Environ Biol Fish (2013) 96:405–417
DOI 10.1007/s10641-012-0046-x

Survival of captured and relocated adult spring-run Chinook salmon *Oncorhynchus tshawytscha* in a Sacramento River tributary after cessation of migration

Christopher M. Mosser · Lisa C. Thompson · Joshua S. Strange

Received: 21 March 2012 / Accepted: 21 May 2012 / Published online: 24 July 2012

Abstract We studied the efficacy of the process for capture and upstream relocation of 26 adult spring-run Chinook salmon in Butte Creek, California in 2009. These fish had ceased volitional upstream migration prior to reaching their summer holding habitat. The purpose of the relocation was to move fish upstream of two water diversion dams and release them in a part of the stream from which they could presumably swim to cool summer holding habitat, then spawn in the fall. Fish were netted, transported by truck, given an esophageal radio tag/temperature tag, and released. Radio tagging proved to be a useful technique for determining the survival and movement of relocated fish and temperature tags provide useful information to determine thermal exposure and time of death. Twenty-three tags (88 %) were recovered, compared with a 10 % tag recovery rate for an earlier study using fin clips. Most tags were recovered within 3.5 km upstream and 1 km downstream of the release site. A single tag was recovered 6 km upstream. No fish were determined to have survived to spawn. Temperature tag data indicate that most of the salmon died within 2–6 days after the relocation operation. After preventative measures have been exhausted, future relocations efforts, in any setting, should consider (1) intervention as soon as fish cease volitional migration but before they are exposed to further deleterious conditions (2) monitoring environmental conditions to choose appropriate release sites (3) evaluation of disease transmission risk, and (4) handling practices that minimize potential stress due to air immersion and thermal shock.

C. M. Mosser (✉) · L. C. Thompson
Wildlife, Fish, & Conservation Biology Department,
University of California Davis,
1 Shields Avenue,
Davis, CA 95616-8751, USA
e-mail: cmmosser@ucdavis.edu

J. S. Strange
Yurok Tribal Fisheries Program, Yurok Tribe,
Rte. Box 169 Highway 96,
Weitchpec, CA 95546, USA

Keywords Migration · Rescue · Relocation · *Oncorhynchus tshawytscha* · Spring-run Chinook salmon · Radio telemetry · Monitoring

Introduction

The capture and relocation of anadromous salmonids has been performed for a number of reasons, including the relocation of juveniles during times of stream dewatering and fragmentation (SSCSRT 2003; Pincetich et al. 2009; and Roy Thomas, Carmel River Steelhead Association, pers. comm.) and movement of returning adults over impassible or potentially harmful barriers or around low flow stretches of river (Zimmerman and Duke 1995; Keefer et al. 2008; Engle and Skalicky 2009; Keefer et al. 2010). However, little is known regarding the outcome of the capture and relocation of adult salmonids in general, and specifically California

Central Valley salmonids that have ceased volitional upstream migration due to environmental conditions such as high water temperatures and low flows. We found only one report on the capture and relocation of returning adult salmon in California under such conditions, and no records in the peer-reviewed literature. In 2008 the California Department of Fish and Game (CDFG) conducted a capture and relocation operation on Butte Creek (Garman and McReynolds 2009), a tributary of the Sacramento River, but the benefits to the fish were uncertain, as were the methods used. There are no established best management practices dealing with capture and relocation of salmonids that have ceased upstream migration and that have been exposed to prolonged, stressful, and sub-lethally high water temperatures. Capture and relocation strategies may become more common in the management of listed fish such as the California Central Valley Evolutionarily Significant Unit (ESU) of spring-run Chinook salmon if water temperatures continue to rise and hydrologic regimes shift further due to climate change (Hayhoe et al. 2004; Thompson et al. 2011).

In May 2009, an interagency team began discussing strategies for, and the potential impacts of, capture and relocation (termed "rescue" by these agencies) of listed salmonids under environmental conditions which are known to impede migration, such as high water temperature and/or low flows. The team consisted of representatives from CDFG, National Marine Fisheries Service (NMFS), United States Fish and Wildlife Service (USFWS), Bureau of Reclamation (BOR), and the California Department of Water Resources (CDWR), as well as researchers from the University of California, Davis and California State University, Humboldt. The potential strategies included temporary placement of adults in hatcheries, hatchery spawning programs, egg and juvenile rearing in a hatchery, and immediate upstream relocation. Representatives of these agencies signed a memorandum of understanding (MOU) with key objectives of investigating the effectiveness of rescue plan designs, and monitoring the fate of rescued fish as a means to provide input for future management decisions with respect to the capture and relocation of anadromous fishes that have ceased volitional upstream migration in association with stressful environmental conditions. Especially with regards to listed ESUs of species that migrate or rear in freshwater during warmer, lower flow times of the year, such as coho salmon *O. kisutch*, spring-run Chinook salmon, and summer steelhead *O. mykiss* (NMFS 2009).

The California Central Valley represents the southernmost extent of Chinook salmon distribution on the west coast of North America (Yoshiyama et al. 1998) and these populations are very susceptible to the risk of rising water temperatures and reduced flows (Lindley et al. 2007; Thompson et al. 2011). The Central Valley consists of two main river systems, the Sacramento River system in the north, and the San Joaquin River system in the south. All remaining Central Valley spring-run Chinook salmon populations are in tributaries of the Sacramento River that originate in the Sierra Nevada Mountains (Lindley et al. 2007). The Central Valley spring-run Chinook salmon ESU was state and federally listed as threatened in 1999, with the federal threatened status reaffirmed in 2005 (Good et al. 2005).

Central Valley spring-run Chinook salmon migrate upstream from late February to early July, peaking in April and May, but some fish may be migrating as late as July. The fish migrating in late spring and early summer are those that would be most susceptible to migration cessation. Historically, high elevation upstream reaches with cold, deep pools allowed spring-run Chinook salmon to survive the hot summer in the Central Valley before spawning in the fall, from mid-September to early November (Yoshiyama et al. 2001). Most major rivers and tributaries in the Central Valley have a barrier (e.g., dam for hydroelectric power generation, municipal water storage project, or agricultural diversion) that sets a limit to upstream migration, resulting in loss of greater than 72 % of upstream habitat, prohibiting spring-run Chinook salmon from migrating into the cooler, higher elevation upstream reaches of their historic range (Yoshiyama et al. 1998). Such barriers often divert water which reduces stream flows and potentially increases water temperatures. Historically, spring-run Chinook salmon formed the most abundant Chinook salmon run in the Central Valley and was found in most major tributaries of both the Sacramento and San Joaquin Rivers, numbering from 0.5 to 1.5 million adults per year (Moyle 2002). Currently, Central Valley spring-run Chinook salmon adult escapement estimates are dominated by returns to Butte Creek, which have ranged from an estimated 2,000 to 18,000 fish in the last decade.

