Spring 5-21-2022

Improving Salmon Population Restoration Efforts in California's Central Valley Region

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IMPROVING SALMON POPULATION RESTORATION EFFORTS IN CALIFORNIA'S CENTRAL VALLEY REGION

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Master's Project Spring 2022

USF MSEM

This Master's Project

Improving Salmon Population Restoration Efforts in California's Central Valley Region

by

Long Doan

is submitted in partial fulfillment of the requirements for the degree of:

Master of Science
in
Environmental Management

at the

University of San Francisco

Submitted:

Long Doan 5/19/22
Date

Received:

Advisor Signature 5/19/22
Date

Acknowledgements

There are many who helped me come to this point in my academic journey, but a handful standout. I would like to send my gratitude and love to my parents and sister for supporting me throughout the Program. Without you, I would not be here in the US. I would like to thank my loving wife that always encouraged me, especially when times were tough. You are my pillar of strength, and I cannot thank you enough for helping make everything work. Thank you for taking care of the home and other matters as I focused on my work, and for being there for me. Finally, I would like to thank all of the faculty at USF, especially Prof. Callaway, my Project Advisor. Thank you all for sharing your knowledge and wisdom with me. Thank you also for always encouraging me to grow and expand my mind. It was truly enjoyable experience because of you.

Abstract

Historically, the rivers draining into California's Central Valley Region (CCVR) were abundant with Chinook salmon, migrating in four distinct runs throughout every year, including the Sacramento River winter-run & the Central Valley spring-run. Since the advent of the Central Valley Project in the 1930's, and its 20 federal high rim dams, these salmon runs have become increasingly threatened. Using a comparative analysis research methodology, this Project critically reviews the existing literature to address the research question: how can current practices of Fish Passage Designs (FPDs) and collection-and-transport operations (CTOs) be improved to mitigate impacts created by dams in CCVR? After a critical examination of the research literature, this Project offers two major recommendations to improve current FPD practices: moving away from the use of Denil fishways, in favor of other designs, and creating and maintain proper water velocity and pressure around and within FPDs. Two minor recommendations, namely requiring tag validation studies and engaging in longer term FPD monitoring, are also offered. The Project offers two major recommendations for improving current CTO implementations: emphasizing reducing induced stress during CTOs, and mitigating copepod *Salmincola californiensis* infection prevalence among salmon subjected to CTOs. These recommendations are meant to improve current salmon run restorative efforts in CCVR geared towards delisting the runs from their current endangered listings. These recommendations are also congruent with the two scientific principles that are the bedrock of current conservation management efforts, namely creating functioning, diverse, and interconnected habitats, and improving species viability dependent on spatial factors.

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Introduction

In the California Central Valley Region (CCVR), salmon populations are king, literally. The CCVR is a valley in the interior of California that is home to about 6.5 million people, is between 48.3 km to 96.6 km wide (30 to 60 miles), and extends to 724.2 km (450 miles) from north in the Cascade Mountains to the south in the Tehachapi Mountains. It encompasses approximately 46,620 km^2 (18,000 square mi^2), which is about 11% of CA's land mass (CDFW, 2015). It is primarily divided into two smaller valleys: in the north into the Sacramento Valley (SV), and in the south into San Joaquin Valley (SJV). CCVR includes CA's capital city, Sacramento, in addition to large cities like Fresno, Modesto, and Stockton (Stene, n.d.). It is one of America's major agricultural regions since it has very fertile soil and an extended growing season (CDFW, 2015).

The CCVR watershed is about 155,400 km^2 (60,000 mi^2), which is over a third of CA. Although it includes three main drainage systems, the wet SV in the north (precipitation of around 51 cm, or 20 inches, annually), the SJV in the south that is drier, and the Tulare Basin (TB) to the south of SJV with a semi-arid desert climate (precipitation of around 12.7 cm, or 5 inches, annually) (CDFW, 2015), there are four main river basins present, namely Trinity River Basin (TRB), Sacramento River Basin (SRB), San Joaquim River Basin (SJRB), and the TB (Figure 1). Of these river basins, the SRB and SJRB form the Sacramento–San Joaquin River Delta (SSJRD), which is a large area of canals, and other wetland regions. The SSJRD drains into the San Francisco Bay, and finally ends up in the Pacific Ocean. The TB does not naturally reach the Pacific, although the rivers in the TB are connected by canals to San Joaquin River (NMFS, 2014) (Figure 1).

Historic Salmon Runs in the CCVR

As the National Marine Fisheries Service (NMFS) points out, the rivers draining into the CCVR were once renowned for their large numbers of Pacific salmon, with the Chinook being the only abundant species of salmon, and other species occasionally occurring (NMFS, 2014; NMFS, 2011). Chinook salmon (*Oncorhynchus tshawytscha*), also called king salmon, are the largest of the Pacific salmon (Figure 2). The Chinook can be distinguished from other spawning salmon by their color pattern, especially their spotting on the back and tail regions, and also by

Figure 1: California Central Valley Region River Basins. All four main river basins are shown, along with some of the key dams in the region.
Source: https://en.wikipedia.org/wiki/Central_Valley_Project

the solid black and dark gums of the lower jaw. The spawning males are darker than the females, with a hooked jaw and slightly more humped back (NMFS, 2014).Chinook is the most commercially important anadromous species of fish found in CA (NMFS, 2014). There are four primary life history variants of Chinook found in the CCVR, namely fall-run, late fall-run, winter-run and spring-run. The Sacramento River supports all four runs, while other tributary rivers, and the rivers found in the SJRB, support at least one of these runs (NMFS, 2014; NMFS, 2011). Although all four runs have been important much of the restoration efforts have targeted the winter and spring runs of Chinook. A brief description of these two important runs is given below.

Panel A: Source: https://casalmon.org/

Panel B: Source: https://norcalwater.org/efficient-water-management/salmon/

Figure 2: CA Pacific Chinook Salmon in both panels, with the right panel taken in the Sacramento River.

Winter-run Chinook (Figure 4) originate from the Sacramento River and its tributaries, and they are unique compared to the other runs in the CCVR since they require streams with cold water sources due to the fact that they spawn during the summer months when air and stream temperatures are at their peak (NMFS, 2014). Spawning takes place in the upper Sacramento River basin where clean gravel is required as a spawning substrate (NOAA, 2021). Stream reaches with cold water sources protect embryos and juveniles from warm environmental conditions, since their natural habitat is generally at 5.8°C to 14.1°C (42.50°F to 57.5°F) in the SRB when they spawn and eggs incubate and the fry develop (NOAA, 2021; NMFS, 2014). Adult Chinook also need to have water depth higher than 0.24 m (0.8 feet) and water velocities less than 2.4 m/sec (8 ft/sec), in order to achieve successful upstream migration (NMFS, 2014).

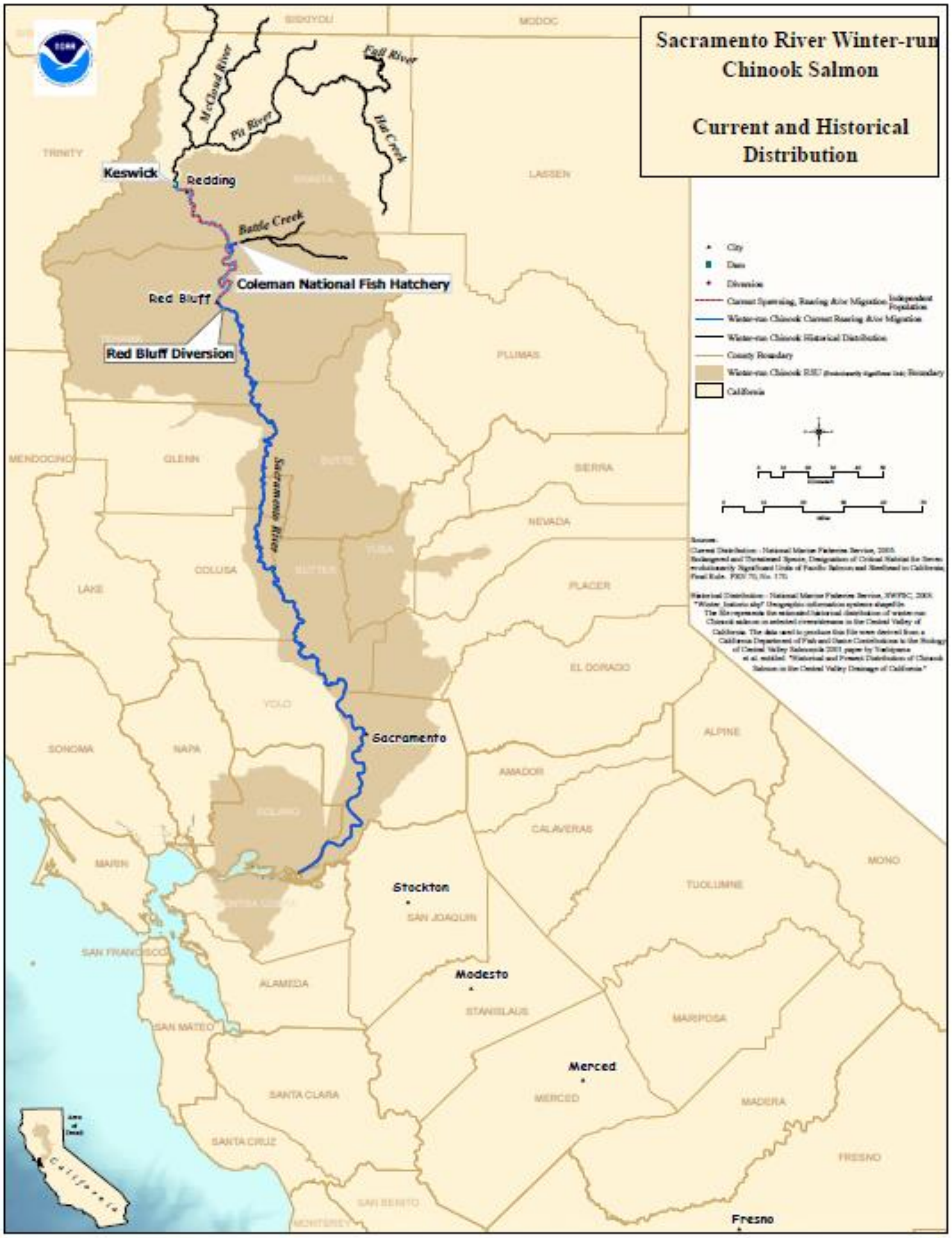


Figure 3: Chinook Winter-Run in the Sacramento River Basin. The map shows the current and historical distribution of these runs, and some key facilities in the CCVR.
Source: NMFS (2014)

For spring-run Chinook (Figure 4), the optimum temperatures are between 5°C and 13°C

