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Out-migration survival of wild Chinook salmon (Oncorhynchus tshawytscha) smolts from Mill Creek through the Sacramento River during drought conditions

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SANTA CRUZ

OUT-MIGRATION SURVIVAL OF WILD CHINOOK SALMON (*ONCORHYNCHUS TSHAWYTSCHA*) SMOLTS FROM MILL CREEK THROUGH THE SACRAMENTO RIVER DURING DROUGHT CONDITIONS

A thesis submitted in partial satisfaction
of the requirements for the degree of

MASTER OF SCIENCE

in

OCEAN SCIENCES

by

Jeremy Notch

June 2017

The thesis of Jeremy Notch
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ABSTRACT

OUT-MIGRATION SURVIVAL OF WILD CHINOOK SALMON (*ONCORHYNCHUS TSHAWYTSCHA*) SMOLTS FROM MILL CREEK THROUGH THE SACRAMENTO RIVER DURING DROUGHT CONDITIONS.

by

Jeremy Notch

Once emerged from the gravel after being spawned in natal streams, Chinook salmon spend many months rearing and growing in freshwater before undergoing smoltification and out-migrating to the ocean. This relatively short period of time is considered to be the most vulnerable and dangerous phase in the life cycle of a Pacific salmon. It is during this phase when smolts navigate around many anthropogenic structures and experience environmental stressors while making their way to the ocean. In California's Central Valley, the few remaining wild populations of Chinook salmon (*Oncorhynchus tshawytscha*) out-migrate through a highly modified riverine and estuary landscape characterized by leveed banks, altered flow and temperature regimes, transformed food webs, and limited floodplain and rearing habitat. Juvenile salmon smolts migrate through these landscapes within a relatively short period of time, requiring them to quickly adapt to changing water conditions and habitat types. Understanding the survival rates of wild smolts from source tributaries to the Pacific Ocean is essential in protecting and restoring these

populations from the low abundances currently observed. When faced with drought conditions out-migrating smolts experience low flows, elevated water temperatures and high densities of predators while out-migrating to sea. In order to assess smolt survival during drought conditions in late spring (April-May), 304 wild smolts were acoustically tagged and tracked from Mill Creek (Tehama County) to the Pacific Ocean between 2013 and 2016. Total outmigration survival to the ocean was 0.3% during these years, with only one fish making it to the Golden Gate and the Pacific Ocean. These survival estimates are some of the lowest ever recorded for salmon out-migrating to the Pacific Ocean, with much of the mortality occurring within Mill Creek and the Sacramento River. Cumulative survival through Mill Creek (rkm 452-441) was 68% (±12 S.E.), and cumulative survival through the Sacramento River (rkm 441-203) was 7.6% (± 16 S.E.) These low survival rates are likely attributed to low flows in Mill Creek and the Sacramento River resulting from critically dry winters between 2013 and 2015, which were reduced even further by water diversions for agriculture in both Mill Creek and the Sacramento River. During periods of higher flow in 2016 survival rates dramatically increased, suggesting that more water in Mill Creek and the Sacramento River is necessary to improve in-river smolt migration survival during the late spring.

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Chapter 1

Introduction

California's Central Valley historically supported some of the largest runs of Chinook salmon in the world. Native American tribes throughout the region relied heavily on these fish, and harvested an estimated 8.5 million pounds annually (Yoshiyama et al. 1998). Similar catch rates were documented by commercial fishing fleets based in San Francisco during peak operations in the mid –late 1800's. The engine behind these enormous runs was the network of rivers draining off the Sierra Nevada mountain range, as well the productive marine waters of the Gulf of the Farallones and the northeast Pacific Ocean. Salmon historically had unimpeded access from the ocean to headwater streams which were fed by cold water from melting springtime snowpack and abundant springs, providing optimum spawning and rearing conditions nearly year-round. Four runs of Chinook salmon - spring, fall, late-fall and winter - evolved within Central Valley watersheds to take advantage of the unique hydrology and habitat available in the Sacramento and San Joaquin River basins. The timing of freshwater entry from the ocean gives each run its name, which have evolved distinct life history strategies to exploit the diverse habitat available in the Central Valley.

Spring-run Chinook salmon enter freshwater during March-June as sexually immature adults, and time their upstream migration during periods of high water discharge from snowmelt. Once reaching elevations > 2,000 ft. they over-summer in deep pools where they mature before spawning in the early fall. Juveniles emerge from gravel nests approximately 2 months after being spawned and feed off their yolk sac before foraging in the stream as fry. Juvenile spring-run out-migrate from natal streams as fry (≤55 mm), parr (>55 to ≤75mm), smolts (>75 to ≤100mm) and yearlings (≥100mm). This range of sizes diversifies the timing of downstream migration and reduces the chances of collapse of a particular life stage in the event of poor survival conditions for a given life-history strategy under varying climate and related freshwater habitat conditions while also helping to avoid density-dependent mortality (Williams 2006). Before entering the ocean all juvenile salmon must begin smoltification; a process that prepares the salmon's osmoregulation system for salt water and changes their coloration to silver and black to help camouflage them in the ocean.

Fall-run Chinook salmon enter freshwater during August – October and spawn shortly after entering natal streams. They are relatively larger fish compared to other runs of salmon because of the extra time spent at sea, where they mature and grow rapidly throughout the summer. Fall-run salmon typically spawn in the lower reaches of rivers near the valley floor during the onset of fall freshets and decreasing water temperatures. After emerging from the gravel fall-run juveniles out-migrate as fry, par and smolts but do not exhibit a yearling life history (Moyle 2002). Juveniles enter the ocean during the same time as other runs, typically April-May when upwelling along the California Coast sets-up nutrient and food rich marine waters.

Late-fall Chinook salmon enter freshwater during November-January and spawn shortly after entering natal streams. Historically late-fall run salmon were found exclusively in the upper reaches of the Sacramento and San Joaquin Rivers, where high winter flows allowed them access to productive spawning and rearing habitat. Late-fall salmon were regarded as the biggest of all salmon returning to spawn in the Central Valley, typically returning as four year old adults (Moyle 2002). After emerging from gravel nests juveniles over summer in natal streams before migrating to the ocean as yearlings (Vogel and Marine 1991).

Winter-run Chinook salmon evolved exclusively in the upper Sacramento River Basin and are found nowhere else on earth (Healey 1991). The McCloud River was the primary spawning tributary for these fish, a river regarded by many historians as one of the greatest salmon rivers in the world and the location of California's first salmon hatchery (Yoshiyama and Fisher 2001). Winter-run salmon enter freshwater during January – March and spawn in July and August. Their sole occurrence in the upper Sacramento River basin is due to the cold water which is supplied all summer by springs off Mount Shasta. Stable cold-water flows made egg incubation and juvenile rearing possible during the hot summer months, a time of year when most Central Valley streams are too warm to support salmon. After emerging from the gravel in late summer/early fall, juveniles migrate downstream as fry and rear in the lower Sacramento River and Delta, or remain in their natal stream before migrating to the ocean as smolts or yearlings.

Natal homing and the diversity in freshwater entry and spawn timing created spatial and temporal segregation between these runs, allowing each to evolve specific traits unique to the habitat types they occupied; winter and spring-run ascending to headwater streams while fall and late-fall run occupied lower elevation stream reaches. This diversity also enabled salmon to spawn and juveniles to rear nearly year-round in over 26 tributaries to the Central Valley (Yoshiyama et al. 2001). Connecting these rivers to the sea was the Sacramento-San Joaquin River Delta - a massive estuary that historically provided over 800,000 acres of rearing habitat for juvenile salmon before they entered the Pacific Ocean (Whipple et al. 2012). This habitat was a critical component in the life cycle of Central Valley salmon, because fry and parr which out-migrate earlier in the year are typically too small for ocean entry, so they use the Delta as a nursery for additional growth before migrating to sea in April-May.

The abundant runs of Central Valley salmon began to slowly fade beginning in the late 1800's, when gold mining took its toll on spawning streams and over-fishing exploited adults in the ocean and rivers. Further collapse of the runs continued into the 1900's as dam construction began in many/most Central Valley tributaries. Impassible dams became migration barriers that removed much of the spawning and rearing habitat for spring-run and winter-run Chinook salmon, and land reclamation in the Delta transformed the productive floodplain rearing habitat into agriculture fields. Most recently the construction of the State and Federal water projects has diverted a large amount of the mainstem Sacramento and San Joaquin river flow coming into the Delta to the Bay Area and southern California via the California Aqueduct for agriculture and municipal uses. What currently remains for Chinook salmon in the Central Valley is 47% of their historic habitat (Yoshiyama et al. 2001) and 50% of the natural stream flow exiting the Delta (Yates et al. 2008). The cumulative effect of these alterations on river flow and habitat has been the decimation of the Central Valley's natural-origin Chinook salmon populations, which are now largely supported by hatchery production. The remaining wild populations of Chinook salmon exist in just a few tributaries to the upper Sacramento River, where pristine spawning and rearing habitat persists and spatial segregation limits them from breeding with hatchery-origin salmon.

In an effort to study the dwindling numbers of Central Valley Chinook salmon, coded wire tagging (CWT) experiments began in the 1960's which aimed at understanding juvenile survival, ocean distribution and harvest rates of primarily hatchery produced salmon (Nandor et al. 2010). These studies inject a small wire (0.25 × 1.1 mm) containing a unique ID into the nasal cartilage of juvenile salmon and couple the procedure with clipping the adipose fin, which indicates the fish is of hatchery origin and contains a coded wire tag. When the marked salmon is captured in the ocean or river, the CWT is extracted and the unique ID is read under a microscope which relates the hatchery of origin, release group and brood year of the fish. These studies have produced some of the foundational knowledge regarding freshwater habitat usage, timing of ocean entry, ocean distribution and proportion of wild vs hatchery salmon returning to spawn in the Central Valley. The CWT studies are still in operation today and currently mark 50 million salmon annually along the west coast of North America (Nandor et al. 2010). While these studies have helped our understanding of hatchery salmon survivorship at large spatial and temporal scales, understanding specific areas where juvenile salmon experience mortality has been widely speculated until recently.

Advances in technology and the need to track salmon at finer scales of space and time led to the invention of miniature acoustic tags, which are surgically implanted into the stomach cavity of juvenile salmon and emit a uniquely coded signal detected by underwater hydrophones. Since its inception in the early 2000's in the Columbia River system, acoustic tagging studies have provided movement and survival rates of juvenile salmon at fine scales through areas of interest containing hydropower dams, large water diversions and known predator hot spots (Harnish et al. 2012; Rechisky et al. 2013; Welch et al. 2008). These tags offer many benefits that CWT studies lack, primarily the fine scale resolution of movement and survival rates of individual fish, as well as real-time detection capabilities of receivers linked to the internet. Currently this technology is the most advanced way of tracking Central Valley salmon smolts across space and time throughout their migration pathway to the ocean. With the growing need to understand survival rates of naturally produced salmon smolts in the Central Valley, my thesis reports on the use of this technology to track the movement and survival rates of wild Chinook salmon smolts originating in Mill Creek.

Mill Creek is a tributary to the upper Sacramento River that supports some of the last remaining populations of wild Central Valley spring-run Chinook salmon; a population that is part of an evolutionary significant unit (ESU) listed as threatened under the federal Endangered Species Act (ESA) since 1999. The pristine spawning and rearing habitat accessible to this population allows for their continued existence, and makes this watershed unique in a landscape dominated by large dams, degraded habitat and hatchery produced salmon. With only three tributaries in the Central Valley continuing to support established runs of wild spring-run salmon (Mill, Deer, Butte Creeks), understanding the dynamics in juvenile out-migration survival is critical to support effective recovery actions for these endangered populations.

In this study I acoustically tag and track out-migrating salmon smolts from Mill Creek to the Golden Gate and the Pacific Ocean during a period of four years (2013-2016), and estimate movement and survival rates throughout different regions of interest. The data collected in this study comes from natural-origin Chinook salmon smolts that are migrating downstream in April and May at sizes >80mm fork-length, which is historically the peak out-migration window for Mill Creek smolts. These fish are representative of the smolt life history, one in which juveniles rear for extended periods of time in the upper watershed before out-migrating to the ocean during late spring. However, juvenile Chinook salmon out-migrate from Mill Creek throughout much of the year as sub-yearlings and yearlings, and downstream migrants that either migrate from June-March or at different sizes (<80 mm) from those tagged in my study most likely have different movement and survival rates compared to the smolts tagged and tracked in this study. In addition, the data collected throughout much of this study was during a series of unprecedented drought conditions (2013-2014-2015) that most likely affected smolt out-migration movement and survival as a result of exceptionally low flows and elevated water temperatures.

Chapter 2 describes the results from this study and includes statistical analysis relating survival to key biological and physical variables.

In an effort to tease apart the low survival rates with potential side effects related to trapping, handling and surgically implanting acoustic tags in juvenile salmon, a tagging effects study was conducted in Mill Creek during spring of 2016. This study was designed to test two assumptions made when conducting survival studies using acoustic telemetry: (a) the tagged fish are representative of the population, and thus the surgical procedure has no effect on their behavior; and (b) the acoustic tag stays inside the fish for the duration of the study. If these assumptions are violated then the data collected during the study are potentially biased and corrections must be made. In order to test these assumptions an experiment was conducted in Mill Creek where three experimental groups of fish were either captured by a rotary screw trap (RST) and acoustic tagged, captured by the RST and not tagged, and a control group. After 30 days the effects of each treatment were analyzed and the rate of tag retention was monitored throughout the study. Chapter 3 describes this study, which allowed us to examine the effects of acoustic tagging on the growth, survival and tag retention in juvenile salmon and helped address concerns about the surgical procedure which juvenile salmon undergo.

The results from this study have implications for future management and recovery actions related to threatened populations of Central Valley spring-run Chinook salmon. As the number of returning adults to Mill Creek continues to decline, more attention is being focused on the factors influencing juvenile and adult survival rates. The data collected in this study can help shed light on specific reaches and regions where Chinook salmon smolts are experiencing low survival rates within a relatively long out-migration corridor. In addition, survival rates estimated over a range of environmental conditions can better inform resource managers of how changes in stream flow and temperature affect the survival dynamics of out-migrating salmon smolts. An improved understanding of survival dynamics in relation to flow and temperature is especially important during drought conditions, as the limited amount of available water should be utilized in a way that promotes both ecosystem and agricultural needs.