Given the current low abundance of Central Valley spring-run Chinook salmon, the successful upstream migration of returning spawners is critical. However, in the two summers prior to this study (2007-2008), some adult spring-run Chinook salmon in Butte Creek ceased volitional upstream migration prior to arriving at their historic summer holding habitat (Garman and McReynolds 2009; C. Garman, CDFG, pers. comm.). No capture and relocation operation was performed in 2007 (Garman and McReynolds 2009). On 2 July 2008, in response to the impending mortality of salmon that had ceased volitional upstream migration, management agencies conducted a fish capture and relocation operation in which 352 adult salmon were marked with fin-clips and released upstream. Though the number of salmon that had ceased volitional migration was low relative to the overall run size on Butte Creek, the operation also provided an opportunity to explore capture and relocation strategies in the event that these migratory cessations become more prevalent in future years. Thirty-six (10 %) of the relocated fish were recovered during summer pre-spawn and fall spawning carcass surveys; five of these fish survived to the spawning season (1.4 % of the 352 total) and the rest were pre-spawn mortalities. The fate of the remaining 90 % of the captured and relocated fish is unknown (Garman and McReynolds 2009).

In the stream reach in which salmon migration ceased, water temperatures exceeded upper thermal limits to migration during the days leading up to the relocations. We defined thermal limits as daily mean temperatures of 21 °C when temperatures were increasing and 23 °C when temperatures were decreasing (Strange 2010). Flows were also dropping rapidly and approaching summer low flow conditions, and irrigation diversions had begun for the season, in combination creating a potential low-flow migration barrier at a diversion dam/bedrock migration constriction.

In the current paper, our goal was to assess the efficacy of capture and relocation procedures recently used for Butte Creek spring-run Chinook salmon. This goal involved four objectives: (1) to improve the estimate of the relocated salmon survival rate; (2) to determine what proportion of fish survived long enough to have the opportunity to spawn in the fall; (3) to determine the extent to which fish would continue their upstream migration from the release site; and (4) to assess capture, handling, tagging, and release techniques.

Methods

Study area

The study area consists of 27 km of spring-run Chinook salmon migratory, summer holding, and fall spawning habitat along Butte Creek, a tributary of the Sacramento River near Chico, Butte County, California (Fig. 1). For three consecutive summers (2007-2009), some adult salmon ceased volitional upstream migration and were found holding in a pool of approximately 2 m depth, about 150 m downstream of the Highway 99 Bridge and 500 m below the Durham Mutual Diversion Dam (Fig. 1). At this location along the creek, there are still two upstream water diversions that salmon must pass before they can navigate unimpeded into their historic spawning and holding habitat.

The release site was at the upstream side of the second diversion, Parrott Phelan Diversion Dam (PPDD), located 3.6 km upstream of the Highway 99 Bridge (Fig. 1). The majority of pre-spawn holding habitat is located further upstream between the Covered Bridge and the Quartz Bowl pool, located at the base of a small waterfall, which is the upstream limit to anadromy for Butte Creek spring-run Chinook salmon in most years.

Water temperature and flow

Water temperature and stream flow was recorded hourly at two different gauge stations and downloaded from the Department of Water Resources California Data Exchange Center (CDEC) database for 2009 (available at http://cdec.water.ca.gov/cgi-progs/queryCSV). The first was the Butte Creek near Durham (BCD) gauge, less than 2 km downstream of the pool where the salmon were holding prior to relocation (Fig. 1). The second was the Butte Creek near Chico (BCK) gauge, located approximately 5 km upstream of the release site.

Fish capture and relocation

On 30 June 2009, all the adult salmon holding at the Highway 99 pool were captured and relocated upstream by experienced fishery personnel from CDFG. Twenty-six fish were moved and there were no subsequent reports of any additional fish found at or downstream of this site.

