North American Journal of Fisheries Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ujfm20

Route Use and Survival of Juvenile Chinook Salmon through the San Joaquin River Delta

Rebecca A. Buchanan [a], John R. Skalski [a], Patricia L. Brandes [b] & Andrea Fuller [c]

[a] Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, 1325 4th Avenue, Suite 1820, Seattle, Washington, 98101-2509, USA

[b] U.S. Fish and Wildlife Service, 850 Guild Avenue, Suite 105, Lodi, California, 96240, USA

[c] FISHBIO Environmental, LLC, 1617 South Yosemite Avenue, Oakdale, California, 95361, USA

Version of record first published: 01 Feb 2013.

To cite this article: Rebecca A. Buchanan , John R. Skalski , Patricia L. Brandes & Andrea Fuller (2013): Route Use and Survival of Juvenile Chinook Salmon through the San Joaquin River Delta, North American Journal of Fisheries Management, 33:1, 216-229

To link to this article: http://dx.doi.org/10.1080/02755947.2012.728178

North American Journal of Fisheries Management 33:216–229, 2013

ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1080/02755947.2012.728178

ARTICLE

Route Use and Survival of Juvenile Chinook Salmon through the San Joaquin River Delta

Rebecca A. Buchanan* **and John R. Skalski**
Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, 1325 4th Avenue, Suite 1820, Seattle, Washington 98101-2509, USA

Patricia L. Brandes
U.S. Fish and Wildlife Service, 850 Guild Avenue, Suite 105, Lodi, California 96240, USA

Andrea Fuller
FISHBIO Environmental, LLC, 1617 South Yosemite Avenue, Oakdale, California 95361, USA

Abstract

The survival of juvenile Chinook Salmon through the lower San Joaquin River and Sacramento–San Joaquin River Delta in California was estimated using acoustic tags in the spring of 2009 and 2010. The focus was on route use and survival within two major routes through the Delta: the San Joaquin River, which skirts most of the interior Delta to the east, and the Old River, a distributary of the San Joaquin River leading to federal and state water export facilities that pump water out of the Delta. The estimated probability of using the Old River route was 0.47 in both 2009 and 2010. Survival through the southern (i.e., upstream) portion of the Delta was very low in 2009, estimated at 0.06, and there was no significant difference between the Old River and San Joaquin River routes. Estimated survival through the Southern Delta was considerably higher in 2010 (0.56), being higher in the Old River route than in the San Joaquin route. Total estimated survival through the entire Delta (estimated only in 2010) was low (0.05); again, survival was higher through the Old River. Most fish in the Old River that survived to the end of the Delta had been salvaged from the federal water export facility on the Old River and trucked around the remainder of the Delta. The very low survival estimates reported here are considerably lower than observed salmon survival through comparable reaches of other large West Coast river systems and are unlikely to be sustainable for this salmon population. More research into mortality factors in the Delta and new management actions will be necessary to recover this population.

The Central Valley of California marks the southern limit of Chinook Salmon *Oncorhynchus tshawytscha* in North America (Healey 1991). Chinook Salmon population abundances in this region have been much reduced from the 19th century in response to a number of factors, including habitat loss, hatcheries, and water development (e.g., pumping water out of the basin; Healey 1991; Fisher 1994). Today, the Sacramento–San Joaquin River Delta is a highly modified environment with levees and drained fields replacing tidal wetlands, and riprap replacing natural shoreline. Demand for Delta waters is high. State and federal water export facilities extract water from the southern portion of the Delta (Figure 1) for agricultural, industrial, and municipal use throughout California. The Delta provides drinking water for approximately 27 million Californians and irrigation water for more than 1,800 agricultural users, and 4.6–6.3 million acre-feet of water are exported from the Delta annually (DSC 2011). This intense exporting combined with tidal fluctuations can sometimes cause net flows in the Delta to be directed upstream rather than downstream (Brandes and McLain 2001). Pollution from industry, agricultural and urban runoff, and erosion are also concerns (DSC 2011). Both native and nonnative species of

---

*Corresponding author: rabuchan@u.washington.edu
Received March 28, 2012; accepted September 5, 2012

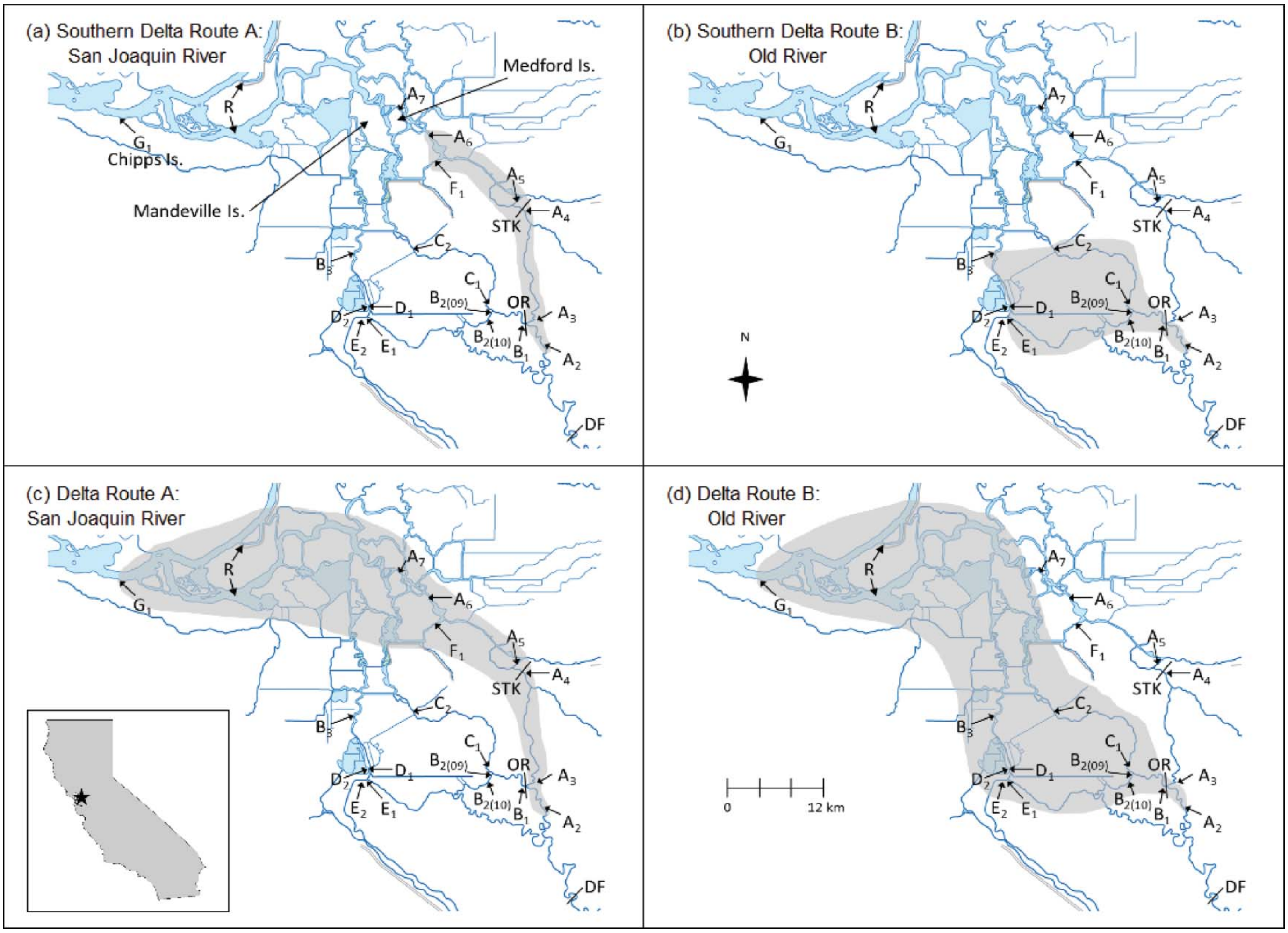

FIGURE 1. Acoustic telemetry receiver sites throughout the San Joaquin River Delta for the juvenile Chinook Salmon tagging studies in 2009 and 2010. The region included in each major route through the study area is shaded for the Southern Delta for the **(a)** San Joaquin River and **(b)** Old River routes and through the entire Delta for the **(c)** San Joaquin River and **(d)** Old River routes. Sites in the San Joaquin, Old, and Middle rivers are labeled A, B, and C, respectively. The label for site B2 includes the study years 2009 (09) and 2010 (10). Sites A7, C1, and G1 were used only in 2010. Mossdale is denoted by A2, Chipps Island at river kilometer 0 by G1, the federal water export facilities by E1 and E2, and state water export facilities by D1 and D2. The city of Stockton is near sites A5 and A6. Sites B3 and C2 are located near California Highway 4. Release sites are designated as follows: DF = Durham Ferry (2009, 2010), OR = Old River (2010), STK = Stockton (2010), and R = release after salvage and trucking. Route-specific survival and route entrainment probability were estimated for the Southern Delta in 2009 and 2010 and for the entire Delta in 2010. [Figure available in color online.]

predatory fish (e.g., Striped Bass *Morone saxatilis*, Largemouth Bass *Micropterus salmoides*, White Catfish *Ameiurus catus*) inhabit these areas and feed on migrating smolts, as do avian predators including double-crested cormorants *Phalacrocorax auritus* and white pelicans *Pelecanus erythrorhynchos*. All of these factors lower survival of migrating salmon smolts relative to historical conditions.

