Kern Fan Groundwater Storage Project

FEASIBILITY REPORT

Appendix H: Ecosystem Benefit in the Delta Technical Report

October 21, 2019
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Irvine Ranch
WATER DISTRICT

Rosedale-Rio Bravo
WATER STORAGE DISTRICT

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October 17th, 2019

TECHNICAL MEMORANDUM

Subject: Chinook Salmon, Steelhead and Green Sturgeon Benefits from Kern Fan Groundwater Storage Project

Prepared for: Irvine Ranch Water District

Prepared by: Brad Cavallo

This technical memorandum provides a description of background, methodology, assumptions and results for an assessment of anadromous fish benefits resulting from the Kern Fan Groundwater Storage Project (Project). Anadromous fish species evaluated included four endangered species, three occurring in the Feather River (Central Valley Spring-run Chinook, Central Valley Steelhead, and the Southern Distinct Population of Green Sturgeon) and one occurring only in the Sacramento River mainstem (Sacramento Winter-run Chinook).

1. Project operations for ecosystem benefits

Cramer Fish Sciences (CFS) consulted with MBK Engineers and Irvine Ranch Water District to recommend how 18 thousand acre-feet (TAF) of additional water supply made available by the proposed Project could be used to provide the greatest benefit to endangered anadromous fish species occurring in the Feather River. CFS recommended a pulse released from Lake Oroville in the month of April. CALSIM analysis provided by MBK Engineers indicated the Project could, with 1922-2003 hydrology under a 2030 future condition, provide for seven April flow pulses (of 18 TAF) in dry or critically dry years. Under a 2070 future condition, the Project can provide for five April flow pulses (of 18 TAF) in dry or critically dry years.

CFS recommended and assumed the 18TAF would be applied as a 3.75 day, 2,400cfs increase in Feather River flows released from the Thermalito Afterbay Outlet (TAO). Releasing this water from the TAO is important because the Feather River downstream of TAO has no ramping criteria for flows greater than 2,500 cfs (NMFS 2016a).

2. Methods for assessing anadromous fish benefits

2.1. Chinook salmon

Our quantitative analysis focuses on assessing benefits to outmigrating juvenile spring-run Chinook originating from the Feather River. Effects of the Feather River flow pulse downstream of the confluence with the Sacramento River and through the Delta were analyzed for Feather River origin spring-run Chinook, and also for Sacramento River basin juvenile spring-run Chinook and juvenile winter-run Chinook.

2.1.1. Feather River Analysis

The Feather River hosts natural and hatchery origin spring-run Chinook. NMFS considers both in-river and hatchery spawning Feather River spring-run Chinook salmon to be part of the listed CV spring-run Chinook salmon ESU (NMFS 2016b). NMFS, in their most recent five-year review of CV spring-run, assigned a recovery priority for spring-run Chinook salmon in the Feather River of 5 (with 1 being the highest priority, 12 being the lowest priority) (NMFS 2016b). These determinations are based upon the evolutionary legacy the Feather River spring-run stock represents, because the stock continues to exhibit a CV spring-run Chinook salmon migration timing, and because of habitat and management improvements required as part of the Oroville Facilities FERC Relicensing Settlement Agreement.

Name	Value	Description	Source
SmH	2 million	Annual spring-run hatchery smolts released at Gridley.	FRH Spring Chinook HGMP
SmN	2 million	Annual natural origin spring-run juvenile production reaching apprxoimately Gridley on the Feather River.	Natural origin spring-run Chinook are produced on the Feather River, but abundance is uncertain. This value is approximated based on likely in-river spawning coupled with expected enhancements identified in the FRH Spring Chinook HGMP and FERC Reclicensing Biological Opinion (NMFS 2016a)
MIGm	0.62	Fraction of natural smolts emigrating in April	NMFS (2016a)
MIGp	0.125	Fraction of days in month with flow pulse	Duration of flow pulse (3.75 days) divided by 30
relm	0.5	Fraction of FRH smolts released in April	FRH Spring Chinook HGMP
relf	0.5	Fraction of FRH smolt release which be coordinated to coincide with flow pulse	Jason Kindopp (CDWR), personal communication
B0	-2.1	Smolt survival in the Feather River (untransformed value)	See text
B1	1.47	Flow survival effect (untransformed value)	NMFS (2017), Table B1. See text for more details.
Qm	variable	Standardized Feather River flow by month	CALSIM output
SmS	3.2 million	Annual natural origin spring-run smolts from the Sacramento River basin excluding the Feather River basin (estimated from spawning escapement, fecundity, egg-fry survival data)	See Table 2
SmW	2.1 million	Annual winter-run smolts from the Sacramento River (estimated from spawning escapement, fecundity, egg-fry survival data)	See Table 2
Sa	0.0144	Mean survival rate for smolts to return as adults	Zeug et al. (2012). See text for more details.
Sa max	0.0192	Maximum survival rate for smolts to return as adults	Zeug et al. (2012). See text for more details.
Sa min	0.0096	Miimum survival rate for smolts to return as adults	Zeug et al. (2012). See text for more details.

Table 1. Values, descriptions and sources for inputs and parameters used for the quantification of Project ecosystem benefits.

There are two components of the Feather River spring-run Chinook salmon analysis: 1) smolts released by FRH, and 2) juvenile spring-run Chinook salmon naturally produced in the Feather River. FRH annually produces 2 million spring-run Chinook smolts released into the Feather River. Natural origin spring-run Chinook are certainly produced in the Feather River, but their abundance is currently unknown (NMFS 2016a). Given expected habitat enhancements of the Feather River and the requirement to segregate spring and fall-run in the immediate future (see NMFS 2016a), we conservatively assume an average of 2 million natural origin spring-run smolts will be produced naturally by the Feather River by the time the Project is completed. Additionally, we assume all FRH spring-run Chinook releases will occur at Gridley. Though future FRH release locations are unknown, the California Hatchery Scientific Review Group has recommended all hatchery production be released as close to the source hatchery as possible (CA HSRG 2012). Given this recommendation and concerns about straying Feather River Hatchery spring-run Chinook (see NMFS 2016a), future spring-run Chinook releases downstream of the Yuba River confluence (e.g. Boyd's Pump) are unlikely.

Other data and sources used to evaluate effects of the proposed Project on the survival of Feather River spring-run Chinook salmon are summarized in Table 1. Related source flow data and calculations are available upon request in an Excel spreadsheet "FR_analysis_v3".

The monthly number of FRH produced spring-run smolts entering the Sacramento River (Sm_{FRH}) from the Feather River is estimated by

(eq1) $$Sm_H * rel_m * relf * surv_m$$

and the monthly number of natural origin spring-run smolts entering the Sacramento River from the Feather River (Sm_{FRW})is estimated by

(eq2) $$Sm_N * MIG_m * MIG_p * surv_m.$$

Survival for both hatchery and natural origin smolts are modeled as a function of monthly Feather River flows

(eq3) $$logit(surv_m) = B0 + B1 * Q_m$$

where B0 and B1 are model parameters (Table 1), and where Q_m is monthly Feather River flows standardized relative to all monthly Feather River flow observations (provided by CALSIM). Monthly flow data (1922 through 2003) representing two future conditions (2030 and 2070) and two scenarios (Project and no project) were provided by MBK Engineers (see MBK 2018). A total of four different CALSIM scenarios were analyzed.

	Sacramento Basin Spring-run		***Winter-run***	
Data Type	**Reference**	**Data**	**Reference**	**Data**
Total In-river Escapement	GrandTab (March 2010), 10 yr Avg	8,924	GrandTab (March 2010), 10 yr Avg	7,634
Pre-spawning mortality	Garman & McReynolds 2005-08	5.53%	Poytress & Carillo 2010	5%
Percent Female	Garman & McReynolds 2005-08	55%	Killam 2009	54%
Fecundity	DWR 2009	5300	Poytress & Carillo 2010	3859
Egg to Fry Survival	Poytress & Carillo 2010	33%	Poytress & Carillo 2010	33%
Fry to Delta Survival	USFWS, unpublished data	53%	USFWS, unpublished data	53%
Total Juveniles Reaching Delta		**4,200,000**		**2,600,000**
Percent smolts entering delta	USFWS Sacramento Trawls	86%	USFWS Sacramento Trawls	82%
Total Smolts Reaching Delta		**3,600,000**		**2,100,000**

Table 2. Values, descriptions and data sources used to estimate average Sacramento River basin spring-run and winter-run Chinook smolt production reaching the Delta (i.e. inputs for the Delta Passage Model).

The flow survival relationship (eq3) was developed by the NMFS Southwest Fishery Science Center as part of a life cycle modeling effort for winter-run Chinook salmon (NMFS 2017). The NMFS LCM is under continuous development, but the model (including this flow-survival function) were used in the NMFS Biological Opinion for California Water Fix (http://www.westcoast.fisheries.noaa.gov/central_valley/CAWaterFix.html). Of course, survival differences between the Sacramento and the Feather River are likely to occur. To address these expected differences, we utilized available Feather River spring-run Chinook acoustic tagging data to estimate B0, but relied upon the estimate of B1 from NMFS (2017). Survival per river kilometer data from Figure 2-30 (NMFS 2016a) were converted to a reach-specific survival estimate of 0.11, representing survival from Gridley to the confluence with the Sacramento River. Transforming 0.11 as necessary for the logit scale shown in eq3 yields a value of -2.1 for B0. The resulting relationship between Feather River flow and spring-run Chinook survival is depicted in Figure 1. Ideally, a Feather River flow-survival relationship would be based solely upon observations from the Feather River. However, since few observations of Feather River survival were available, we combined available Feather River information with findings from the NMFS winter-run Chinook life cycle modeling effort. Though there is uncertainty about the Feather River flow-survival relationship depicted in Figure 1, scientific literature from Central Valley tributaries affirms a positive relationship between Feather River flow and juvenile salmon survival is likely. Investigations into the relationship between river discharge and juvenile salmon survival in the Central Valley have primarily focused on the Sacramento-San Joaquin Delta and several studies have reported significant positive relationships (Newman 2003, Perry 2010). Less attention has been focused on the Feather River or other upstream tributaries. However, there are multiple lines of evidence to suggest a positive flow-survival relationship operates in the Feather River. Within the Central Valley, Zeug et al. (2014) reported a significant positive relationship between river discharge (and discharge variability) and survival for juvenile Chinook salmon in the Stanislaus River. Additionally, Perry et al. (2018) found that survival increased in Delta reaches when high levels of discharge resulted in a switch from bi-directional to unidirectional flow. A positive flow survival relationship for Chinook salmon during spring in the Snake River was reported by Smith et al. (2003). However, flow was correlated with turbidity and temperature complicating attempts to separate out effects. Regardless of the causal mechanism it is clear that increases in flow result in more favorable conditions for juvenile Chinook survival during migration.

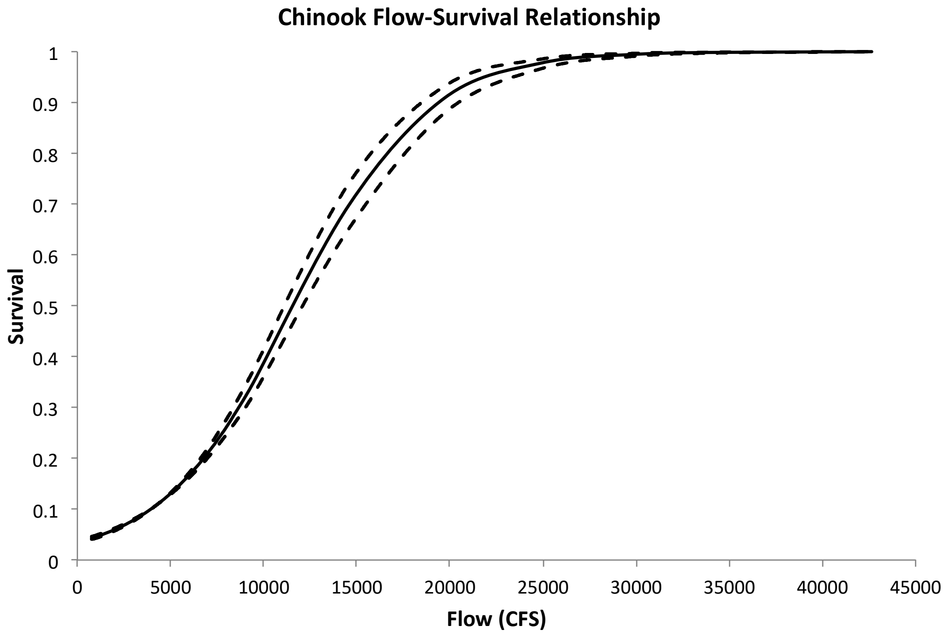


Figure 1. Estimated flow-survival relationship for juvenile Feather River spring-run Chinook salmon. Dashed lines indicate standard deviation associated with parameter B1 as estimated by NMFS (2017).