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Chapter 2

Out-migration survival of wild Chinook salmon (*Oncorhynchus tshawytscha*) smolts from Mill Creek through the Sacramento River during drought conditions

Introduction

Wild stocks of Chinook salmon (*Oncorhynchus tshawytscha*) were historically abundant in all rivers draining into in California's Central Valley (CCV), with population estimates of over two million adults returning to spawn each year (Yoshiyama et al. 1998). Today these populations have severely declined, due in large part to the loss of over 53% of historic spawning and rearing habitat behind large dams (Yoshiyama et al. 2001) (Fig. 1). To mitigate the affects of lost and degraded spawning and rearing habitats hatcheries are now operated on major CCV rivers. Hatcheries currently produce the majority of Chinook salmon returning to spawn in California's CCV as well as those harvested in the ocean fishery (Satterthwaite et al. 2015). The remaining wild populations of Chinook salmon in the Central Valley are isolated in just a few tributaries to the upper Sacramento River where pristine spawning and rearing habitat persists, and spatial segregation limits them from breeding with hatchery-origin salmon.

Despite the pristine spawning and rearing habitat available for wild populations their numbers have severely declined, and in 1999 the CCV spring-run Chinook salmon ESU was listed as threatened under the federal Endangered Species Act (ESA). It is presumed that poor out-migration survival is a proximate cause for the declining populations, due in part to a highly modified river and estuary environment that has reduced rearing potential, combined with altered flow and temperature regimes in the Sacramento River and Delta which has increased populations of non-native predators that benefit from the altered ecosystem. The short window of time during the downstream migration of smolts to the ocean is the most vulnerable phase in the life cycle of a Pacific salmon, and is believed to account for much of the mortality the species experiences (Bradford 1995; Clark et al. 2016; Healey 1991; Rechisky et al. 2012). As a result of water projects in the CCV which create artificially low flows in the winter and spring, simulating drought conditions, smolt survival to the ocean is reduced even further resulting from the effects of elevated water temperatures, reduced flows, decreased turbidity and increased interactions with predator fish (Baker et al. 1995; Becker 1971; Cavallo et al. 2012; Gregory 1993). Without significant habitat improvements in the river and estuary environments, as well as improved instream flows, these effects will likely intensify as the climate in California becomes more extreme as a consequence of anthropogenic climate change, resulting in prolonged droughts which will impair the out-migration survival of juvenile Chinook salmon even further (Yates et al. 2008).

Several studies have found low hatchery smolt-migration survival rates throughout many rivers in the CCV, Delta and estuary (Baker and Morhardt 2001; Brandes and McLain 2001; Buchanan et al. 2013; Michel et al. 2015; Perry et al. 2010). However, little data has been collected on the survival rates of naturally produced Chinook salmon smolts in the CCV, due in large part to the difficulty in capturing these fish as the few remaining wild populations are severely depleted. Wild salmon smolts out-migrate to the ocean across many weeks during the spring compared to hatchery salmon which are typically released in a few large groups. Inferring survival rates for wild smolts based on acoustic telemetry data of hatchery salmon can be misinforming due to differences in fish size, fitness and environmental conditions encountered while out-migrating. In order to manage wild populations for future recovery, understanding the movement and survival rates of naturally produced smolts is necessary to devise effective management strategies.

In this study, I measure the movement and survival rates of acoustically tagged Chinook salmon smolts from a tributary to the upper Sacramento River which supports some of the last populations of wild spring-run Chinook salmon in the CCV. Utilizing an extensive network of acoustic receivers, the movement and survival rates of acoustically tagged juveniles were calculated at fine scales throughout the migratory pathway to the Pacific Ocean. Data collected over four consecutive years (2013-2016) examines survival and movement rates throughout a range of environmental conditions, most notably three consecutive years of drought, and provides insight into how these conditions affect juvenile salmon out-migration survival. I develop and test a series of mixed-effects models to evaluate the potential roles for varying fish size, stream flow and stream temperature on downstream migration survival rates.

Methods

Study Area

Mill Creek is a free flowing tributary to the Sacramento River containing pristine spawning and rearing habitat for Chinook salmon and steelhead trout (*Oncorhynchus mykiss)*. Its headwaters originate in Lassen National Park at an elevation over 8,000ft where numerous springs feed into high elevation meadows. Mill Creek continues to flow south-west through protected land in Lassen National Forest before transitioning into a rugged and deep canyon while flowing through the Ishi Wilderness. During its 100 kilometer course Mill Creek drops over 5,000ft in elevation, providing salmon and steelhead access to some of the highest elevation anadromous fish spawning habitat in the United States. Downstream of the canyon on the valley floor there are two water diversion dams on Mill Creek operated by Los Molinos Mutual Water Company (LMMWC), both of which provide salmon upstream access with fish ladders.

Mill Creek joins the Sacramento River, the largest river in California draining an area of 70,000 km^2, near the town of Los Molinos (Fig. 1). The Sacramento River flows for 289 river kilometers (rkm) downstream of Mill Creek before transitioning into the Sacramento-San Joaquin River Delta. The Sacramento River has two distinct regions, noted as the upper (rkm 441-344) and lower (rkm 344-203) Sacramento River in this study. The upper Sacramento River is in a relatively natural state with expansive gravel bars, riparian habitat and braided channels, whereas the lower Sacramento River is highly modified by agricultural practices and becomes channelized, straightened and its banks covered with cobble to lessen erosion. This study focuses on the movement and survival rates of wild juvenile salmon smolts captured, tagged and released below the upstream diversion dam on Mill Creek.

Fish collection and Tagging

Approximately 10 km upstream from the Sacramento River and directly below the upper diversion dam, a rotary screw trap (RST) was operated to capture migrating salmon smolts. The location is downstream of much of the juvenile rearing habitat, and the smolts captured are more likely to be migrating downstream to the ocean. The 5' diameter RST was deployed in early April each year and operated continuously until catch rates diminished and out-migration ceased as a result of elevated water temperatures (typically late May-early June). Each morning the trap was checked for salmon and cleaned of debris using a long handled dip net. Salmon were placed in a 5-gallon bucket before being transferred to a 100 quart cooler where oxygen was provided with bubblers.

Before undergoing surgery, all salmon were anesthetized in MS-222 buffered by 120mg L^-1 sodium bicarbonate prior to being weighed to the nearest tenth of a gram and measured to the nearest mm of caudal fork length. Acoustic tags were surgically implanted into the peritoneal cavity of the anesthetized fish as described by Deters et al. (2010). The tag weight did not exceed 5% of the fish's body weight, which Brown et al. (1999) found did not affect the growth or swimming performance of hatchery salmon implanted with acoustic tags. Following this guideline allowed smolts as small as 6 grams and 80 mm fork length to be acoustic tagged.

During 2013-2014 fish were released in Mill Creek below the RST approximately 1 hour after recovery. Because these smolts were actively migrating we believed that holding them for extended periods may disrupt their migratory cue, and releasing them soon after recovery was the best option to avoid additional stress. To monitor the salmon after release, periodic snorkel surveys were conducted to ensure that no predators such as Sacramento pikeminnow (*Ptychocheilus grandis*) and smallmouth bass (*Micropterus dolomieu)* were aggregating around the release location and predating on the tagged juveniles. The snorkel surveys were also conducted to observe smolt behavior after recovery and release, revealing that all fish appeared to have functional swimming performance and appeared to school together before finding shade to hold and rest.

After reconsidering our release protocol due to low survival rates observed within Mill Creek during 2013 and 2014 and the possibility that smolts were not fully recovered from surgery, we employed an automated release hamper for 2015 and 2016. This allowed smolts to rest for 12 hours before being released at 10pm and potentially avoid predation while migrating at night. The release hamper also allowed us to observe if smolts had died after surgery when checking it the following morning, which revealed no smolts had died as a result of surgery. We continued to conduct snorkel surveys around the release site to ensure no predators were aggregating around the release hamper.

Acoustic Telemetry

This study uses the Juvenile Salmon Acoustic Telemetry System (JSATS) (McMichael et al. 2010) to track survival and movement rates of migrating smolts from Mill Creek. The acoustic tags (300mg, 10.7mm long x 5mm diameter, Advanced Telemetry Systems) emit a uniquely coded signal at 416.7 KHz programmed with a 5-second pulse rate, giving the tag a 32 day battery life expectancy. JSATS technology is favored over other types of acoustic technology because of the high performance of the tags in noisy environments, with an on-board processor in the receiver which filters out false detections. The acoustic receivers (made by Advanced Telemetry Systems) are positively buoyant, autonomous devices containing a hydrophone that detects and decodes the tag signal to produce a unique ID for each tagged fish. The receivers are equipped with 120 day lithium ion batteries which power the hydrophone, temperature and tilt logger.

Over 140 acoustic receivers were deployed each spring throughout the migration pathway of juvenile Chinook salmon from Mill Creek to the Pacific Ocean (Table 1, Fig. 2). For this study I included 14 reaches between Mill Creek and the Golden Gate Bridge, simplifying the Delta into one reach. Reaches are classified as 20-30 kilometer sections of river where survival rates are of interest, allowing the long migration corridor to be broken into smaller sections which enables small scale patterns in movement and survival rates to be observed over time. The receivers were left in place for 30 days after the last smolt was tagged and released. The receivers were secured to a tree, bridge or structure using ¼" stainless steel cable and fastened by a sleeve which crimps the connection. Between 30 and 100ft of cable is extended from the shore anchor to a location in the channel where the receiver can detect pinging tags. To anchor the receiver on the river bottom, 20-30lbs of weight is secured to the cable and a ~20" cable allows the receiver to float above the weights. The receiver is equipped with a fin to keep it from swaying under water and to keep the hydrophone pointed towards the surface.

Data Analysis

Data analysis was performed using a Cormack-Jolly-Seber (CJS) model for live recaptures (Cormack 1964; Jolly 1965; Seber 1982) using the program MARK (White and Burnham 1999) within the RMark package (Laake and Rexstad 2013) which is written in the R programming language (version 3.0.1). This model works particularly well for juvenile salmon because they tend to exhibit a strict downstream movement behavior once smoltification has begun (Healey 1991). This behavior is advantageous for acoustic telemetry studies in riverine environments due to the linear nature of these systems, which require the fish to pass specific reaches. As the tagged fish are migrating toward the ocean, we assume if no detections are recorded downstream of its last location, that the fish died between its last detection and the next downstream receiver.

When calculating mortality rates, we have to take into consideration detection efficiency of the receiver (how accurate the receiver is at detecting acoustic tags), which can become problematic under certain environmental conditions. High water flows and noise associated with these events can impair the efficiency of the receiver and allow fish to pass undetected, creating uncertainty in its accuracy. To calibrate these estimates the CJS model takes into account the number fish detected at downstream receivers to estimate the accuracy of the upstream receiver, and then uses maximum-likelihood estimates for detection efficiency of all monitor locations (p), all survival estimates (Φ), and 95% confidence intervals for both (Lebreton et al. 1992). With the exception of 2015, we had relatively small sample sizes throughout this study which led to increasing uncertainty in the survival estimates going downstream as fewer fish remained in the system.

Several covariates were considered in an effort to determine which physical and environmental factors were most influential in smolt survival. Specifically, I considered Mill Creek flow at release (cubic feet per second (CFS)), Mill Creek temperature at release (degrees celsius), upper Sacramento River flow (CFS), lower Sacramento River flow (CFS) and fish length (millimeters). The influence of these factors on survival was assessed by allowing each group (year, n=4) and fish released within each group, to have its own set of parameters based on the in situ water conditions throughout each region. In order to compare these covariates against other models, a null model (constant survival through space and time), a base model (reach x year) and a series of models using environmental and physical covariates were constructed to see which were best supported. The purpose of using a base model is to include all sources of mortality that should not be attributed to the environment. The model selection criterion used was Akaike's Information Criterion (AIC)(Akaike 1981), which ranks each model by assigning a score according to how accurate the model is relative to the given data, and penalizes models with more parameters (Eqn.1):

$$1.\quad AIC = 2K - 2(\text{log-likelihood})$$

where K is the number of parameters included in the model, and the log-likelihood of the model reflects the overall model fit (a smaller value indicates worse fit). This equation and the score it assigns allows each model to be compared based on parsimony and not simply goodness-of-fit, with a lower AIC value indicating a better fit. To determine the best model given the data, the Δ AIC, which is the difference in AIC score relative to the top model, is used; as suggested by Burnham and Anderson (2002), AIC values were corrected for small sample sizes (AICc).

In total 16 models were used in the survival analysis which tested a combination of group (year), release flow, release temperature, regional flow (upper Sacramento River, lower Sacramento River) and fish size. Fish length was used rather than weight because both are strongly correlated. Release flow and temperature were allowed to vary for each fish in Mill Creek, but once entering the Sacramento River these values were removed from the models as flow and temperature values change dramatically. Specific flow values for the upper and lower Sacramento River were used for fish during the time they were migrating through these regions. In order to account for the large variations in reach distances survival estimates were standardized by reach length (kilometers). Within the program MARK, survival was transformed using a logit function and related to reach length and a number of environmental and physical parameters (Eqn. 2), while detection efficiency was fixed (i.e., independent of reach). One coefficient (β) for each environmental and physical variable quantifies the linear relationship between that variable and survival. By standardizing the environmental and physical parameters (subtracting the mean value from each raw data point and dividing by the standard deviation), calculated beta coefficients offer a straightforward interpretation across different models and environmental variables. For a change in one standard deviation unit of the environmental variable, survival will change by the amount specified by that model's standardized beta coefficient.

2. Logit (Φ) = $\beta_0 + \beta_1[\textit{Reach Length}] + \beta_2[\textit{Env. Variable}] + \beta_3[\textit{Env. Variable}]$

Survival estimates were calculated using separate reach-specific and regional approaches, respectively. The reach-specific analysis included all 14 reaches in the study from Mill Creek to the Golden Gate (rkm 450 – 1.7), and the regional analysis simplified the pathway by using 3 regions for the analysis; Mill Creek (reach 1, rkm 450-441), the upper Sacramento River (reach 2-5, rkm 441-344) and the lower Sacramento River (reach 6-10, rkm 344-203). These regions were chosen because they exhibit different habitat types and each contain different flow values as a result of water diversions which remove increasingly more water going downstream. I excluded the Delta and San Francisco Bay from the analysis due the small sample size in those reaches. Survival rates per 10 kilometers, hereafter referred to as survival rates, were calculated in order to standardize estimates between reaches of varying distances; this allows patterns to be detected where survival is relatively higher or lower between years and indicates where mortality hot-spots may be occurring.

Results

Total survival for wild smolts emigrating from Mill Creek to the Pacific Ocean was 0.3% during the four years of the study. Of the 304 fish tagged and released, only one was detected at the Golden Gate in 2013. Cumulative survival from Mill Creek to the Sacramento River was 68% (±12 S.E), cumulative survival from Mill Creek through the upper Sacramento River was 23% (±19 S.E) and cumulative survival from Mill Creek through the lower Sacramento River was 7.6% (±16 S.E)(Fig. 3).