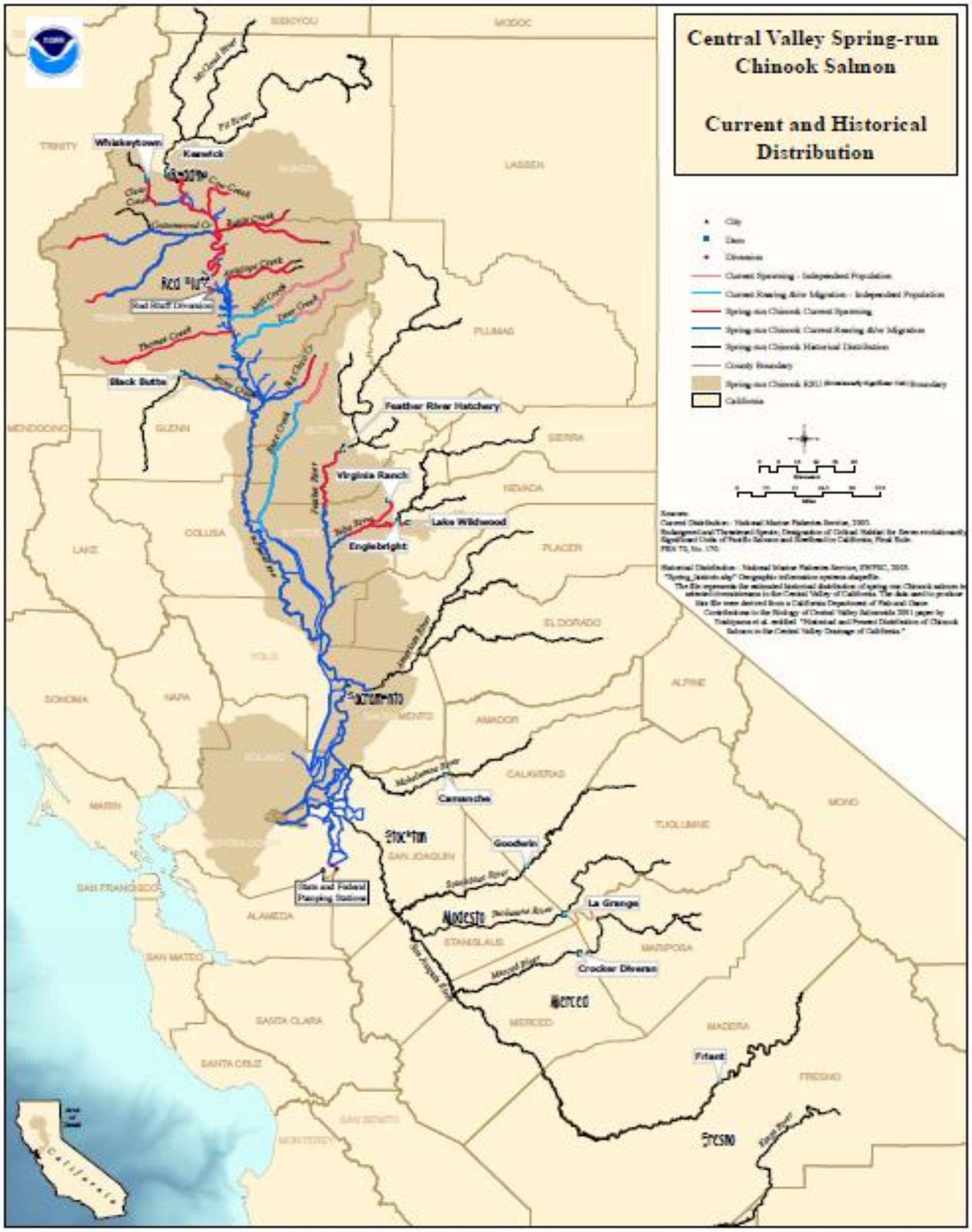


Figure 4: Chinook Spring-Run in the Central Valley. Shows the current and historical distribution of these runs, and some key facilities in the CCVR.
Source: NMFS (2014)

(41°F and 55.4°F). Adult spring-run Chinook in CCVR begin their upstream migration from the ocean in late January and early February, and usually come into the Sacramento River primarily between May and June (NOAA, 2021). Spring-run Chinook normally spawn between mid-August and early October in deep pools with cold water (NMFS, 2014).

The Central Valley Project and Rim Dams

The CCVR has very diverse conditions, and this is the primary reason that anthropogenic canals and reservoirs dominate the CCVR since the region is home to populations that do not get adequate rainfall year-round. As Stene (n.d.) states, the SRB receives about two-thirds to three-quarters of northern California's precipitation, while the SJRB gets about one-third to one-quarter of the precipitation, meaning that the former suffers from flooding, while the latter is affected by both flooding and drought. Yet, the SRB has about one-third to one-quarter of the land, while the SJRB has about two thirds to three-quarters of the land, in northern CA. These varied conditions, and the need to gather and distribute the water reserves throughout the disparate agriculturally rich CCVR led the way to more proactive government projects for water control (Stene, n.d.).

California’s attempts to harness the excess water from the Sacramento River date all the way back to 1870’s. As Stene (n.d.) notes, the U.S. Geological Survey (USGS) initially proposed a plan to build storage reservoirs along the Sacramento River system, and then use these reservoirs to move water from the SV to the SJV utilizing two large canals that are on both sides of the Sacramento River in 1919. In 1921, CA state government started creating a comprehensive water plan meant to achieve conservation, flood control, storage, distribution, consumption, and other uses, for CA water. Salinity control was a major issue, especially in the SSJRD (USBR, n.d.).

The need to maintain a regular water flow to the town of Antioch, and to keep salt water out of Suisun Bay, led to plans for the creation of the 420 foot Kennett dam (later called Shasta dam) in 1930. This was the beginning of the Central Valley Project (CVP), authorized in 1933, and all the federal dams that were built, with money appropriated for its implementation in 1935 (USBR, n.d.). Although the other major CA water project that began in 1960, the State Water Project, also serves the CCVR, it and its 21 dams are not discussed here (Meir, 2013).

As Stein (n.d.) states, the CVP had multiple divisions with distinct, but interrelated operational purposes. The Shasta Dam acts as a flood control dam for the Sacramento River, and Shasta Lake is meant to store and release water downstream (Figure 5). The Trinity and

Lewiston Dams, located in the Trinity River Division (TRD) diverts excess water to the Sacramento River from the northwest, while the Keswick Dam in the Shasta Division (SD) also does this from the east (USBR, n.d.). Downstream from the SD, the Sacramento River Division (SRD) supplies water to counties like Tehama and Yolo for irrigation and other purposes, while one of the main purposes of water releases from SD is for salinity abatement in the Delta Division (DD) (Stein, n.d.).

Further downstream the American River Division (ARD) also is meant to offer flood control, this time on the American and Sacramento Rivers (Figure 5). However, the American Dam was left incomplete due to political infighting. The ARD supplies irrigation water (USBR, n.d.). The Friant Division (FD) to the south east primarily collects or diverts the flow of the San Joaquin River through the Friant Dam, while the Dam itself is meant to provide irrigation water to the south (Stein, n.d.). The New Melones Dam was completed in 1979, and is also meant to offer flood control, but also power generation. In general, the DD is the main hub around which the CVP operationally rotates (USBR, n.d.). The DD has facilities to transport water from the Sacramento River to SJV and to the DD. The San Luis Unit, with the San Luis Dam (SLD), also associated with the DD, provides water storage for the CVP for dry periods. According to Stein (n.d.), the San Luis Reservoir is the largest off-stream storage reservoir in the US.

The primary priorities of the CVP (Figure 5) included navigation improvements, regulation and flood control of the two main rivers. Water use for irrigation and other purposes, and power generation, were not initially high among the priorities (Stein, n.d.). Additions continued in the 1940's and 1950's with several new dams being integrated into the CVP, including the Folsom Dam in 1956. According to USBR (n.d.), the CVP currently consists of 20 dams (ranging from 100 to 600 feet high) and reservoirs, 11 power plants, and 500 miles of major canals (see Figure 5). In addition, there are conduits, tunnels and other related facilities that are part of the CVP. The CVP manages 9 million acre-feet of water annually, including delivering 7 million acre-feet of water for agricultural, urban and wildlife use, of which 5 million acre-feet of water is for farms, which is sufficient to irrigate about 3 million acres of agricultural land (about one-third of total agricultural land in CA), while also providing about 600,000 acre-feet for municipal and industrial use. The latter benefits approximately 1 million households each year.

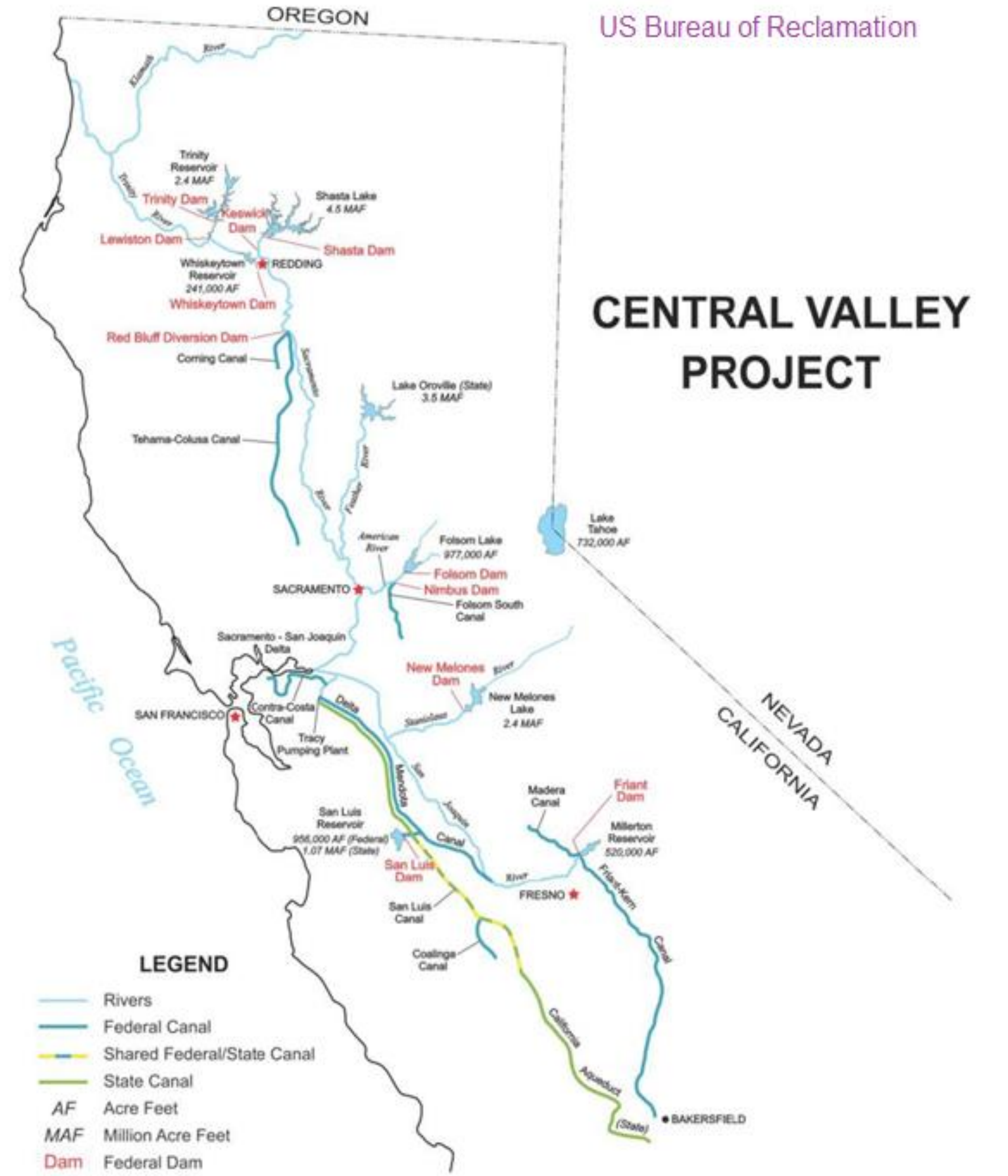


Figure 5: Central Valley Project. Includes all of the rim dams and some of the key related facilities since inception.
Source: https://www.adjuvancy.com/wordpress/2014/03/06/water-water-drop/

The Central Valley Project Improvement Act of 1992 (CVPIA) lead to the reallocation of over 800,000 acre-feet of CVP water in wet years, and 600,000 acre-feet in dry years. The CVPIA was a significant departure for the CVP, since it called for water management efforts to explicitly consider the restoration of CCVR fisheries by listed species (USBR, n.d.). Overall, the CVP is also the most important among the United States Bureau of Reclamation (USBR) projects for flood control, preventing more than $5 billion dollars' worth of flood damage during 1950-1991 (Stein, n.d.).

CVP and Effects on Salmon Populations

There are several ways in which rim dams that were created as part of the CVP directly impacted Chinook salmon populations. The purposes for which the dams were built in the first place, such as to provide water resources to CCVR resident, led to reduced water stream flows and increased water temperatures. The erection of terminal dams also altered the flow and water temperature environments downstream from them (NMFS, 2014). As NMFS (2014) maintain, natural waterways in the CCVR were blocked and impeded by the dam and facility constructions associated with the CVP. The National Oceanic and Atmospheric Administration (NOAA) states that large scale anthropogenic barriers, specifically dams, have blocked nearly 90 percent of adult fish spawning and rearing habitats (NOAA, 2021). This prevented the upstream migration of Chinook for spawning and rearing environments.