Flow pulses produced by the Project occurred exclusively in dry years, with Feather River base flows at less than 3,000cfs. The estimated survival under these conditions occurs at the left side of the curve depicted in Figure 1. On average, we estimate Project flow pulses improve survival relative to the base flow condition by approximately 4.6%

Date	Survvial w/o Pulse	Survvial w/ Pulse	Difference
04/30/1939	0.052	0.097	0.046
04/30/1944	0.060	0.112	0.052
04/30/1960	0.074	0.137	0.063
04/30/1976	0.046	0.088	0.042
04/30/1981	0.046	0.088	0.042
04/30/1985	0.046	0.088	0.042
04/30/1988	0.043	0.082	0.039
		Average:	**0.046**

Table 3. Estimated survival rates for Feather River Chinook salmon with and without the 2,400cfs flow pulse provided by the Project. Source data and calculations visible in the Excel spreadsheet "FR_analysis_v3".

2.1.2. Delta Analysis

Survival rates for Feather River spring-run Chinook, Sacramento River basin spring-run Chinook, and Sacramento River winter-run Chinook from Verona (Sacramento River) to San Francisco Bay were estimated for each flow scenario (with and without the proposed project) using the Delta Passage Model (DPM).

Sm_{FRH} and Sm_{FRW} provided inputs to the Delta Passage Model (DPM) representing Feather River Hatchery origin spring-run Chinook and Feather River natural origin spring-run Chinook, respectively. The number of spring-run (Sm_{SSRC}) and winter-run (Sm_{SWRC}) Chinook smolts entering from the Sacramento River basin are indicated in Table 2. DPM produced annual survival rates for winter and spring Chinook (weighted by monthly emigration timing) are shown in the Excel spreadsheet "Smolt_Surv_to_Bay_V2". A detailed description of the DPM is provided below.

The DPM simulates migration of Chinook salmon smolts entering the Sacramento River at Verona and estimates survival to Chipps Island. The DPM uses available time-series data and values taken from empirical studies or other sources to parameterize model relationships and inform uncertainty, thereby using the greatest amount of data available to dynamically simulate responses of smolt survival to changes in water management. Although the DPM is based primarily on studies of late fall–run Chinook salmon, it is applied here for winter-run and spring-run by adjusting emigration timing and assuming that all migrating Chinook salmon smolts will respond similarly to Delta conditions. The DPM results presented here reflect the current version of the model, which continues to be reviewed and refined, and for which a sensitivity analysis has been completed to examine various aspects of uncertainty related to the model's inputs and parameters.

Although studies have shown considerable variation in emigrant size, with Central Valley Chinook salmon migrating as fry, parr, or smolts (Brandes and McLain 2001; Williams 2001), the DPM relies predominantly on data from acoustic-tagging studies of large (>140 mm) smolts, and therefore should be applied cautiously to pre-smolt migrants. Salmon juveniles less than 80 mm are more likely to exhibit rearing behavior in the Delta (Moyle 2002) and thus likely will be represented poorly by the DPM. It has been assumed that the downstream emigration of fry, when spawning grounds are well upstream, is probably a dispersal mechanism that helps distribute fry among suitable rearing habitats. However, even when rearing habitat does not appear to be a limiting factor, downstream movement of fry still may be observed, suggesting that fry emigration is a viable alternative life-history strategy (Healey 1980; Healey and Jordan 1982; Miller et al. 2010). Unfortunately, survival data are lacking for small (fry-sized) juvenile emigrants because of the difficulty of tagging such small individuals. Therefore, the DPM should be viewed as a smolt survival model only, with its survival relationships generally having been derived from larger smolts (>140 mm), with the fate of pre-smolt emigrants not incorporated into model results.

The DPM has undergone substantial revisions based on comments received through the preliminary proposal anadromous team meetings and in particular through feedback received during a workshop held on August 24, 2010, a 2-day workshop held June 23–24, 2011, and various meetings of a workgroup consisting of agency biologists and consultants. This comparison of survival among Project and baseline alternatives uses the most recent version of the DPM as of July 2015 with several additional modifications described below. The DPM is viewed as a simulation framework that can be changed as more data or new hypotheses regarding smolt migration and survival become available. The results are based on these revisions.

Survival and abundance estimates generated by the DPM are not intended to predict future observed survival. Instead, the DPM provides a simulation tool that compares the effects of different water management options on smolt migration survival, with accompanying estimates of uncertainty. The DPM was used to evaluate overall through-Delta survival for baseline and Project scenarios using CALSIM flow data as inputs for Sacramento River and Delta water conditions. The DPM produced annual survival rates weighted by monthly emigration timing for spring-run and winter-run Chinook salmon.

Model Overview

The DPM is based on a detailed accounting of migratory pathways and reach-specific mortality as Chinook salmon smolts travel through a simplified network of reaches and junctions (Figure 2). The biological functionality of the DPM is based on the foundation provided by Perry et al. (2010) as well as other acoustic tagging–based studies (San Joaquin River Group Authority 2008, 2010; Holbrook et al. 2009) and coded wire tag (CWT)–based studies (Newman and Brandes 2010; Newman 2008). Uncertainty is explicitly modeled in the DPM by incorporating environmental stochasticity and estimation error whenever available.

The major model functions in the DPM are as follows.

1. Delta Entry Timing, which models the temporal distribution of smolts entering the Sacramento River at Verona for each race of Chinook salmon.
2. Fish Behavior at Junctions, which models fish movement as they approach river junctions.
3. Migration Speed, which models reach-specific smolt migration speed and travel time.
4. Route-Specific Survival, which models route-specific survival response to non-flow factors.
5. Flow-Dependent Survival, which models reach-specific survival response to flow.
6. Export-Dependent Survival, which models survival response to water export levels in the Interior Delta reach.

Functional relationships are described in detail in the *Model Functions* section below.

Model Time Step

The DPM operates on a daily time step using simulated flow data and Delta exports as model inputs. The DPM does not attempt to represent sub-daily flows or diel salmon smolt behavior in response to the interaction of tides, flows, and specific channel features. The DPM is intended to represent the net outcome of migration and mortality occurring over one day, not three-dimensional movements occurring over minutes or hours (e.g., Blake and Horn 2003).

Spatial Framework

The DPM version used for this Project is composed of eight reaches and two junctions (Figure 2; Table 4) selected to represent primary salmonid migration corridors where high-quality data were available for fish and hydrodynamics. For simplification, Sutter Slough and Steamboat Slough are combined as the reach SS; and Georgiana Slough, the Delta Cross Channel (DCC), and the forks of the Mokelumne River to which the DCC leads are combined as Geo/DCC. The Geo/DCC reach can be entered by Sacramento Chinook salmon runs through the combined junction of Georgiana Slough and DCC (Junction C). The Interior Delta reach can only be entered from Geo/DCC. Because of the lack of data informing specific routes through the Interior Delta, or tributary-specific survival, the entire Interior Delta region is treated as a single model reach. The four distributary junctions (channel splits) depicted in the DPM are (A) Sacramento River at Fremont Weir (not used for this Project), (B) Sacramento River at head of Sutter and Steamboat Sloughs, (C) Sacramento River at the combined junction with Georgiana Slough and DCC, and (D) San Joaquin River at the head of Old River (not used for this Project). The proportion of fish entering Yolo was set to zero for this Project because the confluence of the Feather River is downstream of this junction. Additionally, survival was not estimated for San Joaquin or Mokelumne rivers because the proposed Project would not affect these systems.

Table 4. Description of Modeled Reaches and Junctions in the Delta Passage Model

Reach/ Junction	**Description**	**Reach Length (km)**
Sac1	Sacramento River from Freeport to junction with Sutter/Steamboat Sloughs	19.33
Sac2	Sacramento River from Sutter/Steamboat Sloughs junction to junction with Delta Cross Channel/Georgiana Slough	10.78
Sac3	Sacramento River from Delta Cross Channel junction to Rio Vista, California	22.37
Sac4	Sacramento River from Rio Vista, California to Chipps Island	23.98
Verona	Fremont Weir to Freeport	57
SS	Combined reach of Sutter Slough and Steamboat Slough ending at Rio Vista, California	26.72
Geo/DCC	Combined reach of Georgiana Slough, Delta Cross Channel, and South and North Forks of the Mokelumne River ending at confluence with the San Joaquin River in the Interior Delta	25.59
Interior Delta	Begins at end of reach Geo/DCC, San Joaquin River via Junction D, or Old River via Junction D, and ends at Chipps Island	NA[a]
B	Combined junction of Sutter Slough and Steamboat Slough with the Sacramento River	NA

Reach/ Junction	Description	Reach Length (km)
C	Combined junction of the Delta Cross Channel and Georgiana Slough with the Sacramento River	NA
[a] Reach length for the Interior Delta is undefined because salmon can take multiple pathways. Also, timing through the Interior Delta does not affect Delta survival because there are no Delta reaches located downstream of the Interior Delta.		