The Vernalis Adaptive Management Plan (VAMP) is a large-scale, long-term (12-year) experimental management program begun in 2000 that was designed to protect juvenile Chinook Salmon as they migrate from the San Joaquin River through the Sacramento–San Joaquin River Delta (Figure 1; SJRGA 2005, 2007, 2010, 2011). Part of the VAMP is a multiyear tagging study to monitor juvenile salmon survival through the Delta; the long-term goal is to relate Delta survival to changes in river flow (discharge) and water export levels in the presence of a temporary barrier at the head of the Old River, which was designed to prevent salmon from entering the Old River (Figure 1). Prior to 2006, VAMP tagging studies relied on coded wire tags (CWTs), which provided information on salmon survival on a large spatial scale using 100,000–300,000 study fish each year (Newman 2008). Starting in 2006, the tagging studies began using micro-acoustic tags, which provide more precise survival information on a smaller spatial scale with much smaller releases groups (e.g., about 1,000 fish). Coded wire tags were discontinued in 2007. Study years 2006 and 2007 were pilot studies providing feedback on design and implementation of the acoustic tag studies. The 2008 study deployed an extensive array of acoustic hydrophones throughout the Delta but suffered from a high degree of premature tag failure (Holbrook et al. 2013). Thus, 2009 and 2010 were the first years that provided sufficient information to estimate salmon survival through portions of the Delta on a relatively detailed spatial scale, yielding the first estimates of how fish distribute across various migration routes. Further, these 2 years represent different hydrologic conditions—very low flows in 2009 and above normal flows in 2010—thus providing preliminary information needed to identify a relationship between survival and flow. Survival through the southern portion of the Delta was estimated in both 2009 and 2010, and survival through the entire Delta was estimated in 2010 (described below; Figure 1). In both years, survival estimates were compared through two major migration routes: the San Joaquin River route and the Old River route. We present here the first spatially detailed estimates of survival and route use by juvenile Chinook Salmon through the lower San Joaquin River into the Delta.

STUDY AREA

Historically, focus has been on the survival of fish through the Delta to Chipps Island, located in Suisan Bay at the confluence of the San Joaquin and Sacramento rivers near Pittsburg, California, at river kilometer (rkm) 0 (Figure 1). Fish moving through the Delta toward Chipps Island may use any of several routes. The simplest route follows the San Joaquin River until it joins the Sacramento River near Chipps Island (Figure 1a, c; route A). An alternative route uses the Old River from its head on the San Joaquin River to Chipps Island, either via its confluence with the San Joaquin River just west of Mandeville Island, or through Middle River or the state and federal water export facilities (Figure 1b, d; route B). Additional subroutes were monitored for fish use but were contained within either route A or route B. Subroute C consists of the Middle River from the Old River to the San Joaquin downstream of Medford Island. Two other subroutes were the water export facilities off the Old River: fish entering either the State Water Project (subroute D) or the Central Valley Project (subroute E) had the possibility of being trucked from those sites and released upstream of Chipps Island. Subroutes C, D, and E were all contained in route B (Old River). Finally, fish that remained in the San Joaquin River past Stockton may have entered Turner Cut and maneuvered to Chipps Island through the interior of the Delta (subroute F). Fish in routes B, C, and F all had multiple unmonitored pathways available for passing through the Delta toward Chipps Island.

Survival through the study area was estimated on two spatial scales: (1) the southern portion of the Delta, which is bounded downstream by the federal and state water export facilities, California Highway 4, and the Turner Cut junction with the San Joaquin River (the "Southern Delta"; Figure 1a, b) and (2) the entire Delta, which is bounded downstream by Chipps Island (the "Delta"; Figure 1c, d). Both the Southern Delta and Delta regions were bounded upstream by the acoustic receiver (site A2) located near Mossdale Bridge, upstream of the Old River junction with the San Joaquin River. The Southern Delta region was entirely contained within the Delta region (Figure 1). In 2009, no acoustic receivers were deployed at Chipps Island, so the study area was limited to the Southern Delta. In 2010, a more extensive detection field was installed, including dual receivers at Chipps Island (G1) (Figure 1). Thus, in 2010, the study area included the entire migration path through the Delta region. Two migration routes were monitored through both the Southern Delta and Delta regions: the San Joaquin Route (route A in Figure 1a, c) and the Old River route (route B in Figure 1b, d).

Since the 1990s, a temporary physical or nonphysical barrier (sound, strobe lights, and a bubble curtain) has often been installed at the head of the Old River with the aim of preventing migrating smolts from entering that river. In 2009 and 2010, a nonphysical barrier was installed there, and its smolt-guidance effectiveness was evaluated in studies concurrent with the VAMP studies (Bowen et al. 2009; Bowen and Bark 2012). The nonphysical barrier was operated during passage of approximately half of each VAMP release group in 2009 or 2010. No physical barrier was installed.

METHODS

Tagging and release methods.—Both study years used the Hydroacoustic Technology, Inc. (HTI) Model 795 microacoustic tag (diameter = 6.7 mm, length = 16.3–16.4 mm, average weight in air = 0.65 g). In 2009 a total of 933 juvenile Chinook Salmon (fall–spring-run hybrids) originating from the Feather River Fish Hatchery were tagged and released between 22 April and 13 May (fork length = 85.0–110.0 mm, mean = 94.8 mm; Table 1). Difficulties in rearing fish to size resulted in an average tag burden (i.e., the ratio of tag weight to body weight) of 7.1% (range = 4.4–10.2%), which was higher than desired (≤5.5%; Brown et al. 2006). Six fish died in 2009 between tagging and release. In 2010, a total of 993 juvenile fall-run Chinook Salmon originating from the Merced River Fish Hatchery were tagged and released between 27 April and 20 May (fork length = 99.0–121.0 mm, mean = 110.5 mm). Tag burden in 2010 was 2.8–5.8% (mean = 4.2%; Table 1). Four fish died in 2010 between tagging and release.

In both years, tagging was performed at the Tracy Fish Facility located in the Delta approximately 30–45 km from the release site(s). Tagging procedures followed those outlined in Adams et al. (1998) and Martinelli et al. (1998). Fish were anesthetized in a 70-mg/L tricaine methanesulfonate solution, buffered with an equal concentration of sodium bicarbonate, and surgically implanted with programmed acoustic transmitters. Typical surgery times were less than 3 min. Nonfunctioning tags were removed from the study. After surgery, fish were placed in 19-L containers with high dissolved oxygen (DO) concentrations (110–130%) for recovery. Each holding container was perforated to allow partial water transfer and held no more than three tagged fish. After initial recovery from surgery, tagged fish were transported in buckets to the release site in transport

TABLE 1. Release data for groups of Chinook salmon smolts used in the 2009 and 2010 Vernalis Adaptive Management Plan studies, where DF = Durham Ferry, STK = Stockton, and OR = Old River. In 2009, releases were pooled into strata for analysis; in 2010, releases from separate locations were jointly analyzed for a single release occasion.

Release location	Release date	Release number	Mean (range) fork length (mm)	Tag burden (%)	Release stratum/occasion
			Study year 2009		
DF	Apr 22	133	96.1 (86–108)	6.9 (5.2–9.0)	1
	Apr 25	134	93.4 (88–105)	7.3 (5.2–9.6)	1
	Apr 29	134	97.1 (87–110)	6.8 (4.5–3.6)	2
	May 2	134	96.6 (87–108)	6.6 (4.4–9.3)	2
	May 6	132	92.6 (85–102)	7.7 (5.5–10.2)	2
	May 9	133	93.9 (88–100)	7.3 (5.4–9.1)	2
	May 13	133	93.8 (90–104)	7.2 (5.3–8.8)	3
			Study year 2010		
DF	Apr 27–28	74	108.0 (102–110)	4.4 (3.5–5.7)	1
	Apr 30–May 1	74	109.1 (103–115)	4.3 (3.1–5.4)	2
	May 4–5	73	109.4 (102–118)	4.3 (3.4–5.6)	3
	May 7–8	70	111.1 (101–119)	4.1 (3.1–5.4)	4
	May 11–12	70	112.0 (99–121)	4.1 (3.1–5.4)	5
	May 14–15	73	112.6 (101–119)	4.0 (3.1–5.3)	6
	May 18–19	70	112.1 (103–119)	3.9 (2.8–5.3)	7
STK	Apr 28–29	35	107.5 (100–115)	4.5 (3.5–5.6)	1
	May 1–2	36	108.5 (100–115)	4.4 (3.4–5.4)	2
	May 5–6	35	110.3 (104–118)	4.2 (3.4–5.0)	3
	May 8–9	36	109.6 (102–117)	4.3 (3.5–5.6)	4
	May 12–13	35	111.2 (105–119)	4.2 (3.3–5.4)	5
	May 15–16	34	112.9 (102–119)	4.0 (3.0–5.2)	6
	May 19–20	31	113.4 (108–119)	3.9 (3.1–5.0)	7
OR	Apr 28–29	36	108.2 (102–117)	4.5 (3.6–5.3)	1
	May 1–2	36	108.5 (102–115)	4.5 (3.5–5.6)	2
	May 5–6	36	108.6 (100–118)	4.5 (3.4–5.6)	3
	May 8–9	36	110.4 (104–118)	4.2 (3.5–5.1)	4
	May 12–13	36	111.8 (104–120)	4.2 (2.9–5.8)	5
	May 15–16	35	113.3 (105–119)	4.0 (3.0–5.2)	6
	May 19–20	32	112.3 (101–119)	3.9 (3.2–5.3)	7

tanks designed to guard against fluctuations in water temperature and DO. Transport to the release site took approximately 45–60 min. At the release site, tagged fish were held in either 1-m^3 net pens (3-mm mesh; first release in 2009) or in perforated 121.1-L plastic garbage cans (2010) for a minimum of 24 h before release.

