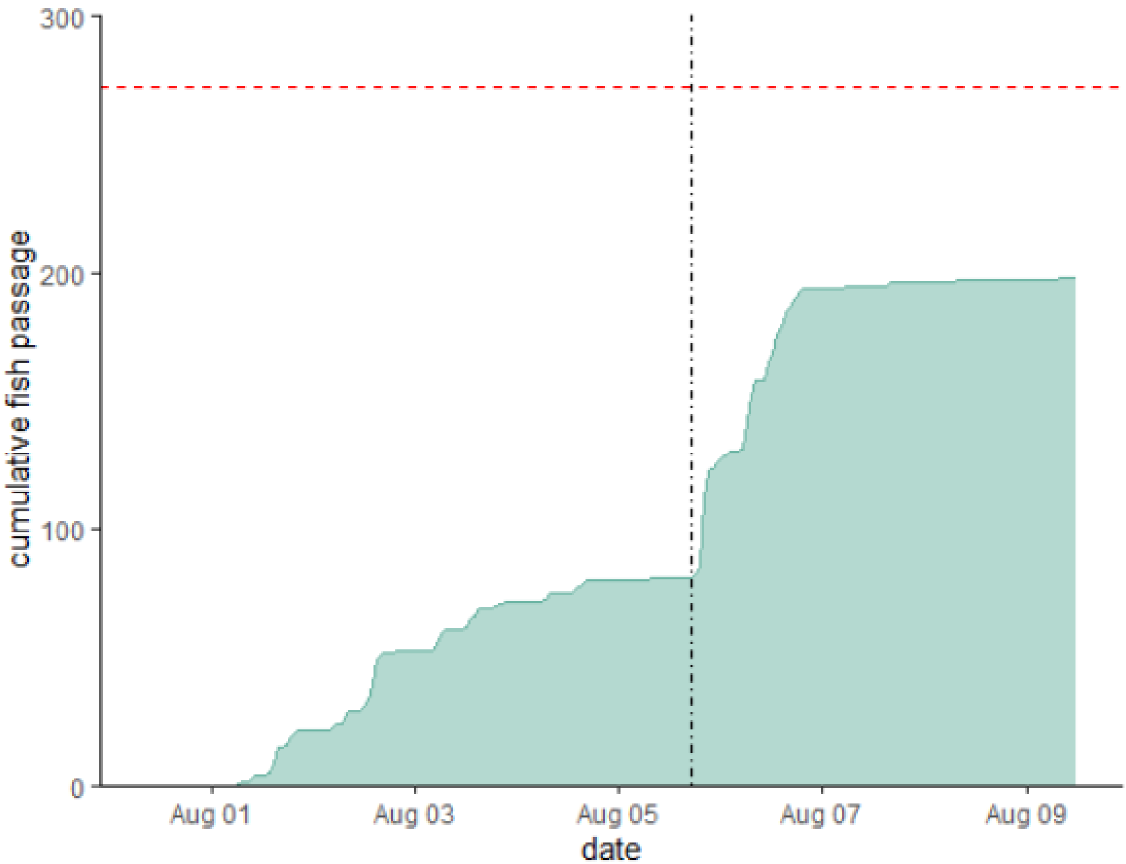

Figure 36. The green area represents the cumulative fish passage of all three BDAs on Sugar Creek over the extent of the experiment. Fish were released between 09:00 and 13:00 on 07/31/2019. The horizontal dashed red line indicates the total number of released fish (278). The vertical dashed black line indicates when the fish-passage-side channel was connected on 08/05/2019 at approximately 17:00. The experiment ended and

the fish were recaptured and relocated back to the upstream pond which they came from at approximately 12:00 on 8/9/2019.

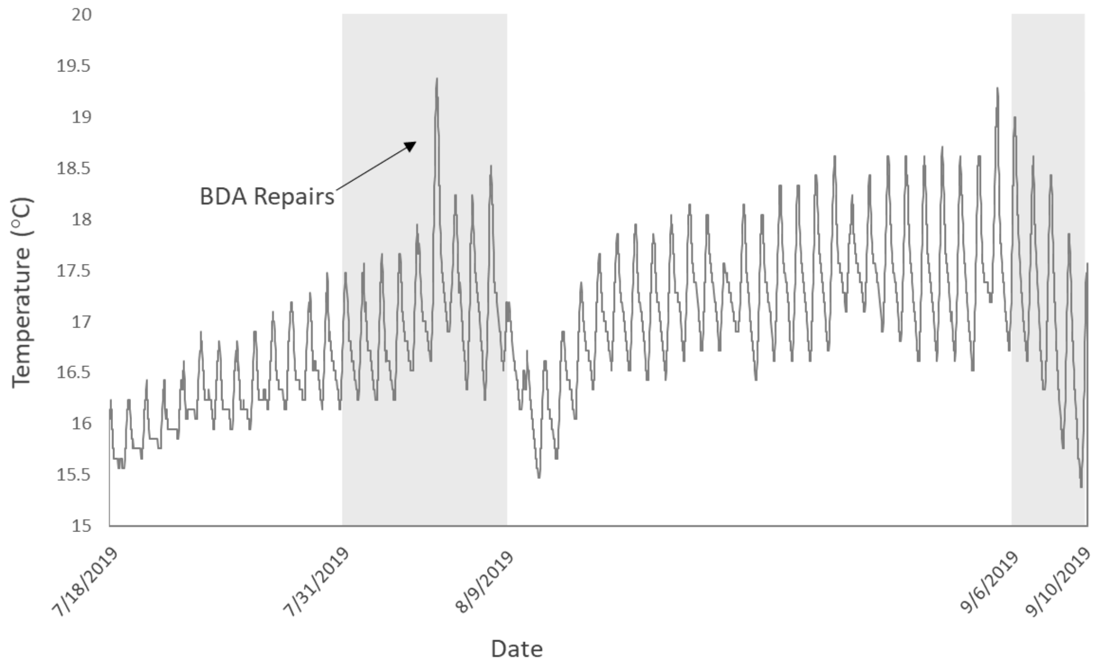

Figure 37. Water temperatures (°C) collected at 15-minute intervals in the habitat unit below Sugar Creek BDA 1.0. The gray panels indicate the start and end dates of the two experiments completed. The arrow indicates the temperature spike recorded on the day when BDA 1.0 was repaired.

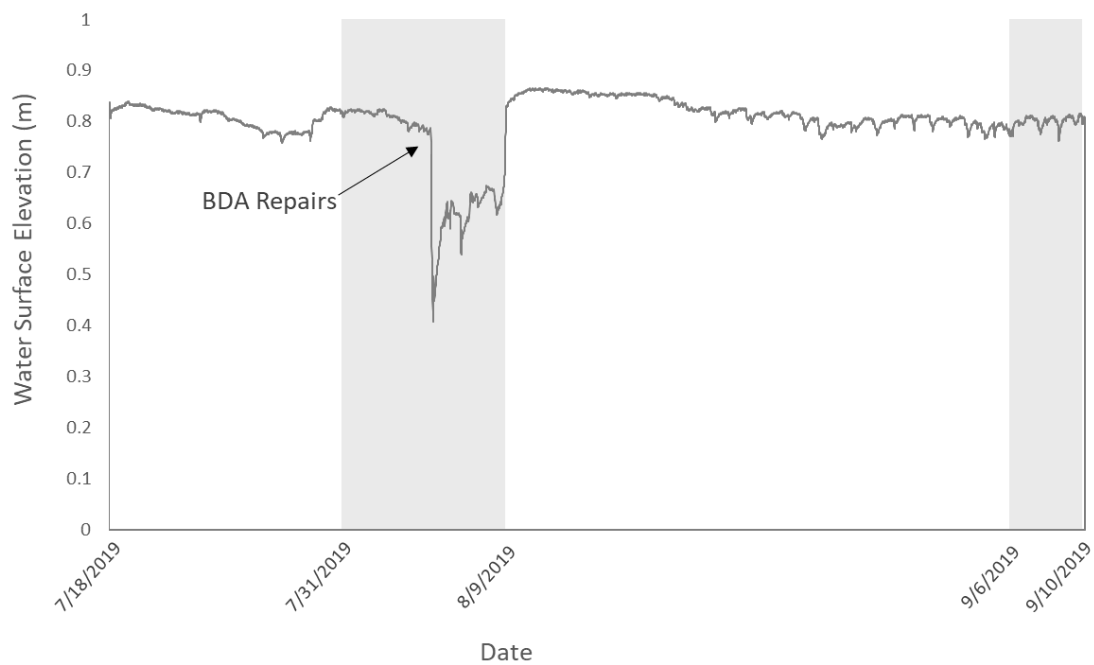

Figure 38. Water surface elevation (m) collected at 15-minute intervals in the habitat unit below Sugar Creek BDA 1.0. The gray panels indicate the start and end dates of the two experiments completed. The arrow indicates the drop in water elevation recorded on the day when BDA 1.0 was repaired.

During the first trial from 07/31/2019-08/09/2019 on Sugar Creek, I observed zero fish mortality and documented six shed-tags during the shed-tag wading exercise. It is unknown whether these fish perished or whether their PIT tag fell out, and as a result, I excluded them from the analysis.

By the start of the second trial on 9/6/2019 on Sugar Creek, a minimal amount of water was flowing down the fish passage side channel and it was visibly not passable for salmonids. This was largely due to the highly permeable condition of the BDA 1.0 wing dam allowing water to flow through the side channel and also due to beavers plugging the top of the fish passage side channel. The subsurface velocity on the downstream side of

BDA 1.0 ranged from 0.006 to 0.012 meters per second on 9/6/2019 prior to repairing the wing-dam (Figure 39). As of 9/9/2019, when the wing dam was patched and the beaver blockage was removed from the top of the fish passage side channel, 21 Coho Salmon (~8%) were observed passing all three BDA structures over the three-day period (Figure 40).

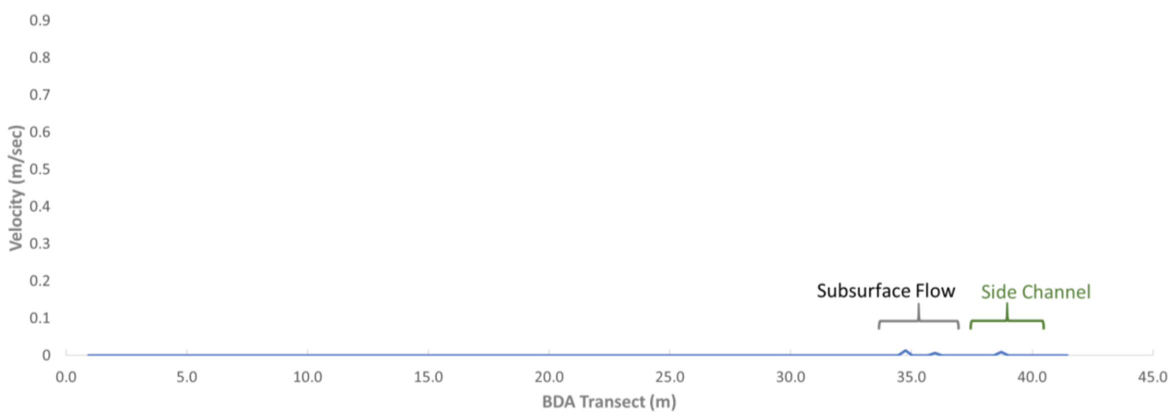

Figure 39. Velocity profile of Sugar Creek BDA 1.0 on 09/06/2019, where maximum velocity measurements were recorded on the downstream side of the BDA at 0.3-meter intervals.

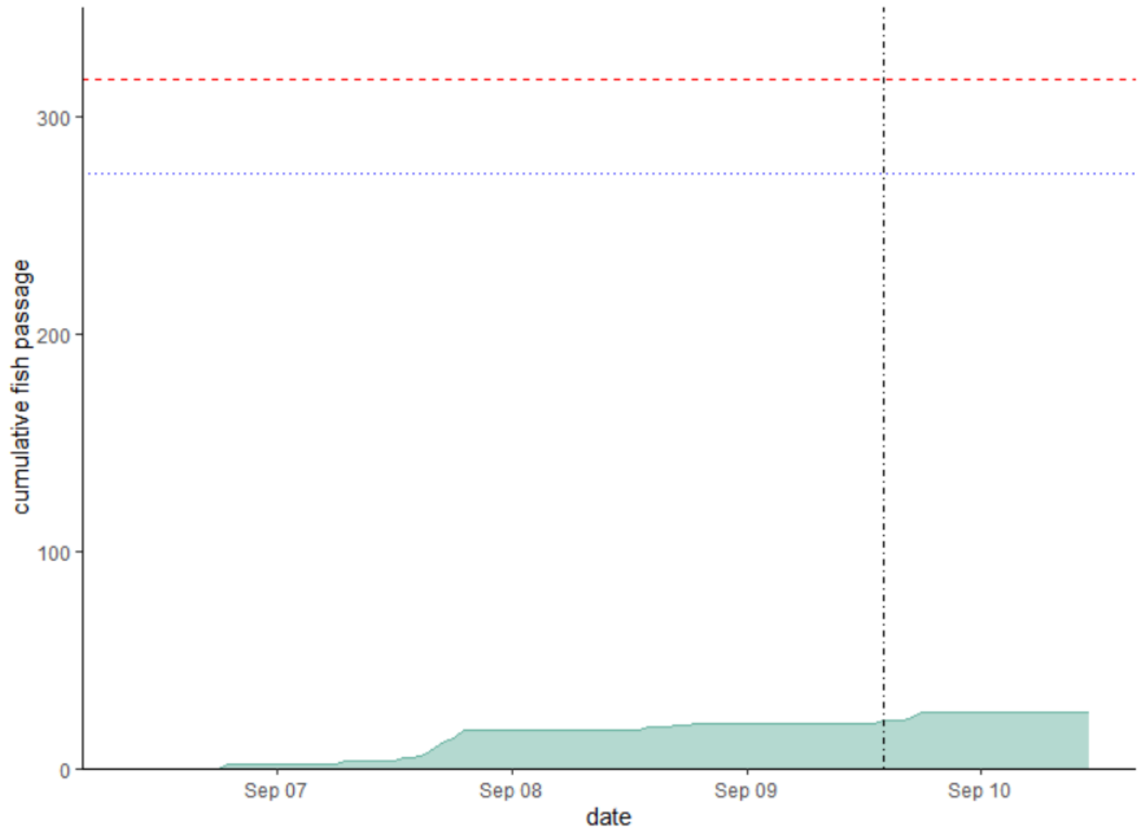

Figure 40. The green area represents the cumulative fish passage of all three BDAs on Sugar Creek over the extent of the experiment. Fish were released at approximately 09:00 to 14:00 on 09/06/2019. The horizontal dashed red line indicates the total number of released fish (317). The horizontal dotted blue line indicates the total number of fish (274) released downstream after accounting for known mortalities (25) and shed-tags (18). The vertical black dotted line indicates when the BDA fish passage side channel was repaired. Fish were recaptured and relocated back to the upstream pond which they came from at approximately 12:00 on 09/10/2019.