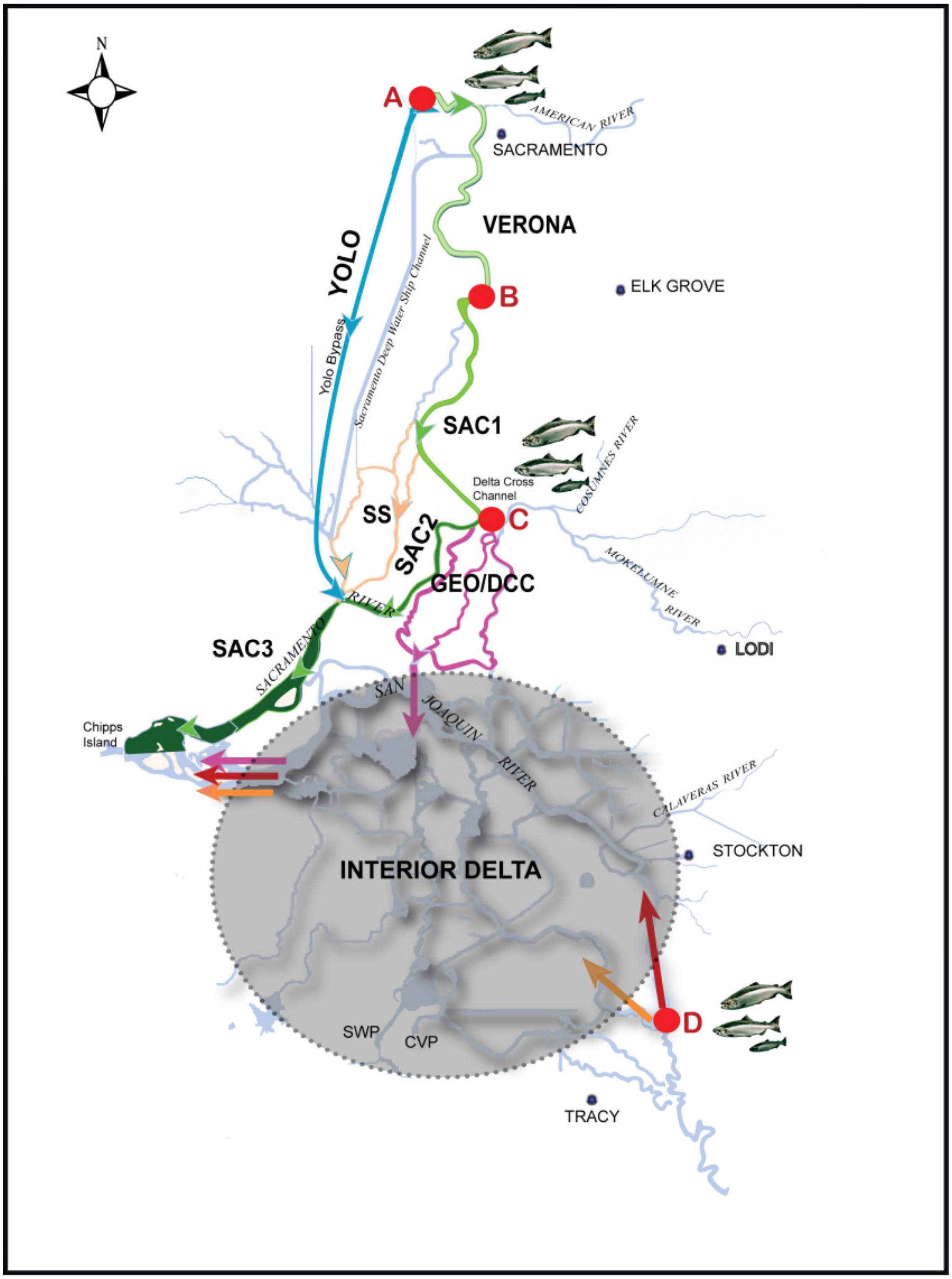


Figure 2. Map of the Sacramento–San Joaquin River Delta Showing the Modeled Reaches and Junctions of the Delta applied in the Delta Passage Model. Bold headings label modeled reaches, and red circles indicate model junctions. Salmonid icons indicate locations where smolts enter the Delta in the DPM. The Yolo reach and junction was not included in this analysis. Smolts enter the Interior Delta from the Geo/DCC reach or from Junction D via Old River or from the San Joaquin River. The San Joaquin and Mokelumne rivers were not modeled in the current Project because the proposed Project would not affect flow in those systems. Because of the lack of data informing specific routes through the Interior Delta, and tributary-specific survival, the entire Interior Delta region is treated as a single model reach.

Flow Input Data

Water movement through the Delta as input to the DPM is derived from monthly (tidally averaged) flow output produced by CALSIM-II. The nodes in CALSIM II that were used to provide flow for specific reaches in the DPM are shown in Table 5.

Table 5. Delta Passage Model Reaches and Associated Output Locations from CALSIM II.

DPM Reach or Model Component	CALSIM Node
Sac1	C169
Sac2	C400
Sac3	C401A
Sac4	C402A
Verona	NA
SS	-1811.574+(Sac1*0.3608831)
Geo/DCC	C401B
South Delta Export Flow	Delta Exports

Model Functions

Delta Entry Timing

Recent sampling data on Delta entry timing of emigrating juvenile smolts for three Central Valley Chinook salmon runs were used to inform the daily proportion of juveniles entering the Delta for each run (Table 6). Because the DPM models the survival of smolt-sized juvenile salmon, pre-smolts were removed from catch data before creating entry timing distributions. The lower 95th percentile of the range of salmon fork lengths visually identified as smolts by the USFWS in Sacramento trawls was used to determine the lower length cutoff for smolts. A lower fork length cutoff of 70 mm for smolts was applied, and all catch data of fish smaller than 70 mm were eliminated. To isolate wild production, all fish identified as having an adipose-fin clip (hatchery production) were eliminated, recognizing that most of the fall-run hatchery fish released upstream of Sacramento are not marked. Daily catch data for each brood year were divided by total annual catch to determine the daily proportion of smolts entering the Delta for each brood year. Sampling was not conducted daily at most stations and catch was not expanded for fish caught but not measured. Finally, the daily proportions for all brood years were plotted for each race, and a normal distribution was visually approximated to obtain the daily proportion of smolts entering the DPM for each run (Figure 3). Because a bi-modal distribution appeared evident for winter-run entry timing, a generic probability density function was fit to the winter-run daily proportion data using the package “sm” in R software (R Core Team 2012). The R fitting procedure estimated the best-fit probability distribution of the daily proportion of fish entering the DPM for winter-run. Timing of Delta entry was backed up to Verona for each run based on estimates of travel time in the reach between Verona and Sacramento calculated from acoustic tag data (Michel 2010).

Table 6. Sampling Gear Used to Create Juvenile Delta Entry Timing Distributions for Each Central Valley Run of Chinook Salmon

Chinook Salmon Run	Gear	Agency	Brood Years
Sacramento River Winter Run	Trawls at Sacramento	USFWS	1995–2009
Sacramento River Spring Run	Trawls at Sacramento	USFWS	1995–2005
Sacramento River Fall Run	Trawls at Sacramento	USFWS	1995–2005

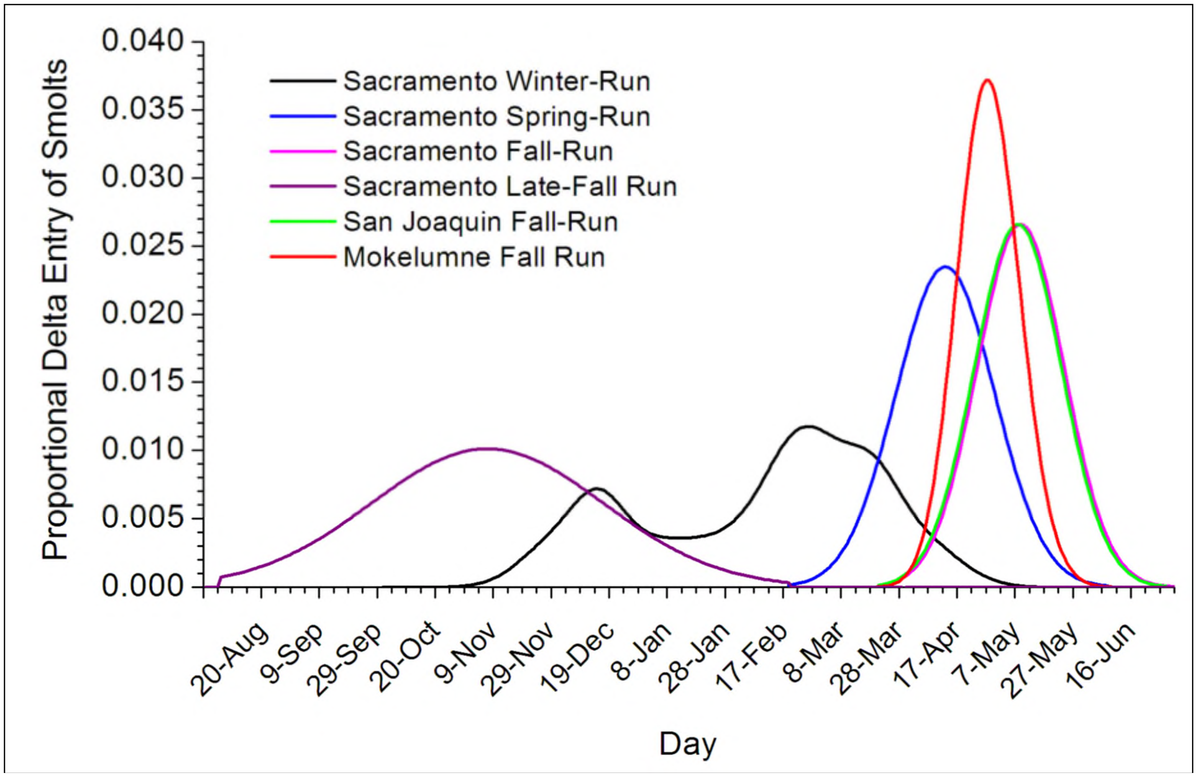


Figure 3. Delta Entry Distributions for Chinook Salmon Smolts Applied in the Delta Passage Model for Sacramento River Winter-Run, Sacramento River Spring-Run, Sacramento River Fall-Run, Sacramento River Late Fall–Run, San Joaquin River Fall-Run, and Mokelumne River Fall-Run Chinook Salmon. For this Project, only spring-winter and fall run in the Sacramento River were modeled.

Migration Speed

The DPM assumes a net daily movement of smolts in the downstream direction. The rate of smolt movement in the DPM affects the timing of arrival at Delta junctions and reaches, which can affect route selection and survival as flow conditions or water project operations change.

Smolt movement in all reaches except the Interior Delta is a function of reach-specific length and migration speed as observed from acoustic-tagging results. Reach-specific length (kilometers

[km]) (Table 4) is divided by reach migration speed (km/day) the day smolts enter the reach to calculate the number of days smolts will take to travel through the reach.

For north Delta reaches Verona, Sac1, Sac2, SS, and Geo/DCC, mean migration speed through the reach is predicted as a function of flow. Many studies have found a positive relationship between juvenile Chinook salmon migration rate and flow in the Columbia River Basin (Raymond 1968; Berggren and Filardo 1993; Schreck et al. 1994), with Berggren and Filardo (1993) finding a logarithmic relationship for Snake River yearling Chinook salmon. Ordinary least squares regression was used to test for a logarithmic relationship between reach-specific migration speed (km/day) and average daily reach-specific flow (cubic meters per second [m^3/sec]) for the first day smolts entered a particular reach for reaches where acoustic-tagging data was available (Sac1, Sac2, Sac3, Sac4, Geo/DCC, and SS):

$$Speed = \beta_0 \ln(flow) + \beta_1;$$

Where β_0 is the slope parameter and β_1 is the intercept.

Individual smolt reach-specific travel times were calculated from detection histories of releases of acoustically-tagged smolts conducted in December and January for three consecutive winters (2006/2007, 2007/2008, and 2008/2009) (Perry 2010). Reach-specific migration speed (km/day) for each smolt was calculated by dividing reach length by travel days (Table 7). Flow data was queried from the DWR's California Data Exchange website (<http://cdec.water.ca.gov/>).

Table 7. Reach-Specific Migration Speed and Sample Size of Acoustically-Tagged Smolts Released during December and January for Three Consecutive Winters (2006/2007, 2007/2008, and 2008/2009)

Reach	Gauging Station ID	Release Dates	Sample Size	Speed (km/day)			
				Avg	Min	Max	SD
Sac1	FPT	12/05/06–12/06/06, 1/17/07–1/18/07, 12/04/07–12/07/07, 1/15/08–1/18/08, 11/30/08–12/06/08, 1/13/09–1/19/09	452	13.32	0.54	41.04	9.29
Sac2	SDC	1/17/07–1/18/07, 1/15/08–1/18/08, 11/30/08–12/06/08, 1/13/09–1/19/09	294	9.29	0.34	10.78	3.09
Sac3	GES	12/05/06–12/06/06, 1/17/07–1/18/07, 12/04/07–12/07/07, 1/15/08–1/18/08, 11/30/08–12/06/08, 1/13/09–1/19/09	102	9.24	0.37	22.37	7.33
Sac4	GES[a]	12/05/06–12/06/06, 1/17/07–1/18/07, 12/04/07–12/07/07, 1/15/08–1/18/08, 11/30/08–12/06/08, 1/13/09–1/19/09	62	8.60	0.36	23.98	6.79

Reach	Gauging Station ID	Release Dates	Sample Size	Speed (km/day)			
				Avg	Min	Max	SD
Geo/DCC	GSS	12/05/06–12/06/06, 1/17/07–1/18/07, 12/04/07–12/07/07, 1/15/08–1/18/08, 11/30/08–12/06/08, 1/13/09–1/19/09	86	14.20	0.34	25.59	8.66
SS	FPT-SDC[b]	12/05/06–12/06/06, 12/04/07–12/07/07, 1/15/08–1/18/08, 11/30/08–12/06/08, 1/13/09–1/19/09	30	9.41	0.56	26.72	7.42

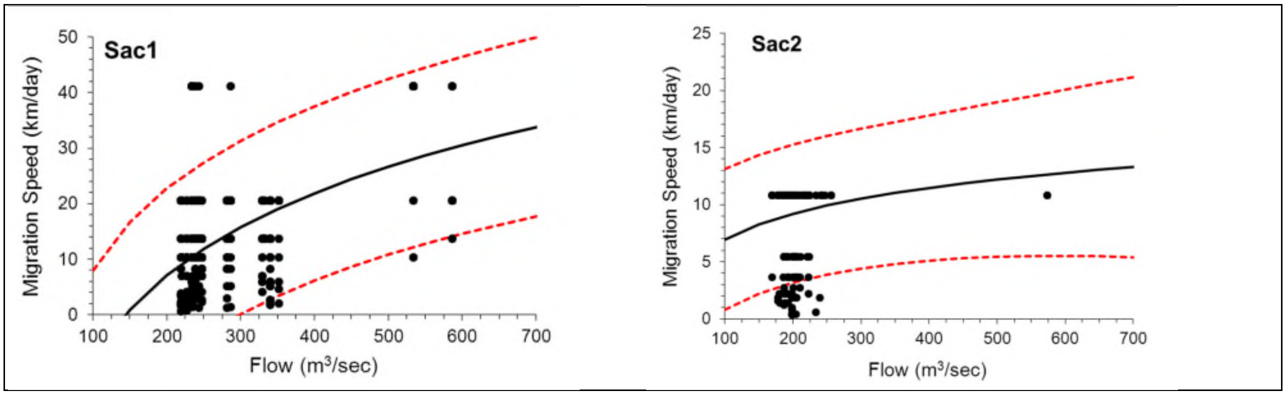
[a] Sac3 flow is used for Sac4 because no flow gauging station is available for Sac4.