In 2009, all fish were released on the San Joaquin River at Durham Ferry, located at approximately rkm 110 (measured from the river mouth at Chipps Island) approximately 20 km upstream of the boundary of the study area (Mossdale Bridge; Figure 1). The release site was located upstream of the study area to allow fish to recover from handling and distribute naturally in the river channel before entering the study area. In 2010, each of seven release occasions consisted of an initial release at Durham Ferry and two supplemental releases, one located in the Old River near the junction with the San Joaquin River and the other located in the San Joaquin River near the city of Stockton (Figure 1). The supplemental releases were designed to provide enough tagged fish in the lower reaches of the study area to estimate survival all the way to Chipps Island, even if survival was low from Durham Ferry.

For each study year, an in-tank tag life study was performed to measure the rate of tag failure under the tag operating parameters (i.e., encoding, range, and pulse width) used in the study. Stratified random sampling of tags across manufacturing lots and tag codes was used to ensure that tags in the tag-life study represented the population of tags released in study fish.

In both study years, tag effects on short-term (48-h) survival were assessed using dummy (i.e., inactive)-tagged and untagged fish that were handled using the same procedures as fish with active transmitters. No significant difference in survival was observed between dummy-tagged and untagged fish over the

48-h period (SRJGA 2010, 2011). Tag effects on longer-term ($\leq$21 d) survival and predator avoidance were expected to be small based on existing studies on effects of acoustic tags on juvenile Chinook Salmon with comparable tag burden (e.g., Anglea et al. 2004).

Water temperatures at the release locations were <20°C during most releases, ranging from 16.1°C to 21.1°C in 2009 and from 14.2°C to 18.8°C in 2010. Temperature increased as a function of distance downstream from Durham Ferry in both the San Joaquin River main stem and the Delta and increased throughout the season. Temperatures in the study area exceeded 20°C starting in mid-May in 2009 and in early June in 2010.

Hydrophone placement.—An extensive array of acoustic hydrophones and receivers was deployed throughout the Delta in each study year, with 19 receivers and hydrophones being deployed in 2009 and 32 receivers (35 hydrophones) in 2010 (Figure 1). Acoustic receivers were named according to migration route (A–G). Chipps Island, the final destination of all routes in 2010, was assigned its own route name (G). At each location, one to four hydrophones were deployed to achieve full cross-sectional coverage of the channel.

Acoustic receivers were located at the Delta entrance (Mossdale, site A2) in both 2009 and 2010, at the Delta exit (Chipps Island, G1) in 2010, and at key points in between in both years (Figure 1). The Mossdale site was moved 1.4 km downstream in 2010 to an acoustically quieter site. All available migration routes were monitored at the Old River (sites A3 and B1) and Turner Cut (A6 and F1) diversions from the San Joaquin River (Figure 1). Receivers were located on the San Joaquin River in Stockton near the Stockton Waste Water Treatment Facility (A4) and near the Navy Drive Bridge just upstream of the Stockton Deep Water Ship Channel (A5) because of concern about salmon survival past the water treatment plant. Receivers were also located at the entrance to the state and federal water export facilities on the Old River (Figure 1). At the federal facility (Central Valley Project, CVP), receivers were placed just upstream and downstream of the trash racks (E1) and in the holding tank (E2), where salvaged fish were held before transportation by truck to release sites in the lower Delta on the San Joaquin and Sacramento rivers (R). At the state facility, receivers were placed both outside (D1) and inside (D2) the radial entrance gates to the Clifton Court Forebay (CCF), the reservoir from which the State Water Project draws water. Both the CVP trash racks and the CCF radial gates are known feeding areas for piscine predators (Vogel 2010, 2011). Receivers were also located downstream in the Old (B3) and Middle (C2) rivers near the Highway 4 bridge. Dual receiver arrays were placed at some sites to provide data to estimate detection probabilities, typically at the downstream boundary of the study area and at sites just downstream of river junctions. Both acoustic lines within each dual array (average 0.3 km apart) were designed for full coverage of the channel. The nonphysical barrier located at the head of the Old River was evaluated via a separate network of hydrophones that were not used in the VAMP study (Bowen et al. 2009; Bowen and Bark 2012).

The locations of the hydrophones were dictated by the possible migration routes (San Joaquin [A], and Old River [B]) and subroutes, and by the two spatial scales on which inference was to be made (Southern Delta and Delta). The acoustic receivers located in Turner Cut (F1) and at the channel markers in the San Joaquin River near the Turner Cut junction (A6) monitored the exit of the San Joaquin route through the Southern Delta region in both 2009 and 2010 (Figure 1a). Likewise, the exit of the Old River route through the Southern Delta region was monitored by receivers at the state and federal water facilities and near Highway 4 in both 2009 and 2010 (Figure 1b). In 2010, the exit of both the San Joaquin route (Figure 1c) and the Old River route (Figure 1d) through the entire Delta region was monitored by dual receivers at Chipps Island.

Signal processing.—The raw tag detection data generated by the acoustic telemetry receivers were processed by identifying the date and time of each tag detection. Unique tags were identified by the period (1/frequency) of the acoustic signal. The 2009 data were processed manually using the HTI proprietary software *MarkTags*. The 2010 data were processed using a combination of automatic and manual processing, manual processing being limited to key detection sites (SJRGA 2011).

The San Joaquin River Delta is home to several populations of predatory fish that are large enough to feed on juvenile salmonids, including Striped Bass, Largemouth Bass, and White Catfish. A predatory fish that has eaten an acoustic-tagged juvenile salmon and then moves past a hydrophone may introduce misleading tag detections into the data. Thus, it was necessary to identify and remove those detections that came from predators. Likely predator detections were identified in a decision process that used up to three levels of spatial–temporal analysis, based on the methods of Vogel (2010, 2011): near-field, mid-field, and far-field. Near-field analysis required manual processing of the raw acoustic telemetry data, and interpreted the pattern of the acoustic signal during detection as an indicator of fish movement near the receiver. Mid-field analysis focused on residence time within the detection field of each receiver, and transitions between neighboring receivers. Far-field analysis examined transitions on the scale of the study area. All available detection data were considered in identifying likely predator detections, as well as environmental data such as river flow and tidal stage, measured at several gaging stations throughout the Delta (downloaded from the California Data Exchange Center Web site: http://cdec.water.ca.gov). The predator decision process was based on the assumptions that Chinook Salmon smolts were emigrating and so were directed downstream, and that they were unlikely to move between acoustic receivers ($\geq$2 km) against river flow. Movements directed upstream against the flow were considered evidence of predation, although short-term upstream movements under reverse flow or slack tide conditions were deemed consistent with a salmon smolt. Unusually fast or slow transitions between detection sites or particularly long residence time at a detection site were also considered evidence of predation. In 2009, the near-field analysis comprised the majority of the predation decision process. In 2010, more emphasis