When the side channel reconnected, velocities at the head of the side channel ranged from 0.3 to 0.4 meters per second and there was some flow going through subsurface orifices (Figure 41). By the end of the repair day on 09/9/2019, only an additional 5 individuals (2%) passed. No additional fish passed in the last 16 hours of the experiment. This was not surprising given the limited number of fish detected to have reached the habitat unit below BDA 1.0 and suggests fish were not able to readily pass any of the lower BDAs.

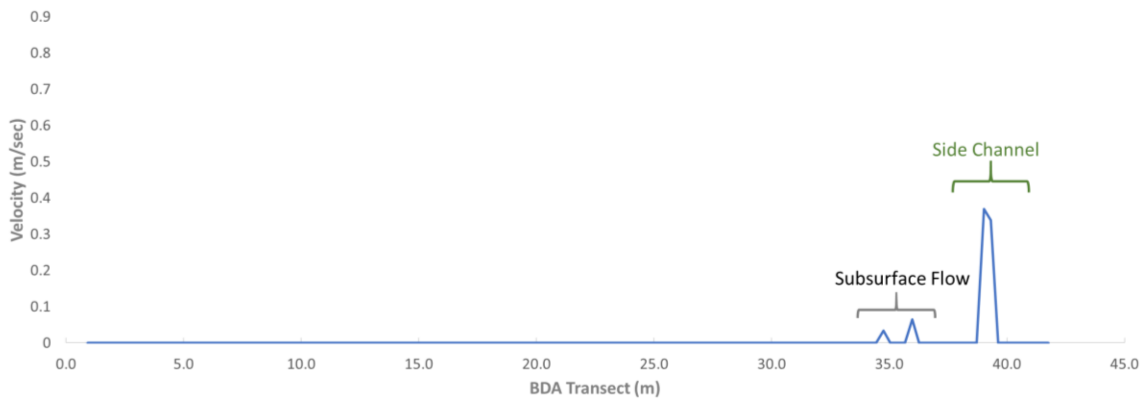

Figure 41. Velocity profile of Sugar Creek BDA 1.0 on 09/09//2019 where maximum velocity measurements were recorded on the downstream side of the BDA at 0.3-meter intervals.

The experiment ended on 09/10/2019 due to a high number of observed fish mortalities, and as many fish as possible were recaptured and relocated back to the habitat unit above BDA 1.0. Unlike the first trial, the water temperatures and water surface elevations in the habitat units below BDA 1.0 were not impaired during the repair work (Figure 37 & Figure 38). This was due to repairing the wing dam and redirecting water going down the side channel to go down the main channel.

During the second Sugar Creek trial from 9/06/2019-09/10/2019, I tagged 317 Coho Salmon and 25 mortalities were observed on the lower blocknet of the habitat unit where fish were released (~7.8% observed mortality rate). An additional 18 shed-tags were detected during the shed-tag wanding exercise. The fate of the shed-tag fish was unknown, so I did not include them as mortalities, but I did exclude them from my analysis. Of the 124 fish that I did not tag on the day the trial started, only 1 died during the trial (0.8% observed mortality rate) (Table 4). Of the 193 fish that I did tag, 24 died during the trial (12.4% observed mortality rate). The chi-squared test of independence suggested that there was a significant difference in survival between the recently and previously tagged individuals, X2 (1, N = 317) = 14.053, p = 0.0002. This suggests that fish marked on the same day as the experiment were more likely than previously marked fish to die. This could imply that the fish marked on the day of the experiment had lower survival and potentially reduced swimming ability. This is justification to account for marked fish during the logistic regression analysis and report the passage rates separately for two groups.

Table 4. Two-by-two contingency table comparing the survival and time of tagging of juvenile Coho Salmon during the September 2019 experiments on Sugar Creek.

	Died	Survived
Previously Marked	1	123
Marked Same Day	24	169

I fit four logistic regression models for each trial with fork length as a fixed effect and for the September 2019 trials, I included a term to account for newly-tagged fish (called the mark term below). Fork length was standardized to aid with model convergence and to reduce potential issues with multicollinearity. I excluded one fish from the September experiment that was over 100 mm, as it was clearly not part of the same young of the year cohort and might behave differently from the rest of the fish. For the first trial, the models with fork length and the models with just the intercept were all within two delta AIC scores (Table 5) and the intercept models were slightly better. For the second trial, the models that accounted for fork length and mark performed better when compared to the models with just mark (Table 5). Given the interrelatedness between the models and datasets and the relatively close delta AIC scores for the first set of trials, I included fork length in all models used for plotting figures and producing final passage estimates.

Table 5. Model selection table for the Sugar Creek passage experiments. Trial 1 refers to the experiments that were completed from 7/31/2019-8/9/2019, and Trial 2 refers to the experiments completed from 9/6/2019-9/10/2019. "Mark" indicates whether fish were marked on the same day or during a previous sampling effort. Mark was included in all of the models for Trial 2 due to the high mortality rate associated with fish marked on that day.

Experiment	*Data Subset*	*BDA(s)*	*Models*	*df*	*AICc*	*delta*	*weight*
Trial 1	**Whole Experiment**	**1.0, 1.1, & 1.2**	**Passage ~ Intercept Only**	**1**	**299.50**	**0.00**	**0.70**
	Whole Experiment	1.0, 1.1, & 1.2	Passage ~ FL	2	301.16	1.66	0.30
	Before Repairs	**1.0, 1.1, & 1.2**	**Passage ~ Intercept Only**	**1**	**368.75**	**0.00**	**0.71**
	Before Repairs	1.0, 1.1, & 1.2	Passage ~ FL	2	370.58	1.84	0.29
	Whole Experiment	**1.1, & 1.2**	**Passage ~ Intercept Only**	**1**	**269.98**	**0.00**	**0.70**
	Whole Experiment	1.1, & 1.2	Passage ~ FL	2	271.66	1.68	0.30
	Whole Experiment	**1.2**	**Passage ~ Intercept Only**	**1**	**223.43**	**0.00**	**0.70**
	Whole Experiment	1.2	Passage ~ FL	2	225.14	1.70	0.30
Trial 2	**Whole Experiment**	**1.0, 1.1, & 1.2**	**Passage ~ FL + Mark**	**3**	**132.60**	**0.00**	**0.95**
	Whole Experiment	1.0, 1.1, & 1.2	Passage ~ Mark	2	138.46	5.86	0.05
	Before Repairs	**1.0, 1.1, & 1.2**	**Passage ~ FL + Mark**	**3**	**118.73**	**0.00**	**0.93**
	Before Repairs	1.0, 1.1, & 1.2	Passage ~ Mark	2	123.88	5.15	0.07
	Whole Experiment	**1.1, & 1.2**	**Passage ~ FL + Mark**	**3**	**142.19**	**0.00**	**0.94**
	Whole Experiment	1.1, & 1.2	Passage ~ Mark	2	147.74	5.55	0.06
	Whole Experiment	**1.2**	**Passage ~ Mark**	**2**	**352.35**	**0.00**	**0.54**
	Whole Experiment	1.2	Passage ~ FL + Mark	3	352.69	0.34	0.46

There was no evidence for or against an effect of fork length on the probability of passaging all three BDAs during the first trial. This is indicated by the AICc scores that were within two points for the intercept only models and the fork length models (Table 5), in addition to the relatively flat prediction curve from the logistic regression used to predict passage of all three BDAs (Figure 42). The probability of passing each sequential BDAs was slightly lower but the relatively similar point estimates and overlapping confidence intervals between BDAs suggest that fish that passed at least one BDA were likely to pass all BDAs (Figure 43).

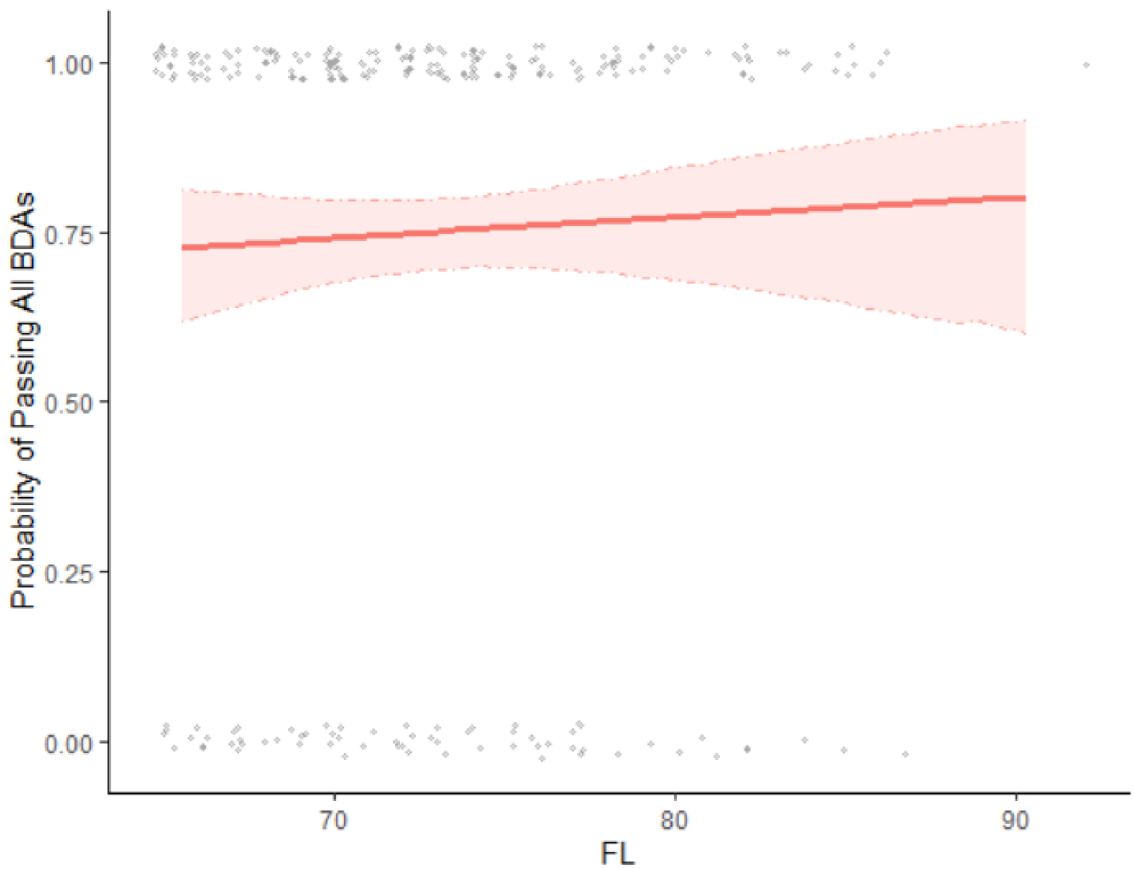

Figure 42. Response curve for the effect of fork length (FL) on passage probability for the first Sugar Creek experiment from 07/31/2019-08/09/2019. The curve was generated

from the logistic regression model that estimated passage of all the BDAs. The curve depicts the probability of passage at specific fork lengths with 95% parametric bootstrap confidence intervals (lighter background). The gray hollow circles display the observed fork lengths for fish that passed (1) and fish that did not pass (0).

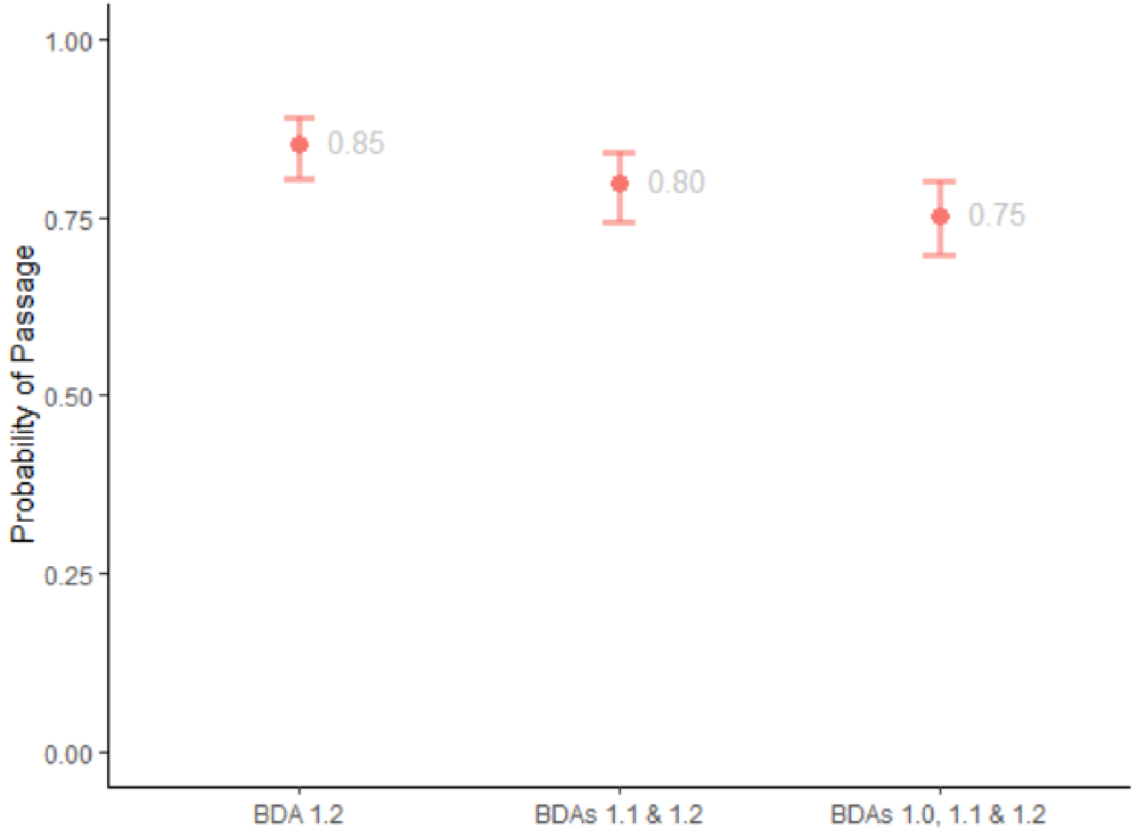

Figure 43. The probability of cumulative passage of the Sugar Creek BDAs while holding fork length fixed at its mean. The bars depict the 95% parametric bootstrap confidence intervals. Experiments were completed from 07/31/2019-08/09/2019.