[b] SS flow is calculated by subtracting Sac2 flow (SDC) from Sac1 flow (FPT).

Migration speed was significantly related to flow for reaches Sac1 (df = 450, F = 164.36, P < 0.001), Sac2 (df = 292, F = 4.17, P = 0.042), and Geo/DCC (df = 84, F = 13.74, P <0.001). Migration speed increased as flow increased for all three reaches (Figure 4). Therefore, for reaches Sac1, Sac2, and Geo/DCC, the regression coefficients shown in Table 8 are used to calculate the expected average migration rate given the input flow for the reach and the associated standard error of the regressions is used to inform a normal probability distribution that is sampled from the day smolts enter the reach to determine their migration speed throughout the reach. The minimum migration speed for each reach is set at the minimum reach-specific migration speed observed from the acoustic-tagging data (Table 7). The flow-migration rate relationship that was used for Sac1 also was applied for the Verona reach.

Table 8. Sample Size and Slope (β_0) and Intercept (β_1) Parameter Estimates with Associated Standard Error (in Parenthesis) for the Relationship between Migration Speed and Flow for Reaches Sac1, Sac2, and Geo/DCC.

Reach	N	β_0	β_1
Sac1	452	21.34 (1.66)	-105.98 (9.31)
Sac2	294	3.25 (1.59)	-8.00 (8.46)
Geo/DCC	86	11.08 (2.99)	-33.52 (12.90)



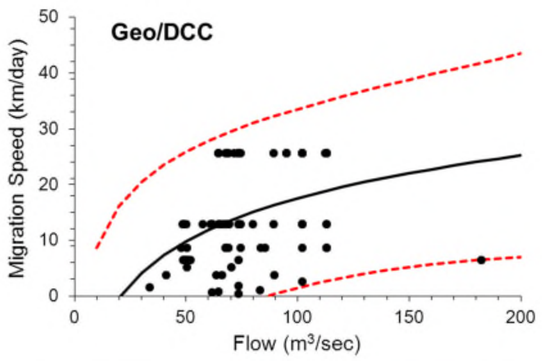


Figure 4. Reach-Specific Migration Speed (km/day) as a Function of Flow (m3/sec) Applied in Reaches Sac1, Sac2, and Geo/DCC. Circles are observed migration speeds of acoustically-tagged smolts from acoustic-tagging studies from Perry (2010), solid lines are predicted mean reach survival curves, and dotted lines are 95% prediction intervals used to inform uncertainty.

No significant relationship between migration speed and flow was found for reaches Sac3 (df = 100, F = 1.13, P =0.29), Sac4 (df = 60, F = 0.33, P = 0.57), and SS (df = 28, F = 0.86, P = 0.36). Therefore, for these reaches the observed mean migration speed and associated standard deviation (Table 7) is used to inform a normal probability distribution that is sampled from the day smolts enter the reach to determine their migration speed throughout the reach. As applied for reaches Sac1, Sac2, and Geo/DCC, the minimum migration speed for reaches Sac3, Sac4, and SS is set at the minimum reach-specific migration speed observed from the acoustic-tagging data (Table 7).

The travel time of smolts migrating through the Interior Delta in the DPM is informed by observed mean travel time (7.95 days) and associated standard deviation (6.74) from North Delta acoustic-tagging studies (Perry 2010). However, the timing of smolt passage through the Interior Delta does not affect Delta survival because there are no Delta reaches located downstream of the Interior Delta.

Fish Behavior at Junctions (Channel Splits)

Perry et al. (2010) found that acoustically-tagged smolts arriving at Delta junctions exhibited inconsistent movement patterns in relation to the flow being diverted. For Junction B (Sacramento River-Sutter/Steamboat Sloughs), Perry et al. (2010) found that smolts consistently entered downstream reaches in proportion to the flow being diverted. Therefore, smolts arriving at Junction B in the model move proportionally with flow. For Junction C (Sacramento River–Georgiana Slough/DCC), Perry (2010) found a linear, nonproportional relationship between flow and fish movement. His relationship for Junction C was applied in the DPM:

$$y = 0.22 + 0.47x;$$

where y is the proportion of fish diverted into Geo/DCC and x is the proportion of flow diverted into Geo/DCC (Figure 5).

In the DPM, this linear function is applied to predict the daily proportion of fish movement into Geo/DCC as a function of the proportion of flow into Geo/DCC.

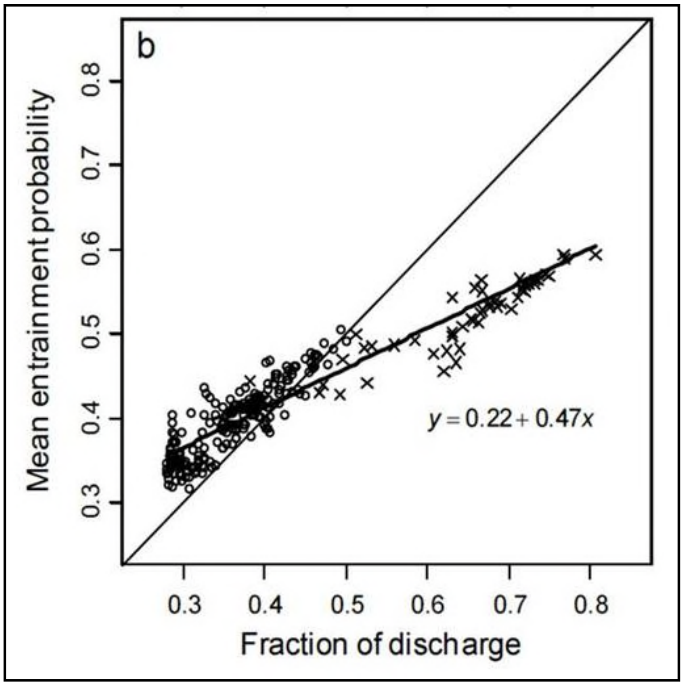


Figure 5. Figure from Perry (2010) Depicting the Mean Entrainment Probability (Proportion of Fish Being Diverted into Reach Geo/DCC) as a Function of Fraction of Discharge (Proportion of Flow Entering Reach Geo/DCC). Circles Depict DCC Gates Closed, Crosses Depict DCC Gates Open.

Route-Specific Survival

Survival through a given route (individual reach or several reaches combined) is calculated and applied the first day smolts enter the reach. For reaches where literature showed support for reach-level responses to environmental variables, survival is influenced by flow (Sac1, Sac2, Sac3 and Sac4 combined, SS and Sac 4 combined, Interior Delta via San Joaquin River, and Interior Delta via Old River) or south Delta water exports (Interior Delta via Geo/DCC). For these reaches, daily flow or exports occurring the day of reach entry are used to predict reach survival during the entire migration period through the reach (Table 9). For Geo/DCC, reach survival is assumed to be unaffected by Delta conditions and is informed by the mean and standard deviation of survival from acoustic-tagging studies.

Table 9. Route-Specific Survival and Parameters Defining Functional Relationships or Probability Distributions for Each Chinook Salmon Run and Methods Section Where Relationship is Described.

Route	Chinook Salmon Run	Survival	Methods Section Description
Verona	All Sacramento runs	0.931 (0.02)	This section
Sac1	All Sacramento runs	Function of flow	Flow-Dependent Survival
Sac2	All Sacramento runs	Function of flow	Flow-Dependent Survival

Sac3 and Sac4 combined	All Sacramento runs	Function of flow	Flow-Dependent Survival
SS and Sac4 combined	All Sacramento runs	Function of flow	Flow-Dependent Survival
Geo/DCC	All Sacramento runs	0.65 (0.126)	This section
Interior Delta	All Sacramento runs	Function of exports	Export-Dependent Survival

For reach Geo/DCC, no empirical data were available to support a relationship between survival and Delta flow conditions (channel flow, exports). Therefore, for these reaches mean reach survival is used along with reach-specific standard deviation to define a normal probability distribution that is sampled from when smolts enter the reach to determine reach survival (Table 9).

Mean reach survival and associated standard deviation for Geo/DCC are informed by survival data from smolt acoustic-tagging studies from Perry (2010). Smolts migrating down the Sacramento River during the acoustic-tagging studies could enter the DCC or Georgiana Slough when the DCC was open (December releases), therefore, group survivals for both routes are used to inform the mean survival and associated standard deviation for the Geo/DCC reach for Sacramento River runs (Table 10).

Mean survival and associated standard deviation for the Verona reach between Fremont Weir and Yolo Bypass were derived from the 2007–2009 acoustic-tag study reported by Michel (2010), who did not find a flow-survival relationship for that reach.

Table 10. Individual Release-Group Survival Estimates, Release Dates, Data Sources, and Associated Calculations Used to Inform Reach-Specific Mean Survivals and Standard Deviations Used in the Delta Passage Model for Reaches Where Survival Is Uninfluenced by Delta Conditions.

DPM Reach	Survival	Release Dates	Survival Calculation	Mean	Standard Deviation
Geo/DCC via Sacramento River	0.648	12/05/06	S_{D1}	0.559	0.194
	0.600	12/04/07–12/06/07	$S_{D1,SAC}*S_{D2}$		
	0.762	1/15/08–1/17/08	$S_{D1,SAC}*S_{D2}$		
	0.774	11/31/08–12/06/08	$S_{D1,SAC}*S_{D2}$		
	0.467	1/13/08–1/19/09	$S_{D1,SAC}*S_{D2}$		
	0.648	12/05/06	$S_{C1}* S_{C2}$		
	0.286	12/04/07–12/06/07	S_{C1}		
	0.286	11/31/08–12/06/08	S_{C1}		

DPM Reach	Survival	Release Dates	Survival Calculation	Mean	Standard Deviation
Source: Perry 2010.					

Flow-Dependent Survival
For reaches Sac1, Sac2, Sac3 and Sac4 combined and SS and Sac4 combined, flow values on the day of route entry are used to predict route survival. Perry (2010) evaluated the relationship between survival among acoustically-tagged Sacramento River smolts and Sacramento River flow measured below Georgiana Slough (DPM reach Sac3) and found a significant relationship between survival and flow during the migration period for smolts that migrated through Sutter and Steamboat Sloughs to Chipps Island (Sutter and Steamboat route; SS and Sac4 combined) and smolts that migrated from the junction with Georgiana Slough to Chipps Island (Sacramento River route; Sac3 and Sac4 combined). Therefore, for route Sac3 and Sac4 combined and route SS and Sac4 combined, the logit survival function from Perry (2010) was used to predict mean reach survival (S) from reach flow ($flow$):

$$S = \frac{e^{(\beta_0 + \beta_1 flow)}}{1 + e^{(\beta_0 + \beta_1 flow)}}$$

where β_0 (SS and Sac4 = -0.175, Sac3 and Sac4 = -0.121) is the reach coefficient and β_1 (0.26) is the flow coefficient, and *flow* is average Sacramento River flow in reach Sac3 during the experiment standardized to a mean of 0 and standard deviation of 1.