Region specific survival rates were relatively consistent in the upper and lower Sacramento River, but varied within Mill Creek (Fig. 4). Survival rates in Mill Creek ranged from 86% (± 7 S.E) in 2016 to 58% (±3.5 S.E) in 2015. Survival rates in the upper Sacramento River ranged from 94% (± 5 S.E) in 2013 to 86% (± 7 S.E) in 2014 and survival rates in the lower Sacramento ranged from 94% (± 7 S.E) in 2013 to 86% (± 7 S.E) in 2014. In 2016 no smolts survived past reach 3 in the upper Sacramento River to allow for survival estimates through the region.

Survival rates between individual reaches followed a similar pattern each year. The lowest survival rates were observed in Mill Creek (reach 1) between 58-86%, followed by increasing survival rates in the first upper Sacramento River reach (reach 2) between 95-100%. Downstream of reach 2 survival rates progressively decreased, with the lowest survival rates observed in reach 6 between 79-89%.

Downstream of reach 6 survival rates generally increased, with estimates in reach 7 between 90-97.5% and reach 8 between 96-100%. Downstream of reach 8 survival rates generally decrease, but the large error bars resulting from the few remaining fish create uncertainty in these estimates (Fig. 5).

Tagged fish fork length varied significantly among years ($P < 0.02$) but fish weight did not vary significantly ($P = 0.24$). Sample sizes of tagged smolts were relatively small each year (n=23-186; Table 2), with the exception of 2015 when 186 smolts were tagged and released. The small sample sizes were likely attributed to limited numbers of smolts available due to low numbers of spawning adults the prior year. The capture efficiency of the RST was also an issue because of the large volume of water going around the trap, with the exception of 2015 when flows were so low that most of the remaining water below the upper diversion dam flowed directly into the RST.

Due to severe drought conditions in 3 of 4 years of this study (2013-2014-2015), study-period flows were significantly lower and water temperatures higher in Mill Creek relative to the historic average (Fig. 6). Flows increased substantially in 2016 resulting from an above average snowpack. Water temperature remained above the historic mean for all study years, but was especially high in 2015 compared to other years. Water flow and temperature were indicative of survival in Mill Creek; higher flows corresponded to higher survival rates (Fig. 7), and lower water temperatures corresponded to higher survival rates (Fig. 8). The interaction of water temperature and flow in Mill Creek in relation to survival found that both have an effect, but flow has greater influence on survival compared to temperature given the values observed during this study (Fig. 9). In the upper and lower Sacramento River this finding remained consistent, with smolts experiencing higher cumulative survival rates during years of higher flow (Fig. 10-11). Models used to estimate survival according to flow alone in the upper and lower Sacramento River were not well supported (Δ AICc = 16.3, 18.3 respectively), indicated by the large discrepancies between the predicted survival confidence intervals and the actual survival data.

Movement speeds were correlated with survival rates among all reaches, with slower movement speeds resulting in lower survival rates and faster movement speeds resulting in higher survival rates (Fig. 12). The slowest average movement speeds were observed in Mill Creek (10.3 km/day ± 3.1 S.D), followed by relatively high movement speeds in reach 2 upon entering the upper Sacramento River (64 km/day ± 9.5 S.D), and the slowest movement speeds through the Sacramento River in reach 4 (43 km/day ± 13.4 S.D). Downstream of reach 6 movement speeds generally increased, and obtained a maximum in the lower Sacramento River in reach 8 (81km/day ± 7 S.D). This peak in movement speed is likely attributed to faster water velocities resulting from channelization and a decrease in sinuosity in the lower Sacramento River.

In the analysis of survival as a function of physical and environmental covariates, the top model indicates that group (year), in addition to flow in Mill Creek and fish size (length) was a better model than the null model (constant survival) and base model (year x reach). Both the reach specific and regional analysis included 16 different models that tested a combination of physical and environmental covariates, release year and reach length. By running both a reach-specific and regional analysis the effects of each covariate could be evaluated separately to see if they have different levels of influence at fine scale vs. larger spatial scales. Each model returned similar results (Table 3), both indicating that flow at release in Mill Creek in addition to fish size and year best explain the variation in survival at both the reach specific and regional scale. The second best supported model for both analyses included flow and temperature in Mill Creek in addition to fish length and release year, with a Δ AIC < 2 for both analyses.

Discussion

This study provides the first estimates of wild Chinook salmon smolt survival from Mill Creek through the Sacramento River. Survival estimates during this study were very low relative to other telemetry studies conducted in the Sacramento River (Michel et al. 2015; Perry et al. 2010), and were most likely influenced by three consecutive years of drought. Water flow in Mill Creek was significantly lower than the historic average spring flow during the three drought years, and water temperatures were slightly above historic spring averages as well (Fig.6). Throughout the study period flows were impaired even further by water diversions for agriculture, which diverted up to 50% of the natural flow and resulted in the lowest spring flows ever recorded in Mill Creek in 2015.

Survival rates within Mill Creek were very low relative to other reaches in the study. In total approximately 70% of the 304 tagged smolts appeared to have survived through Mill Creek and entered the Sacramento River. The lowest survival rates were observed in 2015 when 58% of the 186 smolts tagged and released survived the Mill Creek reach to the Sacramento River. Spring flows in 2015 were some of the lowest on record, due to the combination of an exceptionally low snowpack resulting in decreased runoff, and water diversions which removed all but 50 CFS from lower Mill Creek. Water rights granted to LMMWC allows the water district to divert 130 CFS from Mill Creek throughout the year, but during drought conditions an agreement with the California Department of Fish and Wildlife (CDFW) requires them to leave 50 CFS in-stream for fisheries and ecosystem needs. This amount of water appears to be insufficient for the survival of out-migrating juvenile salmon in April-May, as lower flows and warmer water temperatures resulted in lower survival rates (Fig. 7-8). A similar relationship was documented on Idaho's Snake River, where increased flows resulted in higher survival rates for juvenile Chinook salmon migrating to the ocean (Connor et al. 2003). In addition to flow, higher water velocities were shown to increase survival rates, likely because it promotes rapid downstream migration of juvenile salmon which reduces the exposure time to predators, resulting in higher survival rates (Tiffan et al. 2009).

The low survival rates in Mill Creek may also suggest that the surgical procedure negatively impacts the survivorship of acoustic tagged smolts. When conducting survival studies using acoustic telemetry two assumptions are made: one is that the fish are representative of the population, and thus the surgical procedure has no effect on their behavior; and the second is that the acoustic tag stays inside the animal for the duration of the study. In order to test these assumptions a tag effect study was conducted in Mill Creek during 2016, which is described in more detail in Chapter 3. 50 hatchery smolts were acoustically tagged using the same surgical procedures and held in tanks for 30 days on the bank of Mill Creek. In addition, 50 smolts were sent through the RST to test any effects the trap may have on survival, and 50 smolts were placed in the tanks as controls. The tanks were checked daily for shed tags and dead smolts, and the survival and overall condition of the fish were noted. After 30 days, 10 out of 50 (20%) acoustic tags were shed from the smolts, with the first shed tag occurring after day 10. No tagged smolts died post-surgery from tag implantation, but tagged smolts did grow significantly less than the RST and control group after 30 days.

In this study, only 3 of 304 tagged smolts were detected for more than 10 days. This suggests that tag shedding is not likely an issue in this analysis (Fig. 13). These short survival durations are most likely due to predation, and suggest that Mill Creek and the Sacramento River are exceptionally hazardous regions for out-migrating smolts under the conditions experienced in 2013-2016. In addition, smolts which are tagged and released may experience delayed physical impacts from the tagging procedure, as was seen in the low growth rates for tagged smolts in the tag effects study. This could imply that a proportion of the smolts being studied are experiencing lower survival rates early in the study compared to otherwise healthy smolts, and the survival estimates towards the end of the study area may be biased high because the unfit individuals have already been removed by predators. These predators, which include Sacramento Pikeminnow and smallmouth bass, migrate into Mill Creek during the spring to spawn, and during low flow conditions with relatively warm water temperatures their effectiveness at capturing juvenile salmon can be greatly increased (Cavallo et al. 2012). Warmer water increases the metabolism in predatory fish, and clear water resulting from reduced run-off impairs the predator avoidance behavior of juvenile salmon (Gregory 1993). Compounded with these stressors are anthropogenic structures in Mill Creek such as water diversions, bridge pilings and low-head dams which increase the effectiveness of ambush predators (Sabal et al. 2016).These structures create unnatural locations where predators can lie and wait, striking naïve juvenile salmon as they pass by potentially disoriented after swimming through these obstacles (Brown and Moyle 1981; Sabal et al. 2016).

Another possible reason for the low survival rates in Mill Creek is the amount of time smolts spend in this reach compared to reaches in the Sacramento River (Fig. 12). Movement rates were between 8-14 kilometers per day in Mill Creek compared to 40-80 kilometers per day in the Sacramento River. The slow movement speeds through Mill Creek increases their exposure time to potential risks such as predation and the effects of water diversions, which can both significantly impact survival; water diversions reduce flow which diminishes habitat, resulting in increased predator densities (Mussen et al. 2012). During drought conditions smolt movement speeds were relatively slow compared to 2016 when flow was higher, increasing from 8 to 14 kilometers per day. As a result higher survival rates were observed when movement speeds increased within Mill Creek (58% in 2015 with exceptionally low flow (mean=72 cfs), and 86% in 2016 with near average flow (mean=268 cfs)).

Once smolts leave Mill Creek they experience rapidly changing water conditions in the highly modified habitat and managed flows of the mainstem Sacramento River. Large changes in April-May mainstem flows are experienced because of water diversions that take up to 50% of the river flow before joining the Delta (Fig. 14). Water diversions for out of stream uses by agriculture typically increase during April-May, the same time Mill Creek smolts out-migrate through the Sacramento River (Fig. 15), which is relatively late in the spring compared to other salmon in the CCV (Vogel and Marine 1991) as a result of the high elevations at which they are spawned and rear. The effect of these artificially low flows, which were significantly lower than the historic average during the study period (Fig. 16), can have implications for predator abundances and their prey capture efficiency. Low flows lead to more favorable spawning conditions for alien fish species (Larry and Marissa 2009), which leads to established populations over time if more natural flow regimes are not implemented (Marchetti and Moyle 2001). In addition, low flows are correlated with low turbidity levels (Feyrer and Healey 2003) which can influence the rate of predation on migration juvenile salmon, with predators more effective at capturing salmon in clear water (Gregory and Levings 1998).

The lowest survival rates in the Sacramento River were in the first lower Sacramento River reach (reach 6, rkm. 308), which contains large populations of striped bass (*Morone saxatilis*) and other predatory fish throughout the year. Every spring striped bass migrate upstream from the San Francisco Bay and Delta to spawn, and aggregate in this reach due to favorable water temperatures and flow required for spawning (Chadwick 1967). Depending on the population size of striped bass and the number of salmon smolts present, striped bass have been estimated to significantly impact juvenile Chinook salmon populations (Lindley and Mohr 2003) while only accounting for a fraction of their bio-energetic demands (Loboschefsky et al. 2012). The combined exposure time to predators coupled with the long distances that Mill Creek smolts transit through the Sacramento River may lead to significant mortality in the smolt population (Anderson et al. 2005).

The results from this study have implications for future restoration and management actions aimed at threatened and endangered populations of wild Chinook salmon in the CCV. This study shows that juvenile salmon out-migrating as smolts relatively late in the spring experienced very low survival rates from 2013-2016, most likely resulting from flow-mediated predation in a period of drought conditions from 2013-2015 and substantial water diversions in all study years. Data collected over a range of flow and temperature values indicate that survival improves with higher flows and lower temperatures, and during drought conditions a large proportion of smolts may perish within natal streams or shortly after migrating into the Sacramento River. To remedy this situation, especially during drought conditions, supplying enough water instream for smolts during their critical migration window can lead to higher out-migration survival, a situation that may be necessary to support increased returns of spawning adults (Berggren and Filardo 1993; Giorgi et al. 1997; Raymond 1968). Using the data collected in this study, in order to sustain a 90% survival rate for smolts through Mill Creek a minimum of 250 CFS should be maintained during April-May when these fish are actively migrating downstream. This outcome can be accomplished through managing water flows for both agriculture and fisheries needs, and maintaining adequate water flows during critical stages of the salmon life cycle. As the few remaining wild salmon populations in the CCV remain threatened and endangered with extirpation, understanding how habitat and environmental conditions influence their survival is critical to support effective recovery planning and actions.

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Location Name	Reach Number	River Km
MillCk_RST		451
Mill_Ck_Conf	1	441
Abv_WoodsonBr	2	425
Blw_IrvineFinch	3	395
BlwOrd	4	362
ButteBr	5	344
AbvColusaBr	6	308
AbvTisdale	7	269
BlwChinaBend	8	241
Knights	9	224
Blw_FRConf	10	203
I80_Br	11	171
Freeport	12	152
Benicia	13	52
GoldenGate	14	2

Table 1. Receiver location name, reach number, and distance in kilometers from the Pacific Ocean.

Year	Sample Size	Fork Length ± SD (mm)	Weight ± SD (g)
2013	59	84.2 ± 11.4	7.3 ± 3.3
2014	36	83.5 ± 2.9	6.7 ± 0.9
2015	186	86.9 ± 6.2	7.4 ± 2.1
2016	23	85.7 ± 4.0	7.7 ± 1.1
ALL	304	85.9 ± 7.2	7.4 ± 2.2

Table 2. Sample size, weight and length for smolts tagged and released each year.

Reach Specific Model	#Parameters	Δ AICc
year + reach + mill:flow.z + length.z	21	0
year + reach + mill:flow.z + mill:temp.z + length.z	22	0.46
year + reach + mill:temp.z + length.z	21	10.49
year + reach + mill:flow.z	20	11.14
year + reach + lowersac:flow.z + length.z	21	18.5
year + reach + uppersac:flow.z + length.z	21	18.5
reach + year	19	19.94
year + reach + mill:temp.z	20	21.99
year + reach + lowersac:flow.z	20	29.5
year + reach + uppersac:flow.z	20	29.8
reach * year	61	36.83
reach	16	55.45
length.z	3	148.69
temp.z	3	166.68
constant (null)	2	176.94
flow.z	3	177.16
Regional Model	# Parameters	Δ AICc
year + reach + mill:flow.z + length.z	12	0
year + reach + mill:flow.z + mill:temp.z + length.z	13	1.76
year + reach + lowersac:flow.z + length.z	12	7.71
year + reach + mill:flow.z	11	9.44
year + reach + uppersac:flow.z + length.z	12	9.69
year + reach + mill:temp.z + length.z	12	11.34
year + reach + lowersac:flow.z	11	16.3
year + reach + uppersac:flow.z	11	18.3
reach + year	10	20.6
year + reach + mill:temp.z	11	21.89
reach * year	25	25.8
reach	7	38.2
length.z	3	144.6
temp.z	3	163.01
flow.z	3	171.39
constant (null)	2	171.54

Table 3. Survival models for different study design factors, ordered from best to worst according to AIC scores. Parameters were standardized for the analysis, thus the .z notation (z score). The Δ AICc statistic represents the distance of that model from the best supported model.