These effects meant that salmon populations were affected, both in terms of mortality and morbidity (Ben Ammar et al., 2020). Historically, the rivers draining into the CCVR were abundant with salmon, especially Chinook (NMFS, 2014). Yet, the Chinook numbers in the CCVR began declining in the late 1800's (in 1880 the total annual commercial catch was 5 million kg, or 11 million pounds), all the way up to 1939, when the total commercial catch was recorded at less than 1.4 million kg, or three million pounds (NMFS, 2014). Overfishing, compounded by hydraulic gold mining, led to precipitous declines in the Chinook populations. Dam construction, and the erection of other anthropogenic barriers to salmon migrations, like reservoir facilities, that came about in the 1930's as explained below, led to the further decline of this anadromous fish species (Stene, n.d.). In addition, the altered hydrology of the SSJRD, coupled with other dam related consequences such as loss of tidal marsh, riparian and floodplain habitat, barriers to historic habitat, and poor water quality, led to continuous declines in the Chinook populations, and with it calls for restorative practices (NMFS, 2014).

The CVP had affected migratory salmon populations, which led to the listing of salmon populations in CCVR under the Endangered Species Act (ESA) (Stene, n. d.). The winter-run Chinook had their numbers peak in 1969, the highest since CVP was initiated, to about 118,000 at the Red Bluff Diversion Dam in the SRB (Figure 5). Then by 1990 this salmon population had dropped to less than 6,000 (less than 5 percent the number in 1969) after steadily declining numbers since 1969. Due to widespread outcry against this decline the USRB instituted mitigating policies to try to curb the precipitous decline. This did lead to populations regaining their numbers somewhat in the early 1990's, but they were still a far cry from the recorded numbers seen even in 1969. The numbers have seen modest increases lately, but still far from what they were even in 1969 (NMFS, 2014).

Salmon Population Recovery Efforts in the CCVR

The National Marine Fisheries Service (NMFS) identifies recovery as a process "… by which listed species and their ecosystems are restored and their future is safeguarded to the point that protections under the Endangered Species Act (ESA) are no longer needed" (NMFS, 2014, p. i). Currently, based on the ESA listing status, the Sacramento River winter-run salmon is listed as endangered, due to "(1) the continued decline and increased variability of run sizes since its first listing as a threatened species in 1989; (2) the expectation of weak returns in future years as the result of two small year classes (1991 and 1993); and (3) continued threats to the winter-run Chinook salmon" (NMFS, 2014, p. 10). By contrast, the spring-run are currently categorized as threatened, but were proposed as endangered in 1998, since they were seemingly rooted out of all of the tributaries of the SJRB, which were their historical habitats (NMFS, 2014).

In the face of these challenges, the NOAA and the NMFS have undertaken salmon restoration efforts, based on two key scientific salmonid conservation rationales (discussed below). First is that, "…functioning, diverse, and interconnected habitats are necessary for a species to be viable. That is, salmon and steelhead recovery cannot be achieved without providing sufficient habitat" (NMFS, 2014, p. ii). That is, a life stage specific threat assessment, and structured mitigation strategies, are required (NOAA, 2021; NMFS, 2014). The second principle is that, "a species' viability is determined by its spatial structure, diversity, productivity, and abundance" (NMFS, 2014, p. ii). While productivity and population growth are obviously important, spatial structures (populations across landscapes, distribution of those that spawn in a population, and the processing that account for these distributionary patterns), and diversity, are equally important (NMFS, 2014).

Conservation management of fish migrations developed predominantly to restore the free movement of migratory fish like salmon in ecosystems that are fragmented by dams and other structures because fragmentation of habitats significantly increases fish vulnerability (Lennox et al., 2019). As NOAA (2021) convincingly contend, offering strategies to provide passage for these two salmon variants to navigate rim dams is of paramount importance to restoring these salmon runs, and subsequent populations. Therefore, two current restoration practices undertaken by the NOAA and NMFS are fish passage designs (FPDs) and collection-and-transport operations (CTOs).

Silva et al. (2018) consider FPDs, or fishways as they call them, as "any structure deliberately created to facilitate safe and timely fish movement past an obstacle" (Silva et al., 2018). The history of FPDs dates back to 1800 Europe, and FPDs need to take, and traditionally have taken, into account downstream as well as upstream passage (Silva et al., 2018). Current research on FPDs consider salmon physical abilities, spawning behavior and their sensitivity to selected sensory stimuli (Lennox et al., 2019; Birnie-Gauvin et al., 2018; Rahel and McLaughlin, 2018; Silva et al., 2018). Additionally, Silva et al. (2018) state that while traditional FPDs have relied on mostly an engineering approach in their designs and implementation, due to newer research, the current FPDs are taking into overall account fish behavior and the modelling of ways to prioritize passages in river networks around dams.

Kock et al. (2021) state that rim dams pose a particularly difficult challenge for migrating salmon because of their height, and CTOs (they call these trap-and-haul) are very useful and widely used in salmon restoration efforts. The typical implementation of CTO is differentiated to accommodate juvenile versus adult salmon in CCVR. Collection facilities that are located in dam forebays collect juvenile salmon and transport them in vessels downstream. These are fish-hauling tanker trucks that also have supplemental oxygen for the fish during transport. Adult migrants are collected for upstream transportation by tanker in trapping facilities that are usually found in the dam tailrace (NMFS, 2014). A major consideration in these processes is parasitic infections, a subject I argue that is not sufficiently addressed currently in salmon restoration efforts in CCVR.

Transporting either of these salmon in one direction is considered one-way CTO (in the literature called one-way trap-and-haul), and if both stages of the salmon are being transported then that is considered two-way CTO (or two-way trap-and-haul in the literature) (Lusardi and Moyle, 2017). Lusardi and Moyle (2017) also mention that CTO is now a routine fish management tool, especially from dams where FPDs are not existent or practical. Their work is primarily aimed at using the results of multiple such efforts to understand what works and does not, and offer suggestions for improvement. This is especially complicated when large rim dams are present, as is the case in the CCVR. (Kock et al., 2021; NMFS, 2014).

This paper focuses on offering a critical review of current FPD and CTO practices undertaken in the CCVR, providing analyses of their effectiveness and offering two major improvements, along with a few minor recommendations, to these practices. The main research question posed and answered is the following: How can current practices of FPD and CTO be improved to mitigate impacts created by dams in CCVR? While answering the main research question and providing recommendations, the Project answers the following sub-questions:

- What are some impacts of dams in terms of mortality/morbidity?
- How effective are FPDs in mitigating some of these negative impacts of dams?
- How can current FPDs used in CCVR be improved?
- How effective are CTOs in mitigating some of these negative impacts of dams?
- How can current CTOs used in CCVR be improved?

Methods

The research method exclusively used for this study was a comparative analysis based on critical reviews of the literature. The research papers and documentations are selected based on year of publication, relevance, and an informal assessment of impact, based both on cross-references and Project Advisor recommendations. No data analysis or field study is undertaken. The critical review sources used could be broken down in terms of format type, accessibility, and peer review, as follows: peer reviewed journal articles (62 in total); book publications (1 in total); federal and local governmental publications with peer review (6 in total); and governmental and agency websites and resources (5 in total).

Evidence/Results

Impact of CVP Dams on Chinook Migration

Silva et al. (2018) maintains that the use of barriers such as dams greatly modifies and threatens the ecological integrity of rivers, and that mitigation procedures are essential to counter negative effects on fish migrations, both of juveniles moving downstream and adults Chinook migrating upstream. Some of these results ecological degradation and loss of habitat related effects were discussed above. In addition to those, Crook et al. (2015) point out that dams create very wide-ranging impacts in aquatic biota, dams serve as physical and behavioral barriers to salmon moving longitudinally, thereby changing patterns of ecological connectivity in river systems, such as those in the CCVR (Keefer et al., 2008). Unlike other ecosystems that provide for multiple pathways for movement, river and stream systems only provide for linear or dendritic movement, which amplify the negative effects (Bellmore et al., 2019). Although most of the research has examined these effects on shorter time scales such as a single migration cycle, and in the aftermath of a single disturbance, research needs to be undertaken to look at intergenerational effects, and the combined impacts of dams with other forms of human disturbances, such as chemical pollution, noise pollution, and water abstraction (Lennox et al., 2019; Silva et al., 2018).

Research has shown that, for migrating salmon, their internal state, their physiological and stress related changes for example, leads to changes in their migration patterns, such as choosing potentially suboptimal paths (Lennox et al., 2019). Research has also shown that migration-related behavioral changes, at both the individual and collective levels, in turn lead to changes in internal states (Birnie-Gauvin et al., 2019). These changes are greatly modified when they have to pass through barriers such as high rim dams found in CCVR: for example, when juveniles are moving downstream and they have to navigate dams through either a surface flow bypass or through the turbine, their stress levels significantly heighten, leading to increased morbidity, along with the attendant rise in mortality (Kock et al., 2021). These interrelated and interdependent changes are evidenced in the relationship between stress levels and nutritional status on the one hand, and the distance traveled by salmon during migratory journeys, and the eventual passage success by the Chinook (Lusardi and Moyle, 2017; Tort, 2011). Non-lethal biopsies of blood, gill or other tissues are used to identify and quantify the internal states of the salmon, while movement patterns can be observed in lab experiments or by using telemetry for remote monitoring (Birnie-Gauvin et al., 2019; Lennox et al., 2019).

Navigating passage through high rim dams during migration, and the attendant increase in induced stress responses and some behavioral changes that accompany them, have been shown to affect mortality and morbidity in salmon. Exposure to dams and the turbines have been known to cause physiological and stress responses in migratory fish, including salmon (Keefer et al., 2021). Ammar et al. (2020) measured induced cortisol levels in salmon smolts during handling and passage through turbines. They concluded that in addition to handling, when salmon went through spillways if water speeds were not optimum, or if the water level was too high, this led to more strikes due to from more collisions with spillway structures, water columns or with other fish, and subsequent shocks, resulting in higher stress levels (Ammar et al., 2020).

The enhanced immune-stimulation that was usually observed and was triggered via an oxidative stress-defense mechanism triggered when navigating dams was not permanent (Keefer et al., 2021; Ammar et al., 2020; Tort, 2011). However, as impermanent as the triggered enhanced immune-stimulation that was observed, over time this chronic stress, such as those that salmon encounter when navigating through multiple dams in CCVR, may lead to eventual immune system degradation, and higher risk of infections and mortality as well (Ammar et al., 2020; Keefer et al., 2008). Therefore, delayed mortality of salmon, due to navigating dams, has been observed in many studies (Ammar et al., 2020). This is turn leads to poor results in restoration efforts.

In addition to cortisol production, carbohydrate metabolism and glucose consumption and production are also affected during dam passage, for both juveniles and adult salmon (Goodwin et al., 2014; McElroy et al., 2012). Passage through turbines disrupted these processes, but not as much as the cortisol response noted above (Ammar et al., 2020). Energy expenditures are important to examine because energy availability is so critical to salmon health and survival. Because salmon migrations are very taxing energetically, it has been hypothesized that salmon would adopt efficiencies in swimming to decrease energy usage and costs (Crozier et al., 2017; Hinch and Rand, 2000).

Modelling behavioral responses encountered when adult Chinook salmon navigated 24 distinct river reaches (922 km distance) over eight dams on the Snake River, Crozier et al. (2017) found that the slower moving fish suffered disproportionately larger rates of mortality compared to faster moving fish. They also found greater variations in passage efficiencies, especially when interacted with increasing temperatures, between the slow and fast swimming salmon (Crozier et al., 2017). Therefore, FPDs should be designed to keep salmon moving at acceptable faster speeds to reduce mortality and increase survival.

Upstream swimming adult salmon generally face currents that are faster as they near dams. Yet, research shows that when relatively low currents were encountered (speeds less than 0.25 meters per second), salmon were very efficient (ground speeds equaled or exceeded swimming speeds) because they used small reverse-flow vortices that were created by rough substrates or river banks to reduce drag and assist upstream passage. Yet, this was not so when the current was fast or inconsistent, such as during a dam passage (Hinch and Rand, 2000). Salmon orient their swimming in the direction of faster flowing water to swim more efficiently and to use the currents, and if water velocity and pressure are not suitable or consistent, as is the case usually around dams, then more energy is expended than is optimal (Goodwin et al., 2014; McElroy et al., 2012).