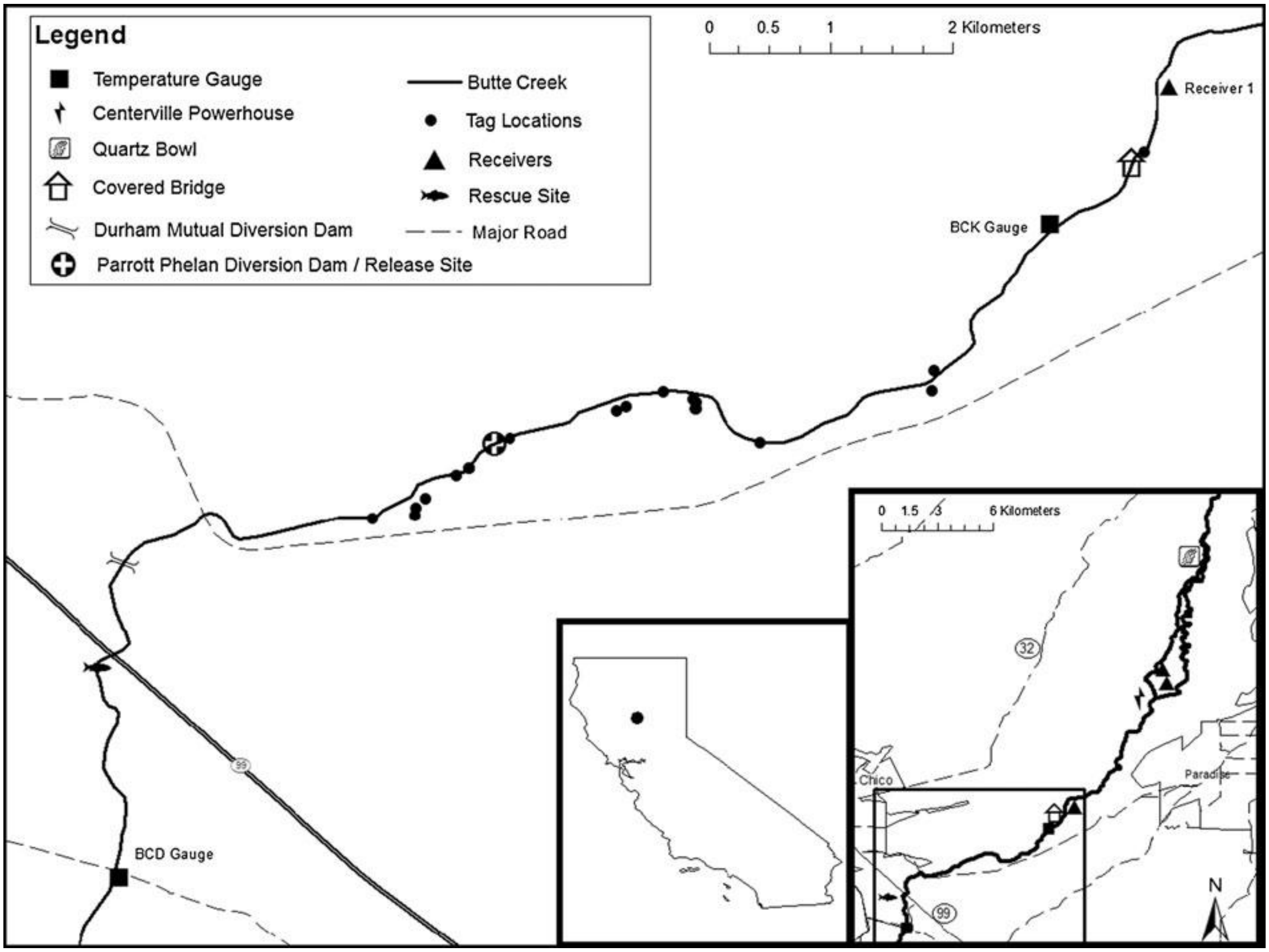

Fig. 1 Map of Butte Creek including spring-run Chinook salmon spawning and holding habitat, rescue site, release site, and surrounding areas. Inset, left - Location of study area within California. Inset, right - Rescue location, release location, and key points within the salmon holding and spawning habitat. Receiver 1 was located just upstream from the Covered Bridge. Receiver 2 was located approximately 100 m upstream of the Centerville Powerhouse. Receiver 3 was located 1 km upstream from the Centerville Powerhouse. Main - Rescue location, release site, and locations of recovered radio tags. The salmon were released a few meters upstream of the Parrott Phelan Diversion Dam. Note: The five radio tags recovered by local residents do not have exact GPS points, so GPS location was estimated based on conversation with the local residents. All five of these radio tags are represented by a single point

Due to the location of the pool where the fish ceased migration, the capture and relocation procedures were arduous for both the agency personnel and the fish. A mobile net pen was created from a modified pontoon boat with a net draped across the pontoons and into the water, and a cable that allowed movement of the boat across the creek. The pool was surrounded by a weighted seine net while dip nets were used to move salmon to the pontoon net pen. The pool was adjacent to a footpath up the riprapped levee bank, approximately 8-m high, which was used to transport the fish up to the hatchery truck parked on river right; the only vehicle access point. Salmon were passed up the hill in the dip net, hand to hand, by approximately 20 CDFG personnel and placed into the holding tank of a standard CDFG hatchery truck, which had a compressed oxygen aeration supply. The truck was then driven 10-min to the release site. The water temperature in the hatchery truck tank was not measured prior to transport, but was estimated to be approximately 17.5 °C based on the temperature of water taken from the truck and used at our tagging station.

Fish tagging

Fish were radio tagged after they had been trucked upstream to the release site. Esophageal radio tags were inserted by a tagger with extensive experience installing both radio and acoustic esophageal transmitters in adult Chinook salmon. Radio tags were ATS F1845 non-coding, temperature sensitive, pulsed esophageal implant tags transmitting between 149 and 151 MHz, pulsing approximately once per second (Advanced Telemetry Systems, Isanti, MN, USA). Each radio tag frequency was unique and transmitted no less than a difference of 0.010 MHz from another tag. Prior to installation, all tags were checked for optimal frequency due to potential drift. Twenty-one radio tags had an iButton™ (AlphaMach, Mont St. Hilaire, Canada) archival temperature logger attached to the bottom of the radio tag, recording hourly temperature at 0.125 °C increments, up to a maximum of 26.375 °C.

Each fish was placed dorsal side down in a cradle inside a 400-L water-filled tub. The cradle included a cover for the eyes and head of the fish. Two pieces of surgical tubing were placed around the radio tag reduce regurgitation rates and improve tag retention (Keefer et al. 2004a). A plastic PVC tube coated with glycerol was used to insert the tag into the stomach. The antenna extended out of the mouth and was bent backwards. Each fish was then immediately released into the creek at an access point directly upstream of PPDD. Dissolved oxygen (DO) and temperature of the tub water were monitored during the tagging process and maintained between 10-15 mg DO/L and approximately 17.5 °C by replenishing with water from the hatchery tank truck.

The capture, relocation, and tagging process required four air immersions. Three air immersions were less than 10 s each. Transport of the fish up the levee hill to the transport truck required an air immersion up to 1 min. The water temperature in the transport truck was approximately 2.5 °C colder than the stream at the time of capture, and 2.0 to 2.5 °C colder than the stream at the time of release.

Demographics

Sex and fork length data for non-relocated fish were obtained from the CDFG spawner carcass survey for Butte Creek (CDFG, unpubl. data). We measured fork length of relocated fish, and determined sex when possible, while the radio tag was being installed. The eighth tagged fish showed signs of columnaris (*Flavobacterium columnare*) infection, so all subsequent fish were inspected for infection or injury. CDFG staff collected dorsal and pelvic fin clips for potential genetic analysis.

We tested the hypothesis that the sex ratios of the relocated and non-relocated fish were equal with a two-sided binomial test of equal proportions at a significance level of $\alpha=0.05$. We tested the hypothesis that mean length differed between relocated fish and non-relocated fish with an independent two-group t-test performed separately for males and females. The statistical package 'R' was used for all data analyses (R Development Core Team 2010).

Fish monitoring

We monitored radio tag movement with stationary logging receivers, and a mobile non-logging receiver. For stationary tracking, three Orion™ digital, logging receivers (Sigma 8, Newmarket, Ontario, Canada) were installed along the creek on private properties. The first was installed 0.5 km upstream of the Covered Bridge (approximately 5.5 km upstream of the release site), to allow detection of fish entry into spawning habitat (Fig. 1). The second and third receivers were installed approximately 100 m and 1.0 km upstream of the Centerville Powerhouse. Stationary receivers were located to monitor entry into the historic spawning and pre-spawn holding habitat, and direction of movement up to and above the Centerville Powerhouse, which is positioned in the middle of the spawning habitat. Receivers were situated based on proximity to key locations, researcher access, and safety of receivers from vandalism. Data were downloaded from receivers on a weekly basis.

We performed mobile tracking 1 to 2 days per week by swimming, hiking, or kayaking the creek, depending on location, with an SRX400 (LOTEK, Newmarket, Ontario, Canada) mobile receiver, stored in a waterproof case (Pelican™), and a three element Yagi antenna. We tracked between Quartz Bowl Pool and the release site (24 km) repeatedly between 1 July 2009 and 27 October 2009. However, due to logistical restraints, we were not able to track along all stream reaches each week. Every reach between the Quartz Bowl pool and the capture location was manually surveyed at least twice, including a final sweep of the entire study area. Most survey effort was spent surveying between the Skyway overpass downstream of the release location, and the Centerville Diversion

Dam. Radio tags were tracked down, and recovered if possible. If a fish was suspected to be dead, after its tag had been heard in the same location for more than 2 weeks, we did a thorough search of the creek and riparian area to recover the tag and look for evidence of the fate of the fish.

Fish mortality

Recovered tags were categorized based on our level of confidence regarding fish mortality. Category 1 tags were from fish that were confirmed dead, that is, a fish for which the tag was found lying within the carcass or bones of the fish. Category 2 tags were found on land but not within a carcass, or in the water in close proximity to salmon remains (< 5 m) with obvious animal sign (e.g., guano, feathers, otter feces) present nearby, indicating that a predator or scavenger may have eaten the remains. Fish with a tag in Category 2 were presumed dead. Category 3 tags were found in the water distant (> 5 m) from any salmon remains or animal sign, so the tag may have been regurgitated and the fate of the fish was less certain.