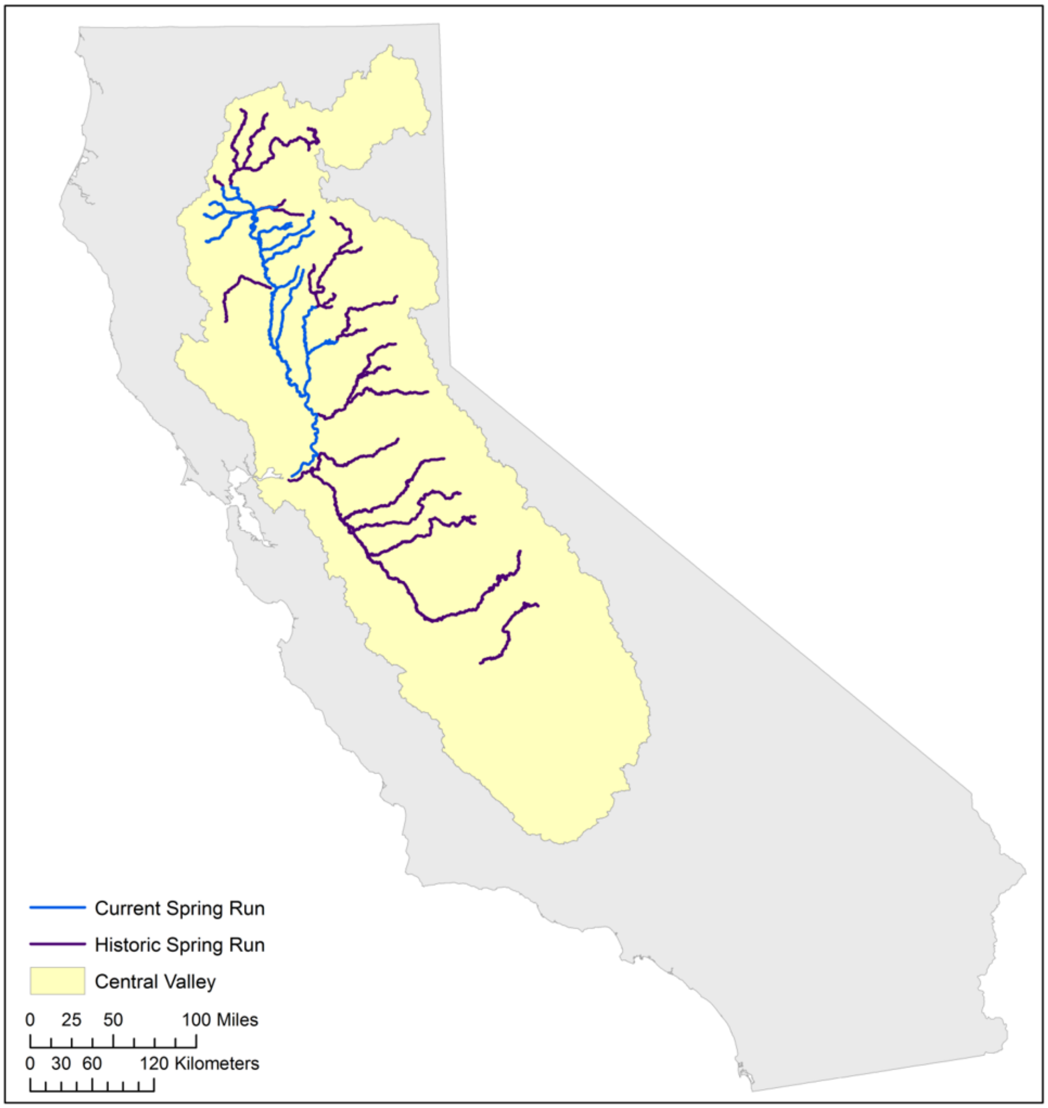


Figure 1. Current (blue) and historic (purple) distribution of spring-run Chinook salmon in California's Central Valley

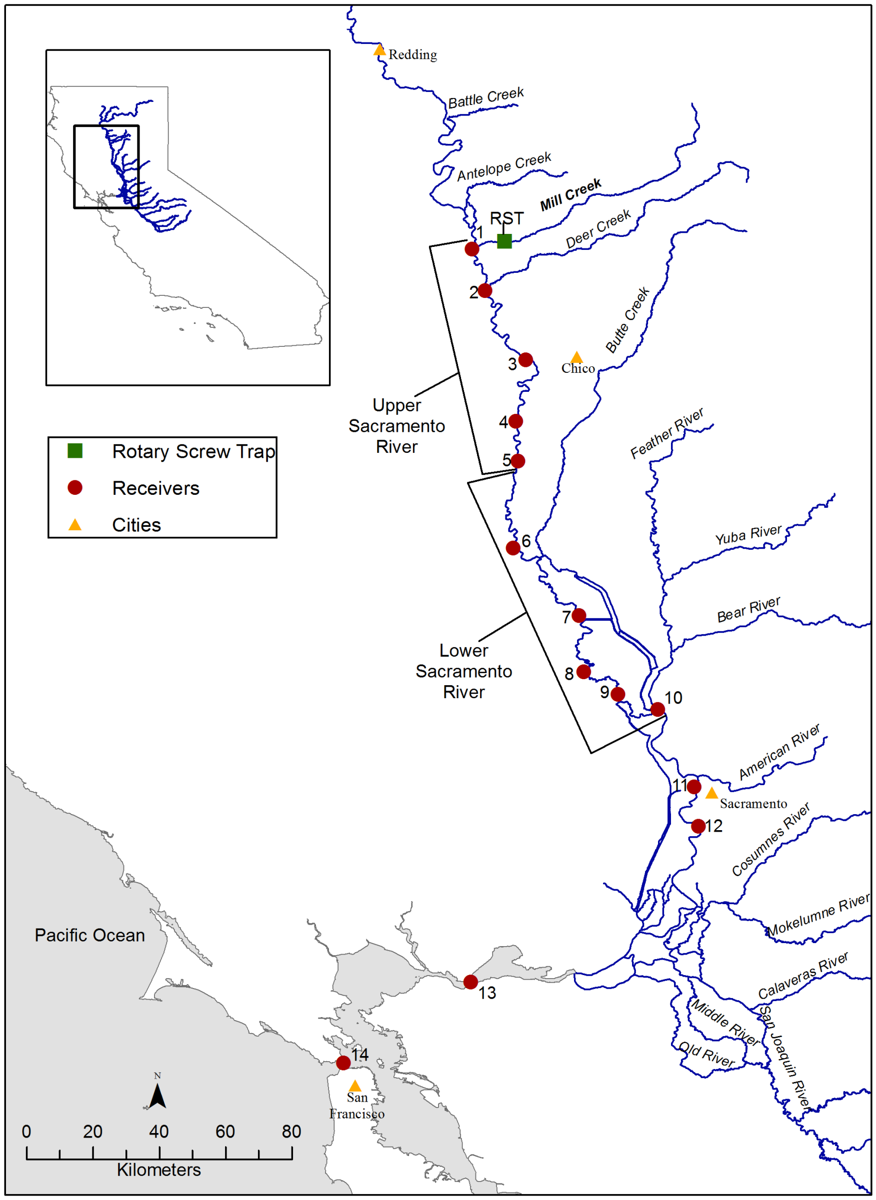


Figure 2. Location of all 14 reaches used for this study, including Mill Creek, the lower Sacramento River and upper Sacramento River. Each red dot indicates where acoustic receivers were placed to detect out-migrating smolts.

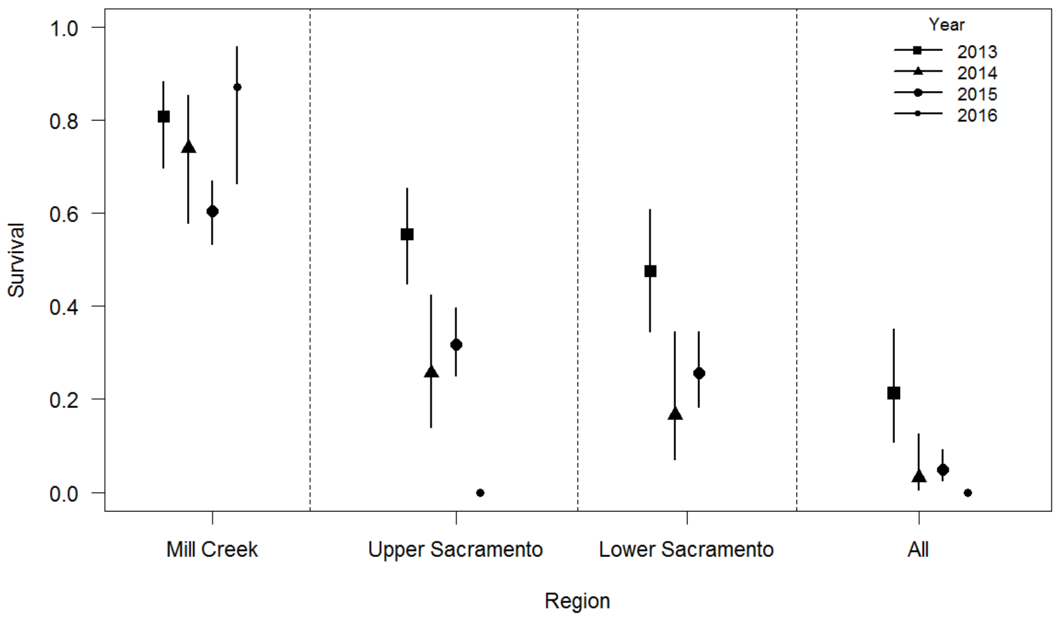


Figure 3. Cumulative survival estimates within each region and total survival throughout all regions for each study year. Error bars represent 95% confidence intervals.

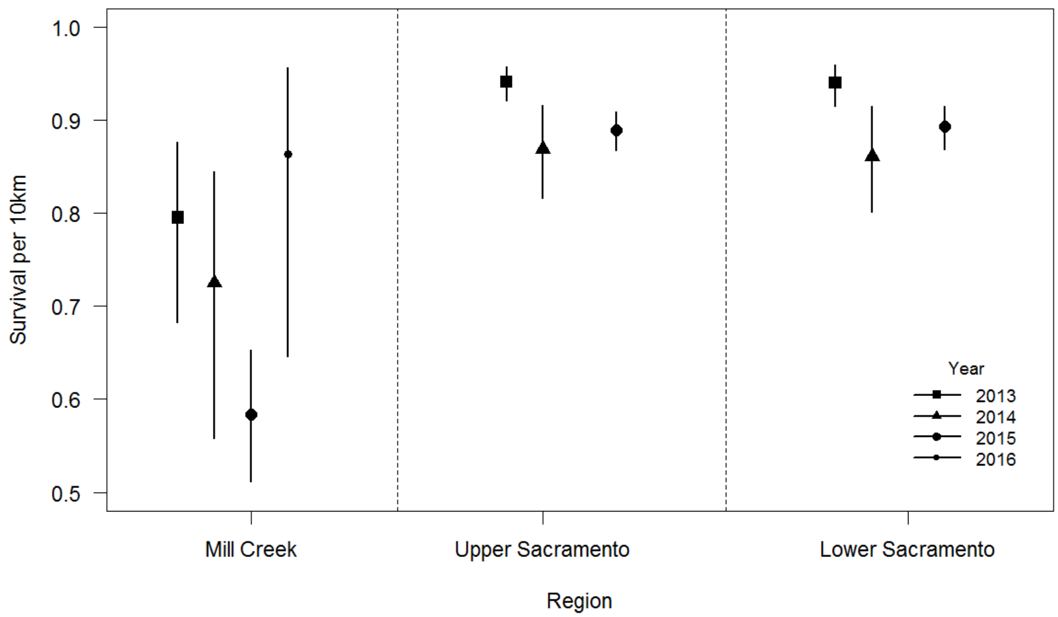


Figure 4. Region specific survival calculated per 10 kilometers in Mill Creek, the upper Sacramento River and lower Sacramento River. Error bars represent 95% confidence intervals. In 2016 no fish made it through the second reach of the upper Sacramento River.

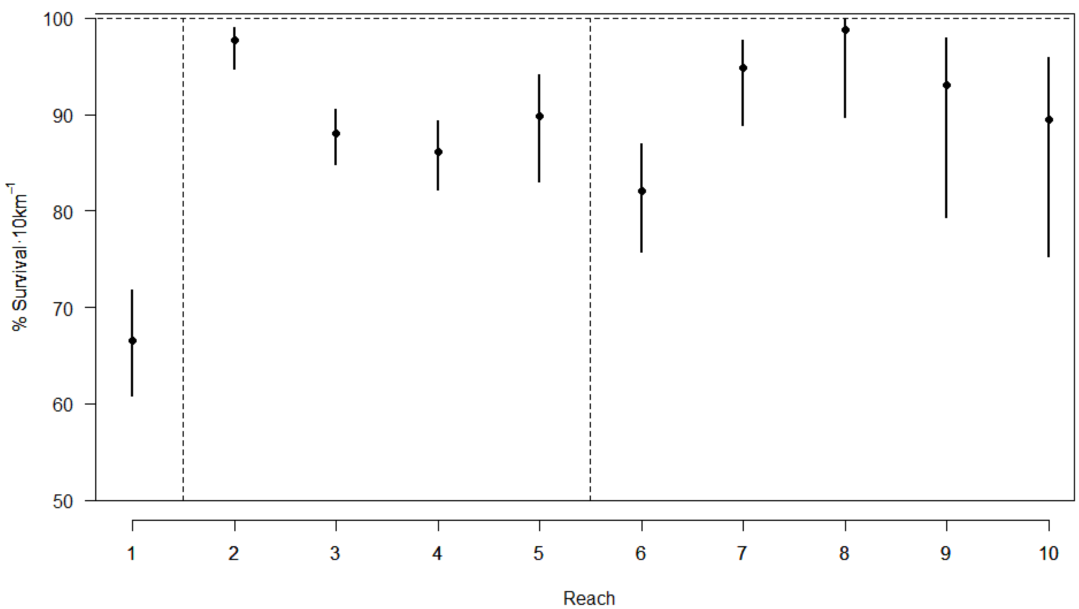


Figure 5. Reach specific survival rates through Mill Creek (reach 1), the upper Sacramento (reaches 2-5) and lower Sacramento River (reaches 6-10) averaged for all years of the study. Dashed vertical lines separate each region. Error bars represent 95% confidence intervals.