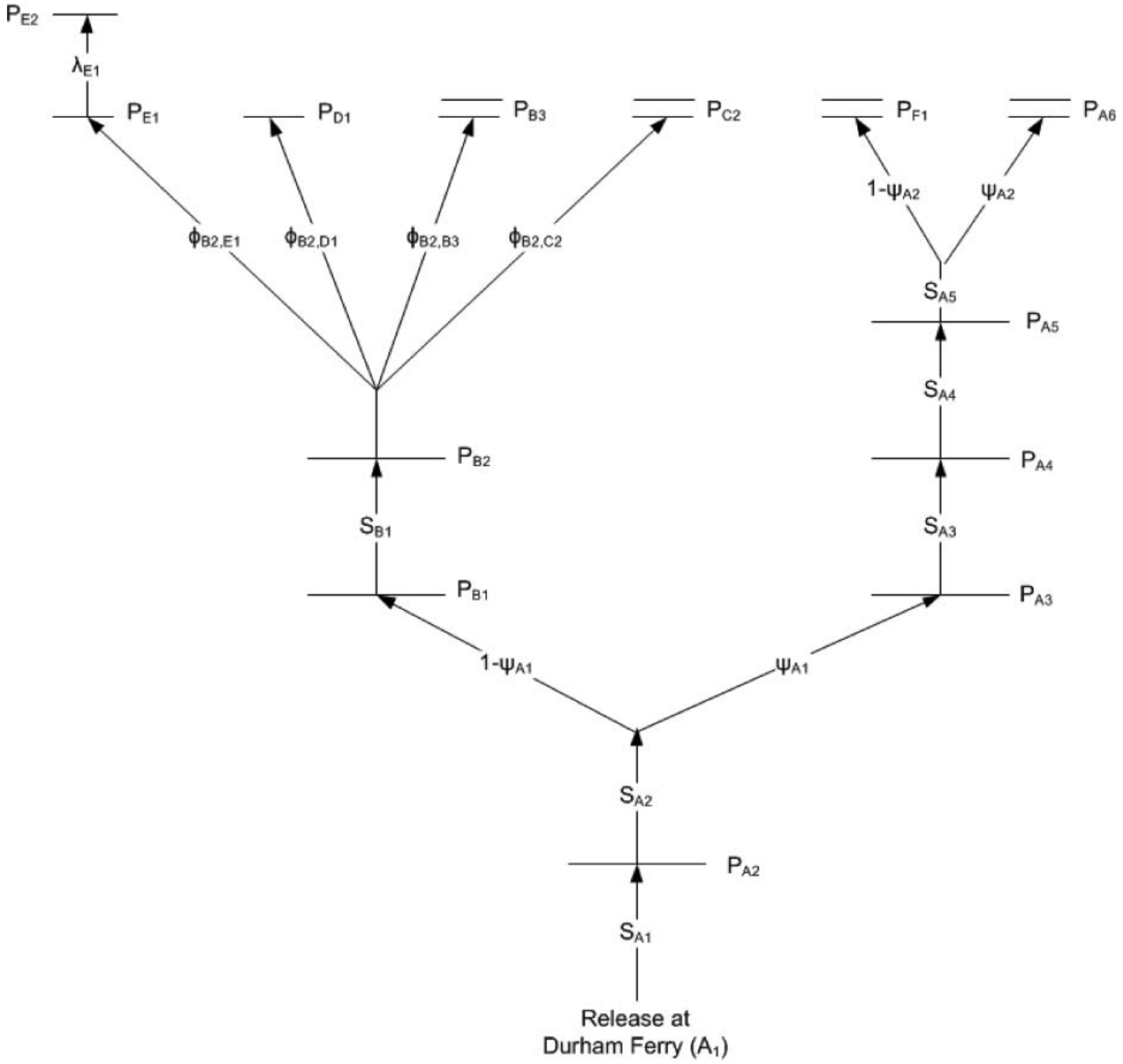

FIGURE 2. Model schematic for the 2009 Chinook Salmon smolt tagging study. Horizontal lines indicate acoustic receivers; parallel lines indicate dual receiver arrays. Model parameters are salmon reach survival (S), detection probabilities (P), route entrainment probabilities (ψ), transition probabilities ($\phi = \psi S$), and "last reach" parameters ($\lambda = \phi P$).

was placed on travel time, residence time, and movements in relation to river flow (mid-field and far-field analysis).

After removing the suspected predator detections, the processed data were converted to individual detection histories for each tagged fish. The detection history identified the chronological sequence of sites where the tag was detected. In the event that a tag was detected at a site or river junction multiple times, the last path past the site or river junction was used in the detection history as the best depiction of the final fate of the fish in the region.

Statistical survival and migration model.—A multistate statistical release–recapture model (Buchanan and Skalski 2010) was developed and used to estimate salmon smolt survival, detection probabilities, and route-use ("entrainment") probabilities (Figures 2, 3). The release–recapture model was similar to the model developed by Perry et al. (2010), with states representing the various routes through the Delta. Detection sites (acoustic receivers) were named according to route.

The release–recapture models used for both study years used parameters that denoted the probability of detection (P_{hi}), route entrainment probability (ψ_{hl}), salmon reach survival (S_{hi}), and transition probabilities ($\phi_{kj,hi}$) equivalent to the joint probability of movement and survival, where h and k represent route, i and j represent detection sites within a route, and l represents junctions within a route (Figures 2, 3). The transition probability $\phi_{kj,hi}$ from site j in route k to site i in route h included all

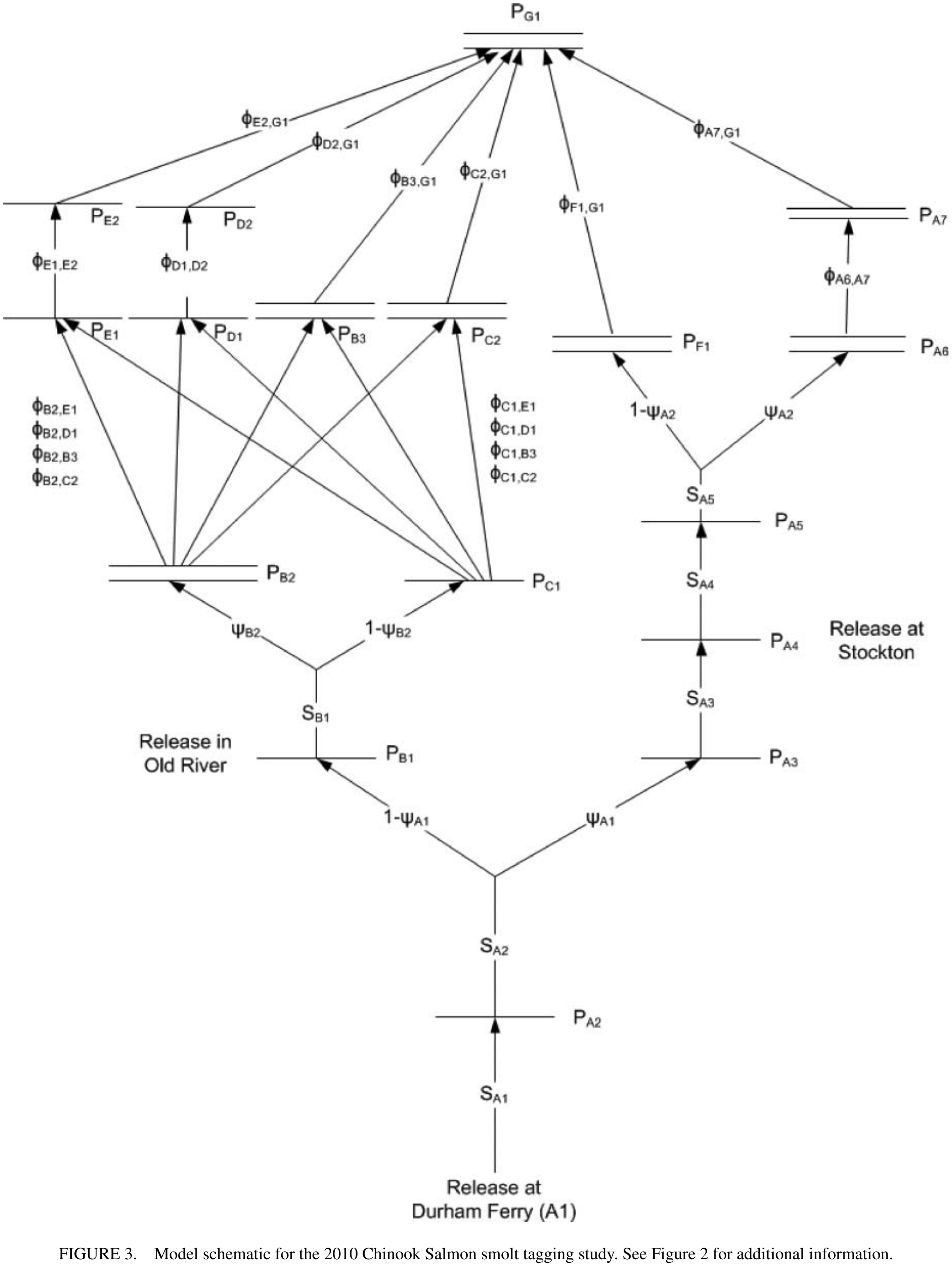

FIGURE 3. Model schematic for the 2010 Chinook Salmon smolt tagging study. See Figure 2 for additional information.

possible routes between the two sites and was used when it was not possible to separately estimate the route entrainment and survival probabilities. Unique transition parameters were estimated at receiver D1 located outside the radial gates of the Clifton Court Forebay depending on gate status at the time of fish arrival (open or closed) in the 2010 study. Gate status data were unavailable for the 2009 study.

In some cases, it was not possible to separately estimate the transition probability to a site and the detection probability at the site. This occurred primarily at the entrances to the water export facilities (E1 = CVP trash racks, and D1 = first CCF receiver) due to sparse data. In these cases, the joint probability of survival from the previous receiver to receiver i in route h was estimated as $\lambda_{hi} = \phi_{kj,hi} P_{hi}$. We assumed that the detection probability was 100% at the radial gate receivers inside Clifton Court Forebay and in the holding tank at the Central Valley Project. These assumptions, necessary in the absence of receivers located downstream of those detection sites and unique to those routes, were reasonable as long as the receivers were operating.

A multinomial likelihood model was constructed based on possible capture histories under the assumptions of common survival, route entrainment, and detection probabilities and independent detections among the tagged fish in each release group. The likelihood model was fit using maximum likelihood in the software Program USER (Lady and Skalski 2008), providing point estimates and standard errors of model parameters and derived performance measures.