For the first Sugar Creek trial, the probability of passing all three BDAs before and after the side channel was connected was comparable. The probability of passing the the BDAs was slightly higher after the side channel was connected (Figure 44), but the confidence intervals from before and after the repair largely overlapped. It is possible that fish that were not able to pass through the subsurface passageway were more able to pass when the side channel was connected.

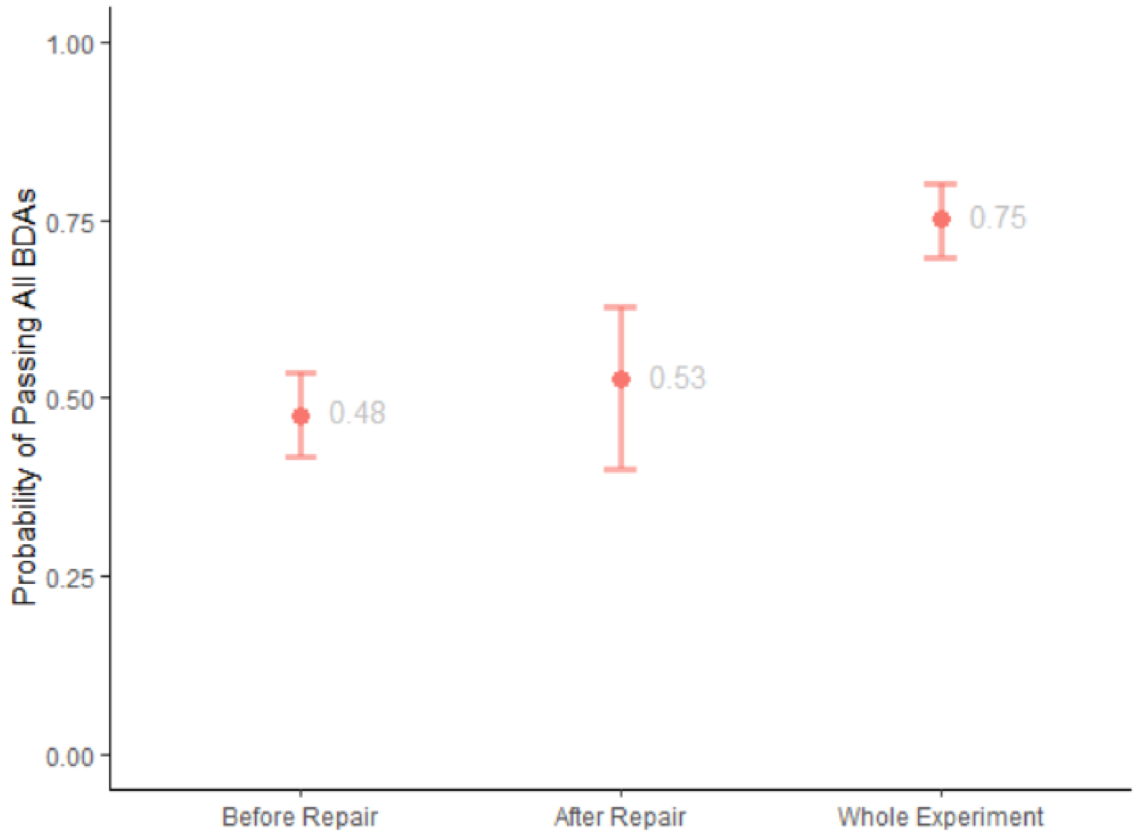

Figure 44. The probability of passaging all three of the Sugar Creek BDAs before and after the side channel was connected for the July experiment, in addition to the probability of passing the BDAs over the whole duration of the experiment. Fork length was fixed at its mean. The bars depict the 95% parametric bootstrap confidence intervals. The whole experiment and before repair models were used to estimate the probability of passage after repair by subtracting their probabilities and dividing by one minus the before repair probability, p(whole) – p(before) / (1-p(before)) = p(after). Experiments were completed from 07/31/2019-08/09/2019.

During the second trial, there was evidence that fork length and mark affected the probability of passing all three BDAs. This is indicated by the AICc scores that were lower for the models that included both terms (Table 5). For fish that were previously marked, fork length had a positive effect on fish passage (Figure 45). In comparison, fish that were marked on the same day had a much lower probability of passing the three BDAs overall, and fork length did not appear to make a meaningful impact of the probability of passage.

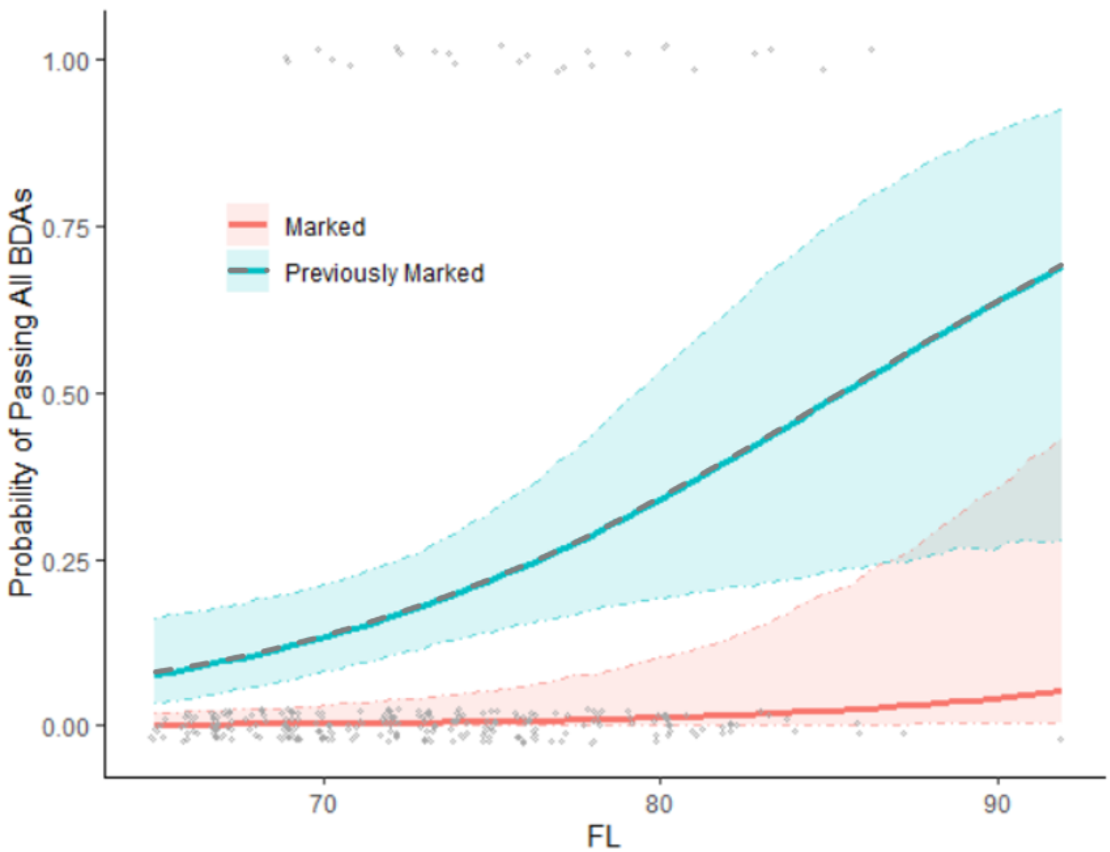

Figure 45. Response curves for the effect of fork length (FL) and mark on passage probability for the September 2019 Sugar Creek experiment. The curves were generated from the logistic regression model that estimated passage of all the BDAs for the September experiment. The curves depict the probability of passage at specific fork lengths for marked and previously marked Coho Salmon with 95% parametric bootstrap confidence intervals (lighter background). The gray hollow circles display the observed fork lengths for fish that passed (1) and fish that did not pass (0).

The passage probabilities varied between BDAs and marked cohorts. Overall, the probability of passing BDAs was much lower for the September trial compared to the first trial, but that is to be expected given the shorter duration of the experiment. The probability of passing just BDA 1.2 was comparable between the marked and previously marked cohorts, but previously marked fish had a slightly higher probability of passage (Figure 46). Passing BDA 1.1 and 1.2 was noticeably lower when compared to just passing BDA 1.2, and marked fish had a much lower passage probability for all BDAs above BDA 1.2. The passage probabilities did not differ between passing just the lower two BDAs and passing all three BDAs. This suggests that fish that were able to pass BDA 1.1 were also readily able to pass BDA 1.0. These results suggest that potentially BDA 1.2 and BDA 1.1 were limiting passage.

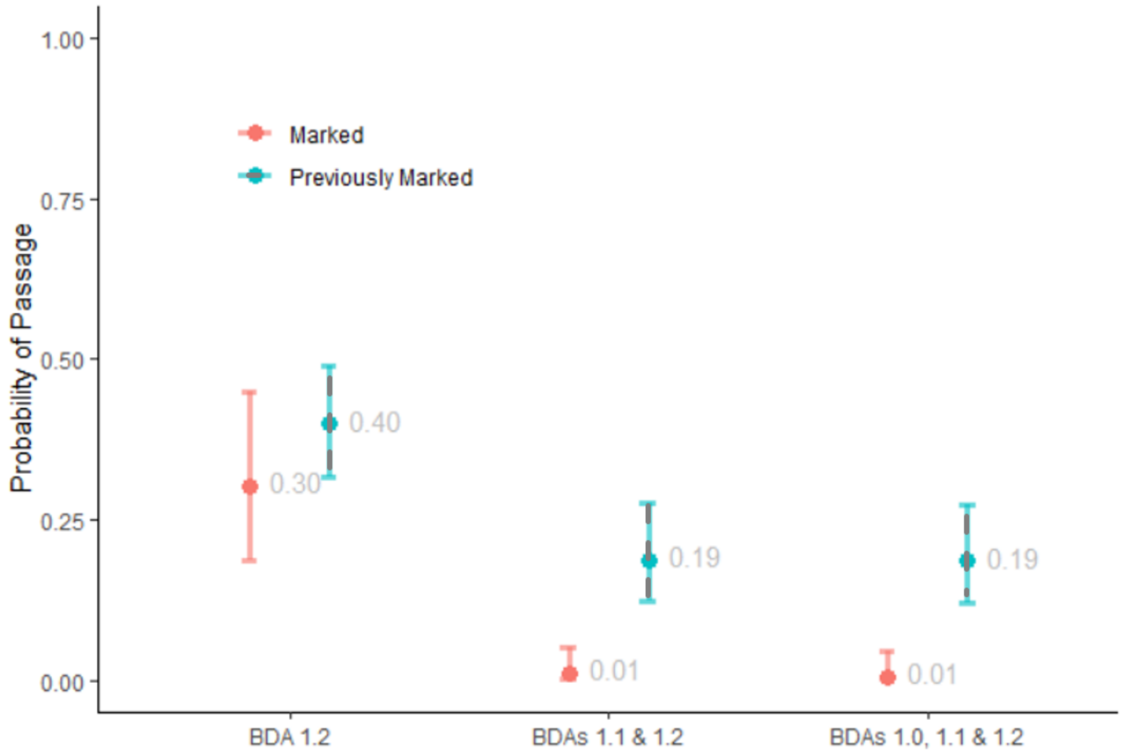

Figure 46. The probability of cumulative passage of the BDAs while holding fork length fixed at its mean and accounting for the effect of mark for the September 2019 Sugar Creek experiment. The bars depict the 95% parametric bootstrap confidence intervals.

For the second Sugar Creek trial, the probability of passing all three BDAs was higher before the side channel was reconnected (Figure 47). Due to the limited number of fish that were detected below BDA 1.0 (Figure 32), it makes sense that few fish passed after the repair to BDA 1.0 if there was a BDA downstream that was limiting passage. Previously marked fish had a much higher probability of passing the BDAs throughout the entire experiment.

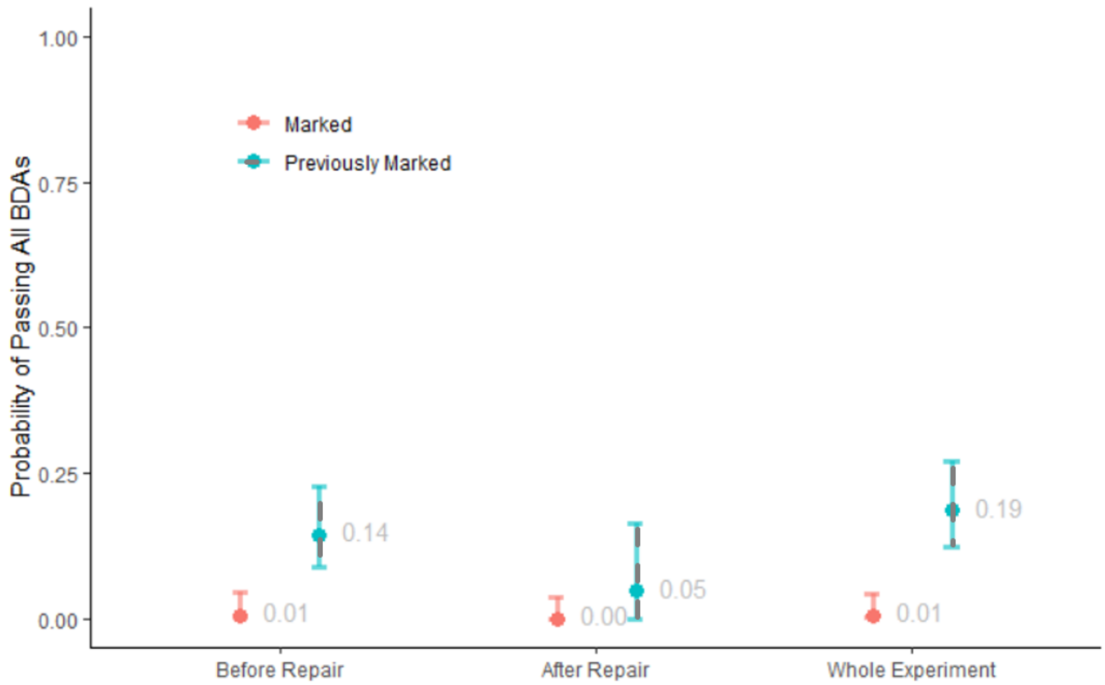

Figure 47. The probability of passing all three of the BDAs before and after the side channel was connected, in addition to the probability of passing the BDAs over the whole duration of the September Sugar Creek experiment. The marked and previously marked cohorts for the September experiment are plotted separately. Fork length was fixed at its mean. The bars depict the 95% parametric bootstrap confidence intervals. The whole experiment and before repair models were used to estimate the probability of passage after repair by subtracting their probabilities and dividing by one minus the before repair probability, p(whole) – p(before) / (1-p(before)) = p(after).