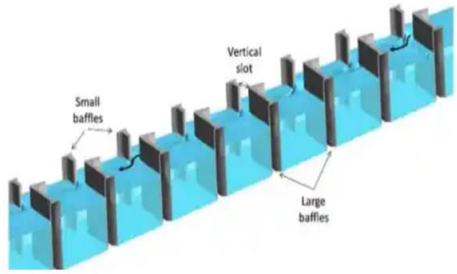
Fish Passage Design as a Restoration Strategy

Creation of FPDs

A FPD, or a fishway, is a series of such passage configurations. The creation and testing process for FPDs is very important, since such economically expensive and laborious processes are usually undertaken only for species that have significant economic value, like salmon (Zielinski and Freiburger, 2021; Williams et al., 2012). In a lab setting, a potential FPD configuration is tested to see how fish swim past it, and subsequently tested to see what hydraulic conditions the fish gravitate towards and which they avoid. Repeated testing is then undertaken with various modifications to evaluate different conditions, such as weir heights, vane arrangements, slot openings with variable numbers, and gradients to change water velocity and turbulence (Izzo et al., 2016; Williams et al., 2012). This repeated testing with modifications leads to the selection of a particular FPD structure that works for a particular species (Rahel et al., 2018).

In some cases, if the species has to travel a high vertical distance to get by the entire passage, such as when Chinook encounter high rim dams in CCVR, there might need to be resting or holding areas for them to pause along the way (Rahel et al., 2018; Williams et al., 2012). In general, there are four commonly used types of FPDs, three of which are used in CCVR (CDFW, 2022a). These four types are pool and weir, pool and slot, natural, and Denil

Panel A: Pool and Weir FPD



Panel A: Pool and Slot FPD

Panel C: A Natural FPD

Panel D: A Denil FPD

Figure 6: Four commonly used types of FPDs used, with Panels A, B and D used in CCVR in various configurations.
Source: https://theconstructor.org/water-resources/types-fish-ladders-fishways/33911/

(Figure 6). As Clay (1995) details, pool and weir FPDs are created as a series of small pools in steps. Salmon are expected to swim over dividers that are placed from pool to pool. The second kind of FPD found in CCVR is pool and slot (also called vertical slot fishways) (CDFW, 2022). This is where salmon swim through a series of small pools, that are placed in steps that have openings for them to navigate through the divider between pools (Clay, 1995). Fishways that look like natural channels, with substrates like rocks and timber, and with consistent water flows, slopes etc., are called natural fishways (Figure 6) (Raabe et al., 2019; Noonan et al., 2012; Clay, 1995); however, natural fishways are not used in CCVR. CCVR does have FPDs that use a Denil format, which incorporates a steep flume with vanes that are placed to dissipate water flow and decrease water velocity (Noonan et al., 2012; Clay, 1995).

Given these general considerations, it is important to consider the following question: Which FPDs designs have performed better with salmon? To answer this question, Noonan et al. (2012) conducted an information-theoretic evaluation, by using the Akaike's information criterion they tried to identify which of the models examined explained observed upstream navigation successes, and review of articles on FPDs done between 1960 and 2011 (65 articles in total). They did not perform a formal meta-analysis. When the FPDs were compared based on type, Denil FPDs (Figure 7) had the lowest efficiency compared to pool and weir, pool and slot, and natural fishways (Noonan et al., 2012). Generally, as the slope of the FPD increased, upstream passage efficiency decreased very significantly (Rahel et al., 2018).

In addition, passage efficiency increased significantly with water velocity as well as FPD length (Noonan et al. 2012). Although longer lengths would mean greater energy expenditure, they found that since longer lengths were found in FPDs that had faster flow speeds and less slope, length was positively correlated to passage efficiency. Type of FPD and length of FPD were the best fishway predictors for passage efficiency (Noonan et al., 2012). These results are also found by other researchers, who generally find that Denil designs are less preferable to other FPDs (Celestino et al., 2019; Mallen-Cooper and Stuart, 2007).

Research showed that energy costs were more related to FPD steepness than to length, and generally FPDs that are very short tend to be steep, thus increasing energy costs to navigate them, while conversely longer FPDs have shallow or gradual inclines lowering these costs. Because Denil FPDs tend to be steep, they resulted in the largest energy costs for migrating salmon. Thus, fishway length and steepness were negatively correlated (Mallen-Cooper and Stuart, 2007). Therefore, Denil fishways are not generally preferred both because of their shortness as well as steepness (Noonan et al., 2012; Mallen-Cooper and Stuart, 2007). Yet, the Denil configuration is most commonly used for salmon restoration practices in the CCVR, possibly because species specific traits of Chinook might favor a vertical slot Denil configuration, such as Chinook's jumping abilities (Williams et al., 2012; NMFS, 2011). In this Project I argue for a reconsideration of this practice below in favor of two other currently used FPDs.

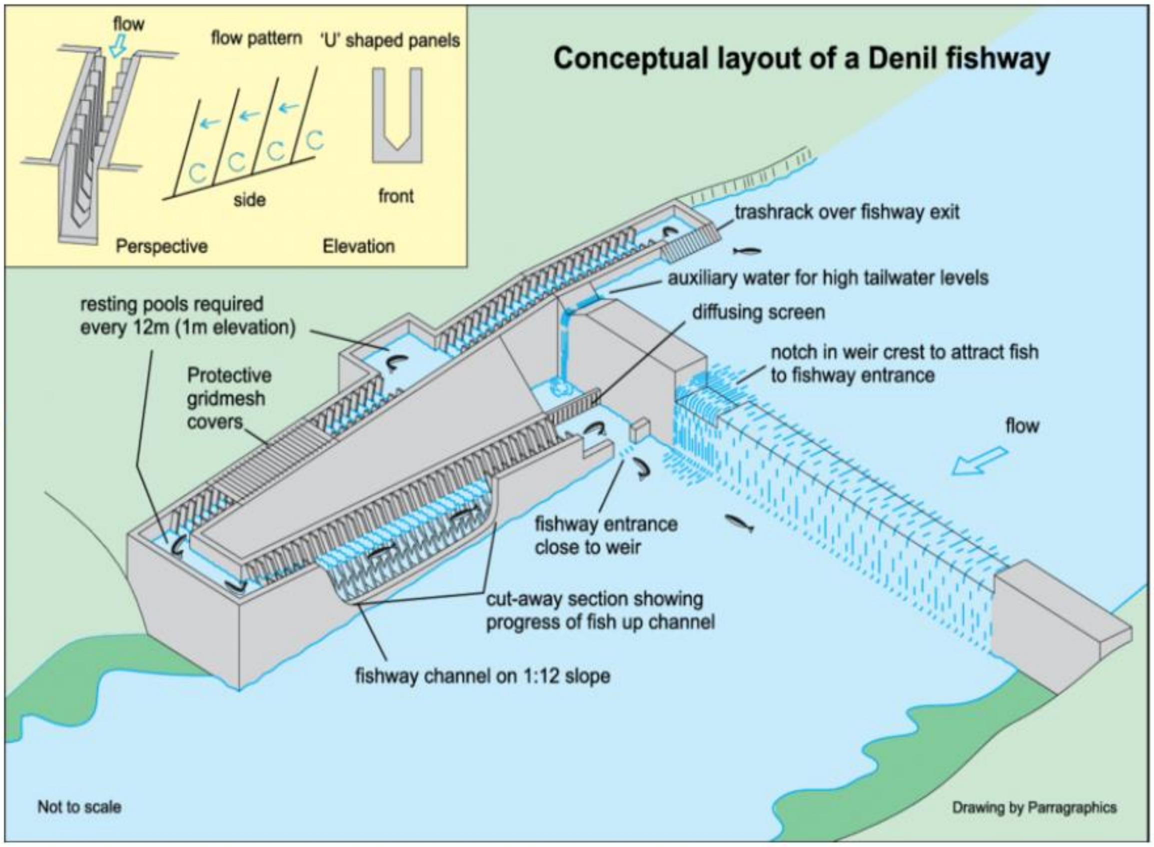


Figure 7: Conceptual layout of a FPD that features a Denil design for upstream passage. Salmon enter from center left entrance at base of dam.
Source: https://www.researchgate.net/figure/Conceptual-layout-of-a-Denil-fishway_fig2_237346843

Using and in-depth longitudinal design, Keefer et al. (2021) answered questions around the effectiveness of FPDS by monitoring eight dams on the Columbia and Snake rivers for over 15 years, including several runs of Chinook. Usually, FPDs are assessed based on at least a couple of sets of metrics. The first set of metrics are fish passage efficiency metrics that examine passage success (Keefer et al., 2021, p. 3), namely:

(1) Fishway attraction efficiency, from tailrace entry to approach a fishway opening;

(2) Fishway entrance efficiency, from fishway approach to fishway entry;

(3) Fishway passage efficiency, from fishway entry to pass a dam; and

(4) Dam passage efficiency, i.e., full-project passage efficiency from tailrace arrival past a dam.

A second metric of interest in determining FPD effectiveness is fish passage times, which indicates or sums the total time elapsed from tailrace, fishway, and full-project segments, and in the case of CCVR, past several dams and reservoirs as applicable. Therefore, the greater total time elapsed between multiple dam navigations, when compared to the time taken in the absence of those multiple dams over the distances measured, the less effective FPDs are in facilitating migration (Keefer et al., 2021; Crozier et al., 2017).

Keefer et al. (2021) found that nearly all the salmon that entered dam trailraces entered fishways. Estimated tailrace-to-forebay passage efficiency for all the salmon was consistently high, averaging 96.6% across 245 run×year×dam combinations. This is a passage efficiency metric and not a survival metric. This average value is very high, and one of the highest recorded, but is not for full dam passage as explained (Keefer et al., 2021). In terms of full-dam fish passage, Keefer et al., (2021) saw more variation, with median run×year×dam values ranging from 5–65 hours in terms of passage time taken. In addition, Keefer et al. (2021) concluded that fishways were "biologically effective," in that there were rapid migration rates seen, with median speeds in the range of 28-40 kilometers per day, and the adjusted upstream migration survival rate was 67-69%. These rates, observed in this large scale study, were seen despite the salmon navigating rivers with several dams (Lennox et al., 2019; Williams et al., 2012).

General Considerations for FPDs

Magnetic senses, olfactory and visual cues, and learning are critical to fish navigation, including salmon, and different spatial strategies have evolved due to natural selection (Lennox et al., 2019). For salmon, it is important to study any changes in timing, efficiencies of routes taken, and the accuracy of migration undertaken, since these are all critical to ensure that the salmon arrive at their destinations in the appropriate amount of time, and with the required energy reserves (Keefer et al., 2021). General survival metrics, for both upstream and downstream hover between 60-75% in the literature, when navigating dams, with downstream migration rate on average being slightly higher than upstream migration rate (Keefer et al., 2021; Lennox et al., 2019; Williams et al., 2012).

Sand and Karlsen (2000) studied fish sensitivity to extremely low-frequency linear acceleration, also called infrasound, as low as less than 1Hz. They hypothesized that salmon and other species use ambient infrasound in the oceans for orientation purposes in migrations. Salmon are able to detect changes in surface wave patterns that in turn indicate changes in water depth levels as well as proximity to barriers such as land formations (Sand and Karlsen, 2000). These findings are not directly applicable to FPDs, and instead pertain to fish ocean navigation. Yet, the findings can possibly be evaluated in light of the support for pool and weir and pool and slot FPDs presented above: since both of these designs allow for slightly faster and steady water flows due to their lack of slope and greater length, they could potentially facilitate orientation and easier navigation for the salmon. I could not find verification of this hypothesis in the literature though.

In addition to concerns related to navigation, factors affecting salmon locomotion also need to be considered. Salmon swimming capacity is vital, especially when they have to pass through dams (Lennox et al., 2019). This is why building effective fish passage structures are vital. These FPDs have to take into account the fact that migrations are energetically very costly for the salmon, and therefore a premium should be placed on ensuring that salmon maintain efficient and judicious use of their energy stores and capacities when they are migrating (Brownscombe et al., 2017). These findings tie in well with the results presented above that showed that Denil FPDs are more energetically costly than pool and weir and pool and slot designs, in general.

Relatedly, Goodwin et al. (2014) found that routes that elicit attraction, without also eliciting repulsion, seem to be very effective after fish discover a passage path. Salmon orient their swimming in the direction of faster flowing water, therefore if there is mean flow that is faster, proper FPDs should make use of these faster mean flows (Enders et al., 2012; Hinch and Rand, 2000). When fish experience water accelerations, an attraction is created, while repulsion is created when decelerations are noticed (Goodwin et al., 2014; Kemp et al., 2005). As shown above, since pool and weir and pool and slot designs elicit faster mean water flows, thereby creating a natural attraction, these are again shown to be preferred over the much steeper and shorter Denil designs.