Perry (2010) estimated the global flow coefficient for the Sutter Steamboat route and Sacramento River route as 0.52. For the Sac3 and Sac4 combined route and the SS and Sac4 combined route, mean survival and associated standard error predicted from each flow-survival relationship is used to inform a normal probability distribution that is sampled from the day smolts enter the route to determine their route survival.

With a flow-survival relationship appearing evident for group survival data of acoustically-tagged smolts in reaches Sac1 and Sac2, Perry's (2010) relationship was applied to Sac1 and Sac2 while adjusting for the mean reach-specific survivals for Sac1 and Sac2 observed during the acoustic-tagging studies (Figure 6; Table 11). The flow coefficient was held constant at 0.52 and the residual sum of squares of the logit model was minimized about the observed Sac1 and Sac2 group survivals, respectively, while varying the reach coefficient. The resulting reach coefficients for Sac1 and Sac2 were 1.27 and 2.16, respectively. Mean survival and associated standard error predicted from the flow-survival relationship is used to inform a normal probability distribution that is sampled from the day smolts enter the reach to determining Sac1 and Sac2 reach survival.

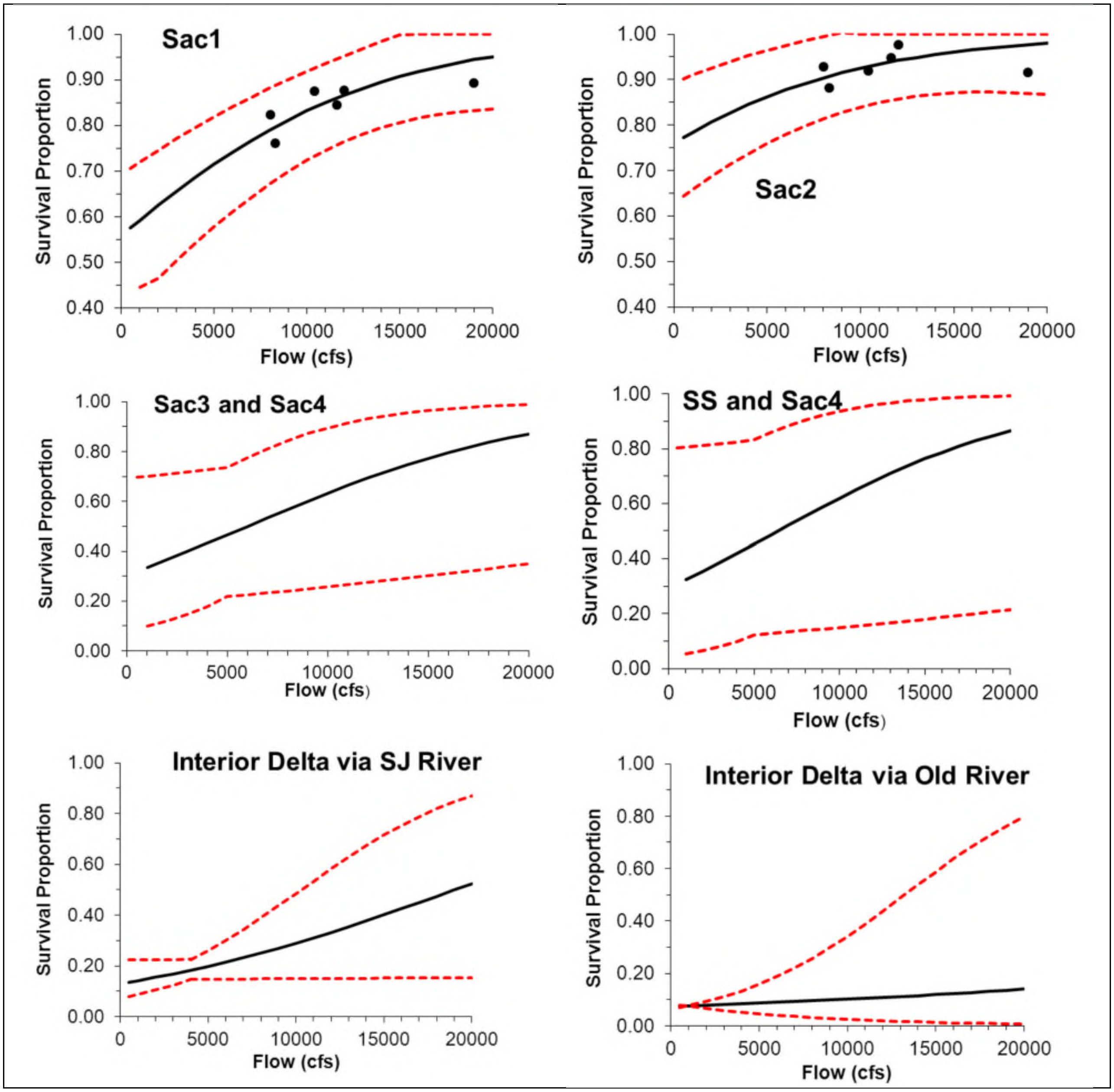


Figure 6. Route Survival as a Function of Flow Applied in Reaches Sac1, Sac2, Sac3 and Sac4 combined, SS and Sac4 combined, Interior Delta via the San Joaquin River, and Interior Delta via Old River For Sac1, Sac2, Sac3, and Sac4, circles are observed group survivals from acoustic-tagging studies from Perry (2010). Raw data are not available from Newman (2010) for Interior Delta via San Joaquin River and Interior Delta via Old River from Newman (2010). Solid lines are predicted mean route survival curves, and dotted lines are 95% confidence bands used to inform uncertainty. Survival of smolts through the Interior Delta via the San Joaquin and Old River were not modeled in the current Project.

Table 11. Group Survival Estimates of Acoustically-Tagged Chinook Salmon Smolts from Perry (2010) and Associated Calculations Used to Inform Flow-Dependent Survival Relationships for Reaches Sac1 and Sac2.

DPM Reach	Survival	Release Dates	Source	Survival Calculation
Sac1	0.844	12/5/06	Perry 2010	$S_{A1} * S_{A2}$
Sac1	0.876	1/17/07	Perry 2010	$S_{A1} * S_{A2}$
Sac1	0.874	12/4/07-12/6/07	Perry 2010	$S_{A1} * S_{A2}$
Sac1	0.892	1/15/08-1/17/08	Perry 2010	$S_{A1} * S_{A2}$

Sac1	0.822	11/31/08-12/06/08	Perry 2010	S_{A1} *S_{A2}
Sac1	0.760	1/13/09-1/19/09	Perry 2010	S_{A1} *S_{A2}
Sac2	0.947	12/5/06	Perry 2010	S_{A3}
Sac2	0.976	1/17/07	Perry 2010	S_{A3}
Sac2	0.919	12/4/07-12/6/07	Perry 2010	S_{A3}
Sac2	0.915	1/15/08-1/17/08	Perry 2010	S_{A3}
Sac2	0.928	11/31/08-12/06/08	Perry 2010	S_{A3}
Sac2	0.881	1/13/09-1/19/09	Perry 2010	S_{A3}

Exports are standardized as described for flow. Uncertainty in these parameters is accounted for by using model-averaged estimates for the intercept, flow coefficient and export coefficient. The model-averaged estimates and their standard deviations are used to define a normal probability distribution that is resampled each day in the model. San Joaquin River flows downstream of the head of Old River that were modeled by Newman (2010) ranged from -49 cfs to 10,756 cfs, with a median of 3,180 cfs. Exports modeled by Newman (2010) ranged from 805 cfs to 10,295 cfs, with a median of 2,238 cfs.

Export-Dependent Survival

As migratory juvenile salmon enter the Interior Delta from Geo/DCC for Sacramento races they transition to an area strongly influenced by tides and where south Delta water exports may influence survival. The export–survival relationship described by Newman and Brandes (2010) was applied as follows:

$$\theta = 0.5948 * e^{(-0.000065 * Total\_Exports)}$$

where θ is the ratio of survival between coded wire tagged smolts released into Georgiana Slough and smolts released into the Sacramento River and Total_Exports is the flow of water (cfs) pumped from the Delta from the State and Federal facilities.

θ is a ratio and ranges from just under 0.6 at zero south Delta exports to ~0.27 at 12,000-cfs south Delta exports (Figure 7).

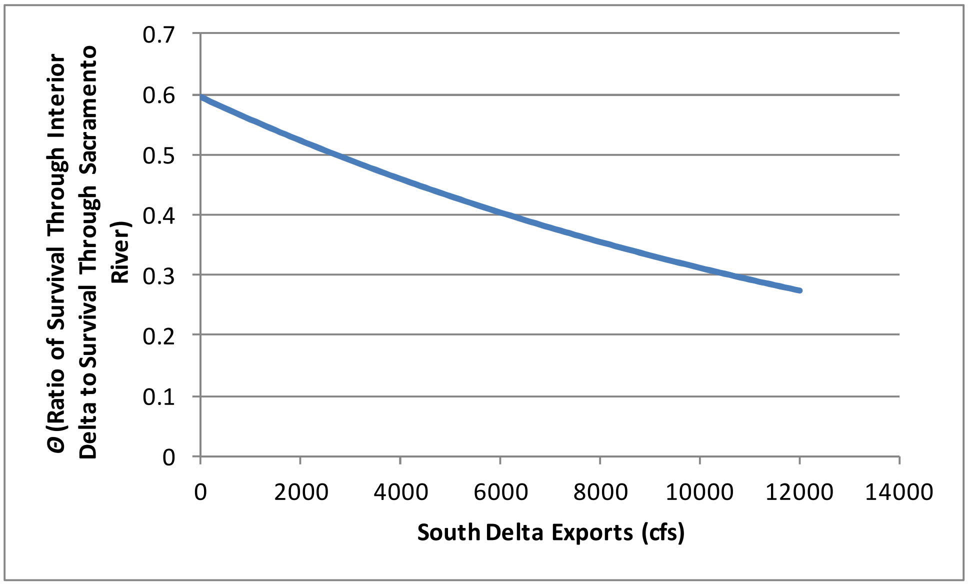


Figure 7. Relationship between θ (Ratio of Survival through the Interior Delta to Survival through Sacramento River) and South Delta Export Flows. Source: Newman and Brandes 2010.

θ was converted from a ratio into a value of survival through the Interior Delta using the equation:

$$S_{ID} = \frac{\theta}{S_{Geo/DCC}} * (S_{Sac3} * S_{Sac4});$$

where S_{ID} is survival through the Interior Delta, θ is the ratio of survival between Georgiana Slough and Sacramento River smolt releases, $S_{Geo/DCC}$ is the survival of smolts in the Georgiana Slough/Delta Cross Channel reach, $S_{Sac3} * S_{Sac4}$ is the combined survival in reaches Sac 3 and Sac 4 (Figure 8).

Uncertainty is represented in this relationship by using the estimated value of θ and the standard error of the equation to define a normal distribution bounded by the 95% prediction interval of the model that is then re-sampled each day to determine the value of θ.

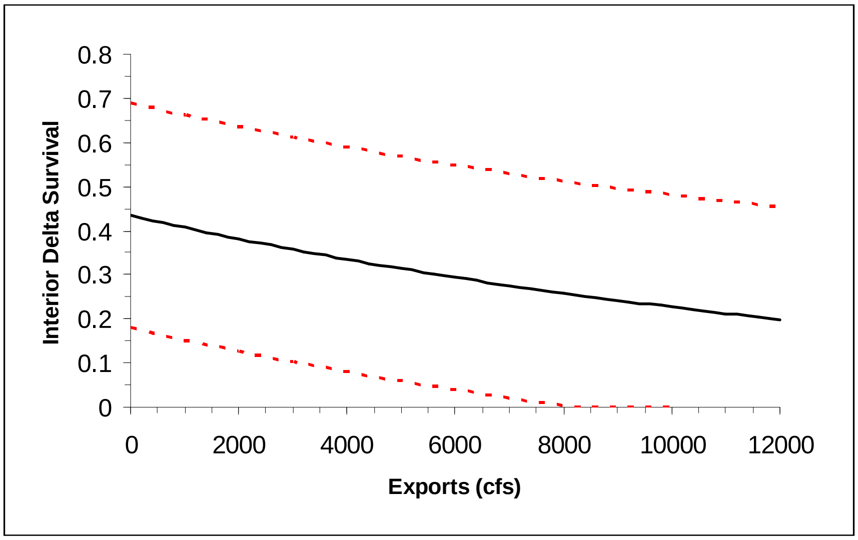


Figure 8. Interior Delta Survival as a Function of Delta Exports (Newman and Brandes 2010) as Applied for Sacramento Races of Chinook Salmon Smolts Migrating through the Interior Delta via Reach Geo/DCCSurvival values in reaches Sac3, Sac4, and Geo/DCC were held at mean values observed during acoustic-tag studies (Perry 2010) to depict export effect on Interior Delta survival in this plot. Dashed lines are 95% prediction bands used to inform uncertainty in the relationship.