Hatchery Experiments

A total of 743 of the 800 released individuals (~93%) were successfully recaptured after the 16 jump trials. Across all treatments, 52% of the fish were able to pass the jumping structures during the one-night trial periods. Fish were observed passing all four of the different treatments, but at different rates (Table 6). In general, when the jump height increased, fewer juvenile steelhead were able to pass the structures. In addition, as steelhead became larger over the study period, passage rates increased.

Table 6. Contingency table with summaries of juvenile steelhead passage for the four jump trials combined. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020. Above and Below indicate recapture location- fish recaptured Above the barrier passed the BDA. The column headers describe the treatment types (jump height and material of the BDA).

	24 cm, Board	34 cm, Board	40 cm, Willow	44 cm, Board	**Total**
Below	44 (24%)	81 (45%)	115 (58%)	117 (64%)	**357**
Above	139 (76%)	98 (55%)	82 (45%)	67 (36%)	**386**
Total	**183**	**179**	**197**	**184**	**743**

During the first week of the trials from 06/01/2020-06/05/2020, the raceway discharge, crest depth and water temperatures were noticeably lower from the rest of the trials, but after the first week of the jump tests, the physical parameters appeared to stabilize (Table 7). The juvenile steelhead fork lengths steadily increased throughout all of the experiments, and the standard deviation of fork lengths also increased (Table 7). There were three trials when a considerable number of steelhead trout were not recaptured, as they likely escaped through tiny openings between the downstream net screen and the raceway edges. Because the fate of the non-recaptured fish was unknown, success rate was based only on recaptured fish.

Table 7. Summary of the parameters for the hatchery jump trials. Each row represents a specific trial and the columns summarize the physical parameters, fork length (FL) mean and standard deviations (SD), and the passage results. The number in the “Type” column indicates the jump height (mm) and a ‘W’ indicates that woven willows were utilized for that trial and B indicates that a board was used for the weir crest. A total of 50 juvenile steelhead trout were released at the start of each trial, but some were not recaptured or some escaped the study area.

Week	Sample	Type	Discharge, CMS	Crest Depth, cm	H20 Temp, °C	Fish Mean FL, Mm	Fish SD FL, mm	Fish Recaptured, Total	Fish Above, Total	Fish Below, Total	Fish Success, Rate
1	1	40 cm, W	0.003	0.4	14.9	53	4	49	0	49	0
1	2	44 cm, B	0.004	3	14.7	54	4	46	0	46	0
1	3	24 cm, B	0.004	3.4	15.2	56	3	39	27	12	0.69
1	4	34 cm, B	0.004	2.6	16	56	5	31	2	29	0.06
4	13	34 cm, B	0.008	3.3	16.6	61	7	50	24	26	0.48
4	14	44 cm, B	0.007	4.1	17.1	62	7	50	6	44	0.12
4	15	24 cm, B	0.008	3.7	16.8	62	7	50	30	20	0.6
4	16	40 cm, W	0.008	0.3	16.7	63	7	50	15	35	0.3
6	21	34 cm, B	0.008	3.7	16.2	70	7	50	29	21	0.58
6	22	24 cm, B	0.008	3.8	16.8	72	9	49	43	6	0.88
6	23	40 cm, W	0.007	0.6	16.9	73	8	49	35	14	0.71
6	24	44 cm, B	0.007	3.7	16.8	73	8	40	24	16	0.6
8	29	44 cm, B	0.008	3.8	16.1	82	7	48	37	11	0.77
8	30	34 cm, B	0.008	4	16.5	83	8	48	43	5	0.9
8	31	24 cm, B	0.008	3.8	16.2	80	8	45	39	6	0.87
8	32	40 cm, W	0.008	0.4	16.3	84	10	49	32	17	0.65

Passage success ranged by trial from 0-90%, and noticeably increased for three of the four trial types throughout the experiment (Figure 48). The lowest jump height of 24 cm did not appear to significantly limit juvenile steelhead passage at any period throughout the experiments, while the other three trials appeared to have reduced passage during earlier trials when fish were small (Figure 48). Larger steelhead on average were more successful at passing all of the BDA trials (Figure 49).

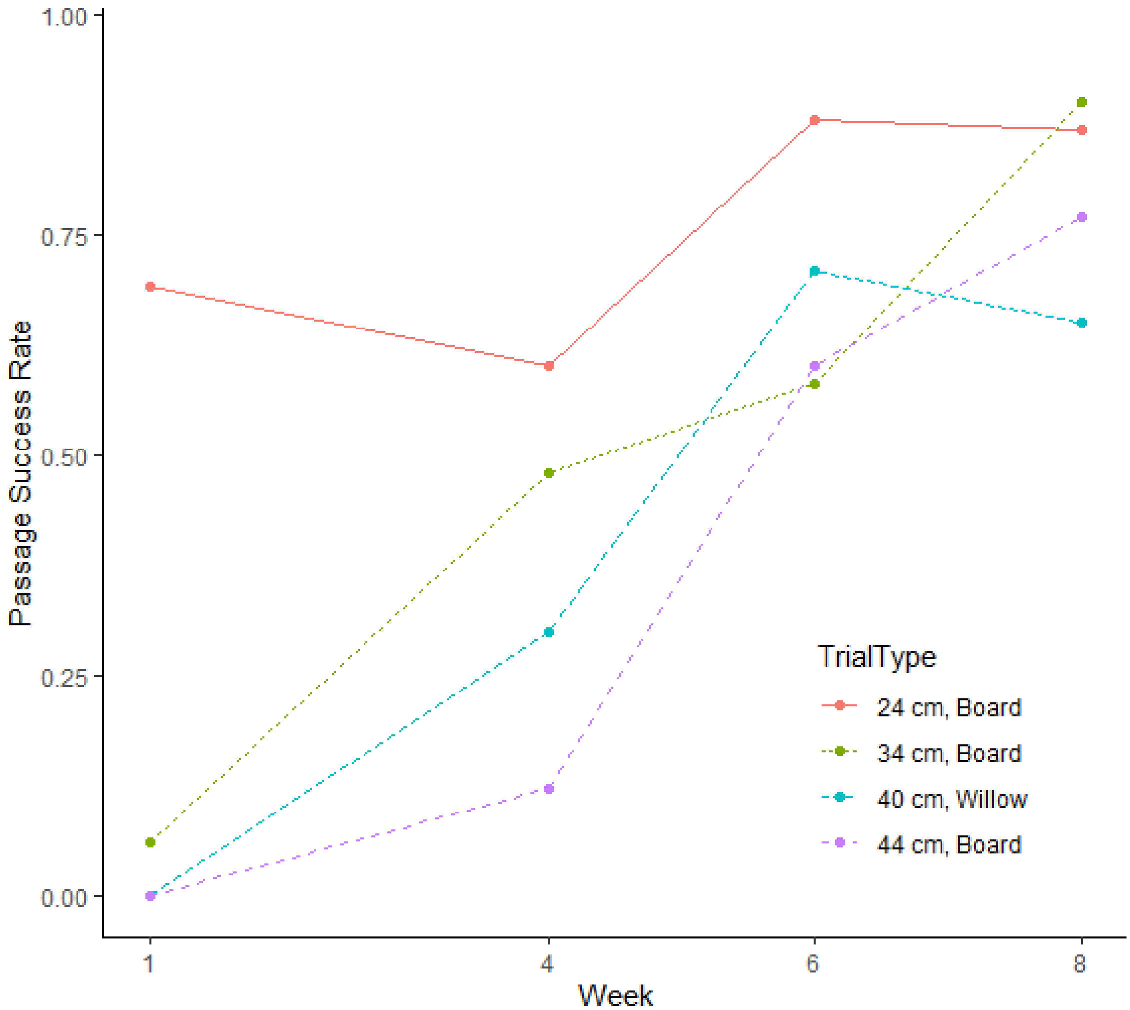

Figure 48. Passage success rate by week for the four different jump trial types. Each line depicts a different trial type, and each point represents a sample period. The jump tests were completed on weeks 1, 4, 6, and 8. The order of the graph at week 4 matches the order of the legend. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

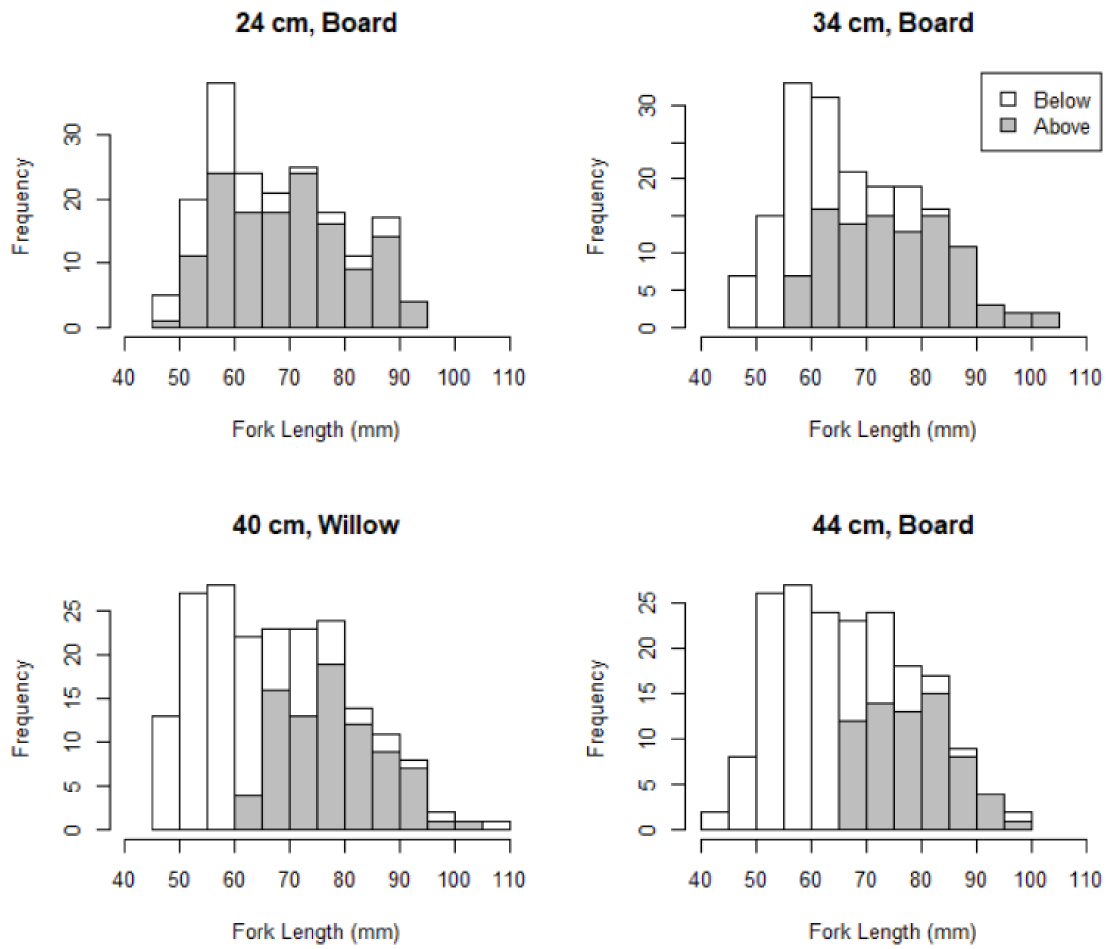

Figure 49. Histogram depicting passage frequencies by fork length for the jump experiment trial types. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

The woven willow treatment did not appear to make a significant difference in passage compared to the 34 cm and 44 cm treatments. When the woven willow insert was placed on top of the 30 cm weir crest, the jump point was 40 cm, so it was not surprising that the passage rate for the woven willow trials was on average between the 34 cm and 44 cm trials (Table 6 and Figure 48).

I fit a mixed-effects logistic regression model with trial, fork length, fork length squared, and water temperature as fixed effects and sample as a random effect. The model-averaged variance for the random effect of sample was 0.51. A Loess diagnostic plot suggested non-linear effects associated with fork length, and as a result, I included a polynomial term for fork length to the model to address the violation of linearity. All continuous variables were standardized to aid with model convergence and to reduce potential issues with multicollinearity. Two of the 16 possible model combinations were within two delta AICc scores (Table 8). These two top models included (1) the global model with all aforementioned terms and (2) the global model that excluded water temperature. These two models accounted for 0.994 of the model weights (Table 8). The top models were used to calculate model-averaged odds-ratio parameter estimates (Table 9). The trial with the lowest jump height (24 cm, Board) had the highest passage rate as was therefore used as the reference group. Fish in the 24 cm jump trial type had much higher odds of passing the BDA structures compared to all other trials (Table 9). The model-averaged parameter estimates were used to calculated the probability of passage for each trial type (Figure 50).