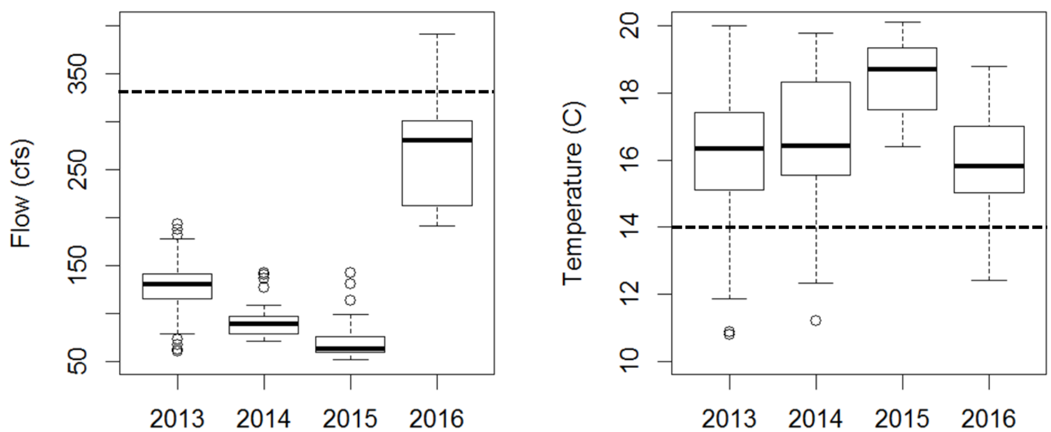


Figure 6. Stream flow (left) and water temperature (right) measured downstream of water diversions in Mill Creek during the study period for each year. Water flow is measured in cubic feet per second (CFS). The dashed line represents the historic mean flow and temperature downstream of water diversions during the study period.

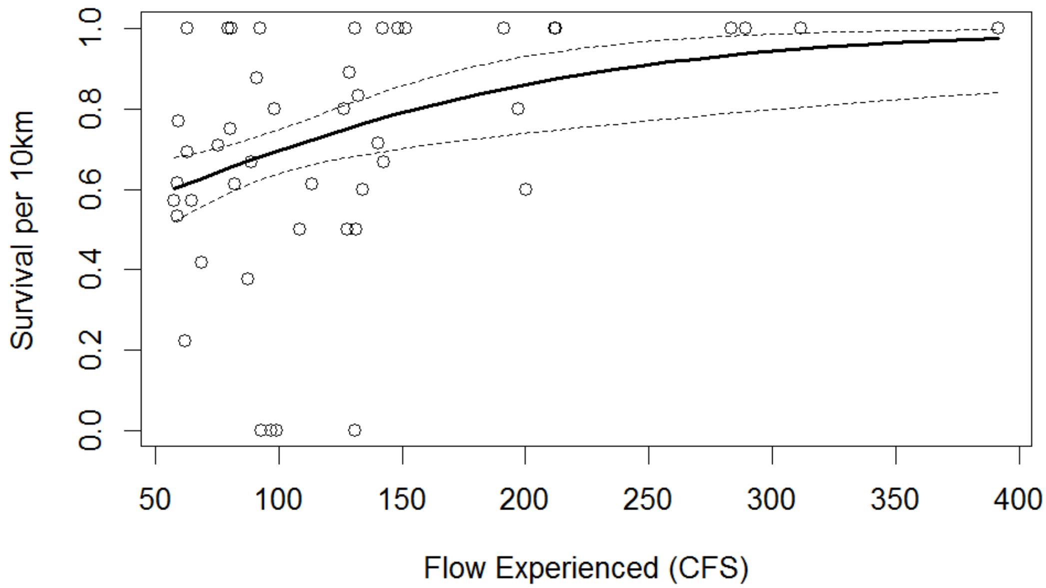


Figure 7. Smolt survival predicted in Mill Creek (solid line) during 2013-2016 as a function of flow at release, including upper and lower 95% confidence intervals (dashed lines). Dots represent the actual survival rates observed through Mill Creek for groups of fish released at the specified flow value. Note that historic April/May stream flow in Mill Creek (1987-present) is 352 CFS ± 190 CFS.

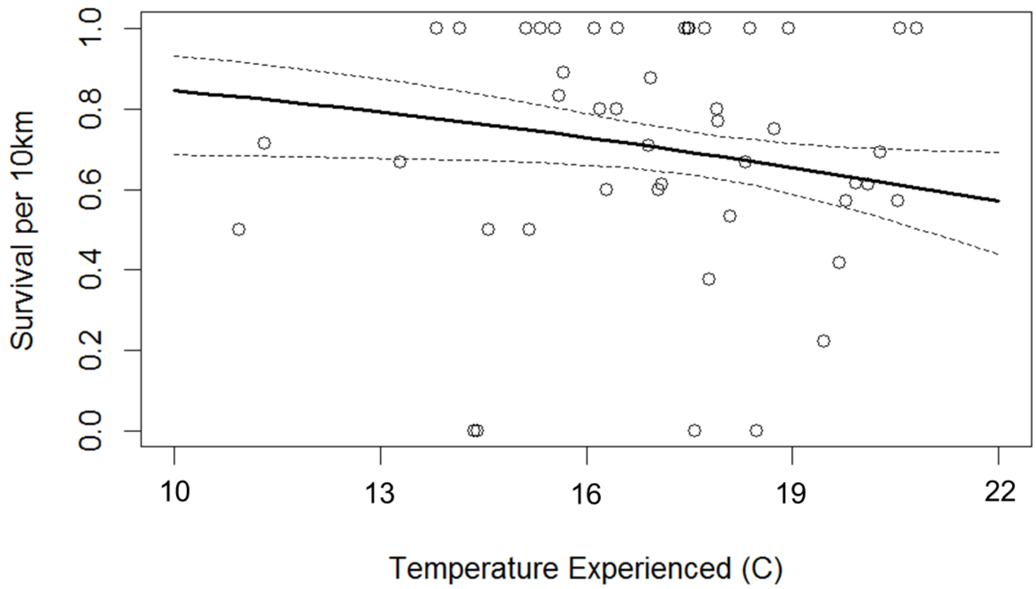


Figure 8. Smolt survival predicted in Mill Creek (solid line) during 2013-2016 as a function of water temperature at release, including upper and lower 95% confidence intervals (dashed lines). Dots represent the actual survival rates observed through Mill Creek for groups of fish released at the specified temperature. Note that historic April/May stream temperature in Mill Creek (1987-present) is 13° C ± 5°.

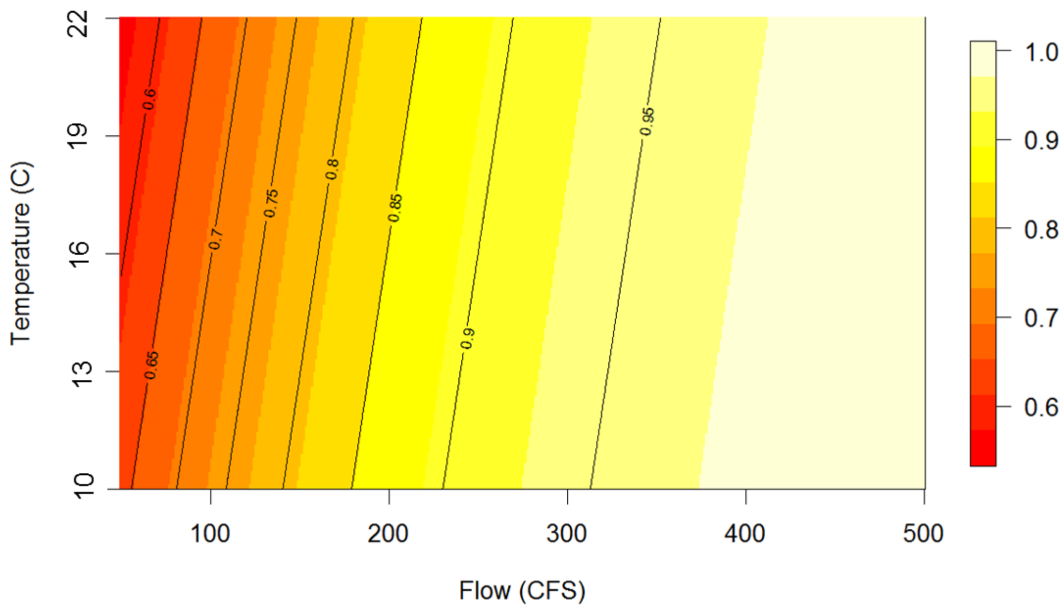


Figure 9. Contour plot of survival rates per 10km predicted in Mill Creek as a function of flow and temperature. The changes in color and black lines indicate the various survival rates predicted at each flow and temperature value. This graph shows that survival rates depend upon both parameters, but flow has more influence in survival compared to temperature.

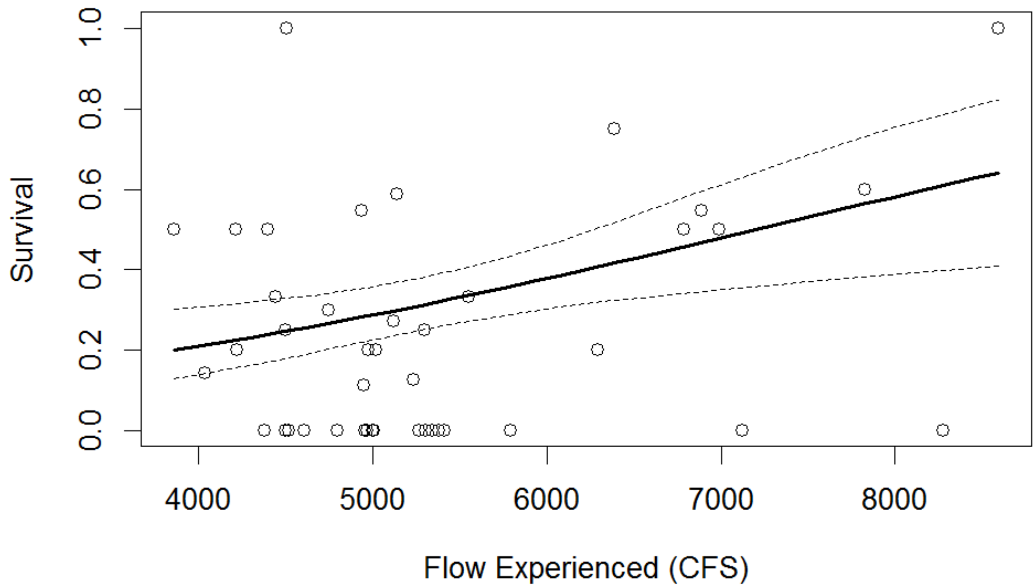


Figure 10. Cumulative survival predicted through the upper Sacramento River (solid line) during 2013-2016 as a function of flow at Butte City Bridge (reach 5, rkm. 344), including upper and lower 95% confidence intervals (dashed lines). Dots represent the cumulative survival rates for groups of fish through the upper Sacramento River at the specific flow values.

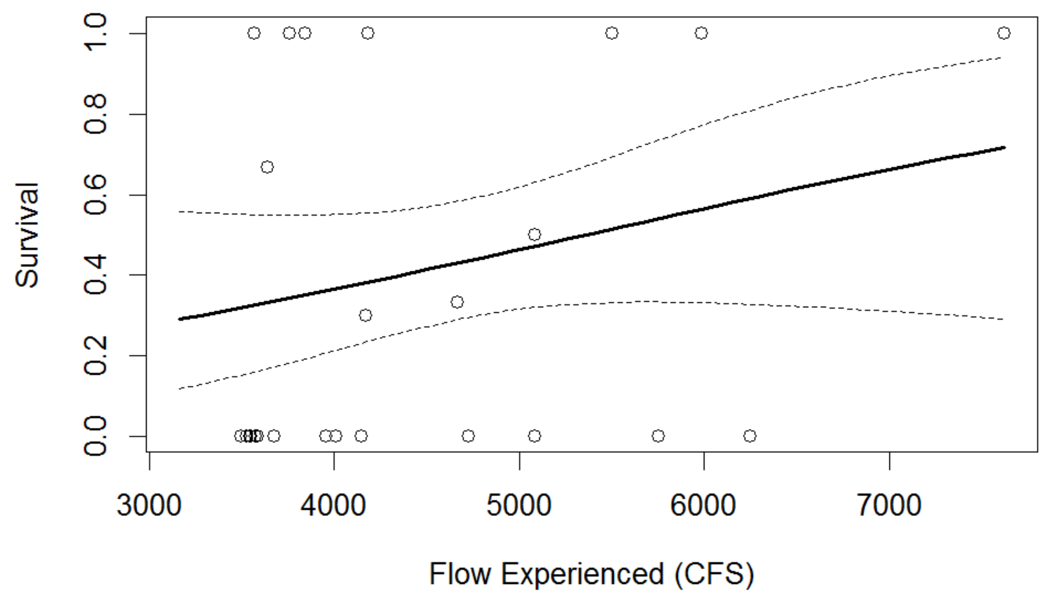


Figure 11. Cumulative survival predicted through the lower Sacramento River (solid line) during 2013-2016 as a function of flow at Wilkins Slough (reach 8, rkm. 241), including upper and lower 95% confidence intervals (dashed lines). Dots represent cumulative survival rates for groups of fish through the lower Sacramento River at the specific flow values.