Additionally, effective FPDs require biological knowledge of salmon behavioral patterns around barriers such as dams, as these lead to variable flows, and gradients in velocity and turbulence (Williams et al., 2012). It is important to build appropriate hydraulic conditions that the fish can readily use, and most FPDs have shortcomings because these biological and hydraulic factors are not effectively considered (Enders et al., 2012). Fish like salmon generally approach a dam via shorelines and require sufficient velocity gradients. For comparison, the attraction flows used at FPDs in the USA, France and the UK typically range from 5 to 10% of the total discharge at a dam (Williams et al., 2012). The more perpendicular to the river, and the lower the entrances are situated downstream, the more poorly fish like salmon will use the entrances (Williams et al., 2012; Enders et al., 2012).

Studies have shown that fish reject traveling through FPDs with undesirable hydraulic conditions, and if these are not properly calibrated, with adequate attraction flows, or if they are placed incorrectly, salmon will not utilize them (Keefer et al., 2021; Enders et al., 2012). This is especially problematic for downstream migrant salmon, since they have to move with the flow and therefore might not have enough time to assess appropriate cues to effectively bypass dams (Williams et al., 2012). Most importantly, the entrance to the FPD needs to possess attractive properties, such as high velocity water discharge, while avoiding low velocity discharge (Izzo et al., 2016; Williams et al., 2012). So most FPDs have their entrances as close as possible to the dam (not too far downstream or in the middle of the dam) and have the flow of the current move the fish into the FPDs using large enough flow volume, velocity and good turbulence characteristics.

In summary, in addition to the literature that examined and presented results on the different types of FPDs, their creation processes, and their suitability for salmon restoration efforts, research clearly shows that effective FPDs need to pay attention to magnetic senses, olfactory and visual cues, and other factors of learning that are critical to fish navigation. Proper FPDs need to consider factors affecting salmon locomotion as well, since migrations are energetically very costly. In order to facilitate minimal costs during migration, FPDs need to offer routes that elicit attraction, via faster mean flows, without also eliciting repulsion due to variable flows, and also in general offer less gradients in velocity and turbulence. These factors are considered in my recommendations below for improving current FPDs in CCVR.

Upstream Migration Considerations for FPDs

Upstream adult salmon are swimming into flows that allow them as much time as they need to navigate around a dam, thereby providing them the time to choose possible passages with more care as compared to those swimming downstream (Nyqvist et al., 2017). They have greater time to select areas with flows that have acceptable velocity gradients, either at the bottom (where velocities are low) or at the top of the water column where velocities are higher (Williams et al., 2012; Enders et al., 2012). For upstream migrating salmon, FPDs have proven to be quite effective (Keefer et al., 2021; Nyqvist et al., 2017; Noonan et al., 2012).

However, even with well-designed FPDs, fish species are different, and there are variation even within species (Williams et al., 2012). For example, Chinook behavior and swimming patterns are different from sockeye, and not all of them will use an FPD in the same manner (Rahel et al., 2018). Also, it is important to consider the cumulative time spent by fish like Chinook in passing through a succession of FPDs in rim dams as they travel upstream (Keefer et al., 2021; Nyqvist et al., 2017). FPDs that are placed along multiple dam routes might reduce the viability of upstream migrating salmon under certain conditions, especially if other confounding factors, anthropogenic and natural, delay the timing of such journeys (Nyqvist et al., 2017; Bunt et al., 2016). Therefore, efficiency and effectiveness are key in upstream FPD implementations, and as the discussions above have shown, Denil fishways do not generally perform well on these metrics (Keefer et al., 2021).

As discussed above, salmon adopt specific behavioral strategies to navigate dams and FPDs, including using water velocity to minimize energy expenditure, which become very important when considering upstream passage. The literature shows that generally fish navigate pathways to minimize their energy expenditure during migration, and show that especially for upstream migration, lower-cost migration pathways are preferred (McElroy et al., 2012). Using swimming speeds measured by tailbeat frequency captured via stereovideography and bank-side observations at various sites, Hinch and Rand (2000) found that in the presence of slower currents were present, salmon were more efficient: salmon propelled themselves upstream in a way that made their migration speeds greater than their measured swimming speeds, using drag reducing small reverse-flow vortices as detailed above. They were however less efficient when fast currents were encountered, where their swimming speeds were faster, using more energy

(McElroy et al., 2012; Hinch and Rand, 2000). The authors hypothesized a balancing between energy usage in migration versus fitness costs associated with spawning delays (Hinch and Rand, 2000).

To recap, the literature shows that in addition to the general and fish specific considerations that need to be considered during creating and implementing FPDs, we need to consider specific requirements of adult upstream migrating salmon. Even though adult salmon have more time to select optimal path during upstream migration, creating suitably fast flows to follow during dam passage will be important. In addition, FPDs that are not steep, not energy taxing, and that even provide and account for facilitating factors such as reverse-flow vortices that reduce drag, are shown to be very effective. These are some of the recommendations for current FPDs in CCVR presented below.

Downstream Migration Considerations for FPDs

Effective downstream FPD construction is very difficult due to the lack of time salmon have to find the entrances and navigate the passageway, unlike when swimming upstream. Unlike in the upstream migration, where both behavioral and swimming capabilities play important roles, since downstream migration moves mostly with the flow, behavioral adaptations are more salient than swimming capabilities (Izzo et al., 2016). This is even more important, since downstream passage is undertaken when salmon are juveniles: far larger populations of juveniles swim downstream compared to the populations of adults that swim upstream (Cogliati et al., 2019; Johnson et al., 2005). Even with these life cycle and the stream flow direction considerations, current FPDs have done a good job in creating efficient passageways: for both salmon and non-salmon, studies showed that in FPDs downstream passage efficiency (68.5%) was higher than upstream efficiency (41.7%) (Noonan et al., 2012). As explained above, these numbers are for full dam passage upstream and downstream, and for partial passage (tailrace-to-forebay passage) these rates were very high. In general, salmon were significantly more successful than non-salmon in navigating FPDs both upstream (61.7 vs. 21.1%) and downstream (74.6 vs. 39.6%) (Noonan et al., 2012).

Given the life cycle considerations noted above, salmon behavior changes with their maturity/size and physiological state, as well as ambient light distribution (Williams et al., 2012; Iwata, 1995). Iwata (1995) showed that small sub-yearling Chinook salmon smolts (usually the spring-run) migrated close to the shoreline, while yearling Chinook smolts migrated in the middle where flow was the highest. Johnson et al. (2005) showed that the yearling Chinook smolts (the winter-run) follow the natural flow of the river, through turbines, unless screens are in place, or there are easy to find, more attractive, flow routes available. These findings are considered in the recommendations I offer in this Project for creating effective surface bypass flows that create and maintain attractive water flows for juveniles during downstream migration.

Williams et al. (2012) state that fish like salmon, both as juveniles and adults, try to stay in areas that have consistent water velocity (avoid quick changes) and that have less turbulence and lower velocity gradients (McElroy et al., 2012). Especially salmon juveniles migrate to the bottom of the flow and this needs to be taken into account when developing turbine screens (Johnson et al., 2005). Juvenile salmon do not passively float downhill with the stream. Instead, in an attempt to minimize energy expenditure, they change their position in the stream when they come near a dam, and if they feel the water velocity decrease, they actively migrate headfirst moving with the water flow, expending more energy and using valuable energy reserves (Johnson et al., 2005). FPDs for downstream passage that have a juvenile bypass system, sometimes as well as a spillway with a raised weir, take into account this headfirst behavior of salmon juveniles (Figure 8).

As a result of moving headfirst, they will have less time to respond to encountering a dam, presumably the condition that led to changes in the velocity gradient in the first place, or to locating the entrance of a FPD (Johnson et al., 2005). Therefore, FPDs that are created for downstream passage need to place passage openings in easy to discover locations, with suitable attractive water velocity and pressure conditions, for juvenile passage (Figure 8). Salmon, like Chinook, increase their tail-beat speed to slow the downstream travel as a result, and sometimes even move upstream to move away from the areas of inconsistent water velocity, since they have to travel long distances to reach their desired ocean conditions in a short time (Williams et al., 2012; Johnson et al., 2005).

The research clearly points to specific downstream migration considerations that need to be kept in mind for FPDs. Since downstream migration undertaken by juveniles happens at much faster pace they have less time to locate suitable downstream passageways. Therefore, FPDs have to have effective openings that will lead the juveniles into the path of the FPDs, through the use of a less variable, but attractive, water flow, and by having structures that facilitate entry to the FPDs. These are considered in recommendations below.

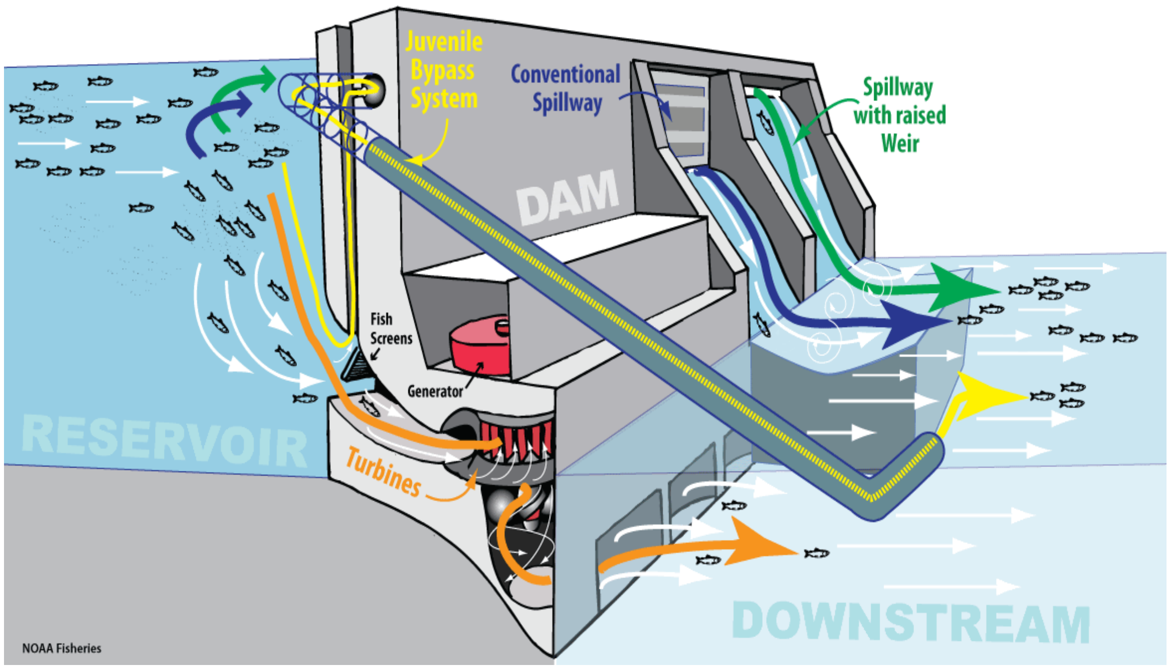


Figure 8: Conceptual layout of a FPD that features a juvenile bypass system, with fish screens. Salmon enter from top left of Figure, and move with the flow bypassing dam.
Source: https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/juvenile-downstream-passage-west-coast

Capture and Transport (CTO) as a Restoration Strategy

Creation of CTOs

Much like FPDs, CTOs need to be created with ultimate salmon population restoration objectives in mind, and also by keeping in mind the differences in implementation of CTO based on juvenile versus adult salmon being considered, was described above. The basic process of collecting salmon in facilities upstream or downstream, and then transporting them by tanker downstream (juveniles) or upstream (adults) was also mentioned above. As with all other fish transport processes, California, along with other states, have adopted protocols to address any stress or other concerns that the salmon might have, following those proposed by federal authorities (Kock et al., 2021; NMFS, 2014). These include considerations such as imposing thresholds for fish density, and not surpassing the maximum threshold in the process of CTOs.