Table 8. Model selection table for the hatchery jump experiments. Bolded models were within 2 delta AIC scores and were used to calculated model averages for the odds-ratio parameter estimates. The zFL indicates the standardized fork length. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

model	*df*	*AICc*	*delta*	*weight*
Passage ~ Trial + zFL + zFL^2	**7**	**640.930**	**0.000**	**0.656**
Passage ~ Trial + zFL + zFL^2 + zWater Temp	**8**	**642.254**	**1.324**	**0.338**
Passage ~ zFL + zFL^2	4	651.168	10.238	0.004
Passage ~ zFL + zFL^2 + zWater Temp	5	652.415	11.485	0.002
Passage ~ Trial + zFL + zWater Temp	7	662.919	21.989	0.000
Passage ~ Trial + zFL	6	664.352	23.422	0.000
Passage ~ zFL + zWater Temp	4	672.624	31.694	0.000
Passage ~ zFL	3	672.938	32.007	0.000
Passage ~ zWater Temp	3	765.668	124.737	0.000
Passage ~ Trial + zWater Temp	6	766.244	125.314	0.000
Passage ~ zFL^2 + zWater Temp	4	767.619	126.689	0.000
Passage ~ Trial + zFL^2 + zWater Temp	7	768.251	127.320	0.000
Passage ~ 1	2	769.796	128.866	0.000
Passage ~ zFL^2	3	771.656	130.726	0.000
Passage ~ Trial	5	771.894	130.963	0.000
Passage ~ Trial + zFL^2	6	773.793	132.862	0.000

Table 9. Summary table for the abundance and passage rates for each trial. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020. The weighted averages for the odds-ratio (OR) parameter estimates and their 95% confidence intervals. The 24 mm, Board Trial was used as a reference group due to having the highest passage rate.

Predictors	*N*	*Below*	*Above*	**OR*	*LCI*	*UCI*
24 cm, Board	183	44	139	Ref	Ref	Ref
34 cm, Board	179	81	98	0.189	0.058	0.610
40 cm, Willow	197	115	82	0.074	0.022	0.247
44 cm, Board	184	117	67	0.053	0.016	0.182
zFL	--	--	--	8.653	5.724	13.082
zFL^2	--	--	--	0.543	0.430	0.686
zTemp	--	--	--	1.257	0.723	2.185

**OR (odds ratio) for the averaged parameters*

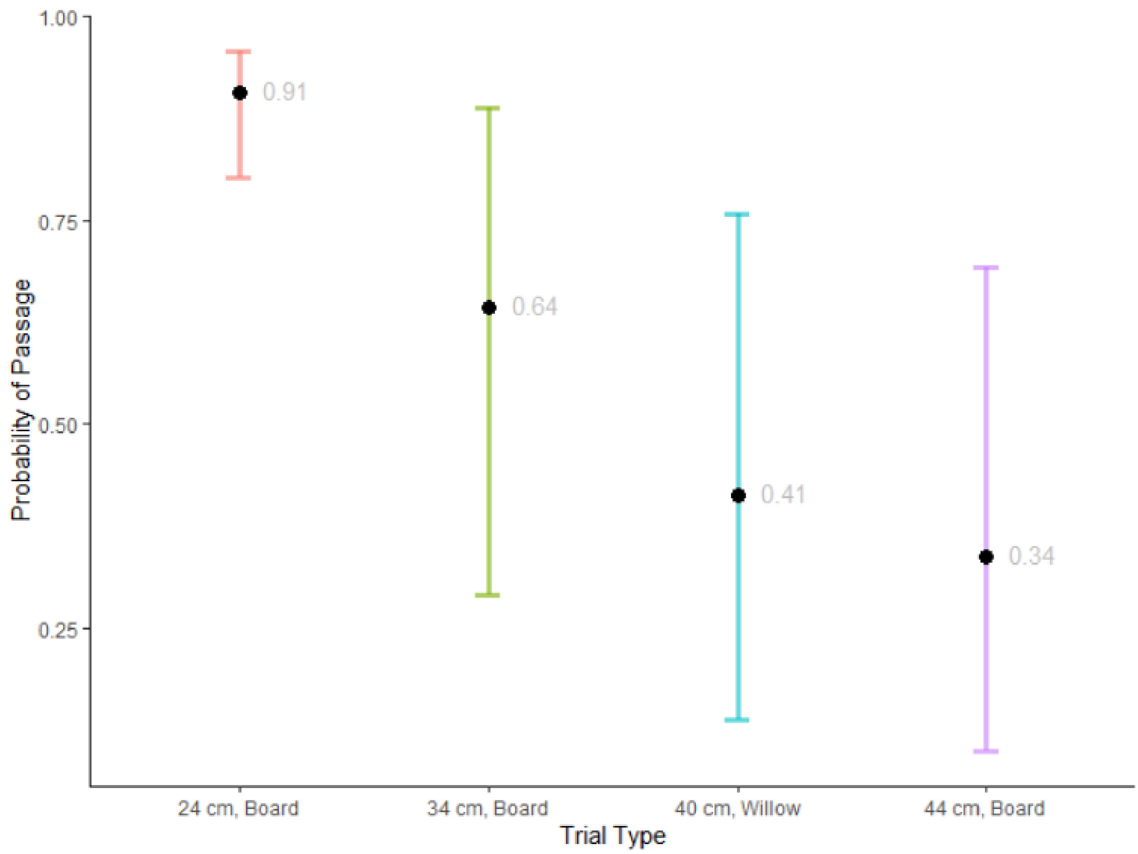

Figure 50. The probability of passage for trial type based on the model-averaged parameter estimates while holding the additional fixed effects at their mean. The bars depict the 95% parametric bootstrap confidence intervals. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

The fork length and polynomial fork length terms appeared in both of the best models (Table 8), and neither of the term's 95% confidence intervals overlapped with 1, suggesting fork length is a significant predictor of passage for this dataset (Table 9). The effect of fork length on passage varied between trial (Figure 51). The model-averaged odds-ratio parameter estimate for fork length was 8.7, while the estimate for the polynomial fork length term was 0.5 (Table 9). The LOESS diagnostic plot (Figure 52) and these model estimates imply that there is not a simple positive or linear relationship between passage and fork length. However, I suspect much of the non-linearity can be explained by data sparsity for the larger size classes in which just a few of the larger individuals did not pass the higher treatments but accounted for a significant proportion of the fish in that size class (Figure 52). I hypothesize that this non-linear relationship in the data is not ecologically or biologically based, but rather a function of the limited number of larger individuals and a few of them just randomly did not pass.

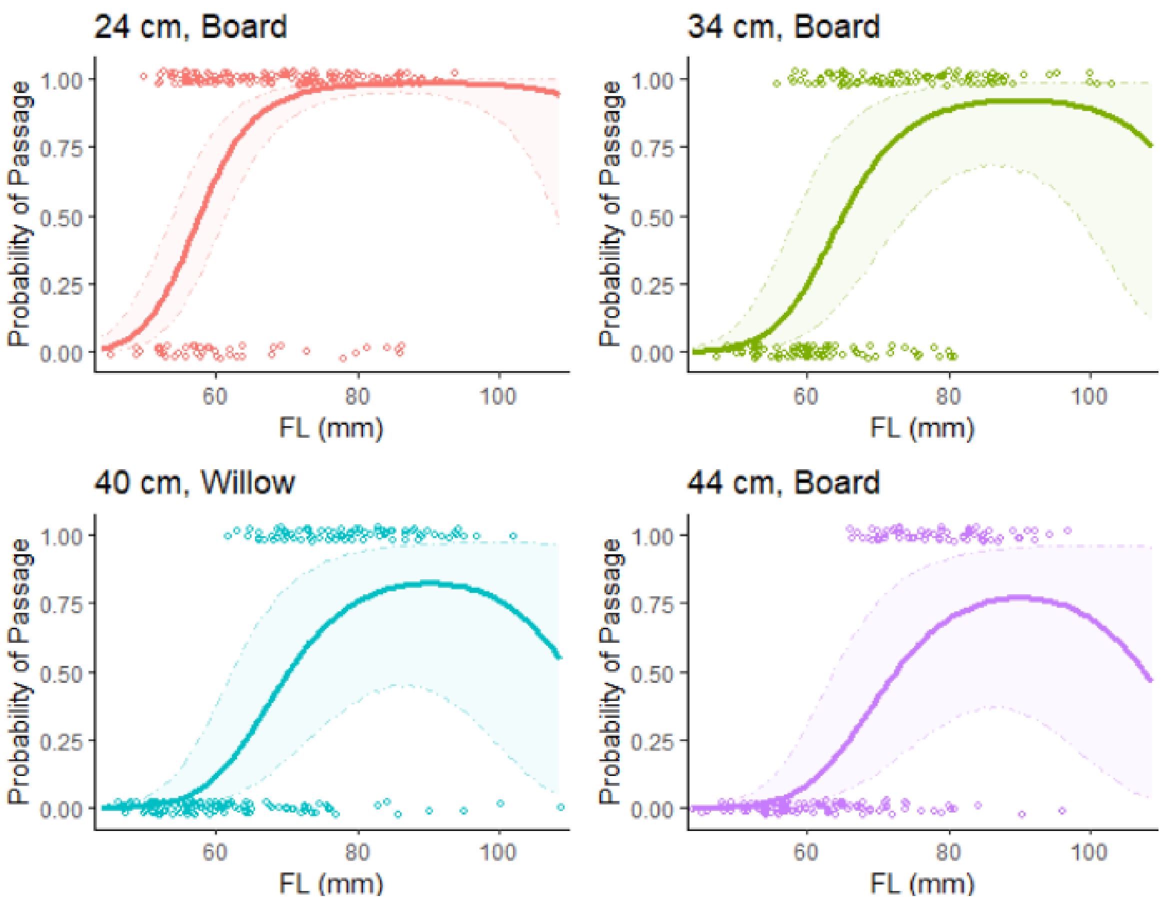

Figure 51. Response curves for the main effect of fork length (FL) on passage probability for the averaged optimal models. Each curve depicts the probability of passage at specific fork lengths for the different trial types with 95% parametric bootstrap confidence intervals (lighter background) while all other variables are held at their mean value. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

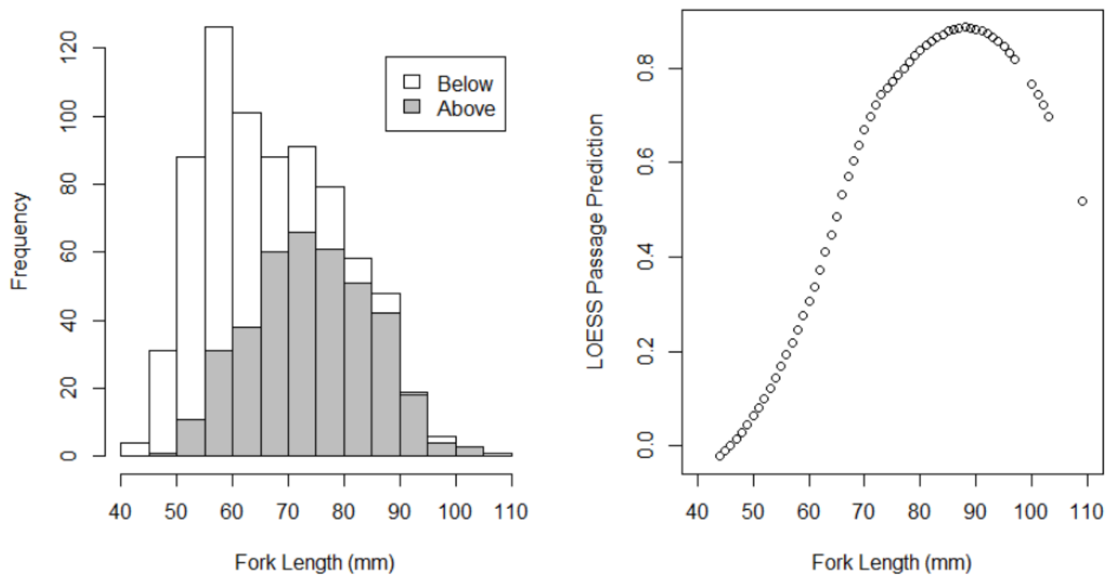

Figure 52. Stacked histogram of fork lengths for all jump trials, with passage indicated as below or above (left panel). LOESS plot depicts a smoothed line of how the average value of passage changes with fork length (right panel). On the left panel, note the data sparsity around 95 mm with a few fish that did not pass and how significantly that affects the LOESS passage prediction curve. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

The water temperature odds-ratio estimate was 1.3, however, the 95% confidence intervals overlapped with 1, suggesting it was not an informative predictor of passage for this dataset. I suspect this might be caused by the limited range in water temperature (14.7 °C–17.1 °C) during the trials. When plotting the passage frequencies by water temperature, there seems to be no real signal between temperature and passage for this dataset (Figure 53).

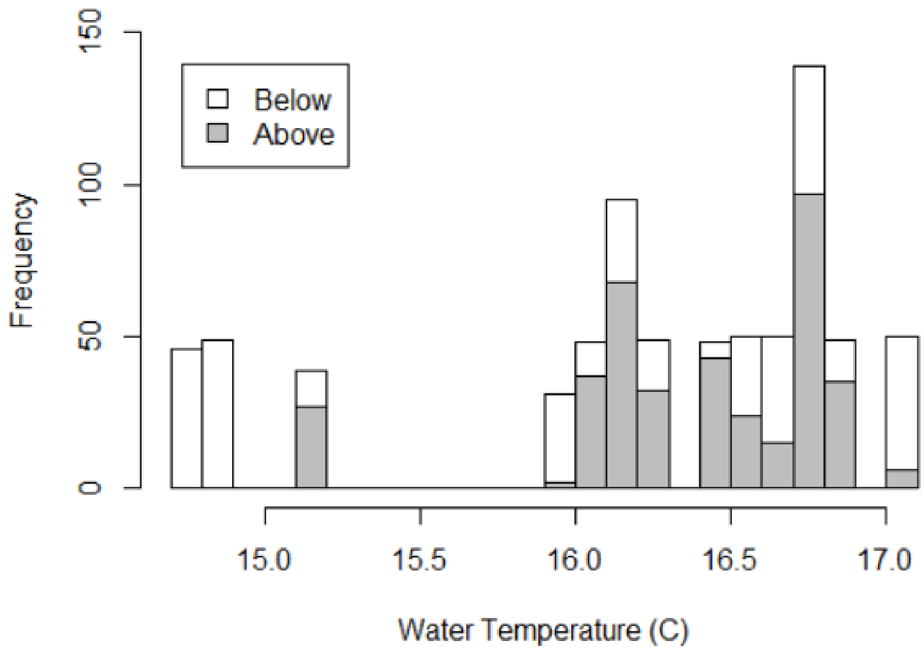

Figure 53. Stacked histogram of water temperature for all jump trials, with passage indicated as below or above. Note the minimal amount of variation in water temperature.