Based on data from recovered archival temperature tags from two dead fish discovered in the water by local residents on 3 July and moved to land, we were able to distinguish between the daily temperature patterns for a fish in or out of the water. It was then possible to estimate the approximate date of mortality of fish whose tags were recovered on land.

Results

Water temperature and flow

Water temperatures first exceeded 21 °C temporarily on 26 May 2009 but were increasing and daily maximum water temperatures exceeded 21 °C continuously for approximately 2 weeks prior to the relocation in 2009 (CDEC station BCD, Fig. 2). Daily mean water temperatures increased from 19.7 °C to 23.7 °C from 17 June to 29 June (Fig. 2). Flows dropped from 7.1 m^3/s on 26 May 2009 to 2.1 m^3/s on the day of the relocation (CDEC station BCD).

Water temperature was 20 °C at the time the fish were captured for relocation (CDEC station BCD). Butte Creek water temperature at the time of release was 20 °C as measured at the BCK gauge. Water temperatures recorded at the BCK gauge also exceeded the literature-value threshold for volitional

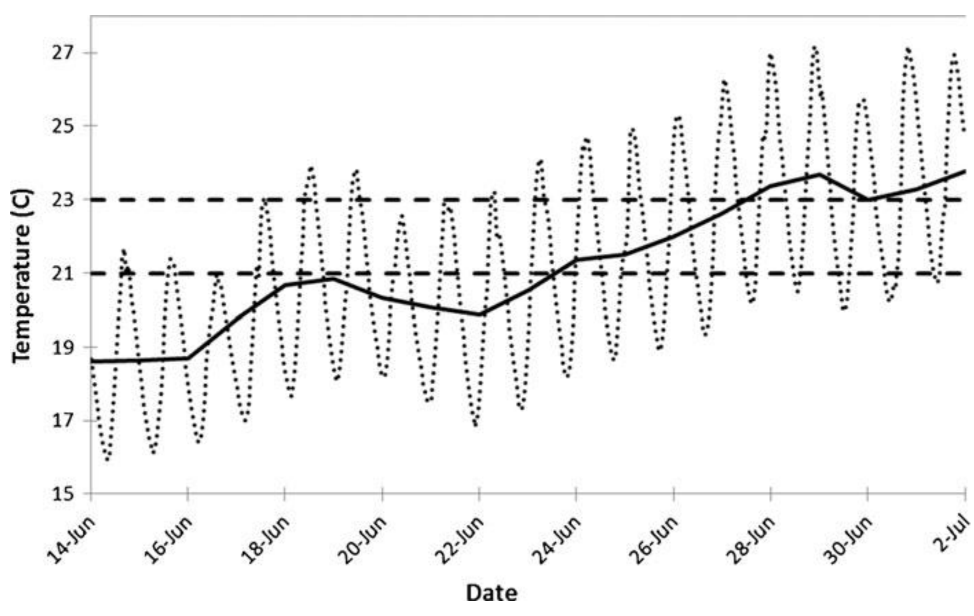

Fig. 2 Water temperature approximately 1 km downstream from the pool where the salmon were holding for a period of 2 weeks prior to the relocation operation. The dotted line is hourly water temperature values from the Butte Creek near Durham gauge station (BCD), extracted from the California Department of Water Resources California Data Exchange Center database. The solid line is the daily mean water temperature. The dashed straight lines indicate the upper thermal limits of migration for adult Chinook salmon: daily mean temperatures of 21 °C when temperatures are increasing and 23 °C when temperatures are decreasing (Strange 2010)

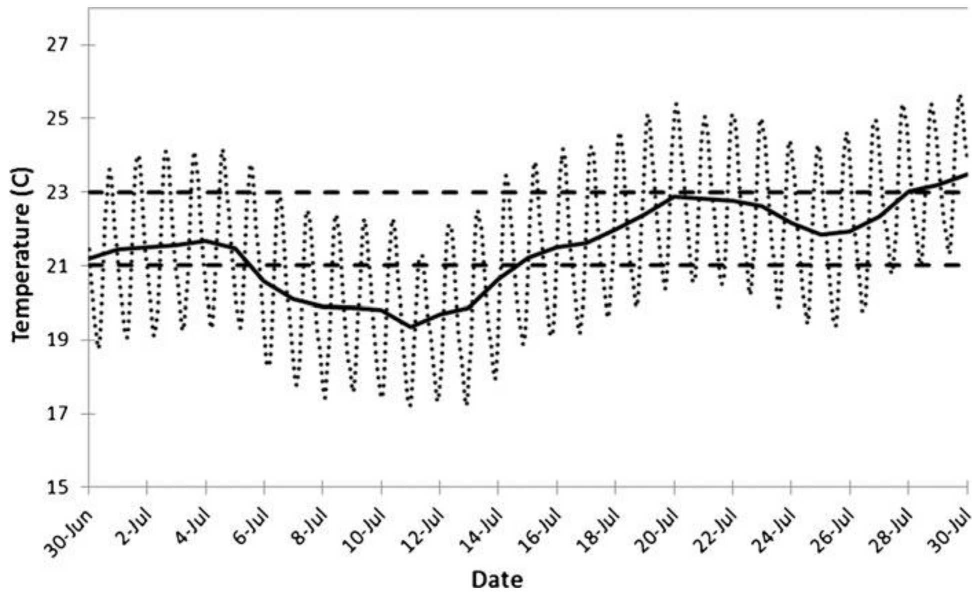

Fig. 3 Water temperature approximately 5 km upstream from the salmon release site. This covers a period of 1 month after the relocation operation. The dotted line is hourly water temperature data from the Butte Creek near Chico gauge station (BCK), extracted from the California Department of Water Resources California Data Exchange Center database. The solid line is the daily mean water temperature. The dashed straight lines indicate the upper thermal limits of migration for adult Chinook salmon: daily mean temperatures of 21 °C when temperatures are increasing and 23 °C when temperatures are decreasing (Strange 2010)

migration (Strange 2010) during the first 5 days after the relocation (Fig. 3).

Demographics

The demographic characteristics of relocated salmon and non-relocated, spawned salmon were generally similar (Table 1). There was no statistically significant difference between the sex ratio of relocated salmon and non-relocated salmon ($p=0.5385$). For the 23 relocated fish to which we were confident in assigning a sex, the male: female ratio was 12 : 11. The sex ratio of non-relocated fish carcasses measured during the spawning period was 251 : 328 (male: female). There was no significant difference between the lengths of the relocated and non-relocated males (p-value=0.3870). However, relocated females were significantly longer than non-relocated females (p-value=0.02357).