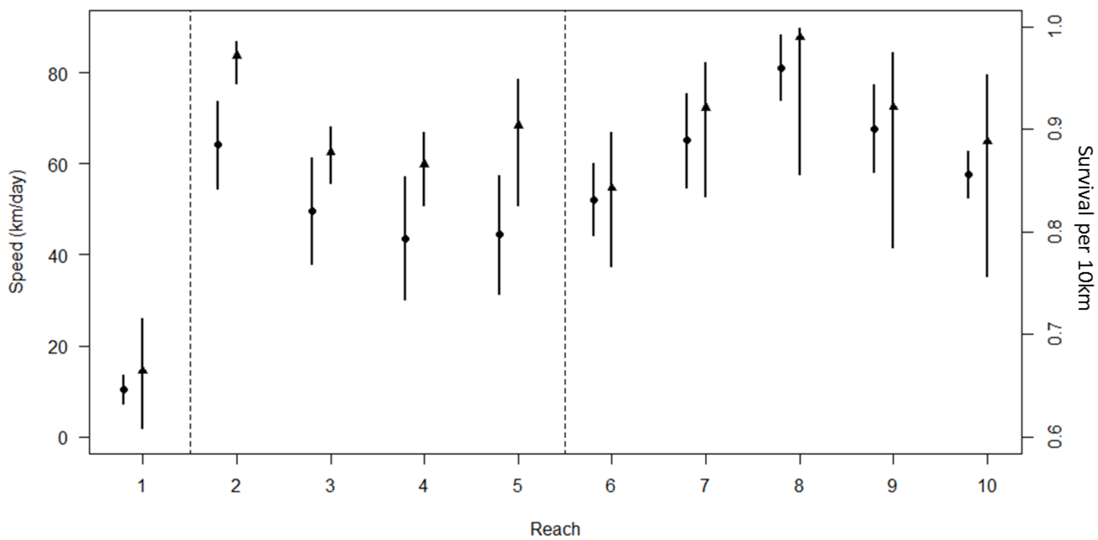


Figure 12. Movement speeds (kilometers per day, dots) and survival rates (per 10km, triangles) averaged for all years through Mill Creek, the upper and lower Sacramento River. The dotted lines are breaks between Mill Creek, the upper Sacramento River and lower Sacramento River. Error bars for movement speeds and survival rates represent one standard deviation from the mean and the upper and lower 95% confidence intervals, respectively.

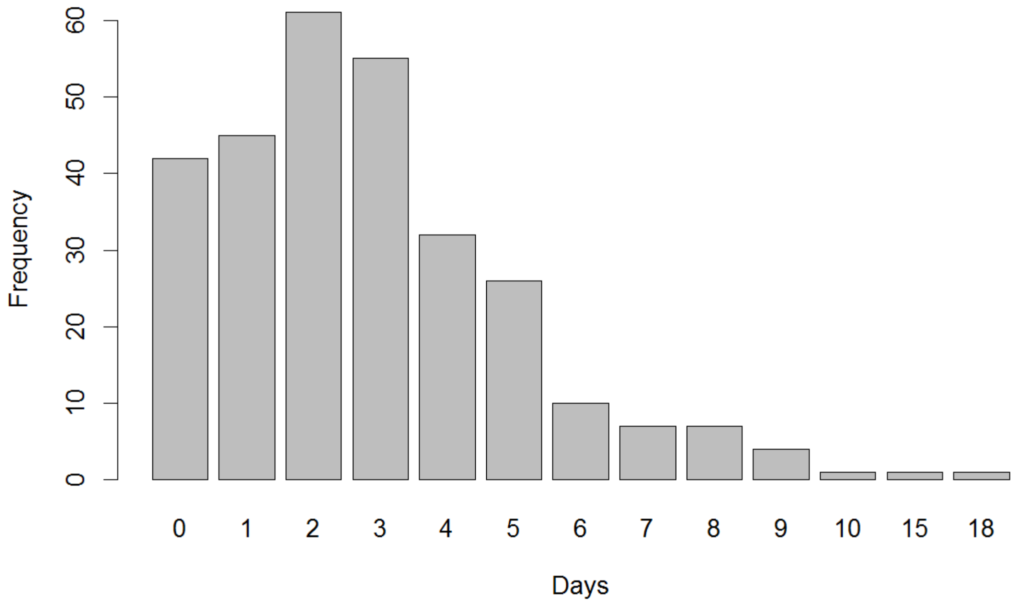
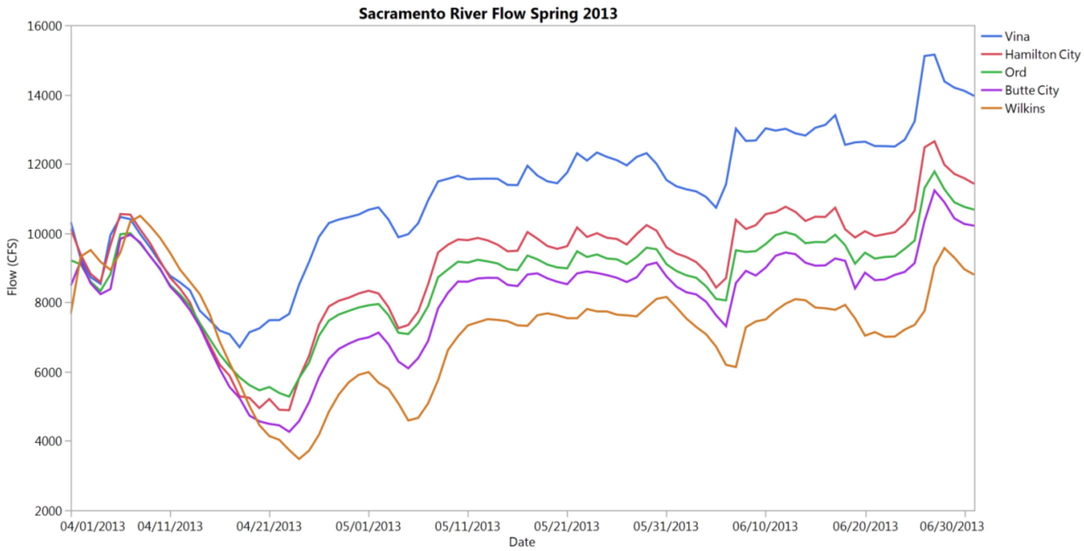


Figure 13. Number of days all 304 tagged Mill Creek smolts were detected after release, and before they were assumed to have died. Day 0 represents smolts that were detected < 24hrs.


Sacramento River Flow Spring 2013
Flow (CFS)
16000
14000
12000
10000
8000
6000
4000
2000
04/01/2013
04/11/2013
04/21/2013
05/01/2013
05/11/2013
05/21/2013
05/31/2013
06/10/2013
06/20/2013
06/30/2013
Date
Vina
Hamilton City
Ord
Butte City
Wilkins

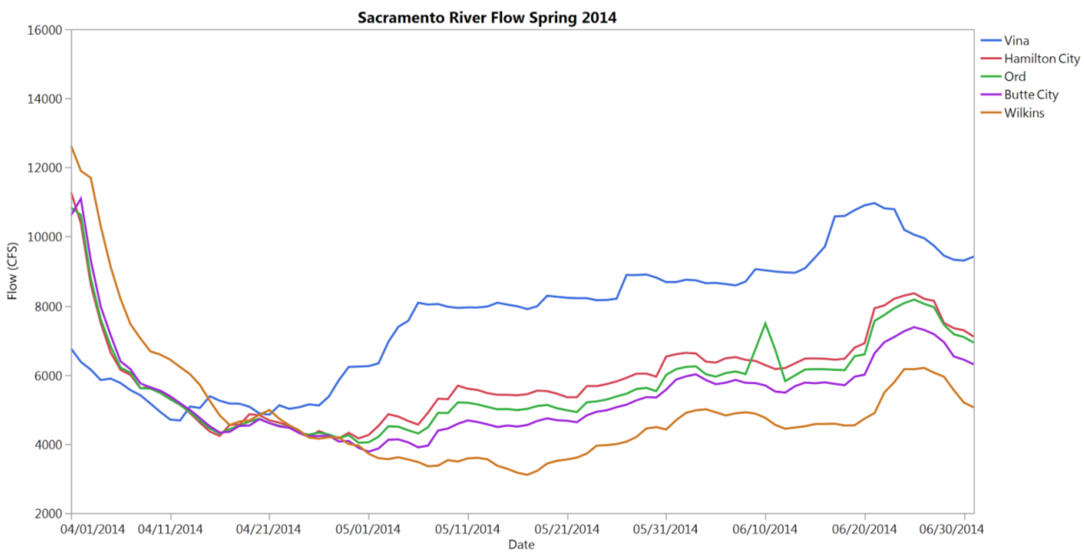

Sacramento River Flow Spring 2014
Flow (CFS)
16000
14000
12000
10000
8000
6000
4000
2000
04/01/2014
04/11/2014
04/21/2014
05/01/2014
05/11/2014
05/21/2014
05/31/2014
06/10/2014
06/20/2014
06/30/2014
Date
Vina
Hamilton City
Ord
Butte City
Wilkins

Figure 14. Flows measured at gauging stations in the upper and lower Sacramento River between 2013-2016. Vina is the beginning of the upper Sacramento River, Butte City is the end of the upper Sacramento River/beginning of the lower Sacramento River, Wilkins Slough is near the end of the lower Sacramento River. The area under each line represents the amount of water diverted in that reach. After water diversions begin mid-April, approximately 50% of the flow is diverted between the beginning of the upper Sacramento and end of the lower Sacramento River.

Figure 15: Length at date of out-migrating juvenile salmon from Mill Creek between 1995-2010. Smolts tagged in this study >80mm tend to leave relatively late in the spring compared to hatchery reared salmon and natural origin yearling-type Chinook salmon. Mill Creek smolts typically out-migrate during the timeframe when water diversions are operating in Mill Creek and the Sacramento River, which is indicated by the shaded box.

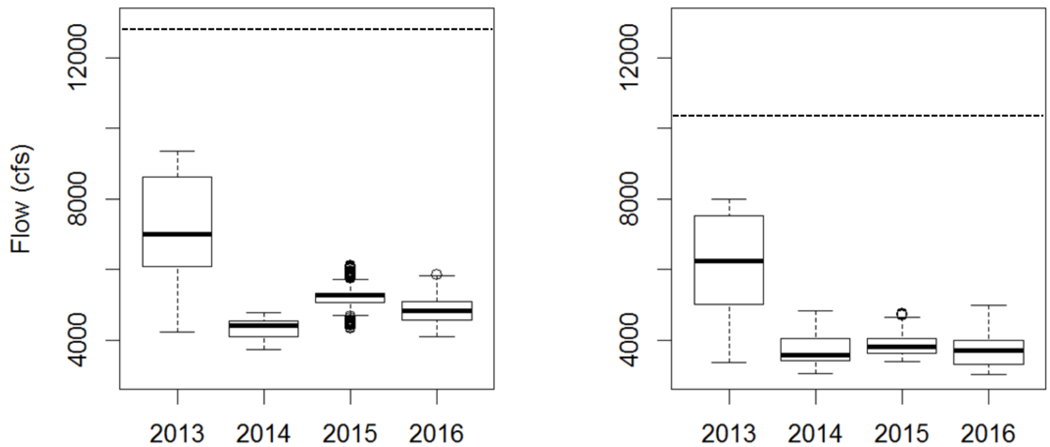


Figure 16. Flow values for the upper (left) and lower (right) Sacramento River during the study period for each year. Flow values are measured in cubic feet per second (CFS). The dashed lines indicate the historic average flow values for each region during the study period (1987-present).

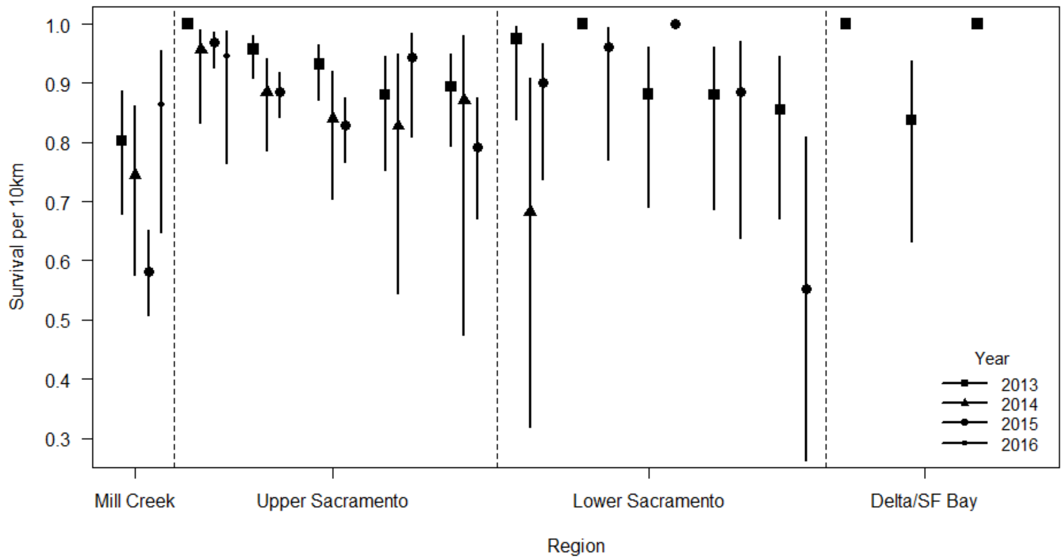


Figure 17. Reach specific survival rates per year throughout each study region, including the Delta and San Francisco Bay.

Chapter 3

Acoustic Tag Retention and Growth Rates in Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) Exposed to Changing Environmental Conditions

Introduction

Acoustic telemetry is a widely-used tool to study the movement and survival rates of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) emigrating to the Pacific Ocean (McMichael et al. 2010; Michel et al. 2015; Perry et al. 2010). To perform these studies acoustic tags are surgically implanted into the peritoneal cavity of the juvenile salmon and closed using dissolvable sutures. Once recovered the salmon is released into the river and is assumed to retain the tag and behave naturally for the duration of the study. With the advent of JSATS (Juvenile Salmon Acoustic Telemetry System) miniature acoustic tags it is now possible to tag and track salmon as small as 80mm. This makes it possible to monitor the movement and survival rates of young of year salmon migrating downstream throughout rivers in California's Central Valley. This study measures the rate of tag shedding and the potential side effects of being captured by a rotary screw trap (RST) and undergoing surgery to implant the acoustic tag in hatchery Chinook salmon smolts.

Since 2013 we have been capturing and tagging wild juvenile Chinook salmon smolts from Mill Creek in Northern California (Tehama County) and tracking their movement and survival rates to the Pacific Ocean over a distance of 450 river kilometers. Once fish are tagged and released we are assuming they exhibit a strictly downstream migration behavior. Underwater hydrophones detect the acoustic tags inside the salmon throughout their migration route at approximately every 20 river kilometers. When the acoustic tag is not detected at the next downstream receiver it is assumed that the salmon has died. An additional reason for the salmon not being detected is tag shedding. Tag shedding occurs when the salmon expels the acoustic tag through the surgical incision or body cavity, making it appear the fish has died when in fact it may not have. Many studies have researched tag retention and growth rates in juvenile Chinook salmon (Ammann et al. 2013; Anglea et al. 2004; Lacroix et al. 2004; Moore et al. 1990; Sandstrom et al. 2013; Tyus 1988) but all of these have been in a laboratory where water conditions are controlled and do not mirror the natural conditions which migrating smolts experience.