A total of 595 of the 600 released individuals (~99%) were successfully recaptured after the 12 subsurface trials but only about 5% of the fish were able to pass the subsurface structures. Fish were only observed passing three of the 12 treatments. No fish were observed passing the treatments with the deeper pipe depth (57.0 cm) (Table 10).

Table 10. Contingency table with summaries of juvenile steelhead passage for the four different subsurface trials combined. The number in the top row indicates the depth of the pipe below the upstream water surface, while the text indicates whether the material in the pipe was branches or twigs. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

	17.6 cm, Branch	17.6 cm, Twig	57.0 cm, Branch	57.0 cm, Twig	**Total**
Below	127 (86%)	140 (94%)	150 (100%)	149 (100%)	**566**
Above	20 (14%)	9 (6%)	0 (0%)	0 (0%)	**29**
Total	**147**	**149**	**150**	**149**	**595**

The downstream pipe velocity was largely determined by the upstream water depth and the material inside the pipe and velocities varied very little within each trial type (Figure 54). The water temperature fluctuated between the trials but stayed within 1.2°C over the duration of the trials (Table 11). The juvenile steelhead grew steadily throughout all of the experiments, and the standard deviation in fish growth also increased (Table 11). Overall, passage success rate was very low among all the subsurface trials (Table 11 & Figure 55). There may be some signal that fish passage is slightly higher for steelhead between 60 mm and 80 mm for these specific treatments (Figure 56). However, there does not appear to be any strong trends in the physical measurement covariates associated with fish passage.

Table 11. Summary of the parameters for the hatchery subsurface trials. Each row represents a specific trial and the columns summaries the physical parameters, fork length (FL) mean and standard deviations (SD), and the passage results. The information in the "Type" column indicates the subsurface pipe depth (mm) and the material used inside the pipe for that trial. A total of 50 juvenile steelhead trout were released at the start of each trial, but some were not recaptured or some escaped the study area.

Week	Sample	Type	Discharge, CMS	Pipe Velocity, m/s	H20 Temp, °C	Fish Mean FL, mm	Fish SD FL, mm	Fish Recaptured, Total	Fish Above, Total	Fish Below, Total	Fish Success, Rate
5	17	17.6 cm, Twigs	0.0075	0.28	16.5	67	6	50	0	50	0
5	18	57.0 cm, Twigs	0.0077	0.42	16.2	68	9	50	0	50	0
5	19	57.0 cm, Branches	0.0077	0.63	16	72	7	50	0	50	0
5	20	17.6 cm, Branches	0.008	0.39	16.3	72	8	47	16	31	0.34
7	25	17.6 cm, Branches	0.0075	0.39	16.1	75	6	50	4	46	0.08
7	26	57.0 cm, Branches	0.0078	0.6	16.8	79	9	50	0	50	0
7	27	57.0 cm, Twigs	0.0077	0.43	16.5	80	8	49	0	49	0
7	28	17.6 cm, Twigs	0.0077	0.27	17.2	82	9	49	9	40	0.18
9	33	57.0 cm, Twigs	0.008	0.47	16.4	92	8	50	0	50	0
9	34	57.0 cm, Branches	0.0078	0.63	17.1	94	8	50	0	50	0
9	35	17.6 cm, Branches	0.0075	0.32	16.5	93	9	50	0	50	0
9	36	17.6 cm, Twigs	0.007	0.29	16.6	94	9	50	0	50	0

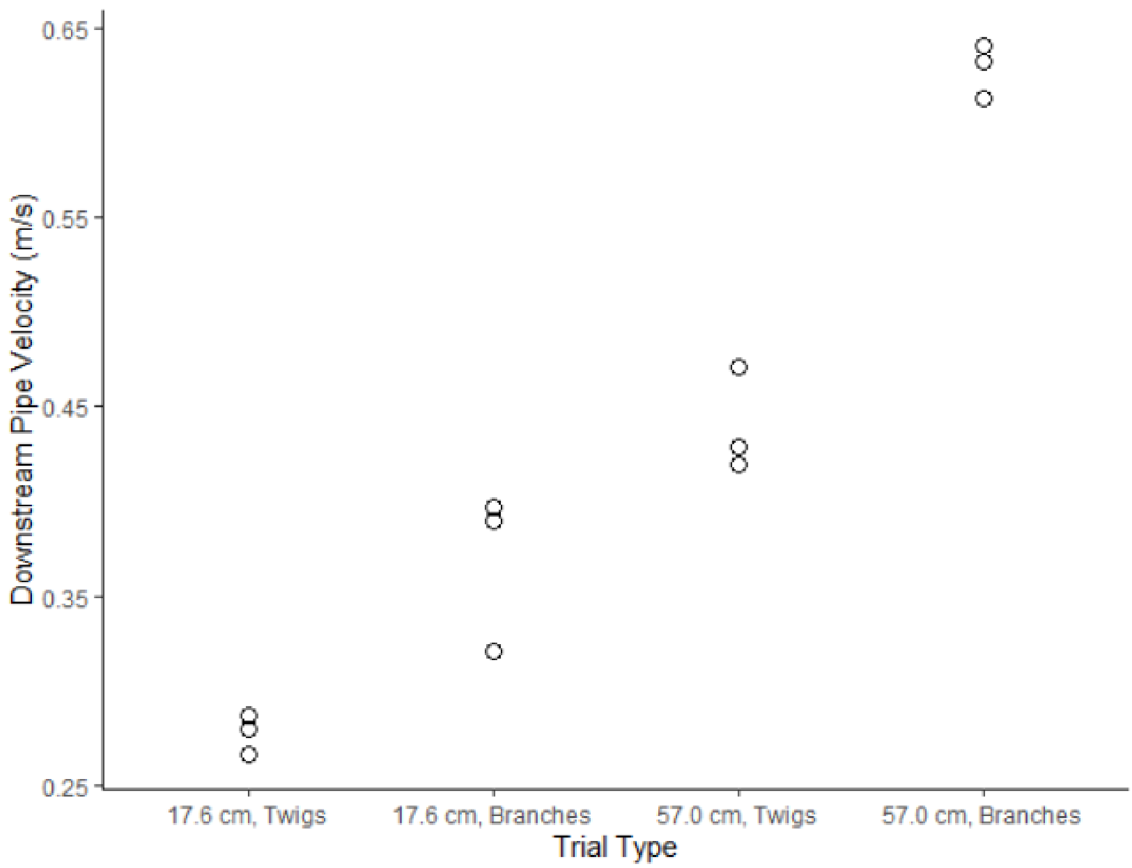

Figure 54. Measured downstream pipe velocity plotted by trial type. The downstream pipe velocities were measured at the outflow of the PVC pipe. Points were jittered vertically slightly to display overlapping points. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

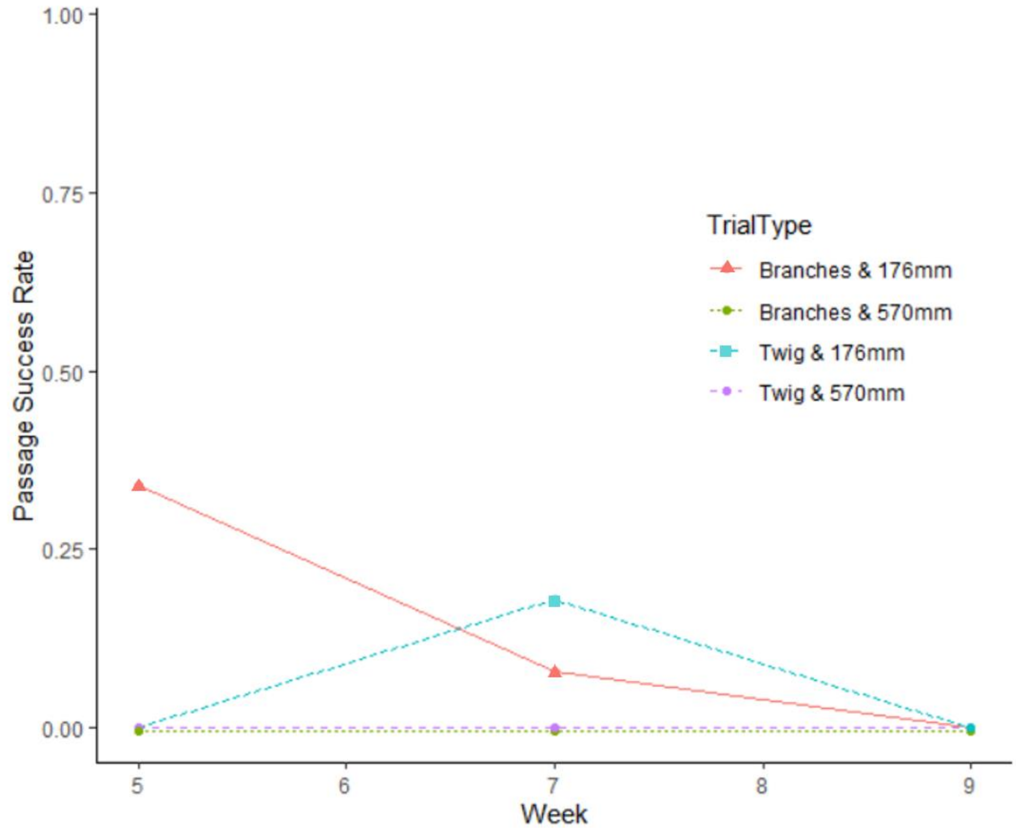

Figure 55. Passage success rate by week for the four different subsurface trial types. Two of the trial types had zero successful passage attempts throughout all trials. Points and lines were jittered to display overlapping data. These trials were conducted on weeks 5,7, and 9 of the summer experiments. Trials were completed at the HSU Fish Hatchery from 06/01/2020-07/24/2020.

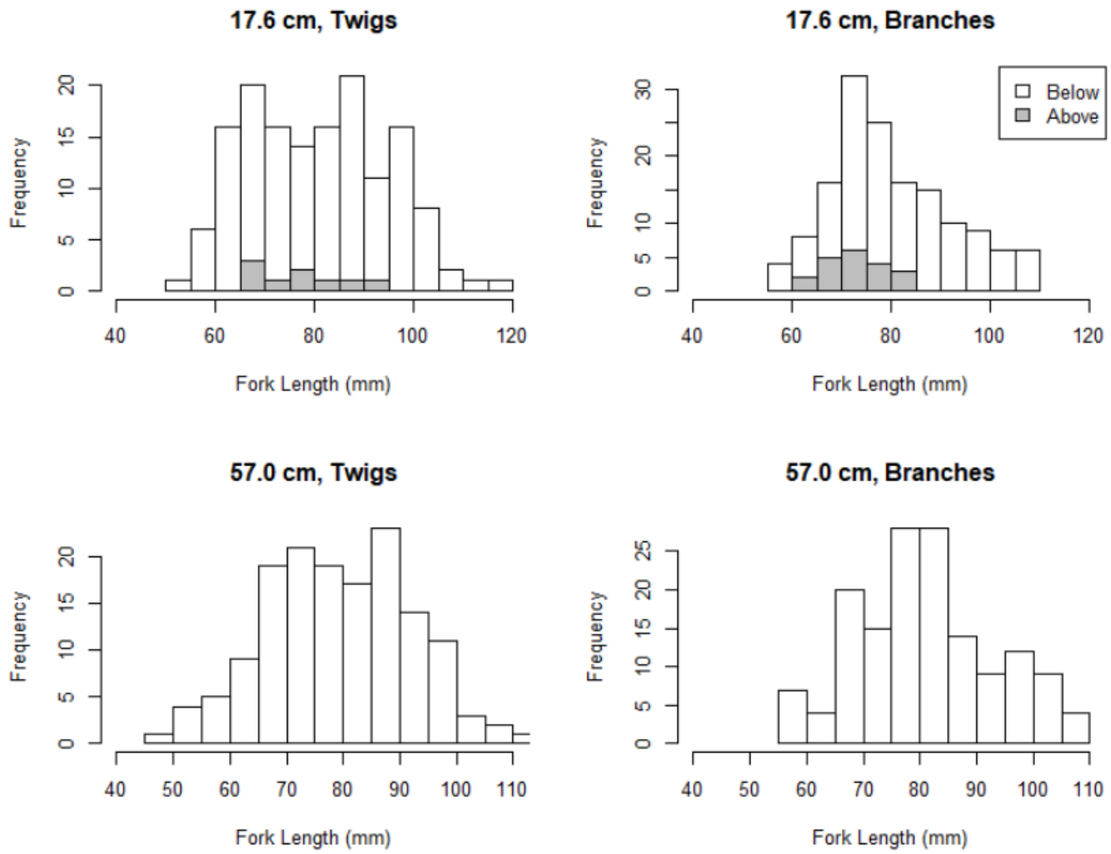

Figure 56. Histogram depicting passage frequencies by fork length for the subsurface experiment trial types.

DISCUSSION

In recent years, researchers studying stream restoration and ecology have discovered the importance of beaver dams to the persistence and resilience of native fauna and flora (Lundquist 2016; Nickelson et al. 1992; Leidholt-Bruner 1992; Pollock, Heim, and Werner 2003; Green and Westbrook 2009). As a result, restoration practitioners have begun installing BDAs to mimic and take advantage of the many benefits of natural beaver dams (Pollock et al. 2015). However, there are many claims that beaver dams and BDAs have negative impacts on fish by blocking fish passage (Bouwes et al. 2016). My research took aims at understanding fish passage as it relates to BDAs, and I gained valuable insights into the various elements that dictate passage.