Disease

Of the 19 relocated fish inspected for columnaris, five (26.3 %) exhibited a visible infection during tagging. One additional female fish was also noted as having marks suspected to be from lamprey parasitism. There was no mention in the 2009 CDFG annual pre-spawn

Table 1 Demographic comparison between the relocated salmon and the salmon that had reached the summer holding habitat and later spawned

Variable	Relocated salmon	Spawned salmon
# of fish	26	§[2687]
Summer mortality [#, (%)]	*23 (100 %)	§126 (5 %)
Male length [(cm), range, (mean)]	80.0–108.0 (94.6)	43.2–117.5 (87.4)
Female length [(cm), range, mean]	77.0–90.0 (82.9)	44.0–99.6 (79.0)
Sex ratio (% female estimate)	48 %	57 %

Mortality estimate for relocated salmon was calculated for recovered tags only. Data for spawned salmon from McReynolds and Garman (2009) and CDFG (unpublished data). An asterisk indicates that only 23 radio tags of the 26 relocated salmon were recovered. The symbol § indicates a mark-recapture estimate mortality report of whether CDFG actively looked for columnaris infection in non-relocated fish and no infections were noted in the report (McReynolds and Garman 2009).

Fish movement and mortality

Radio tags were recovered for 23 of the 26 (88 %) relocated fish. An additional tag was reportedly found by a local citizen, but we were unable to recover and identify the tag. Two other tags were never reported nor recovered. All recovered radio tags were retrieved within approximately 1 month of the relocation operation.

Ten tags were recovered within 1.5 km downstream of the release site, while the other 13 were recovered upstream, mostly within 3.5 km of the release site. The first five recovered radio tags were found by a group of local citizens using the creek for recreation within an estimated 200 m downstream of the release site on 3 and 4 July; three and two fish each day, 3 and 4 days post-relocation, respectively. Only one tag was detected by a stationary receiver, receiver 1, and that tag was recovered upstream of the Covered Bridge, 5.7 km upstream of the release site (Fig. 1). Receivers 2 and 3 did not detect any radio tags, nor were any radio tags recovered near these receivers.

Six of the radio tags were recovered completely out of the water, ranging from a distance of 0.5 m from the water's edge to 12 m away and up a hill, while an additional four radio tags were recovered from water less than 10 cm depth at the bank-water interface. We were able to estimate the date on which the radio tag or salmon carcass was first exposed to ambient air temperature for 15 of the 20 radio tags that had temperature loggers attached. Mortality occurred 2 to 6 days after the relocation event for all these tags (Fig. 4, Table 2). Seven recovered radio tags were classified as category 1, including the five fish found by the local residents on 3 and 4 July. Categories 2 and 3 had eight each.

Discussion

We studied the survival of relocated adult spring Chinook salmon in Butte Creek in 2009 and found that most, if not all, of the relocated fish experienced mortality soon after release. Unpublished coded wire tag data suggest low stray rates into and out of Butte Creek indicating that these fish were likely of Butte Creek origin. Relocated fish were similar in size to fish that migrated volitionally in earlier months, suggests that high post-relocation mortality was due to differing habitat conditions and handling treatments and not necessarily a difference between the fish themselves. In addition, water temperatures at the release site were stressfully high and exceeded the upper thermal limits for adult Chinook salmon migration (Strange 2010) for 5 days post-release. Despite the high mortality of relocated fish, the information gathered addressed objectives specified in the agency MOU and informs the adaptive management paradigm (NMFS 2009) and relocation efforts for adult salmonids in general.

This study showed that radio tagging is an effective means to determine the fate of relocated fish. Direct confirmation or reasonable assumption of mortality was achieved for two thirds of the relocated fish. The fate of the last third of relocated fish was less certain since tag regurgitation was a possibility, but previous studies reported low tag regurgitation rates for adult salmonids when surgical tubing was used (Ramstad and Woody 2003; Keefer et al. 2004a; Naughton et al. 2005). Notably, use of radio tags also resulted in a much higher rate of recovery than fin-clipping fish (10 % in 2008, 88 % in 2009).

Esophageal tagging may have increased the mortality rate of relocated fish in this study but it is difficult to separate the stresses of capture, handling, and relocation from the stress of tagging. Esophageal tags have been installed in adult salmonids in a variety of settings with few problems (Berman and Quinn 1991; Thorstad et al. 2000; Keefer et al. 2004b; Naughton et al. 2005; Newell and Quinn 2005; Goniea et al. 2006; Crossin et al. 2008), including spring-run Chinook salmon (Strange 2010), although gastric rupturing has been known to occur in fish with fully atrophied stomachs (M. Olswang, CDFG, pers. comm.). However, esophageal radio-tagged fish can survive gastric rupture for periods of greater than 15 days post-tagging (Ramstad and Woody 2003). More than half of the fin-clipped fish that were recovered in 2008 were found dead within 2 weeks of the relocation, suggesting that rapid mortality still occurred in relocated fish in the absence of esophageal tagging (Garman and McReynolds 2009).

Preventative actions to reduce the need for fish relocations could be used by managers, based on an