This study examines tag retention, survival and growth in juvenile salmon exposed to natural conditions while being held in tanks placed in Mill Creek, as well as examining the effects of being captured and held overnight in a RST. Throughout the study changing weather patterns and diurnal variations in solar radiation caused fluctuations in water temperature, stream flow and turbidity. These changing environmental conditions, as well as increasing photoperiod during the spring are some of the cues juvenile salmon use to begin smoltification and downstream migration (Wedemeyer et al. 1980). We held juvenile salmon in large tanks for 30 days after being captured by the RST and surgically implanting them with an acoustic tag. Growth and tag retention rates were measured at the end of the study to infer the likely impacts on natural fish we have tagged and released in Mill Creek since 2013.

Methods

Mill Creek is a tributary to the Sacramento River containing pristine spawning and rearing habitat for Chinook salmon and steelhead trout (*Oncorhynchus mykiss*). It originates on Mount Lassen and flows south-west for 33 miles before joining the Sacramento River near the town of Los Molinos. Its watershed drains 435 square miles and is only accessible at two road crossings, with most of its watershed protected within the Ishi Wilderness and Lassen National Forest. It is one of 5 streams currently supporting self-sustaining spring-run Chinook salmon populations in California's Central Valley, a life-history type that requires high elevation habitat in order to over-summer and mature in deep, cold pools. From 1995-2010 a RST was operated by California Department of Fish and Wildlife (CDFW) below Upper Dam on Mill Creek at river km 9 to study the outmigration timing of juvenile Chinook salmon and steelhead trout (Figure. 1). Since April 2013 I have used the same site and RST to capture and tag wild juvenile salmon and steelhead smolts emigrating out of Mill Creek and studied their movement and survival rates through various reaches downstream to the Pacific Ocean.

Hatchery-raised fall-run Chinook salmon smolts were used as surrogates for wild spring-run Chinook salmon juveniles because this population is part of the ESU that is listed as threatened under the ESA and the numbers of wild juveniles captured in the Mill Creek RST is very low. In order to examine RST effects on survival, we designated three treatment groups for this study: RST/untagged, RST/acoustic tagged, and control. The RST/acoustic tagged group experienced capture by the RST and handling associated with it, followed by a surgical procedure to implant the acoustic tag in the peritoneal cavity of the fish. The RST/untagged group experienced capture by the trap and handling associated with it, and the control group was only weighed and measured. Each treatment group consisted of 50 juvenile salmon.

In total 150 juvenile salmon (body mass = 6.4 ± 0.5 g [mean ± SD]; fork length = 81.7 ± 1.9 mm) were taken from Coleman National Fish Hatchery (CNFH) in Anderson, California and transported to upper dam on Mill Creek near Los Molinos, California. Upon arrival the smolts were divided into three groups for the RST/acoustic tag, RST/untagged, and control treatment. For the RST/acoustic tagged and RST/untagged groups, 100 smolts were released upstream of the RST and washed downstream into the trap, where they were exposed to entrainment by the trap followed by holding overnight in the trap. The control treatment was set aside in coolers with aerators and processed the following morning. The two RST groups were collected with dip nets the following morning and then anesthetized in MS-222 buffered by 120mg L^-1 sodium bicarbonate prior to being weighed to the nearest tenth of a gram and measured to the caudal fork. An upper caudal fin-clip marked the RST/acoustic tagged fish, while the RST/untagged fish were marked by a lower caudal fin-clip. These caudal clips are similar to what wild smolts experience after being tagged and released in Mill Creek (for the purpose of collecting a tissue sample for DNA analysis).

The surgery procedure on the 50 RST/acoustic tagged smolts was consistent with the surgeries conducted on wild smolts captured in Mill Creek (see Deters et al.

(2010) for details). The Juvenile Salmon Acoustic Telemetry Systems (JSATS) tags used in this study were manufactured by Advanced Telemetry Systems (ATS), with a tag weight in air of 300mg and size of 10.7 x 5.0 x 2.8mm. After the tagged smolts recovered from surgery all fish were placed into two 490 liter plastic tanks (0.88 m tall x 0.9 m diameter) along the bank of the creek and held for 30 days. Water was supplied to the tanks at a rate of 13.6 liters per minute from a neighboring irrigation canal 0.25 meters above the tank. Two 1.2 cm hoses siphoned water from the canal to the bottom of the tanks and created a current for the salmon to swim in. Half of the smolts from each treatment were placed into each tank (each tank contained an equal number of RST/acoustic tagged, RST/untagged and control smolts).

Each morning the tanks were cleaned, temperature recorded and checked for shed tags using a large magnet to sweep the bottom. In both tanks a temperature logger recorded water temperature every 15 minutes near the bottom and (Figure. 2). Due to technical difficulties in the upstream tank the temperature logger only recorded data for approximately half of the study, which was in general consistent with temperatures in the downstream tank. Dissolved oxygen was recorded intermittently throughout the study, but difficulties with the instrument prevented us from having reliable measurements to analyze. After cleaning and checking the tanks for shed tags the smolts were fed a #2 crumble feed provided by CNFH at a ratio of 2% bodyweight per day, which is the standard feeding protocol for salmon reared in hatcheries (Iwama and Tautz 1981).

The tag retention study lasted for 30 days, which is equivalent to the battery life expectancy of acoustic tags implanted into wild smolts emigrating from Mill Creek. After the study all smolts were euthanized and processed on site. Length and weight measurements were recorded and all acoustic tagged smolts were checked with a metal detector to see if the tag was still present. For salmon that shed their tag it was noted if the tag had been expelled through the incision site or if the tag was pushed through the body wall at another location. Incision healing, inflammation rate, tag bulge and suture absence/presence were also noted.

In order to determine which factors were significant in relation to tag shedding a logistic regression was used to analyze various parameters which were measured throughout the study. The mean daily water temperature, maximum daily water temperature, fish length and weight before surgery were all factors used in the analysis. Data collected during this study allows us to factor in tag shed rates and any surgery-related mortality observed into the previous three years of outmigration survival for smolts tagged in Mill Creek. In addition we measure the growth rates of smolts from different treatment groups to examine growth effects related to the RST and RST/acoustic tag treatments.

Results

After 30 days in the holding tanks, the acoustic tagged salmon shed 10 (20%) of the original 50 tags implanted into the group. The first tag was shed after 9 days, and tag shedding continued for the remainder of the study except for a six day period from day 17-23 (Figure 3). No salmon in this study died as a result of the surgical procedure or from being entrained by the rotary screw trap.

The growth rates of acoustic tagged salmon over the course of 30 days was significantly lower than that of the RST/untagged and control groups (ANOVA, p value = 0.0001). This finding is consistent with other studies that found an initial low growth rate for tagged salmon during the first 30 days, followed by compensatory growth after 30 days where the salmon catches up in weight and length compared to other groups (Adams et al. 1998; Ammann et al. 2013; Sandstrom et al. 2013) . Additionally there was no significant tank effect (p value = 0.65) and no significant interaction between tank and treatment group (p value = 0.28). The body weight and length of the acoustic tagged smolts was initially higher than the other two groups because of the 5% tag to body weight ratio we follow for telemetry studies (Table 1); requiring the smolts to be a minimum of 6 grams in weight for JSATS tags using criteria recommended by Brown et al. (1999).

Average daily water temperature (pvalue = 0.43), maximum daily water temperature (pvalue = 0.45), and fish length before surgery (pvalue = 0.41) were all found to be insignificant in the analysis, and the only factor explaining variation in tag shedding was the weight of the smolt prior to surgery (pvalue = 0.05), which found that smaller smolts were more likely to shed their tags. Fish that shed their tag weighed on average 6.2 grams (SD = ± 0.33 g), compared to the mean group weight of 6.5 grams. The predicted rate of tag shedding was highest for smolts near 6 grams, and declined continuously for larger fish (fig. 4).

Discussion

Acoustically tagged juvenile salmon tracked in biotelemetry studies experience a wide range of environmental conditions as they migrate downstream to the ocean. This novel experiment placed acoustic tagged juvenile salmon in changing water temperatures and turbidity levels and measured the rate of tag shedding, growth and mortality over a 30 day period. The water conditions these fish experienced were similar to the conditions experienced by smolts tagged and released in Mill Creek during the 2016 study. Downstream of Mill Creek in the Sacramento River and Delta, water conditions change as a result of increased solar radiation which warms the water and could potentially increase the rate of tag shedding. This factor, as well as other changing environmental variables such as flow and salinity, should be examined further to see if they also influence the rate of tag shedding.

After 30 days all tagged salmon survived effects from the rotary screw trap and surgical procedure, but shed 20% of the original 50 tags by the end of the study. The first tag was shed after 9 days, which is consistent with other studies that found a delayed start in tag shedding (Lacroix et al. 2004; Welch et al. 2007), and shedding continued for the duration of the study except for a seven day period (fig. 5). This rate of tag shedding is higher compared to other studies which have been conducted in hatcheries or laboratories where water temperatures are relatively cold and stable. Warm water temperatures have been shown to decrease the rate of incision healing after surgery in tag retention experiments, and in some cases prevent wound healing completely compared to fish which experience cold water temperature (Walsh et al.

2000). The water temperatures during this study were relatively warmer compared to other tagging studies (Ammann et al. 2013; Sandstrom et al. 2013; Tyus 1988), but were not consistently high due to diel fluctuations in temperature as well as temperature swings due to changing weather patterns.

While previous studies find warmer water temperatures are associated with increased tag shedding rates (Cooke et al. 2011; Walsh et al. 2000), we found that smolt weight before surgery was the only significant factor impacting tag-shed rates, with smaller fish more likely to shed their tag. Smaller fish naturally have a smaller peritoneal cavity where the acoustic tag is placed, and when the tag is inserted their stomach may put more outward pressure on the tag compared to a larger smolt with a bigger peritoneal cavity. This effect in turn may cause additional pressure on the sutures which hold the tag in place and could ultimately result in the tag being extruded. In addition to fish size, the amount of food in their stomach may be a factor in tag shedding, where higher feeding rates would lead to a more full stomach and cause more pressure on the tag and sutures. All salmon were fed a 2% body weight ration per day, which is consistent with other tag effect studies (Adams et al. 1998) and much lower than feeding rations for salmon rearing in the wild where consumption rates could be as high as 8% bodyweight per day (Sagar and Glova 1988). Given the fact that most smolts tagged and released in Mill Creek exhibit a strictly downstream migration behavior, the amount of time spent rearing and feeding is limited and in turn should lead to lower consumption rates. Additionally smolts tagged in Mill Creek migrate downstream through the Sacramento River, where the natural channel has been replaced with rip rap and primary production has been severely impacted compared to neighboring flood plains (Sommer et al. 2001), resulting in lowered feeding opportunities.

Another finding during this study is that juvenile salmon implanted with acoustic tags grew significantly less than the control and RST/untagged groups in the same tanks. After 30 days the acoustic tagged group weighed on average one gram less than the other groups (Figure 6). This finding suggests that acoustic tagged smolts may not be as fit as control smolts or smolts only captured by the RST, and therefore may experience lower survival rates in the wild. Smolt survival rates in Mill Creek and the Sacramento River have been very low for wild smolts compared to those from other watersheds, and may be attributed to physical effects of tagging combined with the late outmigration timing of these smolts which coincides with greater predator densities in the Sacramento River and Delta (Nobriga 2007). More data needs to be collected in experiments where tagged and untagged smolts are exposed to predators to measure potential differences in predation rates on salmon which are acoustically tagged.

These findings have implications for biotelemetry studies where juvenile salmon survival is based on acoustic tag detections at receiver arrays located throughout a river system. These studies assume the juvenile salmon exhibits a strictly downstream movement behavior, and the absence of detections at subsequent receivers concludes that the fish has died. This study shows that after a certain period of time acoustic tags are being expelled by juvenile salmon, leading to the false assumption that the fish has died. With this data it is possible to calibrate survival estimates for acoustic tagged salmon which are detected for longer than nine days. Travel times for smolts tagged in the upper Sacramento River at CNFH took on average 18.7 days (±2.3 SE) to reach the Golden Gate over a distance of 534 river kilometers (Michel et al. 2013). According to these travel rates approximately 10% of the tags could have been shed from these smolts between 9 and 18 days, which would result in underestimating survival towards the end of their out-migration. For salmon remaining in the system for longer periods of time tag shedding could potentially be much greater, and the data collected in this study may be used to calibrate these estimates to show that survival rates may in fact be higher.

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Treatment	n	Before Weight (g)	After Weight (g)	Before Length (mm)	After Length (mm)	Growth Weight (g)	Growth Length (mm)
Control	50	6.4 (5.5-7.8)	12.5 (9.8-15.5)	81.1 (80-86)	100.2 (94-106)	6.1 (3.5-9.7)	19.1 (11-24)
Tagged	50	6.5 (6-8.4)	11.4 (9-15.4)	82.3 (79-89)	97.9 (92-106)	4.9 (2.4-9)	15.5 (5-23)
RST	50	6.2 (5.5-7.5)	12.3 (9.5-14.9)	81.5 (79-87)	100.1 (94-107)	6.1 (3-9.1)	18.6 (10-28)

Table 1. Before, after and growth weight and lengths for all treatment groups. Values represent the group mean, range in parenthesis.

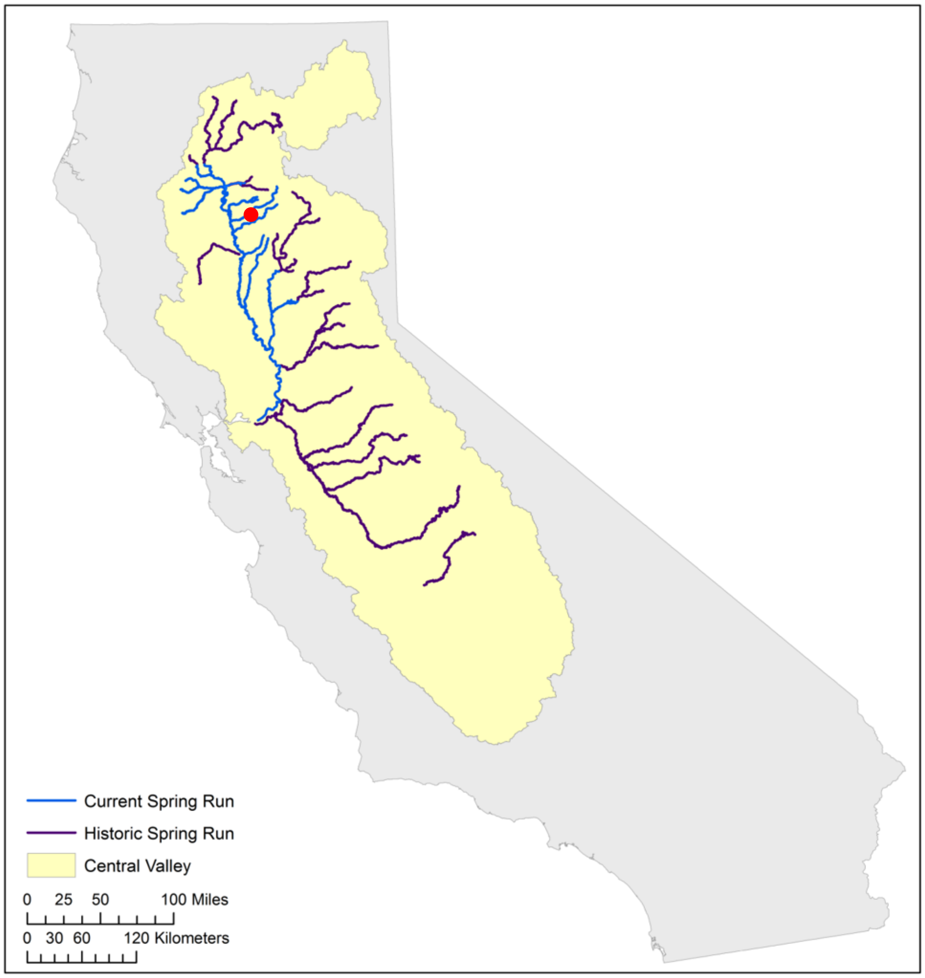

Figure 1. Map of California's Central Valley indicating the historic spring-run Chinook habitat (purple) and current habitat (blue) remaining. The red dot indicates the location of the RST and tag effect study on Mill Creek.