In addition to the model parameters, performance at the migration route level was estimated as functions of the model parameters. The probability of a smolt taking the San Joaquin River route (route A) was ψ_{A1}, while the probability of using the Old River route (route B) was $1 - \psi_{A1}$. Regional passage survival (S_R for region R) was estimated on two spatial scales: the southern Delta (R = SD; 2009 and 2010) and the entire San Joaquin River delta (R = D) from Mossdale Bridge to Chipps Island (2010) (Figure 1). Regional passage survival for region R (R = SD or D) was defined in terms of both the route entrainment probability (ψ_{A1}) and the route-specific survival probabilities:

$$S_R = \psi_{A1} S_{A(R)} + (1 - \psi_{A1}) S_{B(R)}.$$

The route-specific survival probabilities through region R (i.e., $S_{A(R)}$ and $S_{B(R)}$ for R = SD or D) were defined as

$$S_{A(R)} = S_{A2} S_{A3} S_{A4} S_{A5(R)}$$

and

$$S_{B(R)} = S_{A2} S_{B1} S_{B2(R)}.$$

The survival probabilities through the final reaches of each route (i.e., $S_{A5(R)}$ and $S_{B2(R)}$) were defined as

$$S_{A5(R)} = \begin{cases} S_{A5}, & \text{for } R = SD \\ S_{A5}(\psi_{A2}\phi_{A6,A7}\phi_{A7,G1} + [1 - \psi_{A2}]\phi_{F1,G1}), & \text{for } R = D \end{cases}$$

and

$$S_{B2(R)} = \begin{cases} \phi_{B2,B3} + \phi_{B2,C2} + \phi_{B2,D1} + \phi_{B2,E1}, & \text{for } R = SD \\ \phi_{B2,B3}\phi_{B3,G1} + \phi_{B2,C2}\phi_{C2,G1} & \text{for } R = D. \\ \quad + \phi_{B2,D1}\phi_{D1,D2}\phi_{D2,G1} & \\ \quad + \phi_{B2,E1}\phi_{E1,E2}\phi_{E2,G1}, & \end{cases}$$

For fish that reached the interior receivers at the Clifton Court Forebay or CVP in 2010, the parameters $\phi_{D2,G1}$ and $\phi_{E2,G1}$ included survival during and after collection and transport. Although a subroute of the Old River route to Chipps Island, through Middle River from the junction with the Old River (subroute C) was monitored in 2010, no salmon were observed leaving the Old River at that junction (site C1). Thus, the probability of a smolt taking the Middle River route to Chipps Island was estimated to be zero.

In 2009, release groups were pooled into three strata based on release timing, common environmental conditions, and monitoring equipment status: stratum 1 = releases 1–2, stratum 2 = releases 3–6, and stratum 3 = release 7 (Table 1). Malfunctioning acoustic receivers meant that some parameters could not be estimated for some strata. Model selection was used to assess the effect of stratum on model parameters common to multiple strata. In 2010, data from each of the seven release occasions (initial release at Durham Ferry combined with supplemental releases) were analyzed separately. For each release occasion, several alternative survival models were fit, differing in whether the initial (Durham Ferry) and supplemental release groups shared common detection, route entrainment, and survival parameters over common reaches. Model selection was used to find the most parsimonious model that fit all the data, following the general approach described in Burnham et al. (1987) for comparing treatment groups. Detection probabilities were parameterized first, with survival, transition, and route entrainment probabilities parameterized next. Backwards selection was used to identify the farthest reach upstream for which parameters from the initial and supplemental releases could be equated without reducing model fit. The most general models were considered first, with unique parameters for each release group for all reaches, and tested against simpler models with common parameters across the initial and supplemental release groups for the downstream reaches. All models used unique survival and transition probabilities in the first reach downstream of the supplemental release sites. Model selection was performed using the Akaike Information Criterion (AIC) as described in Burnham and Anderson (2002). Final parameter estimates were weighted averages of the release-specific estimates from the selected model, with weights equal to the number of fish from the release group present at the supplemental release site (estimated for the initial release group). Goodness of fit was assessed using Anscombe residuals (McCullagh and Nelder 1989: p. 38).

RESULTS

2009 Results

None of the 50 tags in the 2009 tag-life study failed before day 21. Because all detections of tagged salmon smolts occurred well before day 21 after tag activation, no adjustment for tag failure was made to the survival estimates from the release–recapture model.

Initial survival after release was low in 2009, with estimates of survival from Durham Ferry to the Mossdale Bridge (site A2, approximately 20 rkm) averaging 0.47 ($SE = 0.02$). The majority of the acoustic-tag detections downstream of Durham Ferry were at the upstream sites in the San Joaquin (A2, A3) and in the Old River (B1). Very few tagged salmon smolts were detected at the exit points of the Southern Delta region in either the San Joaquin River route or the Old River route. No tagged salmon were detected at the Turner Cut receivers (F1), the Middle River receivers at Highway 4 (C2), or the interior receivers at Clifton Court Forebay (D2).

Total salmon survival through the Southern Delta region (S_{SD}) was estimable only for stratum 2 (releases 3–6) because the failure of certain acoustic receivers resulted in missing data from the three other release groups. Estimated route-specific survival through the Southern Delta was $\hat{S}_{A(SD)} = 0.05$ ($SE = 0.02$) in the San Joaquin route and $\hat{S}_{B(SD)} = 0.08$ ($SE = 0.02$) in the Old River route (Table 2). Survival estimates through the Southern Delta in the two routes were not significantly different (Z-test, $P = 0.4788$). The route entrainment probabilities at the junction of the Old River with the San Joaquin River were estimated at $\hat{\psi}_{A1} = 0.47$ ($SE = 0.03$) for the San Joaquin River, and $1 - \hat{\psi}_{A1} = 0.53$ ($SE = 0.03$) for the Old River. Consequently, overall survival through the Southern Delta in 2009 was estimated as $\hat{S}_{SD} = 0.06$ ($SE = 0.01$; Table 2).

The first two release groups in 2009 (stratum 1) showed a higher probability of entering the Old River ($1 - \hat{\psi}_{A1} = 0.64$; $SE = 0.04$) than remaining in the San Joaquin ($P = 0.0002$). Release groups 3–6 (stratum 2) showed no preference for either route ($P > 0.05$), with $1 - \hat{\psi}_{A1} = 0.48$ ($SE = 0.04$) for the Old River route entrainment probability. No estimates of the route entrainment probabilities were available for group 7 (stratum 3) because of equipment malfunction.

Median travel time through the Southern Delta reaches ranged from 0.2 d ($SE = 0.2$) from the Stockton USGS gauge (A4) to the Navy Drive Bridge in Stockton (A5; approximately 3 km), to 2.1 d ($SE = 0.3$) from Lathrop (A3) to the Stockton USGS gauge (A4; approximately 15 km).

2010 Results

Failure times of the 48 tags in the tag-life study ranged from 10 to 36 d. The early failure of several tags in the tag-life study made it necessary to incorporate tag-life adjustments into survival estimates (Townsend et al. 2006). The estimated probability of tag survival to the time of arrival at each detection site ranged from 0.987 to Chipps Island (G1) to 0.995 to Mossdale (A2). Tag survival estimates for the supplemental releases at the Old River and Stockton were generally higher than for the initial releases at Durham Ferry.

TABLE 2. Estimates of route-specific survival (S; standard errors in parentheses) of Chinook Salmon smolts through the Southern Delta (SD) and the entire Delta to Chipps Island (D) in the San Joaquin River (A) and Old River (B) and route entrainment probability into the San Joaquin River (A) at the head of the Old River for study years 2009 and 2010. Estimates of survival through the entire Delta are not available for 2009.

		Southern Delta survival			Entire Delta survival		
Release date	Route entrainment $\hat{\psi}_{A1}$	$\hat{S}_{A(SD)}$	$\hat{S}_{B(SD)}$	$\hat{S}_{SD}$	$\hat{S}_{A(D)}$	$\hat{S}_{B(D)}$	$\hat{S}_{D}$
Study year 2009							
Apr 22–25	0.36 (0.04)						
Apr 29–May 9	0.52 (0.04)	0.05 (0.02)	0.08 (0.02)	0.06 (0.02)			
May 13				0.05 (0.03)			
Average	0.47 (0.03)	0.05 (0.02)	0.08 (0.02)	0.06 (0.01)			
Study year 2010							
Apr 27–29	0.48 (0.06)	0.47 (0.07)	0.78 (0.06)	0.63 (0.05)	0.07 (0.03)	0.00 (0.00)	0.03 (0.02)
Apr 30–May 2	0.44 (0.06)	0.40 (0.06)	0.90 (0.04)	0.68 (0.05)	0.01 (0.01)	0.03 (0.02)	0.02 (0.01)
May 4–6	0.39 (0.06)	0.16 (0.04)	0.75 (0.06)	0.52 (0.06)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)
May 7–9	0.52 (0.07)	0.24 (0.05)	0.56 (0.09)	0.39 (0.06)	0.04 (0.02)	0.10 (0.03)	0.06 (0.02)
May 11–13	0.45 (0.06)	0.49 (0.06)	0.88 (0.08)	0.71 (0.06)	0.06 (0.03)	0.13 (0.04)	0.10 (0.03)
May 14–16	0.43 (0.06)	0.11 (0.04)	0.68 (0.29)	0.43 (0.17)	0.01 (0.01)	0.07 (0.02)	0.05 (0.02)
May 18–20	0.59 (0.07)	0.35 (0.06)	0.83 (0.21)	0.55 (0.10)	0.07 (0.03)	0.15 (0.05)	0.10 (0.03)
Average	0.47 (0.02)	0.32 (0.02)	0.77 (0.06)	0.56 (0.03)	0.04 (0.01)	0.07 (0.01)	0.05 (0.01)

All releases in the 2010 study had high initial survival, with estimates of survival from Durham Ferry to the Mossdale Bridge receiver (site A2; approximately 21 km) averaging 0.94 (range = 0.86–1.00). The Old River supplemental release groups had an average estimated survival to the head of Middle River (sites B2, C1) of 0.89 (range = 0.84–0.97). The Stockton supplemental release groups had an average estimated survival to the Navy Bridge in Stockton (site A5) of 0.82–1.07 (average = 0.95). Only a single tag released at either Durham Ferry or the Old River was detected in Middle River, so Middle River was omitted from the survival model. None of the 14 tags detected at Turner Cut were subsequently detected at Chipps Island.