2.1.3. Bay Smolt to Adult Return Analysis

Total annual adult returns of spring-run Chinook salmon were calculated as

$$(Sm_{FRH}+Sm_{FRW}+Sm_{SSRC})*S_{DPM\_SRC}*S_a$$

and total annual adult returns of winter-run Chinook salmon were calculated as

$$Sm_{SWRC}*S_{DPM\_WRC}*S_a$$

Where…
S_{DPM_SRC} is the DPM-based estimate of survival for spring-run Chinook smolts to Delta exit;

S_{DPM_WRC} is the DPM-based estimate of survival for winter-run Chinook smolts to Delta exit;
and where S_a is survival rate for smolts exiting the Delta to return as adults.

As discussed by Zeug et al. (2012), O'Farrell et al. (2012), Winship et al. (2014), Araujo et al. (2015), and others, smolt to adult survival is a function of factors including age and year specific natural mortality, age and year specific harvest mortality, and age at maturity. Since variation in these factors would not be influenced by the Project, we simplified by assuming all salmon matured at age-3 and that no harvest occurred until age-3. With these assumptions, smolt to adult mortality (S_a) was calculated as

$$M_2*M_W*H_3$$

where M_2 is the survival of smolts to age-2, where M_w is overwinter survival of age-2 fish and where H_3 represents the fraction of fish surviving harvest and returning to spawn. Based upon Zeug et al. (2012) we fixed parameter values at 0.64 for M_w and at 0.75 for H_3. Since smolt to adult mortality is known to vary widely from year-to-year and among salmon populations (see Bradford et al. 1995), consistent with Zeug et al. (2012) we allowed M_2 to vary from a mean of 0.03, to a maximum value of 0.04 and to a minimum value of 0.02. The resulting range of values for S_a are shown in Table 2 and also reflected in the summary of results shown in Table 12. The estimated range for S_a are consistent with findings reported by Bradford et al. (1995), Araujo et al. (2015), Winship et al. (2014), O'Farrell et al. (2012), and are therefore considered appropriate for their application to evaluating the proposed Project.

2.2. Green sturgeon

Green sturgeon are a species of ancient fish, highly adapted to benthic environments. Though primarily marine oriented (including bays, estuaries and near coastal environments), adult green sturgeon enter freshwater to spawn. Green sturgeon migrate to freshwater spawning habitats in March-April and spawn from April through June (NMFS 2016). Green sturgeon are broken into two distinct population segments (DPSs): a northern DPS (nDPS) and a southern DPS (sDPS). Currently only the sDPS is listed under the Federal Endangered Species Act. In its 2006 final rule listing the sDPS green sturgeon as threatened, the National Marine Fisheries Services (NMFS) identified the loss of historical spawning habitat restricting spawning to a single river (the Sacramento) as a primary factor in the decline of the species.

Information on the abundance of Green Sturgeon in Central Rivers is limited. Available data suggest an average of 364 adult fish spawn in the Sacramento River, while 25 or fewer sDPS green sturgeon utilize the Feather River each year (NMFS 2016). Under current conditions, spawning in the Feather River is infrequent and consists of few fish relative to the Sacramento River. About Feather River green sturgeon, NMFS (2016) states:

> *"…we can tentatively say that the Feather River accounts for perhaps 2 to 9 percent of the sDPS green sturgeon population. While these numbers may seem low and perhaps insignificant, it is important to realize that the Feather River is highly valuable from a sDPS green sturgeon conservation perspective because the Feather River is the* ***only*** *place outside the Sacramento River where sDPS green sturgeon spawning has been documented, giving the Feather River a prominent role in the recovery of the species."*

The magnitude, duration and frequency of river flow during adult immigration and spawning is thought to be a key constraint on spawning success and adult abundance. On the Sacramento River, spring flow pulses are thought to be necessary for successful immigration and spawning (NMFS 2016). According to NMFS, the number of green sturgeon in the Feather River is likely dependent on flow and associated passage conditions. Green sturgeon in the Feather River are currently exposed to a simplified hydrograph that curtails flows in favor of reservoir storage during spring months. High spring flows associated with the natural hydrograph do not occur within the sections of the Feather River expected to be used by sDPS green sturgeon for spawning.

Flows can also be important for successful upstream passage. The Sunset Pumps diversion is thought to delay or block upstream passage during dry or critically dry water year types. DWR green sturgeon scientists have indicated flows ranging from 2,500 to 3,000cfs would be needed for adult sDPS green sturgeon passage at Sunset Pumps. The Feather River also provides an essential migration corridor for sDPS green sturgeon to access the Yuba River. Thus, Feather River spring flows can influence the migration of sDPS in both the Feather and Yuba Rivers.

Suitable water temperatures and spawning substrates are also important for successful spawning for sDPS green sturgeon. The NMFS indicates the Feather River provides 164,500 m^2 of deep pool habitat likely suitable for spawning. Similarly, water temperatures within potential spawning areas are optimal during the majority of the spawning and early rearing period (NMFS 2016). Thus, the absence of spring flow pulses is thought to be a key factor limiting green sturgeon in the Feather River.

2.2.1. Green Sturgeon Analysis

Spring flow pulse benefits to sDPS green sturgeon are difficult to quantify because empirical evidence specific to the Feather River is lacking. We therefore base our analysis upon observations available for sDPS green sturgeon on the Sacramento River. Specifically, we assume:

1. With a spring flow regime that effectively ameliorates passage problems and allows for successful immigration and spawning, the Feather River, like the Sacramento River, would support an average annual spawning population of 364 adult green sturgeon.
2. Base flows in the lower Feather River in April during dry or critically dry years will be 1,000 cfs (i.e. minimum required flows).

3. A two-week April flow pulse consisting of an additional 1,500 cfs (providing a total river flow of 2,500 cfs) in dry or critically dry years will be necessary (along with appropriate flows in other water year types) to achieve an average annual spawner abundance of 364 adult sDPS green sturgeon in the Feather River.
4. Providing an additional 1,500 cfs for two weeks requires 42 TAF of water to be released from the Oroville Facilities.
5. The annualized benefit to the sDPS green sturgeon population due to the spring flow pulse in (3) would be determined by the recurrence interval of the flow pulse. For example, a flow pulse that occurred in 1 out of every 10 years, would be credited for 10% of population benefit; an additional 36 adult green sturgeon for each year.
6. The annualized benefit to green sturgeon from (5) would be attributed to the Project based on the proportional contribution of the Project to the 42 TAF of water required for the flow pulse. Since the Project will yield 18 TAF toward each flow pulse, this value if 0.43.

2.3. Steelhead

Feather River natural and hatchery produced steelhead are designated as part of the California Central Valley (CCV) Distinct Population Segment (NMFS 2016b). Though natural origin CCV streelhead smolts occur in the Feather River, information on their abundance and emigration timing is highly uncertain (NMFS 2016b). In contrast, annual production of steelhead smolts by Feather River Hatchery (FRH) is well understood. FRH annually releases roughly 450,000 yearling CCV steelhead. FRH steelhead are released into the Feather River in late winter/early spring. For purposes of this analysis we assume all FRH steelhead releases will occur at Boyd's Pump. Boyd's pump is appropriate because it is a commonly used release site, and because it is the only Feather River location where releases have been intensively studied via acoustic tagging. Though future FRH release locations are unknown, the California Hatchery Scientific Review Group has recommended all hatchery production be released as close to the source hatchery as possible (CA HSRG 2012). Boyd's pump would appear the most downstream location that may satisfy CA HSRG recommendations. If future releases are instead made at locations upstream of Boyd's Pump, then this analysis would be underestimating (rather than overestimating) survival benefits associated with a flow pulse.

2.3.1. Feather River through Delta Analysis

Data and sources used to evaluate effects of the proposed Project on the survival of Feather River steelhead are summarized in Table 12. Related source flow data and calculations are available upon request in the Excel spreadsheet "FR_analysis_steelhead".

Table 32. Values, descriptions and sources for inputs and parameters used for the quantification of Project ecosystem benefits.

Name	Value	Description	Source
St_{FRH}	450,000	Annual FRH steelhead production.	NMFS 2016(a)
relf	0.25	Fraction of FRH steelhead smolts expected to be coordinated to coincide with flow pulse	NA
B0	-0.85	FRH steelhead survival to the Golden Gate (log base e scale)	See text
B1	1.47	Flow survival effect (log base e scale)	NMFS (2017), Table B1. See text for more details.
Qm	variable	Standardized Feather River flow by month	CALSIM output
Sa	0.0144	Mean survival rate for smolts to return as adults	Zeug et al. (2012). See text for more details.
Sa max	0.0192	Maximum survival rate for smolts to return as adults	Zeug et al. (2012). See text for more details.
Sa min	0.0096	Miimum survival rate for smolts to return as adults	Zeug et al. (2012). See text for more details.

The annual number of FRH steelhead smolts reaching the Golden Gate Bridge entering the (St_B) is estimated by

(eq4)

$$St_{FRH} * relf * surv_m$$

where survival for hatchery steelhead ($surv_m$) is modeled as a function of monthly Feather River flows

(eq5)

$$logit(surv_m) = B0 + B1 * Q_m$$

where B0 and B1 are model parameters (Table 1), and where Q_m is monthly Feather River flows standardized relative to all monthly Feather River flow observations (provided by CALSIM). Monthly flow data (1922 through 2003) representing two future conditions (2030 and 2070) and two scenarios (Project and no project) were provided by MBK Engineers (see MBK 2018). A total of four different CALSIM scenarios were analyzed.

The flow survival relationship (eq4) was developed by the NMFS Southwest Fishery Science Center as part of a life cycle modeling effort for winter-run Chinook salmon (NMFS 2017). The NMFS LCM is under continuous development, but the model (including this flow-survival function) were used in the NMFS Biological Opinion for California Water Fix (http://www.westcoast.fisheries.noaa.gov/central_valley/CAWaterFix.html). Of course, survival differences between the Sacramento-Feather Rivers and between winter-run Chinook and steelhead are expected. To address these expected differences, we utilized available steelhead acoustic tagging data to estimate B0, but relied upon the estimate of B1 from NMFS (2017). We utilized FRH steelhead survival estimates provided by Kurth and Hampton (2017) who estimated an average survival rate of 0.30 from Boyd's Pump to Verona (Feather River confluence with the Sacramento River). Zeug et al. (2016) estimated survival of 0.45 for acoustically tagged hatchery steelhead smolts from the Sacramento River to the Golden Gate Bridge. The combined survival for these two reaches is 0.13 (i.e. 0.30*0.45) representing survival from Boyd's Pump on the Feather River to ocean entry at the Golden Gate Bridge. Transforming 0.13 as necessary for the logit scale shown in eq2 yields a value of -0.85 for B0 (see Table 12). The resulting relationship between Feather River flow and steelhead survival is depicted in Figure 9. It is important to note that this relationship assumes the Feather River flow pulse provides benefits in both the Sacramento and Feather River, but also does not credit (or discount) the effects of Sacramento River flow changes- effectively assuming Sacramento River flows during FRH steelhead emigration are effectively neutral between Project and Non-Project conditions. CALSIM results reported by MBK indicate this is a reasonable assumption. The Delta Passage Model (DPM) was used to assess Delta effects for spring-run and winter-run Chinook salmon, but was not used for steelhead because of insufficient information from Delta acoustic tagging studies for this species.