Fish passage behavior is a combined outcome of the environmental conditions, physical characteristics of the BDA, the abilities of the fish, and the motivation of the fish. I found that environmental conditions, especially stream flow, can have a significant influence on the probability of fish passage. In general, with adequate stream flow conditions, the BDAs I examined allowed for juvenile fish passage. The physical characteristics of the BDA including the construction, configuration, and composition varied greatly by BDA. The interaction between the physical BDA characteristics and the environmental conditions seemed to play a role in limiting some passage. During the hatchery experiments when the flow conditions were held relatively constant, the abilities of the fish to pass the BDAs seemed to increase as the fish grew in size, but ultimately, in the field experiment, fish ability could not overcome the flow limitations. The motivation of the fish was not something I was able to tease apart from these other factors during the experiments. Similarly, fish preference for specific habitats might also have played a part in my results. During the early season Miners Creek experiments, fish might prefer the downstream habitat due to more cover in the form of depth, downstream bubble curtain, and structure, which might artificially decrease the observed passage rates. In other words, some fish may have made it to the upstream habitat unit then moved back down to the lower unit for better cover and those fish would not have been counted as passing the BDAs. However, understanding juvenile salmonids' motivation and to move and preference for specific habitats can help with interpretation of passage results. Motivation to move is often fueled by benefits and costs related to growth and survival (Einum et al. 2012). Primary benefits to move may include finding more suitable habitat and reduced competition and avoid predation, while some costs might include increased predation during the transition period. Additionally, by placing the juvenile Coho Salmon in shallower, faster moving habitats during my Sugar Creek experiments, it was likely that their motivation to move was increased due to their preference for slow water habitats (Bisson, Sullivan, and Nielsen 1988). During the hatchery experiments, I used GoPro cameras to capture passage attempts and I often documented well over 100 attempts per hour, suggesting that they were motivated and interested in jumping up the waterfall.

The early season Miners Creek experiments provided some insight about smaller juvenile Coho Salmon jumping abilities. During the Miners Creek experiments, juvenile Coho Salmon were about 55 mm in fork length on average and were able to successfully pass BDAs with jump heights that ranged from 20 cm to 36.5 cm. The percentage of fish that successfully passed ranged from 73% for the two combined 20 cm jumps, 79% for the 33 cm jump, to 75% for the 36.5 cm jump, however the uncertainty around these estimates is very large due to the high number of fish that escaped and the resulting low sample size. No previous studies have examined passage for juvenile Coho Salmon less than 65 mm. However, assuming these estimates are in the appropriate range, the passage rates I observed are notably higher than previous work completed with Coho Salmon greater than 65 mm (Symons 1978; Mueller et al. 2008). Other studies have estimated juvenile Coho Salmon passage for a 20 cm jump to be in the range of 17-20% (Symons 1978; Mueller et al. 2008), however the Mueller study was also including the fish successfully swimming through a culvert. The closest experiment in design and results to this study was the 2017 Warm Springs Hatchery jump tests with hatchery Coho Salmon, where they found that approximately 50% of the smallest class size (~70 mm) passed a 30 cm jump in a 24 hour trial (White et al. 2018). It is hard to speculate due to the high degree of uncertainty during the Miners Creek experiments, but the ability for the Miners Creek Coho Salmon to jump higher in comparison to these other studies might be due to their wild genetics. Further, the fact that 55 mm Coho Salmon were able to jump 36.5 cm, supports Pollock's (2019) observation that 47% of the tagged juvenile Coho Salmon choose to leap a 38-40 cm waterfall even when they had the option to use a side channel. Unlike the White et al. (2018) study, but similar to the Mueller study, fork length was not a good predictor of passage at Miners Creek. This might be due to the narrow range of fork lengths for the Miners Creek experiments, where the range of fork lengths was 46-66 mm. Based on the four Miners Creek trials, it is also likely that other physical factors such as velocity and depth at the spill crest could affect the probability of fish passage. Due to the limited number of trials, I was unable to test additional physical factors.

The hatchery experiments provided a more robust examination of jumping ability. I used hatchery steelhead trout for these experiments, as Coho Salmon were not available. It is important to note that the leaping ability of the hatchery fish may not be comparable to fish in the wild due to hatchery selection and rearing procedures (Duthie 1987). During the hatchery jump tests, juvenile steelhead trout were able to consistently pass 24 cm jump heights with passage success of around 75%, while higher jump heights were more achievable as fish increased in size. By the end of the experiment, when steelhead trout were at their maximum size of about 80 mm on average, the four jump treatments of 24 cm, 34 cm, 40 cm and 44 cm, had fairly comparable passage success rates. These findings are consistent with White et al. (2018) observation; they found that the about 80% of all juvenile steelhead trout passed a 15 cm jump height, while the passage of a 30 cm jump height started out low and increased until fish were around 100 mm, at which point the fish passed either barrier at comparable rates (Figure 57). In the White et al. (2018) study, the size of the fish used for the 15 cm jump height had a much smaller fork length range (~80-130 mm) than the 30 cm jump (~60-150 mm) (Figure 57). Since fish smaller than 80 mm were not tested during the 15 cm jump, it is not possible to infer passage differences between the two treatments for smaller sized fish. White et al. (2018) concluded that fish ≤ 60 mm in fork length may not be able to pass jump heights around 30 cm. In 2019, research examining California's hydrological conditions (Lang and Love 2014) and juvenile fish leaping ability (White 2019) fueled the National Marine Fisheries

Service to make the decision to change the maximum hydraulic drop over a weir from no greater than 21 cm to 30 cm (National Marine Fisheries Service 2019). Based on my hatchery research and what White et al. found in 2018 the decision is potentially less conservative than the previous metric and may limit fish passage for smaller steelhead trout. However, it seems like the jump height that starts to limit movement of very small steelhead trout early in their first spring is somewhere in the 24 to 30 cm range.

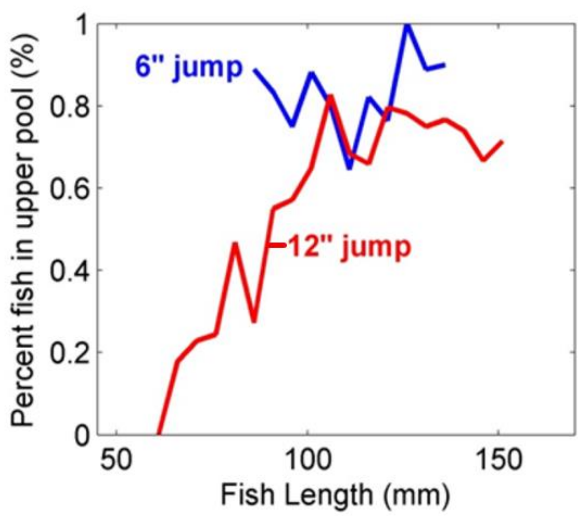

Figure 57. Percentage of steelhead trout that were in the upper pool plotted against the average fork length for each trial for Warm Springs Fish Hatchery fish leaping experiment (Source: White 2018).

The hatchery experiments also shed some light on whether flow complexity at the weir crest and jump point affects fish passage. To my knowledge, no other studies have looked at how an obstructed weir crest impacts juvenile salmonids leaping ability. My experiments suggest that the willow branches did not inhibit the ability of fish to make it into the upstream habitat unit. This was evident because the willow treatment jump height

(40 cm) was about halfway between two treatments without willow (34 cm and 44 cm), and the probability of passage for the willow treatment was on average, in between the two non-willow treatments. However, I only completed four replicates of one set of conditions where the flow remained relatively constant at a jump height of about 40 cm tall and the upstream to downstream width of the willow weaves was only about 8 cm. More research is needed to fully understand how fish passage might change at different levels of these and other factors.

The low-flow experiments conducted on Sugar Creek had mixed results in regards to passage after the fish passage side channel was reconnected. No other studies have directly compared the probability of fish passage with and without access to a side channel. I was unable to identify guidelines for suitable length or slope of side channels embedded with cobbles. In general, most research focused on slope and length is in regards to culverts, where the recommended slopes should be close to zero or similar to the stream gradient (National Marine Fisheries Service 2011; Washington Department of Fish and Wildlife 2009). After the reconnection of the side channel during the first Sugar Creek experiment, there was a significant increase in fish passage, where about 60% of the fish passed in a four-day period. With the current dataset, it is hard to determine whether fish moved due to the deteriorating habitat conditions below BDA 1.0 (motivation), because the side channel was easier to navigate in comparison to the subsurface passageways (passability), or potentially a combination of both factors. It is likely that the increased water temperature and the reduced surface water would trigger fish to move, as fish are often cued by both of these factors to move (Lawrence 2007;

National Engineering Handbook 2007). Regardless of the hypotheses as to why fish moved, the spike in passage over the last four days of the experiment suggests the fish passage side channel provided a pathway that allowed for a significant number of fish to pass the BDA. During the second Sugar Creek experiment, only about 4% passed after the fish passage side channel was connected. However, only a limited number of fish were documented below BDA 1.0, which makes it challenging to draw conclusions about side channel passage from the second experiment. My first experiment on Sugar Creek supports what Pollock (2019) found when he observed juvenile salmonids readily able to pass side channels that were 8 m long with slopes of up to 11% and embedded with cobbles. Based these studies, it does seem like side channels with the aforementioned conditions can adequately facilitate fish passage.

One concern related to fish passage side channels that came up during the experiments, is whether the narrow passageway potentially creates a hotspot for predators to capture migrating fish. Engineered fish passage structures often cite a similar problem with avian and mammalian predation where fish are concentrated to a single passageway (National Engineering Handbook 2007). During the Sugar Creek passage experiments, I documented a heron taking a juvenile steelhead trout from a garter snake at the head of the side channel (Figure 58), and I regularly saw herons staged at that same location. Predation is often cited as a cost associated with dispersal movements of juvenile salmonids (Einum et al. 2012), and the degree to which fish passage side channels might affect the risk of predation during redistribution periods could be the topic of future research. Conversely, BDAs have also been credited to reduce predation risk by providing deep water habitat refuge (Bouwes et al. 2016) that would otherwise not be available in some streams.

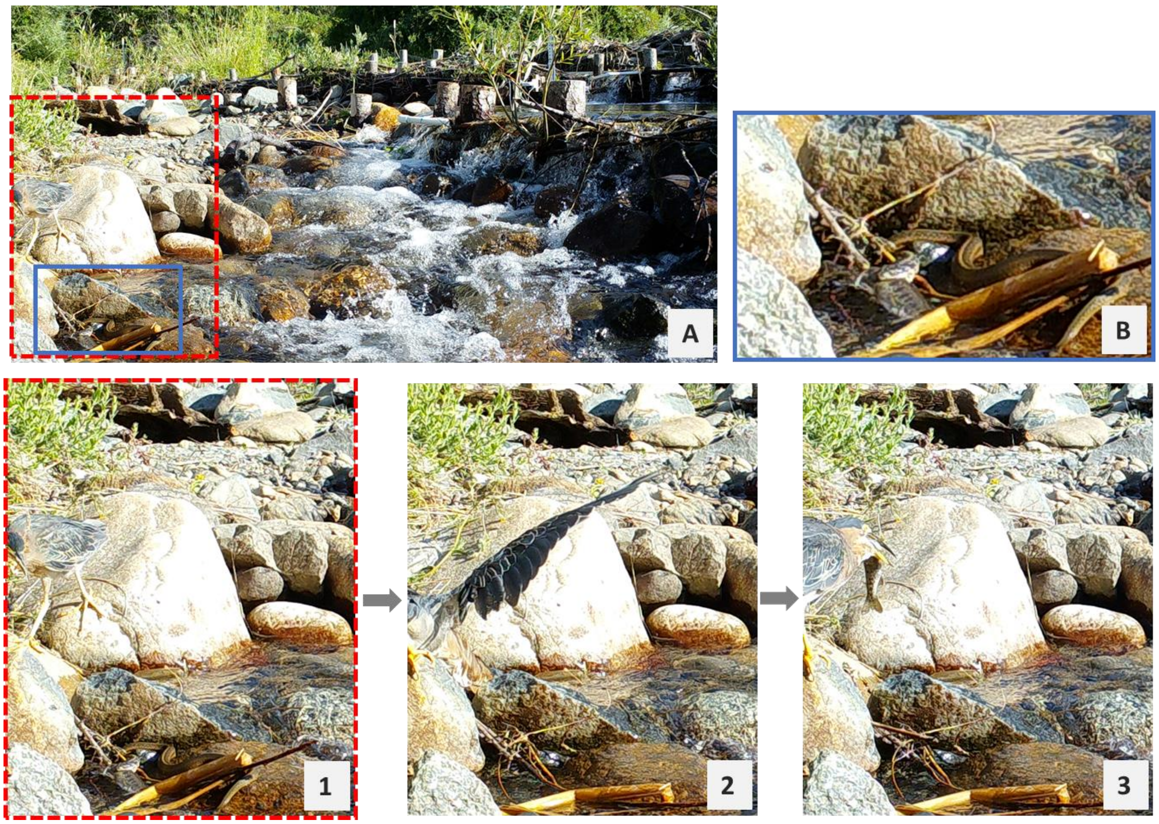

Figure 58. Images of a green heron taking a juvenile steelhead trout from a garter snake. Images were taken on 08/11/2019 and are oriented looking upstream at the side channel of Sugar Creek BDA 1.2. Photograph A on the top left shows the fish passage side channel on BDA 1.2 with the garter snake with the steelhead trout and the heron approaching from upstream. Photograph B on the top right is a magnified shot of the smaller box in photograph A showing the garter snake catching a trout. Photograph 1 in the lower left is a magnified shot of the larger box in photograph A, and is the first in the timeseries (1-3) of the heron taking the steelhead from the garter snake.

The Sugar Creek experiments and hatchery experiments led to mixed conclusions about subsurface passage. Likewise, while current literature and expert opinions also differ on this topic (Davee, Charnley, and Gosnell 2017; Pollock et al. 2015), the ability for juvenile salmonids to navigate through interstitial spaces in beaver dams and BDAs has not been explicitly studied. In the summer of 2011, the Department of Fish and Wildlife hypothesized that juvenile Coho Salmon observed downstream of a real beaver dam on Sugar Creek may have wriggled through interstitial spaces to make it to the upstream pond habitat (Olswang 2015). During my 2019 Sugar Creek experiments, I documented a considerable number of juvenile Coho Salmon that were able to pass the Sugar Creek BDA 1.0 through subsurface orifices before the fish passage side channel was connected during both experiments. About 30% of the Coho Salmon passed through subsurface holes within the first six days of the first trial and about 21% of the previously marked Coho Salmon passed through subsurface holes within the first four days of the second trial. However, during both field trials, the passage rate tapered off after several days, and paired with snorkel observations of fish concentrating below the orifices in BDA 1.0 during the first trial, it might suggest that some fish were unable or unmotivated to pass the BDA through subsurface holes.