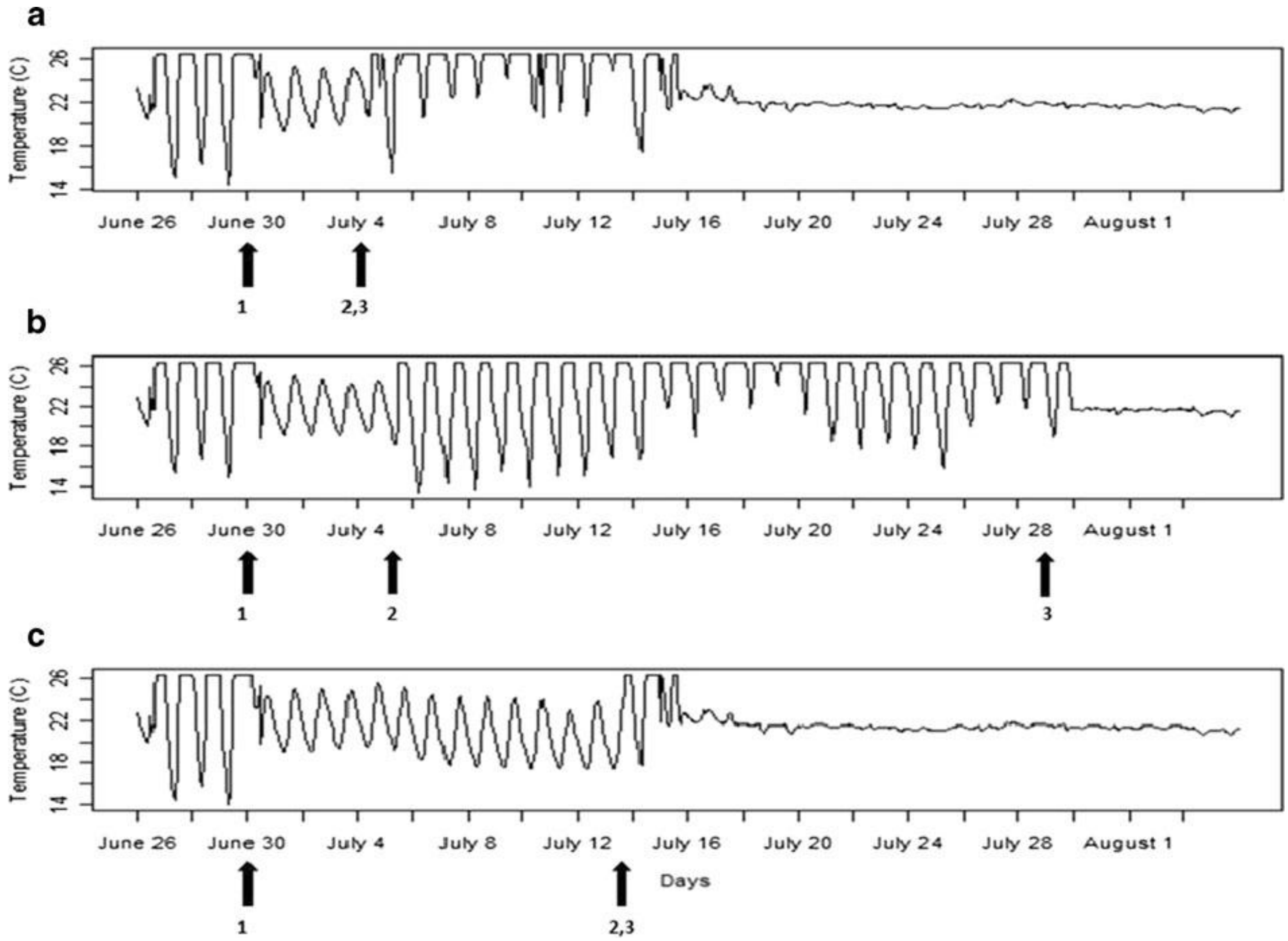

Fig. 4 Water temperatures experienced by relocated salmon and air temperatures experienced by carcasses and/or tags on land, extracted from temperature loggers attached to radio tags, following tag recovery. **a** Temperature data from the tag in one of the fish found in the water by a local resident and removed from the water on a known date, 4 July 2009. This shows the temperature signal for carcasses (radio tags) that were removed from the water on an unknown date and subsequently located on a later date. **b** Temperature data from a radio tag found approximately 12 m up a hill in a heavily wooded area on 29 July 2009. This fish would have been missed during a typical in-river carcass survey. Although the tag was recovered a month after the fish was released, the thermograph data indicate that the carcass (tag) was removed from the water 4-5 days after the relocation operation. **c** Temperature data from a radio tag recovered in water on 13 July 2009 with no carcass in close proximity as per the category 3 criteria. In such cases we assumed that the date of mortality is the date of tag recovery Note: The upper limit of thermographs is 26.375 °C. Arrows on thermograph plots indicate (1) relocation date, (2) maximum date of estimated mortality, and (3) date of tag recovery

understanding of likely causative factors that lead fish to cease volitional migration in a given setting. Using preventative actions is particularly important given the low relocation survival rate observed in this study. In Butte Creek, the interaction of high water temperatures and reduced flows likely led to migration cessation for a minor portion of the spring Chinook salmon run in 2009 and other years. Water temperatures that exceed the upper thermal limits to migration will cause fish to cease migration regardless of flow; conversely, low flows and physical passage barriers can impede migration regardless of water temperatures. For example, just upstream of the capture location, the combination of a diversion dam (Durham Mutual) and igneous rock formations may form a physical migration barrier at low flows. Potential preventive actions could include minimum flow requirements, low-flow barrier modifications, pulsed flows, and replacing or augmenting surface water with groundwater temporarily to increase flows and reduce water temperatures.

While we were unable to confirm specific causes of mortality, we did identify several potential contributing factors and best management practices that should

Table 2 Data matrix for all radio tagged fish

Mortality category	Migration distance (km)	Estimated time to death (d)	Time to tag recovery (d)	Length (cm)	Sex	Comment
Unrecovered	§	§	§	87	*	*
Unrecovered	§	§	§	90	F	NA
Unrecovered	§	§	§	78	F	NA
1	-0.2	3	3	90	F	NA
1	-0.2	3	3	95	M	columnaris
1	-0.5	4	13	79	F	*
1	-0.2	3	3	92	M	NA
1	-0.2	3	4	108	M	*
1	1.7	5	21	87	*	columnaris
1	-0.2	3	4	104	M	NA
2	2.2	6	21	84	F	NA
2	0.5	13	13	79	F	NA
2	-0.3	3	13	91	M	NA
2	-0.5	29	29	85	F	*
2	1.5	¤39	39	80	M	NA
2	1.8	¤21	21	87	F	NA
2	3.9	5	29	83	F	NA
2	5.7	2	33	71	*	*
3	1.6	2	21	80	F	lamprey marks
3	-0.7	2	29	80	M	columnaris
3	1.3	21	21	97	M	NA
3	3.5	4	29	77	F	columnaris
3	1.8	21	21	95	M	columnaris/ gill scars
3	-0.4	13	13	102	M	*
3	1.7	¤29	29	90	M	NA
3	1.8	4	21	101	M	*

The § symbol indicates that a value was not available because the radio tag was not recovered. An asterisk indicates missing data. The symbol ¤ indicates that no estimate of day removed from water was available due to that particular radio tag not having an associated temperature logger. Mortality category describes (1) tags found directly in a dead fish carcass or bones; (2) tags found <5 m from a carcass or animal sign; (3) tags found >5 m from any carcass or animal sign; or unrecovered tags. Negative distance indicates that the tag was found downstream of the release site

be considered in future relocation attempts, regardless of the setting, after preventative measures have been exhausted. These include (1) intervention as soon as fish cease volitional migration but before they are exposed to further deleterious conditions (2) monitoring environmental conditions to choose appropriate release sites (3) evaluation of disease transmission risk, and (4) handling practices that minimize potential stress due to air immersion and thermal shock.

Earlier intervention would likely expose salmon to fewer days at sub-lethally high temperatures but would potentially require more than one relocation if additional fish continued to arrive. Relocated salmon in Butte Creek were exposed to water temperatures that exceeded the ultimate upper incipient lethal temperature for Chinook salmon, 25.1 °C (Brett 1952), for four consecutive days prior to their relocation (Fig. 2). Relocation efforts would likely be more successful if a potentially smaller, but less stressed group of fish were relocated earlier. The relocation in 2009 in Butte Creek did not occur earlier due to personnel constraints and because it was anticipated that fish might continue swimming upstream volitionally after a brief holdover. However, in future years or other settings fish could be relocated as soon as they cease volitional upstream migration. Citizen volunteers and local watershed groups may be able to provide manpower on short notice and for multiple relocations; for example, the Carmel River Steelhead Association has been capturing and transporting adult steelhead above a barrier on the Carmel River for 35 years (Roy Thomas, Carmel River Steelhead Association pers. comm.).