Ideally, a Feather River flow-survival relationship would be based solely upon observations from the Feather River. However, since few observations of Feather River survival were available, we combined available Feather River information with findings from the NMFS winter-run Chinook life cycle modeling effort. Though there is uncertainty about the Feather River flow-survival relationship depicted in Figure 9, scientific literature Central Valley tributaries affirms a positive relationship between Feather River flow and juvenile salmon survival is likely. Investigations into the relationship between river discharge and juvenile salmon survival in the Central Valley have primarily focused on the Sacramento-San Joaquin Delta and several studies have reported significant positive relationships (Newman 2003, Perry 2010). Less attention has been focused on the Feather River or other upstream tributaries. However, there are multiple lines of evidence to suggest a positive flow-survival relationship operates in the Feather River. Within the Central Valley, Zeug et al. (2014) reported a significant positive relationship between river discharge (and discharge variability) and survival for juvenile Chinook salmon in the Stanislaus River. Additionally, Perry et al. (2018) found that survival increased in delta reaches when high levels of discharge resulted in a switch from bi-directional to unidirectional flow. A positive flow survival relationship for Chinook salmon during spring in the Snake River was reported by Smith et al. (2003). However, flow was correlated with turbidity and temperature complicating attempts to separate out effects. Regardless of the causal mechanism it is clear that increases in flow result in more favorable conditions for juvenile Chinook survival during migration.

Flow pulses produced by the Project occurred exclusively in dry years, with Feather River base flows at less than 3,000cfs. The estimated survival under these conditions occurs at the left side of the curve depicted in Figure 9.

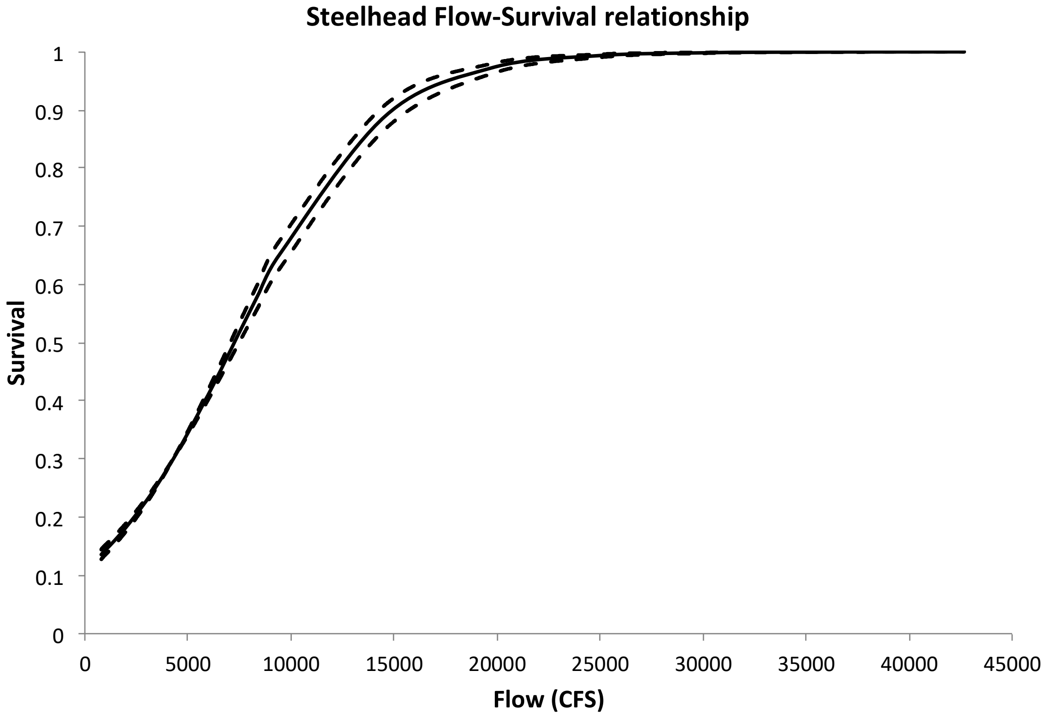


Figure 9. Estimated flow-survival relationship for juvenile Feather River Hatchery steelhead. Plotted flows are for the Feather River only- Sacramento River flows are not included in this relationship. Dashed lines indicate standard deviation associated with parameter B1 as estimated by NMFS (2017).

2.3.2. Bay Smolt to Adult Return Analysis

Total annual adult returns of steelhead were calculated as

$$St_B * S_a$$

where S_a is survival rate for steelhead smolts from Bay exit to return as adults.

Survival probabilities for smolts returning to freshwater as adults are relatively well understood for Chinook salmon (see Zeug et al. 2012, Araujo et al. 2015, Winship et al. 2014, O'Farrell et al. 2012), but are less documented for steelhead. Unlike salmon, steelhead are iteroparous spawners and exhibit other complex life histories which complicate estimation of survival from ocean entry to adult return. Given the lack of steelhead specific estimates, we rely upon available Chinook salmon information.

For Chinook salmon, smolt to adult survival is a function of factors including age and year specific natural mortality, age and year specific harvest mortality, and age at maturity. Since variation in these factors would not be influenced by the Project, we simplified by assuming all steelhead matured at age-3 and that no harvest occurred until age-3. With these assumptions, smolt to adult mortality (S_a) was calculated as

$$M_2 * M_W * H_3$$

where M_2 is the survival of smolts to age-2, where M_w is overwinter survival of age-2 fish and where H_3 represents the fraction of fish surviving harvest and returning to spawn. Based upon Zeug et al. (2012) we fixed parameter values at 0.64 for M_w and at 0.75 for H_3. Since smolt to adult mortality is known to vary widely from year-to-year and among salmon populations (see Bradford et al. 1995), consistent with Zeug et al. (2012) we allowed M_2 to vary from a mean of 0.03, to a maximum value of 0.04 and to a minimum value of 0.02. The resulting range of values for S_a are shown in Table 12 and also reflected in the summary of results shown in Table 14.

3. Results from quantifying anadromous fish benefits

3.1. Chinook results

Using simulated flows and water project operations, our analysis shows substantial net benefits to spring-run and winter-run Chinook (Table 13). The range of estimates shown in Table 13 demonstrated the influence of parameter uncertainty on estimated benefits. Though the magnitude of benefits are variable, our quantitative analyses demonstrates a consistent, strongly positive effect on adult abundance for spring-run and winter-run Chinook salmon.

Table 13. Estimated net change in adult Chinook salmon resulting from 50 years of proposed Project operations under four future conditions relative to no project.

	Spring-run		Winter-run	
Future Condition	Mean	Range	Mean	Range
2030	1011	(674-1348)	109	(73-145)
2070	715	(476-953)	73	(48-97)

As expected, benefits for Chinook salmon occur in years when the Project allows for a Feather River flow pulse. In most years, Chinook salmon are not affected positively or negatively by the Project. For spring-run Chinook, years with flow pulses produce 121 to 354 additional adult Chinook from each of the seven Project flow pulses occurring in the 2030 future condition (Figure 10). The 2070 future condition allowed for five Project flow pulses producing from 168 to 375 additional spring-run adults for each flow pulse event (Figure 10).

Reductions in estimated annual adult Chinook occur in some years as a result of increased Delta diversions associated with the Project, but these losses are outweighed by much larger benefits which accumulate across all years (Table 13).

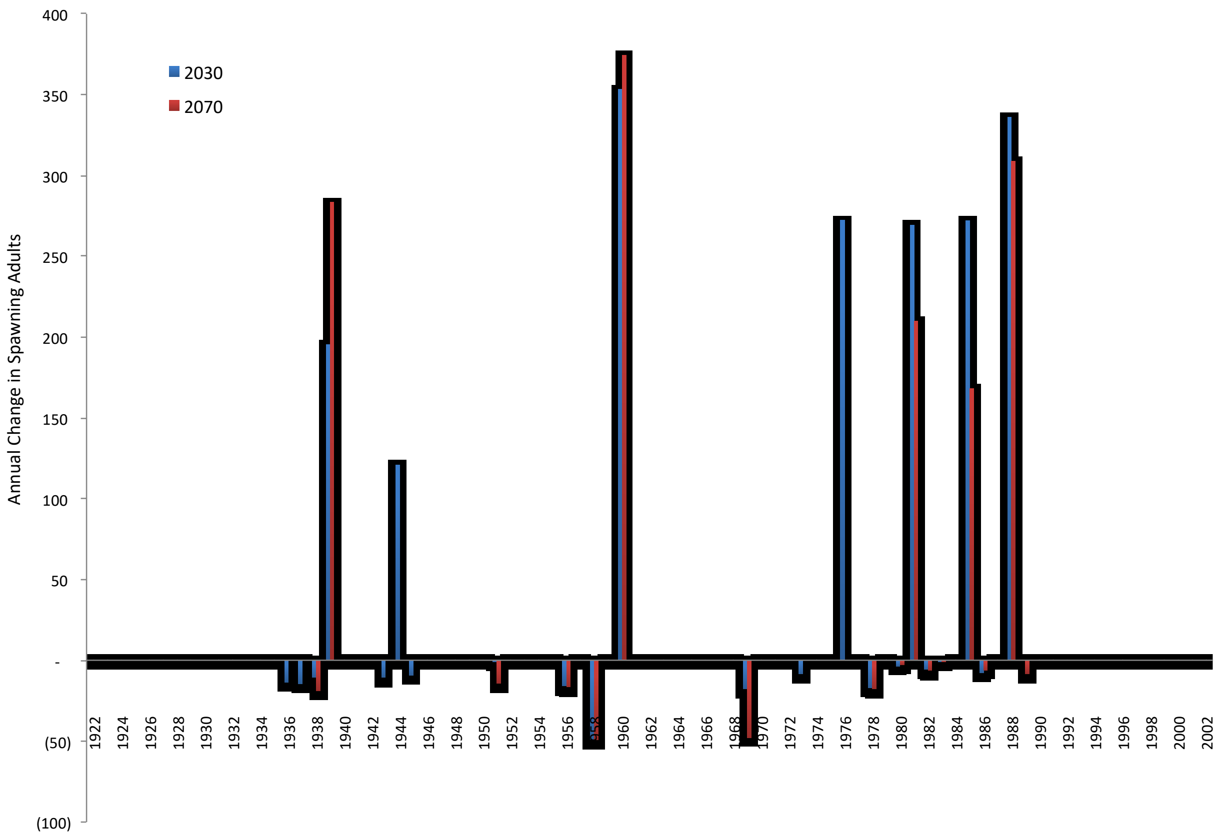


Figure 10. Annual change in adult spring-run Chinook spawners returns associated with the under 2030 and 2070 future conditions.

Benefits from the Project are also apparent for winter-run Chinook salmon. Though winter-run Chinook salmon are not present in the Feather River, the flow pulse originating from the Feather River reaches the Sacramento River and provides benefits from Verona to Delta exit. In most years, winter-run Chinook salmon are not affected positively or negatively by the Project. Benefits ranging from 26 to 57 additional adult Chinook winter-run occur with the seven Project flow pulses associated with the 2030 condition, and with the five Project flow pulses for the 2070 condition (Figure 11). Most winter-run Chinook smolts emigrate through Delta prior to April and are thus are sometimes exposed to increased winter exports associated with the Project. As with spring-run Chinook, Delta losses for winter-run Chinook occur but are outweighed by larger benefits which accumulate across all years (Table 13).