My Sugar Creek experimental study design shared a lot of similarities to the work completed by Pollock (2019), but there were differences in timing and I included the lowest BDA (1.2) for my experiments. There were noticeable differences in the available jump and subsurface passageways in the BDAs (Figure 59). During the 2017 experiments there were four weir flow jump points for the upper two BDAs, while during my 2019 experiments, there was only one jump point. Over a 21-day period in October and November of 2017, 91% of the tagged Coho Salmon were detected above the upstream BDA, while during the 2019 trials, 73% were observed passing over nine-days in July and August, and 21% of the previously tagged fish moved over a four-day period in

September (Pollock 2019). During both Pollock's experiment and my first experiment, a significant number of fish were observed passing BDA 1.0 within the first few days, but not to the same degree during the September 2019 experiment. Although it is hard to directly compare these results due to the differences in the duration of the experiment periods and the addition of BDA 1.2, it does seem like passage during the September experiment was slightly attenuated by low-flow conditions. Nevertheless, the fact that 21% of the fish passed in a four-day period during baseflow conditions should not be understated and it speaks to the ability of the juvenile Coho Salmon to pass beaver dams and BDAs.

Figure 59. Sugar Creek BDAs during Pollock's work in 2017 (top) compared to the 2019 experiments (bottom). Note the loss of weir flow jump points on BDAs 1.0 and 1.1 between the two years.

Passage success varied by BDA structure, available passageways, experiment timing, environmental conditions and fish size. In general, side channels and weir flow jump points appropriate to the size of the fish seemed to adequately facilitate passage, while more research is still needed to better understand subsurface passage. The main limitation to fish passage in the Scott River watershed was not the BDAs but rather reduction in surface water. In the context of climate change that is predicted to increase the severity of droughts and floods, BDAs can be an effective tool to mitigate the deleterious effects of a changing climates and help provide critical habitat essential for the survival of endangered salmonid species.

During the hatchery subsurface experiments, only about 5% of the juvenile steelhead trout were able to pass the constructed orifices. This suggests that I was not able to produce subsurface conditions that could consistently promote fish passage, and this was even after modifications to the initial subsurface parameters to try to promote passage. There are a lot of different variables that could affect subsurface passage and that warrant further investigation including pathway length, slope, velocity, and orifice size, to name a few. Furthermore, there is a large amount of heterogeneity in BDA construction, configuration, and composition as exemplified by the Sugar Creek and Miners Creek BDAs. These factors vary from BDA to BDA and ultimately affect subsurface passage. Compared to weir flow jump points and fish passage side channels, subsurface passage would be challenging to accurately evaluate on real BDAs given the concealed nature of the parameters that might affect passage. Further, to ensure that fish passage side channels and weir flow locations are connected and to increase water retention in the upstream pond, interstitial spaces are often filled with cobble, straw, and clay, which would ultimately obstruct the subsurface passageways.

When managing BDAs for fish passage, restoration practitioners and regulators should consider the potential advantages and disadvantages of different potential passageways (Table 12). Fiori (2016) hypothesized that juvenile salmonids prefer to pass BDAs first by swimming up a side channel, followed by jumping at a spill point, and lastly by wriggling through subsurface holes. Both my field and hatchery experiments support this claim. During my research, I observed that when fish had access to a side channel, passage was highly likely. Both species were regularly able to pass jump heights 24 cm, and as fish got larger, they were able to pass larger jumps. Fish were also observed passing subsurface, but in a less consistent manner. Given the set of advantages and challenges associated with each type of passage, there are circumstances where one passageway might be more suitable over another give stream conditions and project funding (Table 12).

Table 12. Advantages, challenges, and suggested implantation setting for each of the identified passageways.

Side Channel (Swim)	Weir Flow (Leap)	Orifice Flow (Wriggle)
Advantages		
• Known and measurable passage criteria • Maximum water retention in upstream pond • Posited as the preferred passageway for juvenile salmonids (Fiori 2016)	• Known and measurable passage criteria • Maximum water retention in upstream pond	• Requires fewer resources to maintain subsurface passage
Challenges		
• Requires additional resources to maintain side channel passage • Beavers may block the head of the side channel • May lead to a predation hotspot • Additional considerations required during the BDA installation phase to accommodate a side channel	• Some jump heights might selectively limit passage • Requires additional resources to maintain weir flow passage • Beavers may block the weir flow	• Hard to adequately assess passage given limited research on the topic of subsurface passage • Subsurface parameters that might affect passage are difficult to measure given their concealed nature • Subsurface passageways will vary greatly between BDAs due to differences in construction, configuration, and composition • Permeable BDAs that promote passage will limit water retention for low-flow periods • Posited as the least preferred passageway for juvenile salmonids (Fiori 2016)
Implementation Setting		
• Beneficial in areas where summer base flow is minimal and BDAs can create pool habitat refugia • Beneficial in tributaries where summer dispersal periods are well understood, and as a result, resources can be focused on maintaining passing during the dispersal period then relaxed during non-dispersal periods	• Beneficial in areas where summer base flow is minimal and BDAs can create pool habitat refugia • Beneficial in tributaries where summer dispersal periods are well understood, and as a result, resources can be focused on maintaining passing during the dispersal period then relaxed during non-dispersal periods	• Beneficial in areas where summer base flow is not an issue, and BDAs are used more for creating winter habitat, retaining sediment, or floodplain reconnection, rather than summer habitat refugia

During the field and hatchery experiments, some BDA structures did limit fish passage, however, it is important to consider the circumstances in which fish did not pass the structures. The experiments that were conducted earlier in the summer had fairly high passage rates, while the lowest passage rate was recorded for the experiment that was conducted during late summer, during base flow conditions. In many streams, juvenile salmon dispersal does not occur during base flow stream conditions, but rather during spring and early summer runoff events, when fry disperse from natal habitat in search of rearing habitat, and fall and winter rains, when parr redistribute to low velocity flow refuges (Lawrence 2007; National Engineering Handbook 2007). Long-distance dispersal and redistribution of juvenile Coho Salmon is comparatively rare during the summer (Quinn 2005). Lang and Love (2014) state, “even in unimpaired stream systems there are flows that fish will not attempt to move upstream due to physical and behavioral reasons, such as at low flows when depths throughout the channel are naturally too shallow”. One of the major limitations of my study was that I displaced juvenile Coho Salmon at somewhat arbitrary times throughout the summer. It is highly probable that some of the times I selected were outside the normal redistribution period for young of the year Coho Salmon, and volitional fish passage would not necessarily be needed, or possible given typical baseflow conditions under current environmental and water extraction conditions. However, current passage regulations do not account for these seasonal physical and behavioral patterns of passage. In the context of stream restoration that aims to improve habitat, regulators might consider relaxing passage regulations when fish are already unlikely to move.

It is important to note that the spring dispersal period of salmonid fry can be significantly impaired by rapid declines in discharge (Irvine et al. 2009; Grantham et al. 2012; Nislow and Armstrong 2012). This is caused by naturally descending flows during the transition to dry summer conditions and can be exacerbated by anthropogenic water withdrawal, which causes a much steeper decline to summer baseflow (Figure 60). The resulting precipitous drop in stream flows can strand fish with or without the presence of BDA structures. Salmonid movements are often cued by continuous and predictable changes in water temperature and stream flow (Lawrence 2007), and when stream conditions change rapidly, it leaves little time for fish to seek refuge. During the Miners Creek passage experiments, a few of the trials were not completed because the flow between BDAs was completely disconnected, but I observed habitats approximately 0.2 km downstream not associated with BDAs that were disconnected even prior to the BDAs disconnecting. This suggests that the limited passage was a function of stream flow rather than the BDA structures themselves. Based on the Miners Creek passage experiments, when there was adequate flow, the BDAs were passable for juvenile Coho Salmon.

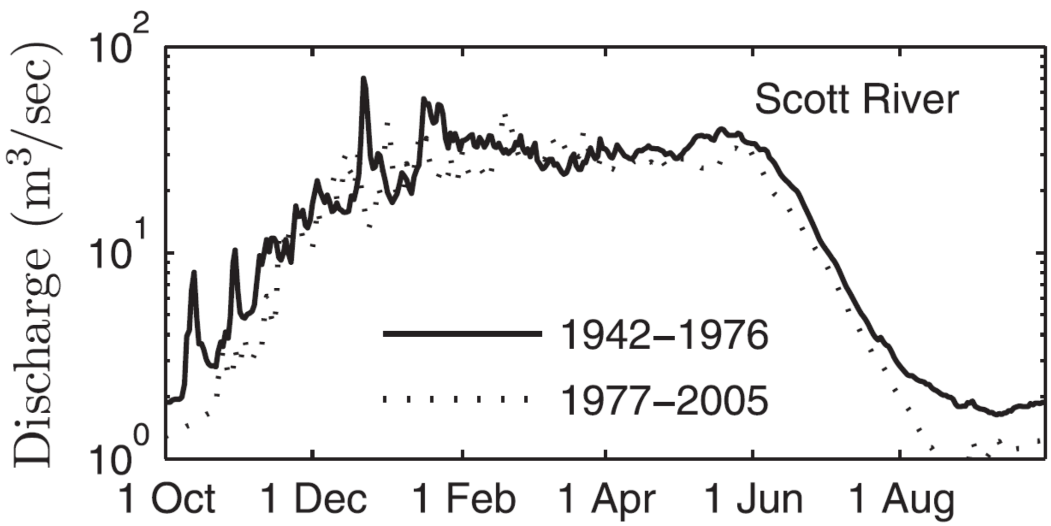

Figure 60. A rain-snow hydrologic regime with base flow period during summer for the Scott River, where the mean Historic-Period (1942-1976) and Modern-Period (1977-2005) hydrographs are depicted (Source: Van Kirk and Naman 2008). Irrigation withdrawal increased significantly since the 1950s and led to less water during the summer low-flow period. Discharge is shown on a logarithmic scale to facilitate visual comparison of modern and historic periods at low discharge values.

Even in situations where BDAs limit fish passage, at the population level or even for individuals stranded downstream of the structures, the added benefits of BDAs may outweigh the detriment of limiting fish passage. Pollock (2019) brought up the philosophical question of how to weigh the benefits and potential costs of using BDAs in restoration. BDAs add considerable area of suitable habitat for endangered species in areas that would otherwise dry up or provide little habitat. Fish that are born or are able to disperse upstream of the BDAs can utilize the enhanced habitat, which may increase the survival rate at the population level. Additionally, BDAs increase groundwater storage, keeping water on the landscape later into the summer even downstream of the structure

(Pollock et al. 2015) and decreasing summer water temperatures by enhancing groundwater – surface water connectivity (Weber et al. 2017). Increased area of downstream wetted habitat with cooler water temperature may benefit the population even if BDAs limit some fish passage. Bouwes et al. (2016) found that the installation of BDAs significantly increased the density, survival and production of juvenile steelhead trout in a highly degraded, incised stream and did not limit the ability of fish to disperse. BDAs have the potential to provide large-scale benefits and aid in the recovery fish populations negatively impacted by stream habitat degradation (Bouwes et al. 2016). Evolutionarily, at the population level, it might make sense to argue that if BDAs and natural beaver dams block some fish from passing and they perish as a result, then that is natural section against the less-fit individuals that were unable or unwilling to pass the structures leaving survivors with higher fitness. Unfortunately, many salmonid populations are only a fraction of the abundance that they once were (National Marine Fisheries Service 2014) and losing any significant portion of a cohort could further exacerbate the collapse of the species. Additionally, the inability to pass might be a function of anthropogenic water use, where streams can dewater at unnatural rates, and provide little to no clues for fish to migrate. Imposing selection to these altered conditions may not increase long-term fitness. However, in systems with close to historic fish abundances and natural hydrologic regimes with little anthropogenic water use, the argument that loss of some individuals due to passage limitations represents an important mechanism of selection is a logical hypothesis.

RECOMMENDATIONS

Based on the high degree of variation in stream conditions, BDA configurations, and project objectives, it is unlikely that a one size-fits-all approach to managing BDA fish passage would be the best approach. If we want to increase the effectiveness of BDAs, resource managers and funders should consider more long-term maintenance and monitoring to ensure that the BDAs are functioning as intended. As with natural beaver dams, beavers will maintain and repair structures daily, and while it would be impractical to monitor the structures that frequently, it is important to regularly monitor and repair BDAs if the goal is to provide consistent passage opportunity.

A solid understanding of the natural and manipulated hydrology of a system in addition to the salmonid redistribution periods of the system where the BDAs are implemented could help structure sensible fish passage regulation. It would be helpful to establish a biologically-based metric by which to maintain passage. For instance, on the lower Klamath River BDAs, the Yurok Tribe reached an agreement with CDFW that once the stream is at low-flow conditions, the organization responsible for the BDAs is no longer required to maintain fish passage (Beesley, Silloway, and O’Keefe 2021).

While it was very exciting to see fish pass through subsurface passageways during the first Sugar Creek experiment, there are still a lot of unknowns about what promotes subsurface fish passage. Ultimately, more research is needed to determine which characteristics facilitate subsurface passage. Until further research is conducted, I would not suggest assuming subsurface fish passage is possible on any BDA. As a result, side channel and weir flow passage criteria should be used to assess fish passage in the interim. Further, as I found that passage varied between streams and between the natural and hatchery environments, it may be beneficial to complete additional passage experiments on BDAs other than the Sugar Creek BDAs.

Historically, beavers and their dams were ubiquitous in the Pacific Northwest. Today beaver populations are still only a fraction of what they once were, and currently in California, it is unlawful to reintroduce or relocate beavers. Based on all of the benefits that beaver dams provide, California should update current laws to allow for the reintroduction of beavers where it makes sense. If beavers were allowed to be reintroduced, beavers would be willing to do a lot of stream restoration with no pay and work 365 days a year. In general, places were beavers and BDAs coincide, beavers will take on the work that it takes to maintain the BDAs.

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