When designing and effectively implementing CTOs, it is vital to pay attention to the induced stress the salmon are under, similar to considerations for FPDs. This stress has been shown to significantly affect fish performance and subsequent survival once they are released (Keefer et al., 2021; Keefer et al., 2008; Ward et al., 1997). There are multiple stages of the CTO processes when salmon can experience increased stress levels. Generally, during certain phases of CTOs where induced stress plays an acute role, such as during salmon collection, transfer, containment and holding, and then transport, pertinent structures should not have turbulent water conditions (Schreck et al., 2006). They should also be free of sharp angles and edges that can cause physical harm to the salmon (Kock et al., 2020; NMFS, 2014). Studies have shown that offering shade or darkened conditions during CTO, especially in shallow water, is very significant not only in reducing stress but also increasing survivorship due to decreased risk of predation (Sabal et al., 2021; Schreck et al., 1995).

More generally, water to water transfers are extremely important. Research shows that minimizing handling of fish through the use of nets and other means, and instead letting the salmon flow into holding areas and into tankers for example, where water to water transfer is maintained throughout, both in upstream and downstream CTOs implementations, is very effective at reducing induced stress in salmon (Sabal et al., 2021). Non water to water transfers are known to induce a lot of stress in fish (Schreck et al., 1995).

Induced stress is especially a consideration during CTO facility operations and handling processes (Schreck et al., 2006; Schreck et al., 1995). If netting is unavoidable, then certain specific precautions are necessary to minimize impacts: soft mesh should be used while knotted twine should not be used; mesh size matters since too large of a mesh size leads to the fish going them at least partially, leading to eye injuries as snouts can easily go through the mesh and hit other fish in the net; fish density is very important if nets are used, especially in the case of juveniles and female salmon, so as to not crush fish at the bottom of a net (Cogliati et al., 2019).

Salmon CTOs in CCVR often uses tagging as an essential element of the program administration, so that restoration efforts can be monitored and salmon population metrics, such as those related to survivorship and replacement rates, can be monitored (NMFS, 2014). In terms of stress inducing activity perspective, tagging has the potential to be a very stressful activity

(Schreck et al., 2006). A very simple way to reduce the potential stress caused by tagging is to combine tagging along with another stressful activity during CTOs, so that the overall number of stressful events is reduced along with the sequential timing of stress inducing activities (Kock et al., 2020). An example would be to tag salmon while they were being loaded to the transport vessel, or as they are to be released, rather than before loading takes place or after (Schreck et al., 1995).

Figure 9: Transport tanker used in CCVR. The tanker is equipped with oxygen and is monitored for appropriate salmon density thresholds.
Source: Source: https://www.theguardian.com/us-news/2021/jun/11/california-to-transport-17m-salmon-to-the-sea-by-truck-as-drought-bites

Overcrowding is also a very important consideration in the transportation tanks (Figure 9), and this step is vital to reducing any additional stress the salmon might experience, especially juveniles (McMichael et al., 2021; Congleton et al., 2000). Dissolved oxygen content and water temperatures are regulated and monitored. This ensures that while the "water-to-water" transfer method is maintained, salmon stress levels are reduced as much as possible. Although in some cases fish are released into ponds to "relieve stress" after transport to mitigate some of the stress caused by the displacement, this is not a practice usually undertaken in the CCVR (NMFS, 2014; NMFS, 2011).

An often overlooked measure, but one that is also quite easy to implement, is the timing of CTOs. Proper timing has been shown to add to significant reductions of stress in fish, and particularly salmon, who are subjected to CTOs (Cogliati et al., 2019; Schreck et al., 1995). Cogliati et al. (2019) for example point out that juvenile salmon perform better when they are released during dark evening hours. These are the times when fish a more likely to migrate anyway, and it also is the time when they are not as exposed to predators. These two reasons are shown to lead to a reduction in induced stress during CTOs (Cogliati et al., 2019).

It is important to replicate the water conditions that the fish were captured from during and after the transport process (Keefer et al., 2021). Fish often experience osmo-regulatory challenges related to the stress of transfer when the salinity n the transport water is not the same as where they are captured from. Therefore, adding salt to the transport water will help with this (Keefer et al., 2008). In addition, including commercially available additives will help preserve salmon fish integrity, for example ensuring salmon skins do not unnecessarily suffer from abrasions that might be adversely affected due to overcrowding and handling during CTO implementation (Keefer et al., 2021; Keefer et al., 2008).

Related research also shows that the stress that fish like salmon might face during CTOs is significantly reduced if they are released in areas where they are easily able to regain orientation without placing too much burden on their energy demands (Keefer et al., 2021; Bond et al., 2017). As an example, releasing salmon to locations without high-velocity currents will help them assimilate with little energy demands placed on them (Kock et al., 2020). It should also be noted that the release locations should not have substantial predator presence so that the released salmon will have adequate time to recover before being subjected to predation (Cogliati et al., 2019).

In summary, much of the research offers evidence that while CTOs are effective as method of restoration, certain factors need to be closely considered when creating and implementing them. Regardless of whether CTOs are used in one-way or two-way implementations, it is vital to consider the induced stress to the salmon during these processes. All phases of CTOs that have the potential to be stressful need to account for factors such as timing, ambient conditions, structures and tools used, overcrowding, suitable conditions during transportation and optimal conditions during release, so that stress is minimized as much as possible.

Findings from Effective CTOs

Colvin et al. (2018) studied spring run salmon in the Willamette River Tributaries to provide findings and recommendations to decrease mortality during CTOs. Specifically, they wanted to predict hauling mortality and to also pinpoint optimal hauling densities so as to minimize mortality risk (Colvin et al., 2018). Other studies have had similar objectives in mind (Clemens et al., 2009). Using an information-theoretic approach (again by using the Akaike's information criterion as Noona et al. (2012) did for model selection), the authors found that operational and in-river annual conditions mattered as predictors for hauling mortality during CTOs. They also found that the amount of time spent loading the fish to transport, and the density of the fish transports were significantly positively correlated with hauling mortality, echoing similar findings other studies as well (McMichael et al., 2021; Colvin et al., 2015; Congleton et al., 2000). Furthermore, optimum hauling density varied with the number of salmon being hauled and transport truck volume, with the ability to lower hauling mortality by reducing hauling density along with loading time (Colvin et al., 2018; Congleton et al., 2000).

In their review of two-way CTOs, Lusardi and Moyle (2017) identified 10 key clearly defined, measurable, and objective success metrics, and objectives, that were also identified by others. The first is that according to the research there is a vital metric of interest, namely, that the population replacement rate should be greater than 1.0 (Congleton et al., 2000). This is related to the number of returning adults that are the offspring of previous CTO spawners. Monitoring this metric needs to be done using genetic parentage analysis (Lusardi and Moyle, 2017).

Second, there needs to be suitable spawning, incubation and rearing habitats in the rivers to achieve these metrics, and one of the key considerations is that the recipient river has adequate water temperature (Lusardi and Moyle, 2017; Bond et al., 2017). Third is that program success is not affected by effects of climate warming on water hydrological processes and temperatures.

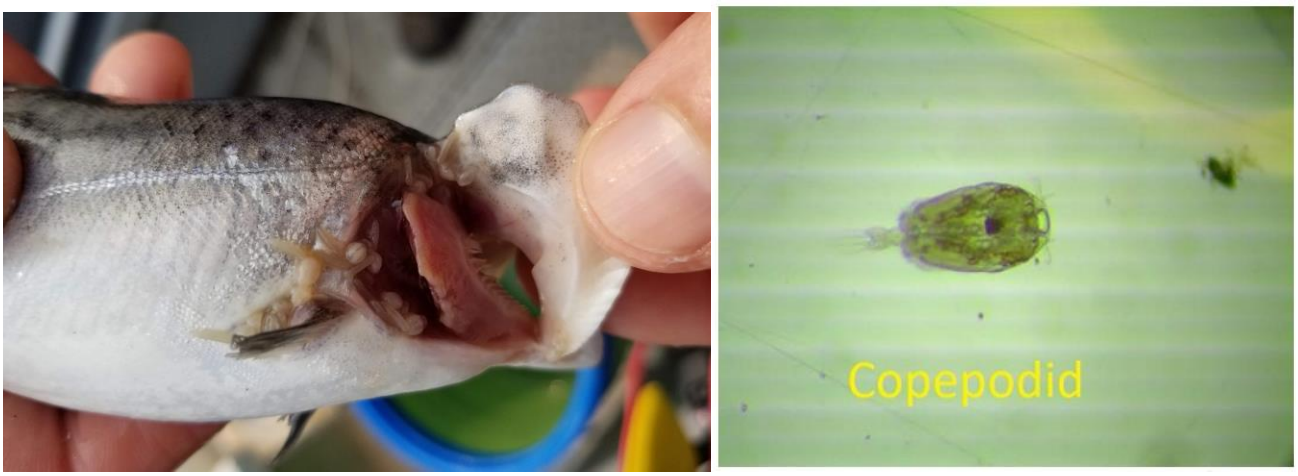
Fourth, captive breeding facilities (e.g., hatcheries) need to be used in combination with CTOs, while ensuring that those are run with established genetic protocols. The key is to increase survival of the offspring once released into the habitat. A secondary objective here is to decrease artificial selection (Lusardi and Moyle, 2017; Bond et al., 2017).

Fifth, effective CTO programs need to ensure that juveniles and adults that are transported between donor and recipient rivers are minimally stressed (McMichael et al., 2011; Keefer et al., 2008; Congleton et al., 2000). Delayed mortality is another consideration during CTO program administration (Congleton et al., 2000). The sixth finding is that trapping juveniles from the recipient rivers has proven to be an effective strategy to sustain CTOs (Keefer et al., 2008). Seventh, there needs to be a good release program for releasing juveniles back into their river of origin that ensures that the juvenile survival rate is high enough (have an adult population as large as those that originally existed in the river) (Clemens et al., 2009; Congleton et al., 2000).

The eighth consideration is that competition between runs of salmon and other fish in recipient habitats is minimized (Keefer et al., 2008). The ninth consideration is that two-way CTOs should be first undertaken in an experimental setting that uses an “adaptive management framework.” Such a framework will have proper monitoring in place in both the donor and recipient rivers, and be cognizant about the entire life cycle of the salmon and the effectiveness of “out-migration capture” (Lusardi and Moyle, 2017). Finally, any good CTO program should be supplemented by other restoration efforts that target all of the life stages of the salmon, and these efforts should be used in conjunction (Kock et al., 2020; Cogliati et al., 2019).

Complications from Copepod Infections

A consideration that is very salient to both FPDs and CTOs, more so for the latter than the former, is parasitic infections. The Chinook restoration efforts in CCVR have not adequately addressed measures undertaken to detect incidence and prevalence of parasitic infections, or actions undertaken to mitigate their effects (NOAA, 2021; NMFS, 2014; NMFS, 2011). This phenomenon of parasitic infection has not been studied well in CTO settings (Kock et al., 2021). Kock et al. (2021) specifically state that more research needs to be undertaken on, “studies of pathogen and parasite prevalence in trap-and-haul facilities and populations; identification of optimal fish transport densities to minimize infection rates; effectiveness tests of antibiotics or other prophylactic treatments on transported fish, where permitted (i.e., with hatchery-origin fish); and studies of the interactions among infectivity rates, collection facilities and transport tanks, environmental risk factors like warm water temperatures, and biological risk co-factors such as elevated stress and immunosuppression" (Kock et al., 2021, page 29).



Panel A Panel B

Figure 10: Typical copepod infection. Panel A shows an infected salmon with the copepod infection clearly visible in the gills. Panel B shows an oval shaped copepodid, the first life stage of *Salmincola californiensis*.
Source: https://nas.er.usgs.gov/queries/greatlakes/FactSheet.aspx?Species_ID=3247

A particular salmon parasite of concern is the freshwater parasitic copepod *Salmincola californiensis* (Figure 10) (Herron et al., 2018). Kabata and Cousens (1973) point out that the life cycle of *Salmincola californiensis* has three distinct phases, namely juvenile copepodid, who are free swimming, then the chalimus that attaches to a host and goes through four distinct growth phases by itself, and finally the adult. The adults are females and they stay attached to the host by a holdfast (called a "bulla"). The adult males attach to the females and die after copulation but do not by themselves attach to a particular host (Sutherland and Wittrock, 1985).