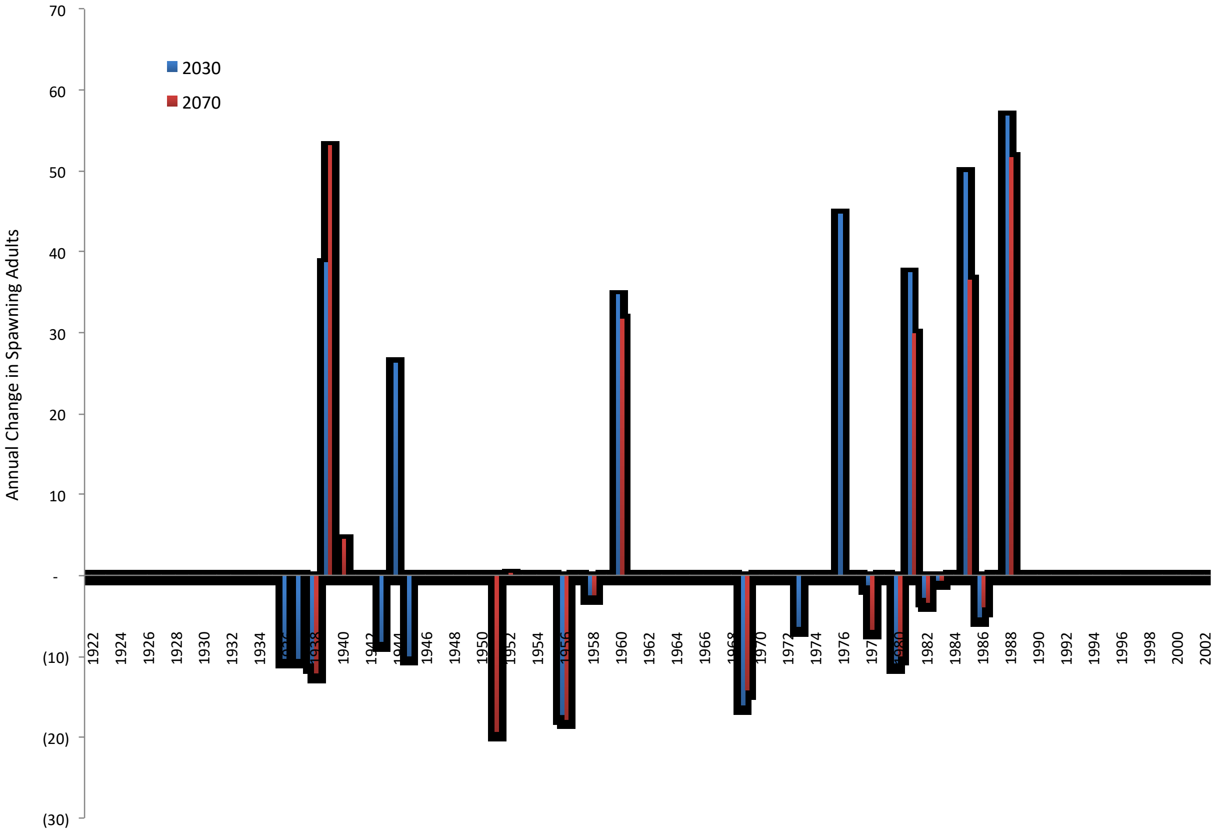


Figure 11. Annual change in adult winter-run Chinook spawning returns associated with the Project under 2030 and 2070 future conditions.

It is important to note that these abundance estimates do not represent a prediction of future spawning escapements. Rather these results reflect a comparison between water project operations using historic hydrologic conditions. The DPM and smolt-to-adult survival (S_a) components of the model analysis represent some major sources of uncertainty, but no practical modeling effort can adequately represent future real-world variation introduced by factors such as changing climate, changing habitat, changing harvest management, changing hatchery management, and shifting ocean productivity. Our modeling application here is consistent with other analytical efforts providing a standardized basis for comparing outcomes between alternative water management while controlling for unknown or uncontrollable future variation in environmental conditions.

3.2. Green sturgeon results

Using simulated flows and water project operations, our analysis shows benefits to green sturgeon abundance. Under the 2030 future condition, April flow pulses with a recurrence interval of once every twelve years are expected. Using the methods described previously, the annualized benefit from this flow pulse attributable to the Project would be approximately 13 additional adult green sturgeon per year.

Under the 2070 future condition, April flow pulses with a recurrence interval of once every sixteen years are expected. Using the methods described previously, the annualized benefit from this flow pulse attributable to the Project would be approximately 10 additional adult green sturgeon per year.

3.3. Steelhead results

Using simulated flows and water project operations, our analysis shows a substantnial net benefits to Central Valley steelhead (Table 14). The range of estimates shown in Table 14 demonstrate the influence of parameter uncertainty on estimated benefits. Though the magnitude of benefits are variable, our quantitative analyses demonstrates a consistent, positive effect on adult abundance of the CCV steelhead DSP.

Table 14. Estimated net change in adult CCV steelhead resulting from 50 years of proposed Project operations under four future conditions relative to no project.

Change in Adult Steelhead Abundance
from 50 years with Project

Future Condition	Mean	Range
2030	95	(63-127)
2070	62	(42-83)

It is important to note that these abundance estimates do not represent a prediction of future steelhead spawning abundance. Rather, these results reflect a comparison between water project operations using historic hydrologic conditions. The smolt-to-adult survival (S_a) component of the model analysis represent some major sources of uncertainty, but no practical modeling effort can adequately represent future real-world variation introduced by factors such as changing climate, changing habitat, changing harvest management, changing hatchery management, and shifting ocean productivity. Our modeling application here is consistent with other analytical efforts providing a standardized basis for comparing outcomes between alternative water management while controlling for unknown or uncontrollable future variation in environmental conditions.

Literature cited

Araujo, H.A., et al. 2015. Modeling population responses of Chinook and coho salmon to suspended sediment using a life history approach. Theoretical Population Biology Vol. 6, May. DOI: 10.1016/j.tpb.2015.04.003

Berggren, T. J., and M. J. Filardo. 1993. An Analysis of Variables Influencing the Migration of Juvenile Salmonids in the Columbia River Basin. North American Journal of Fisheries Management 13(1):48–63.

Blake, A. and M. J. Horn. 2003. Acoustic Tracking of Juvenile Chinook Salmon Movement in the Vicinity of the Delta Cross Channel, Sacramento River, California – 2001 Study Results. Prepared for U.S. Geological Survey and SRI International.

Brandes, P. L. and J. S. McLain. 2001. Juvenile Chinook Salmon Abundance, Disribution, and Survival in the Sacramento–San Joaquin Estuary. Pages 39-137 in R. Brown (ed.). Contributions to the Biology of Central Valley Salmonids, Fish Bulletin 179, Volume 2. Sacramento, CA: California Department of Fish and Game.

Bradford, M.J., 1995. Comparative review of Pacific salmon survival rates. Can. J. Fish. Aquat. Sci. 52, 1327–1338.

California Hatchery Scientific Review Group (CA HSRG). 2012. California Hatchery Review Project, Coleman Steelhead Program Report June 2012. http://cahatcheryreview.com/reports/

California Water Fix (CWF). 2016. Appendix 5.D, Quantitative methods and detailed results for effects analysis of Chinook salmon, Central Valley steelhead, green sturgeon and killer whale. Available: http://www.westcoast.fisheries.noaa.gov/publications/Central_Valley/CAWaterFix/app_5.d_methods.pdf

Healey, M. C. 1980. Utilization of the Nanaimo River Estuary by Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*). U.S. National Marine Fisheries Service Fishery Bulletin 77:653–668.

Healey, M. C. and F. P. Jordan. 1982. Observations on Juvenile Chum and Chinook and Spawning Chinook in the Nanaimo River, British Columbia, during 1975-1981. *Canada Manuscript Report of Fisheries and Aquatic Sciences* 1659:4.

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. Open-file report 2009-1204. U.S. Geological Survey, Reston, VA.

Michel, C. J. 2010. *River and Estuarine Survival and Migration of Yearling Sacramento River Chinook Salmon (Oncorhynchus tshawytscha) Smolts and the Influence of Environment.* Master's thesis. University of California, Santa Cruz. Santa Cruz, CA.

MBK Engineers. 2018. Technical Memorandum: Analysis of Kern Fan Groundwater Storage Project for Water Storage Investment Program. February 16, 2018.

Miller, J. A., A. Gray, and J. Merz. 2010. Quantifying the Contribution of Juvenile Migratory Phenotypes in a Population of Chinook Salmon *Oncorhynchus tshawytscha*. *Marine Ecology Progress Series* 408:227–240.

Moyle, P. B. 2002. *Inland Fishes of California*, Revised and Expanded. Berkeley: University of California Press.

National Marine Fisheries Service (NMFS). 2017. Model description for the Sacramento River Winter-run Chinook Salmon Life Cycle Model. May 9, 2017.

National Marine Fisheries Service (NMFS). 2016a. Endangered species act section 7(a)(2) Biological Opinion and Magnuson-Stevens Fisheries Conservation and Management Act essential fish habitat response and Fish and Wildlife Coordination Act recommendations for relicensing the Oroville Facilities Hydroelectric Project, Butte County, CA. National Marine Fisheries Service, West Coast Region.

National Marine Fisheries Service (NMFS). 2016b. 5-Year Review: Summary and Evaluation of Central Valley Spring-run Chinook Salmon Evolutionarily Significant Unit. National Marine Fisheries Service, West Coast Region.

Newman, K. B. 2008. *An Evaluation of Four Sacramento-San Joaquin River Delta Juvenile Salmon Survival Studies.* U.S. Fish and Wildlife Service, Stockton, CA. Available: http://www.science.calwater.ca.gov/pdf/psp/PSP_2004_final/PSP_CalFed_FWS_salmon_studies_final_033108.pdf .

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.

O'Farrell, M. R., M. S. Mohr, A. M. Grover, and W. H. Satterthwaite. 2012. Sacramento River winter Chinook cohort reconstruction: analysis of ocean fishery impacts. NOAA Technical Memorandum NOAAXTMXNMFSX SWFSCX491.

Perry, R. W. 2010. Survival and Migratory Dynamics of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in the Sacramento-San Joaquin River Delta. PhD dissertation. University of Washington, Seattle.

Perry, R. W. 2010. Survival and Migration Dynamics of Juvenile Chinook Salmon (Oncorhynchus tshawytscha) in the Sacramento-San Joaquin River Delta. Ph.D. Dissertation. University of Washington, Seattle, WA.

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(1):142–156.

Perry RW, Pope AC, Romine JG, Brandes PL, Burau JR, Blake AR, Ammann AJ, Michel CJ. 2018. Flow-mediated effects on travel time, routing and survival of juvenile Chinook salmon in a spatially complex, tidally forced river delta. Canadian Journal of Fisheries and Aquatic Sciences.

R Core Team. 2012. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Available: <http://www.R-project.org>.

Raymond, H. L. 1968. Migration Rates of Yearling Chinook Salmon in Relation to Flows and Impoundments in the Columbia and Snake Rivers. Transactions of the American Fisheries Society 97:356–359.

San Joaquin River Group Authority. 2008. 2007 Annual Technical Report on Implementation and Monitoring of the San Joaquin River Agreement and the Vernalis Adaptive Management Plan. January. Prepared by San Joaquin River Group Authority, Davis, CA. Prepared for California Water

Resource Control Board in compliance with D-1641. Sacramento, CA. Available: <http://www.sjrg.org/technicalreport/>.

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. January. Prepared by San Joaquin River Group Authority, Davis, CA. Prepared for California Water Resource Control Board in compliance with D-1641. Sacramento, CA. Available: <http://www.sjrg.org/technicalreport/>.

Schreck, C. B., J. C. Snelling, R. E. Ewing, C. S. Bradford, L. E. Davis, and C. H. Slater. 1994. Migratory Characteristics of Juvenile Spring Chinook Salmon in the Willamette River. Completion Report. Bonneville Power Administration.

Smith SG, Muir WD, Hockersmith EE, Zabel RW. 2003. Influence of river conditions on survival and travel time of Snake River subyearling fall Chinook salmon. North American Journal of Fisheries Management 23:939-961.

Williams, J. G. 2001. Chinook Salmon in the Lower American River, California's Largest Urban Stream. Pages 1–37 in R. Brown (ed.). Contributions to the Biology of Anadromous Salmonids of the Central Valley, California. *Fish Bulletin* 179:2. Sacramento: California Department of Fish and Game.

Winship, A.J., M.R. O'Farrell and M.S. Mohr. 2014. Fishery and hatchery effects on an endangered salmon population with low productivity. Transactions of the American Fisheries Society, 143(4):957X 971.

Zeug, S.C., P.S. Bergman, B.J. Cavallo, and K.S. Jones. 2012. Application of a life cycle simulation model to evaluate impacts of water management and conservation actions on an endangered population of Chinook salmon. Environmental Modeling and Assessment. 13 p.

Zeug SC, Sellheim K, Watry C, Wikert JD, Merz J. 2014. Response of juvenile Chinook salmon to managed flow: lessons learned from a population at the southern extent of their range in North America. Fisheries Management and Ecology 21:155-168.