Estimates of the probability of fish remaining in the San Joaquin River at the head of the Old River in 2010 ranged from 0.39 to 0.59 across the seven release groups (average = 0.47; *SE* = 0.02; Table 2). Only for release 3 did fish show a statistically significant ($\alpha = 0.05$) preference for the Old River over the San Joaquin River ($P = 0.0443$; one-sided *Z*-test).

Route-specific survival through the Southern Delta region in 2010 had an average estimate of $\hat{\hat{S}}_{A(SD)} = 0.32$ ($SE = 0.02$) in the San Joaquin route and $\hat{\hat{S}}_{B(SD)} = 0.77$ ($SE = 0.05$) in the Old River route. For each release occasion, survival through the Southern Delta was significantly higher in the Old River route ($P \leq 0.003$; one-sided *Z*-test on the lognormal scale), which ended at the water export facilities and Highway 4. Combined salmon survival through the Southern Delta region in 2010 was estimated at $\hat{\hat{S}}_{SD} = 0.56$ ($SE = 0.03$), averaged over all seven release groups (Table 2).

Survival through the entire San Joaquin River Delta region (from Mossdale to Chipps Island, approximately 89 km) was considerably lower than through only the Southern Delta region in 2010, the average overall estimate being $\hat{\hat{S}}_D = 0.05$ ($SE = 0.01$; Table 2). Estimated survival from Mossdale to Chipps Island averaged $\hat{\hat{S}}_{A(D)} = 0.04$ ($SE = 0.01$) in the San Joaquin route, and $\hat{\hat{S}}_{B(D)} = 0.07$ ($SE = 0.01$) in the Old River route. Only the first release group showed a significant difference in survival to Chipps Island between the two routes, survival through the San Joaquin route ($\hat{S}_{A(D)} = 0.07$, $SE = 0.31$) being higher than through the Old River route ($\hat{S}_{B(D)} = 0.00$, $SE = 0$; $P = 0.0100$; Table 2). Lack of significance for other release groups may have been a result of low statistical power. Pooled over release groups, however, estimated survival to Chipps Island was significantly higher through the Old River route than through the San Joaquin River route ($P = 0.0133$).

For tags released at Durham Ferry, the median travel time through the reaches ranged from 0.1 d ($SE = 0.01$) between the two Stockton receivers (A4 to A5; approximately 3 km) to 3.2 d ($SE = 0.5$) from Medford Island (A7) to Chipps Island (G1); of the multiple paths between A7 and G1, the path that used only the San Joaquin River was approximately 46 km long. No tags were observed to move from Turner Cut to Chipps Island, and the median transition from Old River South (B2) to the CVP trash racks (E1) was 0.9 d ($SE = 0.1$).

Among the 29 salmon released at Durham Ferry in 2010 that were subsequently detected at Chipps Island, 31% (9 fish) used the San Joaquin route and 69% used the Old River route. The median travel time from the head of the Old River to Chipps Island was 5.7 d (migration rate = 14.0 km/d) through the San Joaquin route, compared with 7.2 d (7 km/d) for the single fish in the Old River route that migrated in-river past Highway 4, and 2.6 d for the 19 fish in the Old River route that passed through the Central Valley Project. Travel time for the CVP fish included time spent in holding tanks and truck transport to release sites just upstream of Chipps Island, as part of the salvage operation at the facility. It appears that the fastest route through the San Joaquin River Delta to Chipps Island in 2010 was through the Old River and the CVP.

DISCUSSION

The results of 2 years of acoustic-tagging studies reported here shed light on the survival of juvenile fall Chinook Salmon in the San Joaquin River Delta. Although estimated survival was considerably higher in 2010 than in 2009, overall survival was low in both years, and survival and migration rates tended to be higher upstream and lower downstream. This pattern was observed throughout the Southern Delta in both 2009 and 2010 and throughout the entire Delta in 2010. Some reduction in migration rate is expected as fish move downstream because the cyclic tidal environment may reverse the direction of river flow and temporarily push smolts upstream. Slower migration rates, in turn, may lead to lower survival in downstream reaches, with slower-moving smolts being less able to evade predators (Anderson et al. 2005).

When survival estimates were adjusted for reach length (i.e., survival rate = $\hat{S}^{(km^{-1})}$), two regions displayed consistently low survival rates. The San Joaquin River reach from the receiver near the Navy Drive Bridge in Stockton to the Turner Cut junction had an estimated survival rate of 0.85 in 2009 and 0.94 in 2010. The reaches in the southwestern portion of the Old River route (i.e., from the head of Middle River to the entrances of the CVP and Clifton Court Forebay and to the Old River at Highway 4) had comparable survival rate estimates in both years, ranging from 0.83 to 0.90 in 2009 and 0.94–0.95 in 2010. All other Southern Delta reaches had higher estimated survival rates, while the only reach in the full Delta study area with lower survival rate was the San Joaquin River reach from the Turner Cut junction to Medford Island (0.86 in 2010). The San Joaquin River reaches from Stockton to the Turner Cut junction and Medford Island and the western portions of the Old River route warrant further investigation into mortality factors.

The estimated probability of survival throughout the Southern Delta region was generally higher in 2010 than in 2009 in both the San Joaquin River route and the Old River route. In particular, survival in the Old River from the junction with Middle River to the entrance of the water export facilities and Highway 4 appeared considerably higher in 2010 (average estimate = 0.92) than in 2009 (average = 0.16). Overall, the survival estimates through the Southern Delta region in 2009 (average = 0.06) were comparable to the survival estimates through the entire Delta region in 2010 (average = 0.05). Although no direct estimates of survival through the entire Delta were available in 2009, we can conclude that total survival was <0.06. The drop in survival in 2010 from the Southern Delta (0.56) to the entire Delta (0.05) suggests that total survival through the entire Delta in 2009 may have been as low as 0.005. Even considering the uncertainty inherent in the predator decision process, we can conclude that survival through the Delta was very low in 2009. If the survival probability estimated in 2009 was similar to survival in other low-flow years, current recovery efforts for San Joaquin River Chinook Salmon may be inadequate during dry years.

Despite interannual survival differences, the average estimated probability of fish entering the Old River from the San Joaquin (0.53) did not differ between 2009 and 2010. This route's entrainment probability was estimated in the presence of the nonphysical barrier operated at the head of the Old River. The barrier was found to be effective at deterring smolts from entering the Old River in 2010, but not in 2009 (Bowen et al. 2009; Bowen and Bark 2012, "protection efficiency"). Nevertheless, the effect of the barrier on the overall VAMP study results was limited because the barrier was operated only for approximately half of each release group, and estimates of the Old River route entrainment probability probably decreased by <0.1 because of the barrier study.

The 2009 and 2010 survival estimates reported here depend partly on the decision process used to identify and remove possible predator detections. Without removing any suspect detections, overall survival through the Southern Delta region would be estimated at 0.34 in 2009 and 0.79 in 2010 and at 0.11 through the entire Delta region in 2010. Thus, estimated survival would be higher in both years, but the comparisons between 2009 and 2010 and between the Southern Delta and the entire Delta would remain. However, many of the detections producing these higher survival estimates came from tags with considerably longer residence times (e.g., up to 810 h) or longer travel times than expected for emigrating juvenile salmonids (e.g., average residence time of approximately 0.5 h at most detection sites). Additionally, the fit of the statistical survival model declined when the presumed predator detections were included, suggesting that they were unlikely to have come from emigrating salmonids. The results presented here are based on our current understanding of behavior differences between juvenile salmon and predators such as striped bass. Nevertheless, more work needs to be done to develop methods for distinguishing between detections of salmon and detections of predators, especially for acoustic tagging studies in highly complex environments such as the Delta.

There are several possible explanations for the differences in Southern Delta survival observed between 2009 and 2010. River flows in 2009 were very low, whereas 2010 had considerably higher flows (Figure 4). Water exports from the federal and state export facilities occurred at a slightly higher and more variable rate in 2009, the combined average export level being 56.4 m^3/s (range = 38.2–73.3 m^3/s; SJRGA 2010). In 2010, the combined average export level was 43.0 m^3/s (range = 37.4–44.2 m^3/s) (SJRGA 2011). Both lower flows and higher exports may have contributed to the lower survival observed in 2009, although the difference in average export level between 2009 and 2010 is small compared with possible daily variation in export levels (42.5–322.8 m^3/s). Differences in the source and condition of the study fish may also have contributed to performance differences between the 2 years. The 2009 study fish were hybrids of spring and fall-run Chinook Salmon from the Feather River Fish Hatchery (FRH), located in the Sacramento River basin. These hybrid fish tended to be smaller than the 2010 study fish, which were fall-run Chinook Salmon from the Merced River Fish Hatchery (MRH; located in the San Joaquin River basin). Historically, experiments in the San Joaquin Delta have used MRH fish. In 2009, however, low numbers of MRH fish prompted the switch to the FRH for that year's tagging study, despite concern that FRH fish (genetically from the Sacramento River) may not adequately represent survival of San Joaquin fall-run Chinook Salmon (Brandes and McLain 2001). In 2010, rebounding numbers at the MRH allowed us to return to MRH fish for that year's tagging study.