Infestation by this parasitic copepod impairs gas exchange and osmotic regulation in the migrating salmon, and could result in diminished fitness of the salmon and decreased survival of the infected populations, especially when CTOs are undertaken (Herron et al., 2018). While research into the impact of copepod infection in CCVR is not available, the possible impacts need to be studied, measured and addressed (see below). Kock et al. (2021) mention that during CTO, the potential for fish like salmon who are infected by copepod to infect other fish is very high, especially when here is high-density holding and transportation.

Colvin et al. (2015) argue that current diagnostic tests significantly underreport pathogen prevalence in salmon. Although they do not explicitly test for *Salmincola californiensis* and instead test for more common pathogens such as *Apophallus/echinostome metacercariae*, *Parvicapsula minibicornis*, *Nanophyetus salmincola/ metacercariae,* and *Renibacterium salmoninarum*, their findings might be applicable to *Salmincola californiensis* as well. Currently, CCVR uses diagnostic tests such as histology, which have lower sensitivity (Kent et al., 2013). It is not known whether more sophisticated testing framework is used for copepod pathogen detection in CCVR. Colvin et al. (2015) present a methodological approach using occupancy modeling (Lachish et al., 2012; Thompson, 2007).

The occupancy model, that uses hierarchically structured pathogen detection data from tests that are by themselves imperfect diagnostic tests that they built estimated the probability an individual salmon is infected by a pathogen; the probability an organ is infected given the host salmon is infected, and sensitivity of detecting an infected organ given organ infection (Colvin et al., 2015). Colvin et al. (2015) demonstrate the effectiveness of using such models to identify parasitic infection prevalence. As I explain in my recommendations, these insights can be used to create and monitor copepod infection incidence and prevalence in CCVR.

Pathogenic infections are always a risk during CTOs, and therefore proper treatment protocols are vital. One of the contributing factors is overcrowding during CTOs, since this will adversely affect water quality during the holding and transportation stages of an operation (Keefer et al., 2021; Keefer et al., 2008). As Benda et al. (2015) point out, cross infections can be greatly reduced by lowering fish density during CTOs, elevating the flow of the water, and maintaining cool temperatures that end up not providing pathogens the water ambient that they require. Antibiotic treatments are particularly effective at not only killing most pathogens that affect salmon, but also as a strategy for significantly increasing their survival after release (Benda et al., 2015). Of course, it is preferred if there is the possibility of lowering the risk of the salmon being infected in the first place while in the habitat from which they are collected from, or in the holding facility, so steps to possibly do these would be beneficial (Keefer et al., 2021; Keefer et al., 2008).

In terms of possible antibiotic treatments and protocols, Roberts et al. (2004) looked at optimal treatment regiments for copepod *Salmincola californiensis* infection, although not in salmon but rainbow trout. They compared the efficacy of treatment for copepod between a regiment of ivermectin treatment versus manual removal from the gills of the copepod using forceps. For the treatment group, they administered 0.2 mg of ivermectin active ingredient per kg of fish in the first dose with a similar second treatment 14 days later (Roberts et al., 2004). These doses, and the treatment regimens that the authors followed, were found to be therapeutic and effective in other studies as well (Roy et al., 2000; Johnson et al., 1993).

These effects of the two treatment doses, along with the manual removal were followed up and tested (Roberts et al., 2004). In the ivermectin treated trout adult parasites became inert and they changed color as early as within 18 hours of the first dose (Figure 11). The infections started disappearing from day 3 onward and by day 31 all of the female parasites had gone (Roberts et al., 2004; Sutherland, 1990). Notably, the treatment group also saw the cells and areas where the parasites attached starting to heal (Roberts et al., 2004).

Recent studies have highlighted the fact that copepod infection is possibly under-detected in fish subjected to holding, such as those subjected to CTOs, or even those that might congregated around dams, such as those adult salmon who come to reservoirs surrounding dams on their migration upstream (Roberts et al., 2004; Roy et al., 2000; Johnson et al., 1993). Roberts et al. (2004) did comment that their findings were particularly beneficial with regards to treating salmon infected with copepods, and that their dosing recommendations would be effective. They highly recommend an oral dose of ivermectin as an effective treatment option to combat *Salmincola californiensis* infection in salmon (Roberts et al., 2004).

To summarize, the incidence and prevalence of the copepod *Salmincola californiensis* in salmon in CCVR needs to be studied better. By using histology tests, and by combining them with frameworks such as hierarchical occupancy modeling, it is possible to identify and establish clear prevalence rate of *Salmincola californiensis* infection rates in CCVR. Once these rates are identified, they need to be monitored long term. To properly address these infections, an aggressive therapeutic treatment plan needs to be adopted with the use of antibiotics such as ivermectin, suing tried and tested protocols and treatment regimes. These should be critical steps in all salmon restoration efforts undertaken in CCVR, as I point out below.

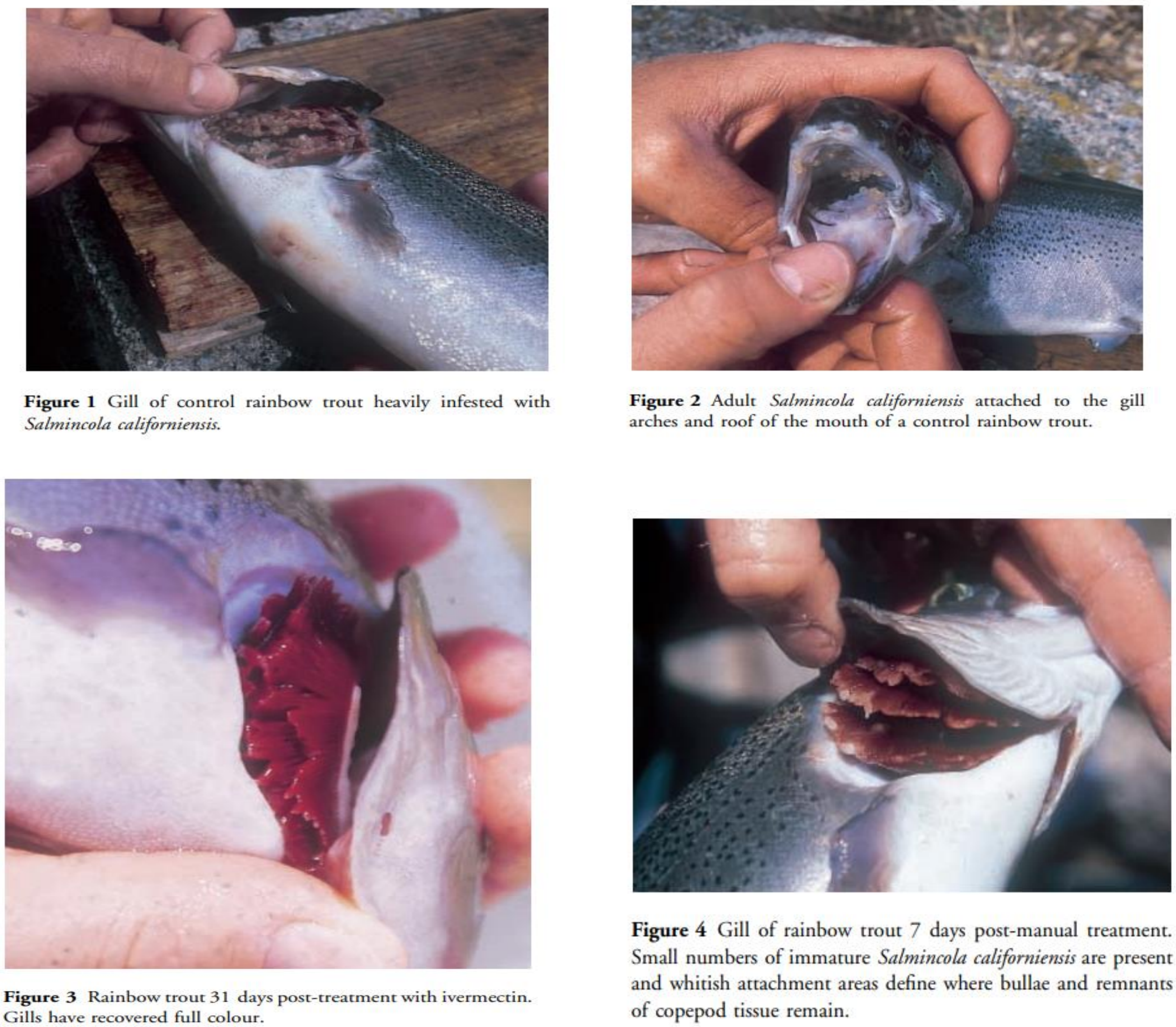


Figure 11: Observed *Salmincola californiensis* infection in treatment trout and post treatment results, as documented by Roberts et al. (2004). The figures and descriptions are taken from Roberts et al. (2004).
Source: Roberts et al. (2004), p. 76.

Discussion

Based on the results presented above, I can tease out answers to the sub-questions that I posed in my Introduction. Overall, FPDs have performed well in the laboratory setting as well as *in situ* as the research suggests. The results presented and discussed above clearly show which FPDs have shown promise and why, while answering the questions laid out in my Project. I summarize and present key areas for improvement using those findings for both FPDs and CTOs in the next section.

The first sub-question was: what are some impacts of dams in terms of mortality/morbidity? Dams are shown to be responsible for mortality and morbidity increases due to multiple factors. Dams lead to ecological connectivity, ecological degradation, and habitat losses, which have negative impacts on salmon migrations. The dams function as physical and behavioral barriers to salmon migration, having direct impacts on their movements, as well as causing behavioral changes. Having to navigate dams changes their internal states, and leads to physiological and stress related changes. This increased stress during dam passage, both downstream and upstream, causes not only cortisol increases, but also affect carbohydrate metabolism and glucose consumption and production. All of these factors certainly lead to greater morbidity and mortality during longer migrations. These effects are in addition to the direct and delayed mortality during downstream passage caused by turbines.

Second, the literature provides an affirmative response in terms of the next research sub-question: how effective are FPDs in mitigating some of these negative impacts of dams? The literature shows, using passage efficiency metrics, that FPDs are effective in enabling salmon navigate dams, even in multiple sequential settings such as those at CCVR. However, the survival rates are still rather low. The research clearly shows how well the Columbia dams have structured their FPDs (Crozier et al., 2017; NMFS, 2011). Columbia dams are similar to those in CCVR in that they use pool and weir, as well as pool and slot FPDs, but notably, they use Denil less (Keefer et al., 2021). As the above results show, the former two designs are more preferred due to their less steep and longer passage way designs. These notable design differences, and their effects on facilitating salmon migration salmon migration through dams, are crucial to the recommendations I offer in below.

The third sub-question was the following: how can current FPDs used in CCVR be improved? This sub-question is answered in the next section on recommendations, where I distill all of the results for effective FPDs and present two major and two minor recommendations for improvements, given current FPD implementations in CCVR.

The fourth research sub-questions was: how effective are CTOs in mitigating some of these negative impacts of dams? As was described above, the research is clear that CTOs are effective in restoration efforts, but a lot of precautions need to be undertaken to minimize stress, and address concerns such as parasitic infections. The research suggests improvements to all phases of CTOs, especially those that are more stressful to the salmon. Factors such as timing, ambient conditions, structures and tools used, overcrowding, suitable conditions during transportation and optimal conditions during release, have to be examined, especially with regards to juvenile versus adults transportation so that stress is minimized as much as possible. If these are emphasized, CTOs can be made very effective. To complement these efforts, proper parasitic infection monitoring and remediation efforts have to run parallel to these. If done in tandem, these infection prevalence abatement efforts have shown to be very successful in restoration efforts. I explain these further in the recommendations below.

Finally, the fifth sub-question was the following: how can current CTOs used in CCVR be improved? As in the third sub-question, this sub-question is answered in the next section on recommendations, where I distill all of the results for effective CTOs and present two major recommendations for improvements, given current CTO implementation protocols in CCVR.

Recommendations

The evidence and results presented and discussed above, along with an examination of current implementations of FPDs and CTOs (respectively) in CCVR have shaped the recommendations presented below. For both FPDs and CTOs XX major recommendations are identified, along with minor recommendations as applicable. Currently, CCVR's implementations of both practices have resulted in salmon populations being restored somewhat (NMFS, 2014; Williams et al., 2012). Latest results also confirm that current restoration efforts have borne fruit (CDFW, 2022b). More improvement would need to be made in order to be able to take Chinook runs, especially the winter and spring runs, off the ESA listing (Keefer et al. 2021; Keefer et al., 2008).