Environmental conditions such as water temperature, flow, and dissolved oxygen must be taken into account at release locations if relocations are to succeed. In this study, relocated salmon were released into water that was upstream of an apparent physical passage barrier but was only slightly cooler than the capture location and still warm enough to be stressful and inhibit upstream migration (Strange 2010). In comparison, summer water temperatures in holding habitat further upstream rarely exceed 20 °C (Thompson et al. 2011), but managers chose the PPDD release site due to concerns over the potential for disease transmission from relocated salmon to earlier-arriving salmon already holding at upstream sites. It is difficult to assess the true level of disease transmission risk; however, given the excessively high water temperature at the release site it could have been predicted that few if any relocated fish would migrate further upstream or ultimately survive to spawn.

Managers must balance the need to minimize possible disease transmission risk with the need to choose release sites with suitable environmental conditions as part of determining the chances of success. Conditions such as water temperature can be easily monitored but accurately evaluating and minimizing disease transmission risk is more difficult. Relocated fish could be screened for columnaris prior to release and any fish having severe infections (i.e., visible gill lesions) could be culled or transported back to the capture location. Screening fish for other potential pathogens such as *Ichthyophthirius multifiliis* can be impossible on short notice or without sacrificing the fish. During the 2009 relocation in Butte Creek, some relocated salmon (minimum of 19 %) were infected with columnaris and the potential did exist for this bacterium to spread to other fish. However, columnaris occurs worldwide (Shotts and Starliper 1999) and is known to occur in the upper reaches of Butte Creek. Columnaris infections were involved in large fish kills in prespawn holding habitat in Butte Creek in 2002 and 2003 along with *Ichthyophthirius multifiliis* (Ward et al. 2004). Healthy fish are resistant to columnaris (Shotts and Starliper 1999), but infections can develop due to environmental stress, minor injuries to skin and gills, and from pathogens that penetrate the epithelium (Holt et al. 1975; Plumb 1999; Ross 2007). In combination, it is unclear what disease transmission risk was posed by the potential release of relocated fish directly into cool holding habitat further upstream as compared to releasing them at PPDD with the assumption that they would migrate to upstream holding habitat.

Handling techniques involving air immersion or rapid temperature changes can be an additional source of stress. Multiple and long duration air immersions are stressful for fish (Lankford et al. 2003; Warren et al. 2004) and may have contributed to mortality in this study. Dip net transportation over distances similar to that of Butte Creek was used for at least one other adult salmonid relocation with a resulting low mortality rate (5 %), although water temperatures were much lower (10 to 16 °C, Daniel et al. 2003). Salmon have been transported inside water-holding containers such as PVC tubes (Ross 2007) or large black plastic bags (R. Thomas, pers. comm.) with aeration provided to minimize stress due to air immersion. Thermal shock may have also affected salmon in our study since fish experienced two rapid temperature changes of approximately 2 to 2.5 °C as they entered and were removed from the tank truck. However, the diel water temperature range the day prior to relocation was 6.7 °C over a period of 10 h, suggesting that thermal shock was a not a major factor contributing to mortality. Monitoring the temperature of the water at capture and release sites, and of the water supplied to the transport vehicle, would allow for adjustment of transport water temperature to minimize thermal shock during relocations.

Fish relocations present managers with a dilemma that is especially acute in the case of threatened salmon species: once salmon have ceased volitional migration the success of relocation is uncertain, but mortality of the fish without intervention is often highly likely. Additional environmental restraints on the volitional upstream movement of adult salmon may increase the frequency of migration cessations and mortality risk unless genetic and/or behavioral shifts induce earlier or later migrations, depending on the run-timing of the population (Quinn et al. 1997). In addition to existing stream flow alterations due to diversions, climate change projections indicate a reduction in snowpack and earlier onset of snowmelt, leading to a subsequent reduction in late spring and early summer flows, as well as an increase in extreme droughts (Hayhoe et al. 2004; Maurer et al. 2007; Thompson et al. 2011). Given these considerations, managers will increasingly need effective tools for solving the dilemma of fish relocations and migration cessations. This study on adult spring-run Chinook salmon in Butte Creek highlighted the dilemma and also informs possible best management practices for successfully conducting and preventing fish relocations regardless of the setting.

Acknowledgments We thank Allen Harthorn, Pamela Posey, Michael Smith, and Scott Gailey of Friends of Butte Creek for hosting stationary radio receivers on their properties, providing excellent local information, and a place to sleep after long days of tracking; Clint Garman and Tracy McReynolds from the CDFG Chico office for providing transportation, great information, and allowing us to go along on the summer carcass surveys; the Yurok Tribe Fisheries Program for supplying radio tags and stationary receivers; Howard Brown of NMFS and Joe Johnson of CDFG for giving us permission to radio tag the salmon; Jim Bundy of Pacific Gas and Electric for providing access to the remote upper reaches of the summer holding habitat; Avery Cook for assistance in fish tracking and receiver maintenance, and finally, to the large group of CDFG, NMFS, and USFWS personnel who worked on the relocation. We also thank two anonymous reviewers for their thoughtful and constructive comments on several earlier versions this paper. This study was funded in part by US Environmental Protection Agency STAR Grant RD-833017.

References

Berman CH, Quinn TP (1991) Behavioural thermoregulation and homing by spring Chinook salmon, *Oncorhynchus tshawytscha* (Walbum), in the Yakima River. J Fish Biol 39:301–312

Brett JR (1952) Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. J Fish Res Board Can 9:265–323

SSCSRT (Shasta-Scott Coho Salmon Recovery Team) (2003) Shasta and Scott River pilot program for coho salmon recovery: with recommendations relating to agriculture and agricultural water use. Prepared for the California Department of Fish and Game, July 28, 2003. p 119

Crossin GT, Hinch SG, Farrell AP, Higgs DA, Lotto AG, Oakes JD, Healey MC (2008) Exposure to high water temperature influences the behavior, physiology, and survival of sockeye salmon during spawning migration. Can J Zool 86:127–140

Daniel M, Gebhards J, Hill R (2003) Johnson Creek artificial propagation and enhancement project operations and maintenance program; Brood year 2000: Johnson Creek Chinook salmon supplementation. 2000-2002 Biennial Report, Project No. 199604300, BPA Report DOE/BP-00004393-6

R Development Core Team (2010) R: a language and environment for statistical computing. R oundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/

Engle R, Skalicky J (2009) Capture, transport and reintroduction of Lower Columbia River fall Chinook salmon into the upper White Salmon River: a conservation measure in preparation for Condit Dam removal. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office

Garman C, McReynolds T (2009) Butte and Big Chico Creeks spring-run Chinook salmon, *Oncorhynchus tshawytscha* life history Investigation 2007-2008. California Department of Fish and Game, Inland Fisheries Division, North Central Region

Goniea TM, Keefer ML, Bjornn TC, Peery CA, Bennett DH, Stuehrenberg LC (2006) Behavioral thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River water temperatures. Trans Am Fish Soc 135:408–419