The smaller size of the 2009 fish resulted in an average tag burden that was higher than in 2010, and also higher than desired ($\leq 5.5\%$; Brown et al. 2006). The higher tag burden in 2009 may have contributed to the high mortality in the first reach after release (Durham Ferry to Mossdale Bridge), where an estimated 53% of study fish died in 2009. However, differences in river conditions and predator distribution may also have contributed to differences in estimated mortality in this reach between the 2 years. Dry conditions and low flows in 2009 may have concentrated predators and prey (smolts) in a smaller volume of water. Higher water temperatures in 2009 may have kept the predators more active (e.g., Niimi and Beamish 1974), and also more likely to reside in the San Joaquin River between Durham Ferry and Mossdale Bridge, where water temperatures tend to be cooler than in the Delta.

Despite the differences in survival between the 2009 and 2010 study years, both studies found that juvenile fall run Chinook Salmon have very low survival through the San Joaquin River Delta, well under 0.10. Our 2010 estimates were similar to the lower range of previous survival estimates of San Joaquin smolts based on CWT data (Brandes and McLain 2001). However, the extremely low survival potentially experienced through the Delta in 2009 would have been lower than the lowest CWT estimates. Even the higher survival observed in 2010 was considerably lower than survival estimates of juvenile late fall-run Chinook Salmon from the Sacramento River through the Delta, which ranged from 0.35 to 0.54 in the winter of 2007 (Perry et al. 2010). The Perry study used comparable methods, with similar study design, tagging, and analysis. However, the late fall run Chinook Salmon used in

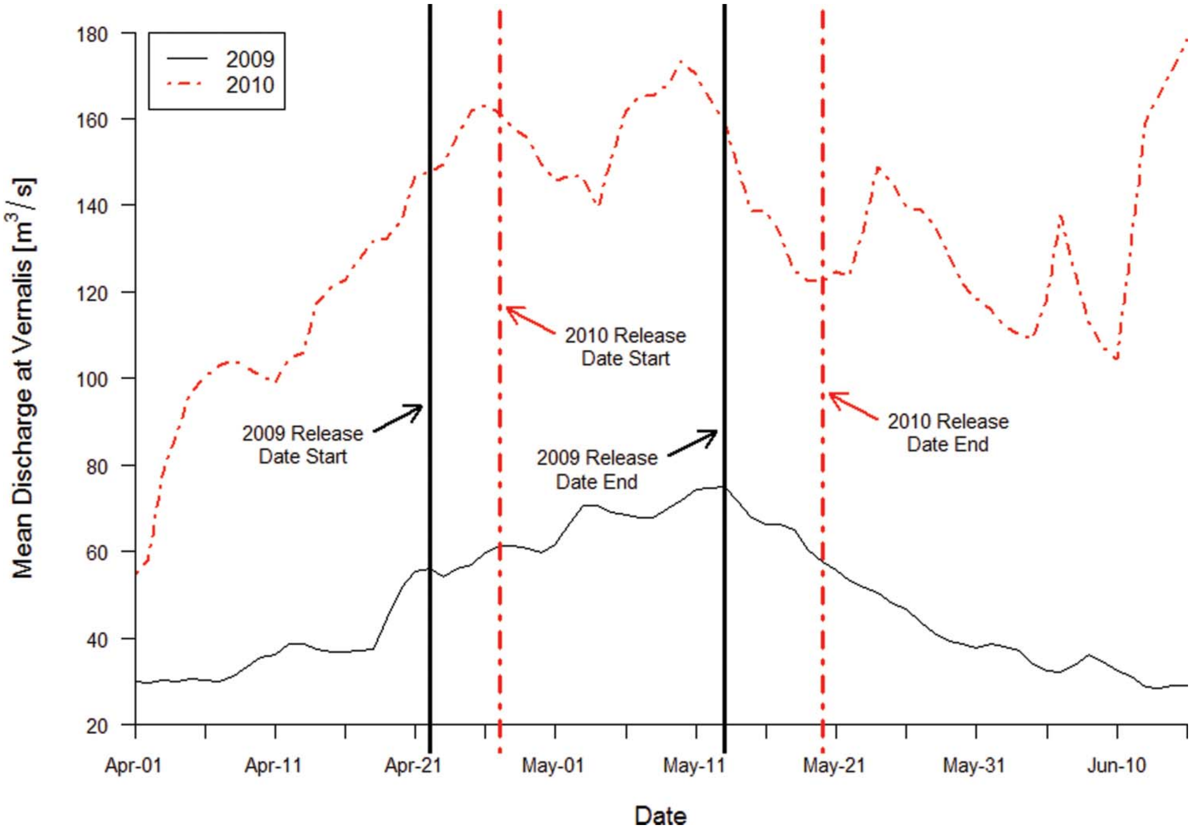

FIGURE 4. Mean daily discharge of the San Joaquin River at the U.S. Geological Survey gauge near Vernalis, California (rkm 113 from Chipps Island), during Chinook Salmon tagging studies in 2009 and 2010. [Figure available in color online.]

the Perry study migrate in winter, whereas the fall-run Chinook Salmon used in the VAMP study migrate months earlier in spring. Thus, not only were the VAMP fish smaller than the Perry study fish, they also migrated when higher predator activity is expected because of warmer temperatures and the striped bass spring spawning migration (Radtke 1966). Thus, there are several possible explanations why the VAMP study may be expected to estimate lower survival than the Perry study.

Estimates of juvenile Chinook Salmon survival through comparable environments in other basins tend to be higher than those observed in the 2009 and 2010 VAMP studies. McMichael et al. (2010) used acoustic tags to estimate survival of Chinook salmon smolts through the lower 192 rkm of the Columbia River to the river mouth; scaled by distance, the survival rate estimates ($\hat{S}^{(km^{-1})}$) were 0.999 for yearlings and 0.998 for subyearlings. Acoustic-tagged spring Chinook Salmon from the Thompson–Fraser river system had estimated survival rates of 0.989–0.997 (average = 0.995) through more than 330 rkm to the Fraser River mouth in 2004–2006 (Welch et al. 2008). These survival rates are considerably higher than both the VAMP-estimated Southern Delta survival rate of 0.92 in 2009 and the estimated entire Delta survival rate of 0.97 in 2010. Even the lowest survival rate estimate reported by Welch et al. (2008) for the Fraser River (0.989 in 2004) corresponds to much higher total survival over a distance comparable to the VAMP study area (approximately 89 rkm). Over this distance, a population with a survival rate of 0.989/km would have an overall survival probability of 0.37, as opposed to the 2010 estimate of 0.05. Although direct comparison with other basins is difficult, it appears that the salmon smolts used in the 2009 and 2010 VAMP studies are not surviving as well on their seaward migration as other salmon population on the western coast of North America.

Part of the VAMP is a management plan based on the assumption that salmon survival to Chipps Island is higher through the San Joaquin River route than through the Old River route. This assumption is based on CWT studies between 1985 and 1990 that consistently found higher (but not statistically significant) point estimates of survival for smolts released in the San Joaquin River downstream of the Old River than for those released in the Old River (Brandes and McLain, 2001). Modeling of these data and other CWT data indicated that keeping salmon out of the Old River improved their survival (Newman 2008). The 2008 VAMP acoustic tag study results, although hampered by a high degree of premature tag failure, suggest that survival to Chipps Island was also higher through the San Joaquin River than through the Old River route in 2008 (Holbrook et al. 2009). Furthermore, there is evidence that salmon from the Sacramento River have a higher probability of reaching Chipps Island if they remain in the Sacramento River rather than entering the central Delta (Newman and Brandes 2010, Perry et al. 2010). Since the 1990s, management has experimented with efforts to keep fish in the San Joaquin River and out of the Old River by installing a barrier (physical or nonphysical) at the head of the Old River. Our results suggest that prevailing ideas about relative survival in the two routes may be too simple, given that we found no conclusive evidence that survival was higher in the San Joaquin River route than in the Old River route. One difference between the 2009 and 2010 study years and previous years was the switch from a physical barrier to testing a nonphysical barrier at the head of the Old River in 2009 and 2010. Historically, the physical barrier at the Old River routed both fish and river flow into the San Joaquin River (SJRGA 2005). In contrast, the nonphysical barrier used in 2009 and 2010 routed fish but not flow into the San Joaquin (Bowen et al. 2009; Bowen and Bark 2012). With salmon smolt survival in the San Joaquin River thought to increase with flow (SJRGA 2007), it is possible that the nonphysical barrier deprived smolts routed to the San Joaquin River of the increased flows necessary for improved survival (Perry et al. 2013). There is also a concern that the larger in-water structure associated with the nonphysical barrier may create habitat for increased predation at the site. More study is needed.

The San Joaquin River Delta represents just a small portion of the entire juvenile out-migration of San Joaquin Chinook Salmon and in recent years has typically been traversed in <2 weeks (SJRGA 2011; Holbrook et al. 2013). With survival through only a portion of the juvenile migration estimated at <0.10, management efforts in the lower San Joaquin River and Delta must be more protective if salmon populations are to persist in this region. However, effective management must be based on a better understanding of the factors influencing mortality than is currently available. More research into salmon use of and survival in the Delta is needed, especially in dry years that may represent future conditions under climate change. In light of increasing human demands for Central Valley water, it is unlikely that salmon survival will improve on its own. If the survival estimates observed in these two studies are representative of the future, only extreme measures have a chance of saving San Joaquin River Chinook Salmon.