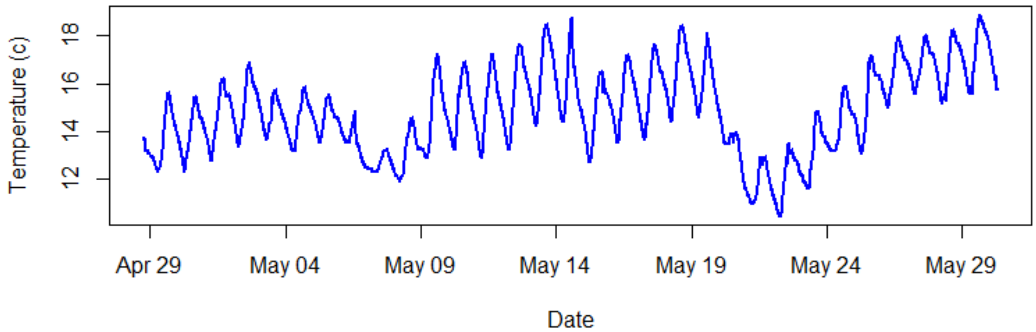

Figure 2. Daily water temperature recordings from holding tanks throughout the study, showing the diel variations the salmon experienced.

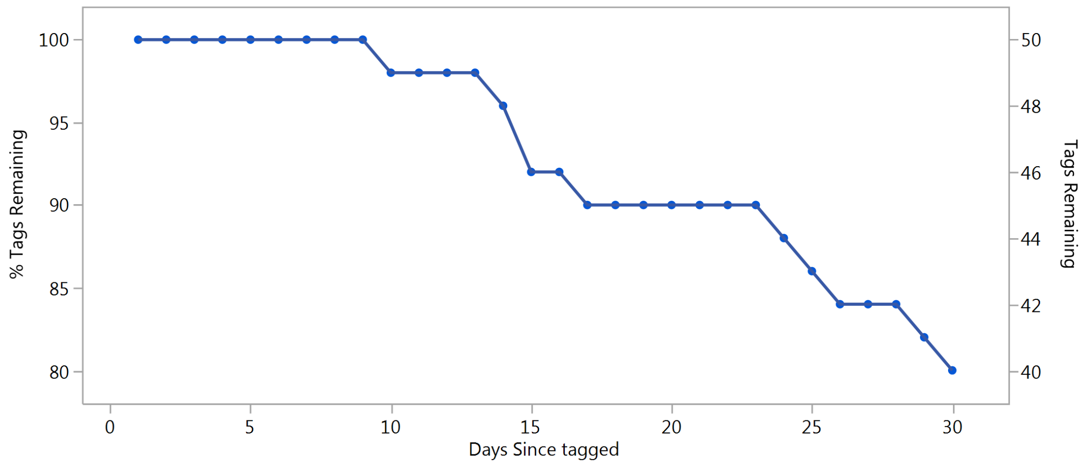

Figure 3. Cumulative number of tags shed and total percent remaining in juvenile Chinook through time over the 30 days study.

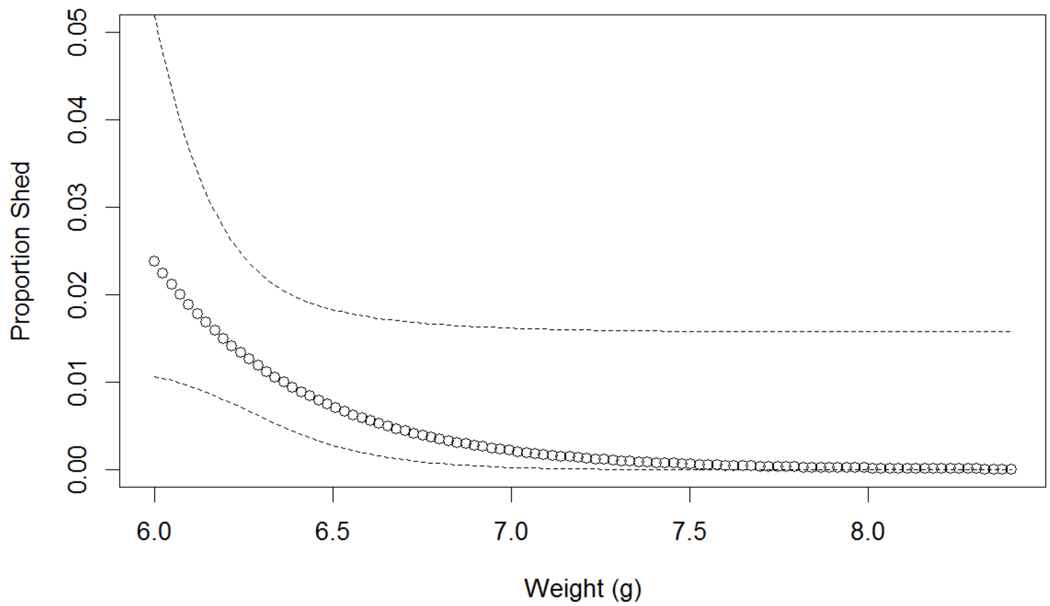

Figure 4. Predicted tag shed rates as a function of weight (grams) before surgery for smolts used during the study. Dashed lines represent the upper and lower 95% confidence intervals.

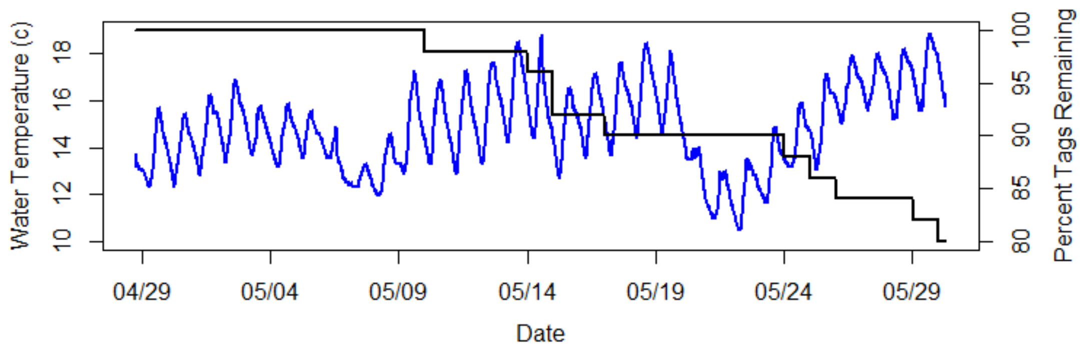

Figure 5. Water temperatures throughout the study in relation to the percent of tags remaining in tagged fish (black line).

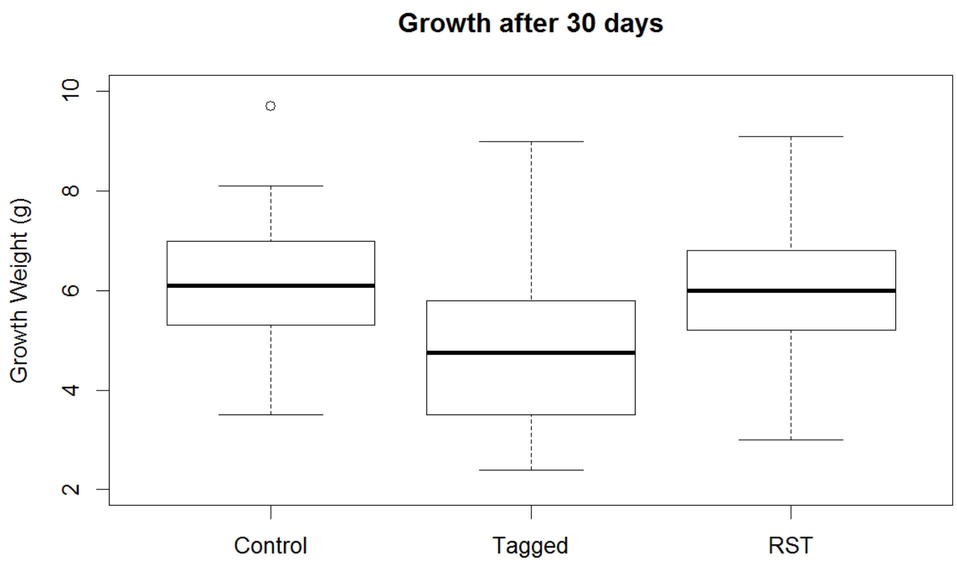

Figure 6. Growth weight in grams for each treatment group, showing the median, 25^{th} and 75^{th} quartiles.

Chapter 4

Conclusion

Central Valley Chinook salmon have endured many modifications to their freshwater habitat over the last 150 years, with the biggest being the inability to access most of their historic spawning and rearing habitat behind large dams. As a result the populations of these fish have been greatly reduced, and in some cases are on the verge of extirpation. Yet on occasion, when high river flows coincide with nutrient and food-rich conditions in the ocean, populations of Central Valley Chinook salmon can rebound greatly. This happened most recently in the late 90's and early 2000's during a series of wet years that were timed perfectly with productive ocean conditions, and resulted in some of the largest salmon runs seen in decades. While these events require both the freshwater and marine environment to correspond with successful out-migration conditions as well as ocean productivity, it is the freshwater side where humans have more control over the system.

In today's era of flood control and water management, the flow regimes of dammed rivers are highly regulated and tend to have the opposite seasonal dynamics of a natural system. Flows are typically high during the summer to deliver water for agricultural uses, and low in the winter/spring when water is conserved to fill reservoirs during the rainy season. This way of managing streamflow for human interests has negatively impacted anadromous fish populations, as these fish have evolved with high winter/spring flows which increase juvenile rearing capacity and help them successfully out-migrate to the ocean as smolts. In many ways the current water management system of the Sacramento and San Joaquin Rivers leave them in a perpetual state of drought, even during wet years when there is plentiful water stored upstream of reservoirs. In addition, small irrigation dams on tributaries such as Mill Creek are having the same effect on flow regimes during the out-migration of salmon smolts but on a smaller scale. These irrigation dams can divert much of the water for out-of-stream uses during the spring, especially during drought conditions when natural runoff is already impaired, leaving low flows for salmon smolts to out-migrate through.

These altered flow regimes present many challenges for salmon smolts out-migrating from Mill Creek during the late spring, which encounter rapidly changing water conditions within a relatively short amount of time. This study shows that with increased flows in both Mill Creek and the Sacramento River, out-migration survival increases. In Mill Creek this finding was extremely evident, with low survival rates observed during periods of low flow, and high survival rates observed during wet years and high stream flow. With these survival estimates throughout a range of flow values, it is possible to implement a minimum flow criteria in Mill Creek to support desired smolt survival rates through the diverted stream reaches. This information will be particularly helpful during drought conditions when the amount of natural runoff may not be enough to satisfy the needs of both water diversions and the aquatic ecosystem in Mill Creek. In addition, water conservation actions may be implemented to help conserve the water diverted from Mill Creek to supply small scale farms and ranches. Using drip rather than flood irrigation, or watering at night rather than mid-day to reduce evaporation rates can help reduce the amount of water needed to accomplish the goals of local farmers while keeping more water in the stream for salmon.

In the Sacramento River, implementing a more natural spring flow regime would most likely increase smolt survival rates through the river and into the Delta. Using the data collected during this study it is possible to develop baseline estimates for smolt survival rates through the upper and lower Sacramento River as a function of flow. While this management strategy may be difficult to execute as a result of the many stakeholders who have interest in the water behind Shasta Dam, if the current trend of declining salmon populations continues this action may gain more support. One way to implement this strategy is to construct off-site storage reservoirs in neighboring valleys to the Sacramento River which are filled during periods of winter runoff, and then drained in the spring to increase the flow in the Sacramento River when water is being conserved behind Shasta Dam. This action would allow the conservation of water for agriculture during the summer yet still provide higher flows for the aquatic ecosystem during the spring, which has in recent years experienced chronically low spring stream flow as a result of the altered flow regime.

In addition to the information gathered on salmon smolt survival rates, this study shows that survival estimates in acoustic telemetry studies may be biased low as a result of tag shedding. When conducting acoustic telemetry experiments it is critical to tag groups of fish that are representative of the population in question. However, when tagging smolts weighing close to 6 grams it becomes increasingly possible that these fish will expel their tag at some point. As a result, correction factors can be implemented into the survival analysis for fish which are close to this weight threshold, and survival estimates can generally be increased for smolts being tracked for longer than 9 days. However, as technology continues to advance, the type and style of acoustic tags will become smaller and allow the tracking of fish much smaller than 6 grams. This will likely change the tag shedding rates associated with salmon of the same size used in this study, and further studies should continue to be conducted into how tag shedding rates respond to different types of acoustic tags.

With the populations of many Central Valley salmon currently in dire straits, the information presented in this thesis will hopefully shed light into the mechanisms impacting salmon smolt survival rates. Understanding how environmental factors such as flow and temperature influence salmon smolt survival, especially during drought conditions, is critical in managing these fish for recovery. The positive correlation between increasing flow and increasing survival makes the simple point that survival improves with higher flows during critical spring-time migration windows. During drought conditions supplying enough water for salmon smolts and agricultural uses will be challenging, but the flow criteria presented in this thesis can be used to determine a minimum flow value that will still promote a desired survival rate.

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