Recommendations for Improving FPDs in CCVR

Major Recommendation: Moving Away from the Use of Denil Fishways

Even though currently CCVR uses Denil fishways, based on the current findings it is recommended that CCVR move away from Denil configurations to either exclusively using pool and weir, or pool and slot (Figure 6), configurations, or exploring the adoption of additional FPD configurations such as natural fishways. Research has shown that adult Chinook salmon in general are less capable of negotiating fish ladders and other passage designs during upstream migration because of their relatively slower swimming speeds and jumping abilities (NMFS, 2011). NMFS (2011) recommend that Denil fishways have a slope of no more than 20% precisely for the latter reason, and it is assumed that this is also the guidelines that will be in place in CCVR. Denil fishways are not preferred both because of their shortness as well as steepness (Noonan et al., 2012; Mallen-Cooper and Stuart, 2007). Therefore, even with current guidelines of less than 20% gradient, Denil FPDs are less desirable than pool and weir, or pool and slot, configurations.

If using pool and weir, or pool and slot, configurations in place of currently existing Denil configurations is selected, then these two have many incumbent advantages, namely, US-wide usage in many regions, currently usage within CCVR, and having extensive laboratory testing to and effectiveness studies to attest to their success (CDFW, 2022a; Keefer et al., 2021; Clay, 1995). In addition, if newer configurations such as natural FPDs are explored, then a more rigorous testing process would be required before they are used in CCVR (NMFS, 2011). NMFS (2011) outline a tiered testing process for any new initiative to go through before NMFS adopts new proposals: the first step is a review of earlier research, second step is a study plan, third is lab research, and the fourth is prototype units being available (NMFS, 2011).

Major Recommendation: Proper Water Velocity and Pressure Around and Within FPDs

Chinook are generally slower moving salmon who prefer steady and moderately slow water currents so as to minimize energy expenditure, and maximize survival and FPD passage efficiency rates both as juveniles as well as adults (Keefer et al., 2021; Crozier et al., 2017; NMFS, 2011). Based on this overall swimming characteristic of Chinook, differentiated strategies to control water flow are recommended for FPDs in CCVR for both upstream and downstream salmon migration below.

Downstream migration is undertaken by juvenile salmon, and it is recommended that existing bypass systems be improved with surface flow bypasses, that use the generally faster upper water column, with three improvements noted in Johnson et al. (2005). These improvements are:

- Forming an extensive flow net in the forebay by using at least 0.7% of total discharge as surface flow bypass discharge;
- Ensuring that the water velocity is increased as salmon approach the surface flow bypass: Johnson et al. (2005) recommend acceleration of around 1m/s per meter as salmon approach the bypass (Kemp et al., 2005);
- Maintaining proper increased water velocities near the entrance of the bypass so as to attract and entrain the juveniles: velocities around .3m/s are recommended;

In addition to these improvements, to control water velocity and attract juvenile salmon to the downstream bypasses, it is recommended that CCVR utilize engineered structures like booms or walls that point away from the dam into the approaching paths of the salmon. As Goodwin et al. (2014) showed, simply placing boom-like structures aligned parallel to the water flow vector might help the salmon not deviate from the mean flow. This will not be the case if structures like booms are placed perpendicular to the flow vector, and this is to be avoided (Goodwin et al., 2014). These walls to elicit attraction and guide juvenile to the mean water flow can be constructed for the forebay so as to increase fish availability to the surface flow bypass as well, as Johnson et al. (2005) recommended.

As far as upstream adult salmon migration is concerned, slowing the water current, and reducing drag, will enable adult salmon swimming upstream enough time to select the best passages through the FPDs as intended, and not just rely on bottom water columns (Nyqvist et al., 2017; Williams et al., 2012; Sand and Karlsen, 2000). A novel strategy to accomplish this is through creating small reverse-flow vortices, by using suitable cobble sizes or bank configurations, should be seriously examined (Zielinski and Freiburger, 2021; Hinch and Rand, 2000). From the research undertaken, it is not clear whether such strategies are being explored or implemented in CCVR (NOAA, 2021; NMFS, 2011). Hinch and Rand (2000) found that this phenomenon even propelled salmon upstream because their migration speeds were greater than their measured swimming speeds, although not enough research exists as to how best conservation management can create such vortices (Crozier et al., 2017; McElroy et al., 2012; Hinch and Rand, 2000).

Minor Recommendation: Improve Current FPD Effectiveness Monitoring Practices

Two minor improvements to current monitoring efforts are recommended, since these will improve long term monitoring of current efforts and the ensuring that restoration objectives are sustained. Current FPD monitoring practices in CCVR are extensive, but they are not necessarily long term (NMFS, 2014; NMFS, 2011). More long-term tagging driven monitoring of FPDs, as well as tracking salmon across multiple seasons, is recommended as an improvement (Cooke and Hinch, 2013). NMFS (2011) state that tagging procedures are key to monitoring the effectiveness of FPD implementation, but it is not known whether there is research to identify potential failures of these tagging devices. Technical validation of electronic tagging equipment is essential so that complications from tag failures or detection inefficiencies are mitigated (Cooke and Hinch, 2013). Therefore, it is recommended that such tag validation studies efforts are also undertaken while engaging in longer term FPD monitoring.

Recommendations for Improving CTOs in CCVR

Major Recommendation: Emphasizing Reducing Induced Stress during CTOs

As explained above, CTOs are potentially very stressful events through multiple stages of their implementation (Ward et al., 1997). The following recommendations are all geared towards ameliorating stress that salmon experience during CTOs and are informed by earlier discussions. Some of these are already undertaken and noted (Lusardi and Moyle, 2017; NMFS, 2014), but it is recommended that they be given the highest priority.

- Ensuring that stable water levels are maintained during all phases of CTO such as salmon collection, transfer, containment and holding, and then transport. Ensuring that turbulent water conditions are avoided as much as possible (Bond et al., 2017; Schreck et al., 2006);
- During all of these phases, tools and facilities used must be free of sharp angles and edges that can cause physical harm to the salmon (Kock et al., 2020);

- As much as possible, implementing CTOs during evening times, or offering shade or darkened conditions during CTOs, especially in shallow water, are highly recommended (Sabal et al., 2021; Schreck et al., 1995);
- Water-to-water transfers, which is already the standard practice, is to be maintained, and dewatering is to be avoided as much as possible. Using nets and other means of direct handling the salmon is to be avoided (Ward et al., 1997);
- Netting is sometimes used in CCVR (NMFS, 2011). In addition to the usual precautions, if netting is to be used the following should be strictly adhered to (Kock et al., 2020; Cogliati et al., 2019):
    - Soft mesh should be used while knotted twine should not be used;
    - Mesh size should be adequate and not oversize;
    - Fish density levels need to be monitored to avoid crushing fish at the bottom;
- As much as possible, it is recommended that CTOs be coordinated so that the number of stressful events is minimized. For example, tagging could be undertaken at the time when salmon are loaded for transport, so that the salmon experience just one stressful event and not two sequential events (Kock et al., 2020; Bond et al., 2017);
- Prioritizing replicating water conditions that the fish were captured from during and after the transport process is recommended. Adding salt to the transport water to do so, and also adding commercially available additives to help preserve salmon fish integrity during transport, are highly recommended (Keefer et al., 2021; Keefer et al., 2008);
- When releasing the salmon, prioritizing releasing them to areas where they are easily able to regain orientation without placing too much burden on their energy demands. As an example, releasing salmon to locations without high-velocity currents, or areas where there isn't substantial predator presence (Kock et al., 2020).

Major Recommendation: Mitigating Copepod Infection Prevalence

As mentioned above, currently CCVR uses diagnostic tests such as histology to track parasitic infections, but these have lower sensitivity (NMFS, 2014; Kent et al., 2013). Additionally, it was difficult to find estimates of copepod incidence, prevalence and mitigation efforts in CCVR. Given this lack of identification, monitoring, and research, the following are recommended to complement CTO efforts:

- It is recommended to establish a research program to study the incidence and prevalence of *Salmincola californiensis* infection in CCVR salmon populations. As Herron et al. (2018) point out, these infections are potentially significant, especially in CTO settings. It is not known if a research program, with proper identification protocols, has yet been undertaken in CCVR;
- To estimate more robustly the true prevalence rates of copepod infection in the salmon populations in CCVR, it is recommended that sophisticated testing frameworks, such as the hierarchical occupancy model used by Colvin et al. (2015) to test probabilities of infection from lesser powerful diagnostic tests, be used. This kind of occupancy modeling framework can be used once a more robust effort for testing for copepod infection is undertaken, as recommended above;
- Parallel to the above-mentioned recommendations for proper identification of the prevalence of copepod infections in the salmon populations in CCVR that are subjected to CTOs, it is also recommended that steps be taken to minimize possible cross infections with copepod and other parasitic infections. These can be done by adhering to the following recommendations:
    - Lowering fish density in during transportation and holding. The probability of infections can be reduced by adhering to guidelines outlined I studies reviewed above (Keefer et al., 2021; Keefer et al., 2008);
    - Maintaining water temperature that is sufficiently cool. Pathogens such as copepod thrive in warmer waters, and therefore efforts need to be made to keep water temperature in line with ambient temperatures from which the salmon came from, and even more if need be (Benda et al., 2015);
- Finally, it is important to explore a complete regime of antibiotic treatments to counter copepod infections. Roberts et al. (2004) clearly show that antibiotic treatments like ivermectin are significantly effective at treating copepod infections in salmon and other fish species. Treatment protocols for salmon subjected to CTOs in CCVR were not found.
- In terms of ivermectin effective dosage and treatment protocols, 0.2 mg of ivermectin active ingredient per kg of fish in the first dose with a similar second treatment 14 days later, is recommended, according to the literature (Roberts et al., 2004). These doses, and

the treatment regimens that the authors followed, were found to be therapeutic and effective in other studies as well (Roy et al., 2000; Johnson et al., 1993), and are highly recommended during CTO implementation.

Conclusion

The above recommended improvements to current FPDs and CTOs in CCVR work very well with the two scientific principles of salmon restoration mentioned above that NOAA and NMFS adhere to: first, the major and minor recommendations offer life stage specific threat assessment, and structured mitigation strategies accordingly as desired; second, the recommendations also focus on spatial structures such as maintaining populations across landscapes, as required. The recommendations are meant to augment current efforts, and address weaknesses of those efforts, as noted. These recommendations, as well as all of the current restoration efforts undertaken in CCVR are geared towards removing Chinook from their current ESA listing. Identifying and combating copepod infections is especially important for both FPD and CTO implementations, given the noted correlation between this parasitic infestation and the fish congregation such as when they gather in reservoirs near dams (Herron et al., 2018).

In order to remove both the winter-run and spring-run Chinook from the ESA listing, NMFS (2014) effectively argues that it will be necessary to implement policies for re-introducing the Chinook to currently unoccupied habitats that have in the past supported these runs of salmon. This is in addition to implementing current mechanisms like FPDs and CTOs for mitigating stressors caused by dam passage. These re-introduction strategies might potentially still be valid even after successful implementation of some or all of the recommendations mentioned above, since dam removal might not be a viable option (Bellmore et al., 2019; NMFS, 2014). As part of such a policy, the CCVR restoration efforts have focused on re-introducing salmon into parts of the McCloud River, Battle Creek, the Yuba River, and the San Joaquin River (NMFS, 2014). As Kock et al (2021) also state, there is also discussions for re-introduction of these runs of salmon above high-head rim dams that are erected on the Yuba and Tuolumne rivers. These efforts, along with other restoration efforts related to FPDs and CTOS have proven to be somewhat successful, and led to a slow resurgence of salmon populations in CCVR (CDFW, 2022b)

Moreover, and in keeping with the two scientific principles articulated above, effective policy instruments and governance structures need to be instituted and enforced to promote, and regulate, restorative practices. Conservation practices such as FPDs and CTOs serve a wide range of management and operational objectives. Yet, as the recommendations also highlight, they need to first and foremost have clearly defined metrics of success and program performance. From a technical perspective, solutions require biologists and engineers to work together to determine proper hydraulic conditions and then to design appropriate practices. From a wider stakeholder perspective, there needs to be concerted, multi-agency actions that also collaborate with the public to find effective solutions. It is by working together, and in concert, would we be able to restore CCVR Chinook salmon back to their former plentiful migratory runs.

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