Good TP, Waples RS, Adams P (2005) Updated status of federally listed ESUs of West Coast salmon and steelhead. U.S. Dept. Commerce. NOAA Tech. Memo. NMFS-NWFSC-66, p 598

Hayhoe K, Cayan D, Field CB, Frumhoff PC, Maurer EP, Miller NL, Moser SC, Schneider SH, Cahill KN, Cleland EE, Dale L, Drapek R, Hanemann RM, Kalkstein LS, Lenihan J, Lunch CK, Neilson RP, Sheridan SC, Verville JH (2004) Emissions pathways, climate change, and impacts on California. Proc Nat Acad Sci 101:12422–12427

Holt RA, Sanders JE, Zin JL, Pilcher KS (1975) Relaxation of water temperature to *Flexibacter columnaris* infection in steelhead trout (*Salmo gairdneri*), coho (*Oncorhynchus kisutch*), and Chinook (*O. tshawytscha*) salmon. J Fish Res Board Can 32:1553–1559

Keefer ML, Peery CA, Ringe RR, Bjornn TC (2004a) Regurgitation rates of intragastric radio transmitters by adult Chinook salmon and steelhead during upstream migration in the Columbia and snake rivers. N Am J Fish Manage 24:47–54

Keefer ML, Peery CA, Jepson MA, Stuehrenberg lC (2004b) Upstream migration rates of radio-tagged adult Chinook salmon in riverine habitats of the Columbia River basin. J Fish Biol 65:1126–1141

Keefer ML, Caudill CC, Peery CA, Lee SR (2008) Transporting juvenile salmonids around dams impairs adult migration. Ecol Appl 18:1888–1900

Keefer ML, Talylor GA, Garletts DF, Gauthier GA, Pierce TM, Caudill CC (2010) Prespawn mortality in adult spring Chinook salmon outplanted above barrier dams. Ecol Freshw Fish 19:361–372

Lankford SE, Adams TE, Cech JJ Jr (2003) Time of day and water temperature modify the physiological stress response in green sturgeon, *Acipenser medirostris*. Comp Biochem Physiol A 135:291–302

Lindley ST, Schick RS, Mora E, Adams PB, Anderson JJ, Greene S, Hanson C, May BP, McEwan DR, MacFarlane RB, Swanson C, Williams JG (2007) Framework for assessing viability of threatened and endangered Chinook salmon and steelhead in the Sacramento-San Joaquin basin. San Francisco Estuary and Watershed Science 5:1–26

NMFS (National Marine Fisheries Service), California Department of Fish and Game, US Fish and Wildlife Service (2009) Interagency fish rescue strategy. Accessed 21 July 2009 http://swr.nmfs.noaa.gov/pdf/Interagency_Fish_Rescue_Strategy_052509.pdf

Maurer EP, Stewart IT, Bonfils C, Duffy PB, Cayan D (2007) Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. J Geophys Res-Atmos 112(D11118):1–12

McReynolds T, Garman C (2009) Butte Creek spring-run Chinook salmon, *Oncorhynchus tshawytscha* pre-spawn mortality evaluation 2009. California Department of Fish and Game, Inland Fisheries Division, North Central Region

Moyle PB (2002) Inland fishes of California. University of California Press

Naughton GP, Caudill CC, Keefer ML, Bjornn TC, Stuehrenberg LC, Peery CA (2005) Late-season mortality during migration of radio-tagged adult sockeye salmon (*Oncorhynchus nerka*) in the Columbia River. Can J Fish Aquat Sci 62:30–47

Newell JC, Quinn TP (2005) Behavioral thermoregulation by maturing adult sockeye salmon (*Oncorhynchus nerka*) in a stratified lake prior to spawning. Can J Zoolog 83:1232–1239

Pincetich C, Bouley P, Steiner T (2009) Summary of relocation of stranded salmonids from isolated pools in the San Geronimo Creek sub-watershed, 2009. http://www.spawnusa.org/cgi-files/0/pdfs/1263600128_2009_Fish_Rescue_report.pdf. Accessed 28 Feb. 2011

Plumb JA (1999) Health maintenance and principal microbial diseases of cultured fishes. Iowa State University, Ames

Quinn TP, Hodgson S, Peven C (1997) Temperature, flow, and the migration of adult sockeye salmon (*Oncorhynchus nerka*) in the Columbia River. Can J Fish Aquat Sci 54:1349–1360

Ramstad KM, Woody CA (2003) Radio tag retention and tag-related mortality among adult sockeye salmon. N Am J Fish Manage 23:978–982

Ross K (2007) Temperature effects on Trinity River, California, adult spring-run Chinook salmon (*Oncorhynchus tshawytscha*) metabolism and survival. MS Thesis: Colorado State University

Shotts EB Jr, Starliper CE (1999) Flavobacterial diseases: columnaris disease, cold-water disease and bacterial gill disease. In: Woo PTK, Bruno DW (eds) Fish diseases and disorders, vol. 3. Viral, bacterial and fungal infections. I Publishing, New York, pp 559–576

Strange JS (2010) Upper thermal limits to migration in adult Chinook salmon: evidence from the Klamath River basin. Trans Am Fish Soc 139:1091–1108

Thompson LC, Escobar MI, Mosser CM, Purkey DR, Yates D, Moyle PB (2011) Water management adaptations to prevent loss of spring-run Chinook salmon in California under climate change. J Water Resour Plann Manage. doi:10.1061/(ASCE)WR.1943-5452.0000194

Thorstad EB, Økland F, Finstad B (2000) Effects of telemetry transmitters on swimming performance of adult Atlantic salmon. J Fish Biol 57:531–535

Ward PD, McReynolds TR, Garman CE (2004) Butte Creek spring-run Chinook salmon, *Oncorhynchus tshawytscha* pre-spawn mortality evaluation 2003. California Department of Fish and Game, Inland Fisheries Division, North Central Region, Administrative Report No. 2004-5

Warren DE, Matsumoto S, Roessig JM, Cech JJ Jr (2004) Cortisol response of green sturgeon to acid-infusion stress. Comp Biochem Physiol A 137:611–618

Yoshiyama RM, Fisher FW, Moyle PB (1998) Historical abundance and decline of Chinook salmon in the Central Valley region of California. N Am J Fish Manage 18:487–521

Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB (2001) Historical and present distribution of Chinook salmon in the Central Valley drainage of California. In: Brown RL (ed) Contributions to the biology of Central Valley salmonids, volume 1. Fish Bulletin 179. The Resources Agency, Department of Fish and Game, State of California, pp 71–176

Zimmerman BC, Duke BB (1995) Trapping and transportation of adult and juvenile salmon in the lower Umatilla River in northeast Oregon—Umatilla River Basin Trap and Haul Program October 1994–September 1995, Annual Progress Report, Report to Bonneville Power Administration, Contract No. 1989BP98636, Project No. 198802200, 50 electronic (BPA Report DOE/BP-98636-2)