ACKNOWLEDGMENTS

Many people and groups were involved in designing and implementing the VAMP study. We thank Natural Resource Scientists, Inc., California Department of Fish and Game, California Department of Water Resources, the U.S. Fish and Wildlife Service (Stockton office), the U.S. Bureau of Reclamation, Normandeau and Associates (Stevenson, Washington), and the U.S. Geological Survey (Columbia River Research Lab and Sacramento office) for their contributions to the study. We also thank Mark Bowen from the U.S. Bureau of Reclamation for access to detection data from the nonphysical barrier study at the head of the Old River, and three anonymous reviewers for their helpful suggestions. Funding for the VAMP study was provided by the signatories to the San Joaquin River Agreement, and funding for analysis and manuscript preparation was provided by the San Joaquin River Group Authority.

REFERENCES

Adams, N. S., D. W. Rondorf, S. D. Evans, and J. E. Kelly. 1998. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behavior of juvenile Chinook Salmon. Transactions of the American Fisheries Society 127:128–136.

Anderson, J. J., E. Gurarie, and R. W. Zabel. 2005. Mean free-path length theory of predator–prey interactions: application to juvenile salmon migration. Ecological Modelling 186:196–211.

Anglea, S. M., D. R. Geist, R. S. Brown, K. A. Deters, and R. D. McDonald. 2004. Effects of acoustic transmitters on swimming performance and predator avoidance of juvenile Chinook Salmon. North American Journal of Fisheries Management 24:162–170.

Bowen, M. D., and R. Bark. 2012. 2010 effectiveness of a non-physical fish barrier at the divergence of the Old and San Joaquin rivers (CA). U.S. Department of the Interior, Bureau of Reclamation, Technical Memorandum 86-68290-10-07, Denver.

Bowen, M. D., S. Hiebert, C. Hueth, and V. Maisonneuve. 2009. 2009 effectiveness of a non-physical fish barrier at the divergence of the Old and San Joaquin rivers (CA). U.S. Department of the Interior, Bureau of Reclamation, Technical Memorandum 86-68290-09-05, Denver.

Brandes, P. L., and J. S. McLain. 2001. Juvenile Chinook Salmon abundance, distribution, and survival in the Sacramento–San Joaquin Estuary. Pages 39–138 *in* R. L. Brown, editor. Contributions to the biology of Central Valley salmonids, volume 2. California Department of Fish and Game, Fish Bulletin 179, Sacramento.

Brown, R. S., D. R. Geist, K. A. Deters, and A. Grassell. 2006. Effects of surgically implanted acoustic transmitters >2% of body mass on the swimming performance, survival and growth of juvenile Sockeye and Chinook Salmon. Journal of Fish Biology 69:1626–1638.

Buchanan, R. A., and J. R. Skalski. 2010. Using multistate mark–recapture methods to model adult salmonid migration in an industrialized river. Ecological Modelling 221:582–589.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach, 2nd edition. Springer, New York.

Burnham, K. P., D. R. Anderson, G. C. White, C. Brownie, and K. H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. American Fisheries Society, Monograph 5, Bethesda, Maryland.

DSC (Delta Stewardship Council). 2011. Available: http://www.deltacouncil.ca.gov/. (13 December 2011).

Fisher, F. W. 1994. Past and present status of Central Valley Chinook Salmon. Conservation Biology 8:870–873.

Healey, M. C. 1991. Life history of Chinook Salmon (*Oncorhynchus tshawytscha*). Pages 311–393 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. University of British Columbia Press, Vancouver.

Holbrook, C. M., R. W. Perry, and N. S. Adams. 2009. Distribution and joint fish-tag survival of juvenile Chinook Salmon migrating through the Sacramento–San Joaquin River Delta, California, 2008. U.S. Geological Survey, Open-File Report 2009-1204, Reston, Virginia. Available: pubs.usgs.gov/. (November 2011).

Holbrook, C. M., R. W. Perry, P. L. Brandes, and N. S. Adams. 2013. Adjusting survival estimates for premature transmitter failure: a case study from the Sacramento–San Joaquin Delta. Environmental Biology of Fishes 96:165–173.

Lady, J. M., and J. R. Skalski. 2008. USER 4: user-specified estimation routine. School of Aquatic and Fishery Sciences, University of Washington, Seattle. Available: www.cbr.washington.edu/paramest. (July 2012).

Martinelli, T. L., H. C. Hansel, and R. S. Shively. 1998. Growth and physiological responses to surgical and gastric radio transmitter implantation techniques in subyearling Chinook Salmon (*Oncorhynchus tshawytscha*). Hydrobiologia 371/372:79–87.

McCullagh, P., and J. A. Nelder. 1989. Generalized linear models, 2nd edition. Chapman and Hall/CRC Press, Boca Raton, Florida.

McMichael, G. A., R. A. Harnish, B. J. Bellgraph, J. A. Carter, K. D. Ham, P. S. Titzler, and M. S. Hughes. 2010. Migratory behavior and survival of juvenile salmonids in the lower Columbia River and estuary in 2009. Pacific Northwest National Laboratory, PNNL-19545, Richland, Washington.

Newman, K. B. 2008. An evaluation of four Sacramento–San Joaquin River Delta juvenile salmon survival studies. CALFED Bay-Delta Program, Project SCI-06-G06-299, Sacramento, California. Available: www.science.calwater.ca.gov./ (November 2011).

Newman, K. B., and P. L. Brandes. 2010. Hierarchical modeling of juvenile Chinook Salmon survival as a function of Sacramento–San Joaquin Delta water exports. North American Journal of Fisheries Management 30:157–169.

Niimi, A. J., and F. W. H. Beamish. 1974. Bioenergetics and growth of Largemouth Bass (*Micropterus salmoides*) in relation to body weight and temperature. Canadian Journal of Zoology 52:447–456.

Perry, R. W., P. L. Brandes, J. R. Burau, A. P. Klimley, B. MacFarlane, C. Michel, and J. R. Skalski. 2013. Sensitivity of survival to migration routes used by juvenile Chinook Salmon to negotiate the Sacramento–San Joaquin River Delta. Environmental Biology of Fishes 96:381–392.

Perry, R. W., J. R. Skalski, P. L. Brandes, P. T. Sandstrom, A. P. Klimley, A. Ammann, and B. MacFarlane. 2010. Estimating survival and migration route probabilities of juvenile Chinook Salmon in the Sacramento–San Joaquin River Delta. North American Journal of Fisheries Management 30: 142–156.

Radtke, L. D. 1966. Distribution of adult and subadult Striped Bass, *Roccus saxatilis*, in the Sacramento–San Joaquin Delta. Pages 15–27 *in* J. L. Turner and D. W. Kelley, editors. Ecological studies of the Sacramento–San Joaquin Delta, part II: fishes of the Delta. California Department of Fish and Game, Fish Bulletin 136, Sacramento.

SJRGA (San Joaquin River Group Authority). 2005. 2004 annual technical report: on implementation and monitoring of the San Joaquin River agreement and the Vernalis Adaptive Management Plan. SJRGA, Report to the California Water Resources Control Board, Davis, California. Available: www.sjrg.org/technicalreport. (February 2012).

SJRGA (San Joaquin River Group Authority). 2007. 2006 annual technical report: on implementation and monitoring of the San Joaquin River agreement and the Vernalis Adaptive Management Plan. SJRGA, Report to the California Water Resources Control Board, Davis, California. Available: www.sjrg.org/technicalreport. (February 2012).

SJRGA (San Joaquin River Group Authority). 2010. 2009 annual technical report: on implementation and monitoring of the San Joaquin River agreement and the Vernalis Adaptive Management Plan. SJRGA, Report to the California Water Resources Control Board, Davis, California. Available: www.sjrg.org/technicalreport. (February 2012).

SJRGA (San Joaquin River Group Authority). 2011. 2010 annual technical report: on implementation and monitoring of the San Joaquin River agreement and the Vernalis Adaptive Management Plan. SJRGA, Report to the California Water Resources Control Board, Davis, California. Available: www.sjrg.org/technicalreport. (February 2012).

Townsend, R. L., J. R. Skalski, P. Dillingham, and T. W. Steig. 2006. Correcting bias in survival estimation resulting from tag failure in acoustic and radiotelemetry studies. Journal of Agricultural, Biological, and Environmental Statistics 11:183–196.

Vogel, D. A. 2010. Evaluation of acoustic-tagged juvenile Chinook Salmon movements in the Sacramento–San Joaquin Delta during the 2009 Vernalis Adaptive Management Program. San Joaquin River Group Authority, Technical Report to the California Water Resources Control Board, Davis, California. Available: www.sjrg.org/technicalreport/. (July 2012).

Vogel, D. A. 2011. Evaluation of acoustic-tagged juvenile Chinook Salmon and predatory fish movements in the Sacramento–San Joaquin Delta during the 2010 Vernalis Adaptive Management Program. San Joaquin River Group Authority, Technical Report to the California Water Resources Control Board, Davis, California. Available: www.sjrg.org/technicalreport./ (July 2012).

Welch, D. W., E. L. Rechisky, M. C. Melnychuk, A. D. Porter, C. J. Walters, S. Clements, B. J. Clemens, R. S. McKinley, and C. Schreck. 2008. Survival of migrating salmon smolts in large rivers with and without dams. PLoS (Public Library of Science) Biologyy [online serial] 6(10):e265. DOI: 10.1371/journal.pbio.0060265.