

Appendix I **Biological Modeling and Analysis**

The National Marine Fisheries Service (NMFS) requested the U.S. Bureau of Reclamation prepare specific biological models and analyses to support NMFS' preparation of their Biological Opinion for the ROC on LTO project. The following sections describe the methods and key assumptions for the seven biological models/analyses prepared: Delta Passage Model, Interactive Object-Oriented Simulation Model, Floodplain Inundation Habitat Analysis, Weighted Usable Area Analysis, Salvage-Density Method, Reclamation Salmon Mortality Model, and SALMOD.

I.1 Delta Passage Model (DPM) Documentation

The DPM simulates migration of Chinook salmon smolts entering the Delta from the Sacramento River, Mokelumne River, and San Joaquin River and estimates survival to Chipps Island. For this application, only survival of fish entering the Delta from the Sacramento River are evaluated. 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 winter-run Chinook salmon smolt surrogates (late fall-run Chinook salmon), it is applied here for winter-run, spring-run, fall-run, and late fall-run Chinook salmon 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 very cautiously to pre-smolt migrants. Salmon juveniles less than 70 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 (Healy 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 BDCP 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 since then from various meetings of a workgroup consisting of agency biologists and consultants. This effects analysis uses the most recent version of the DPM as of September 2015. 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 estimates generated by the DPM are not intended to predict future outcomes. 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 the COS, PA and WOA scenarios. Note that the DPM is a tool to compare different scenarios and is not intended to predict actual through-Delta survival under current or future conditions. In keeping with other methods found in the effects analysis, it is possible that underlying relationships (e.g., flow-survival) that are used to inform the DPM will change in the future; there is an assumption of stationarity of these basic relationships to allow scenarios to be compared for the current analysis, recognizing that it may be necessary to re-examine the relationships as new information becomes available.

I.1.1 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 I.1-1). 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 Delta 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 (see Table I.1-1 for reach description).

Functional relationships are described in detail in the Section *Model Functions*.

I.1.2 Model Time Step

The DPM operates on a daily time step using simulated daily average flows 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 days, not three-dimensional movements occurring over minutes or hours (e.g., Blake and Horn 2003). It is acknowledged that finer scale modeling with a shorter time step may match the biological processes governing fish movement better than a daily time step (e.g., because of diel activity patterns; Plumb et al. 2015) and that sub-daily differences in flow proportions into junctions make daily estimates somewhat coarse (Cavallo et al. 2015).

I.1.3 Spatial Framework

The DPM is composed of nine reaches and four junctions (Figure I.1-1; Table I.1-1) 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 Mokelumne River fall-run Chinook salmon at the head of the South and North Forks of the Mokelumne River or by Sacramento runs through the combined junction of Georgiana Slough and DCC (Junction C). The Interior Delta reach can be entered from three different pathways: Geo/DCC, San Joaquin River via Old River Junction (Junction D), and Old River via Junction D. The entire Interior Delta region is treated as a single model reach³. The four distributary junctions (channel splits) depicted in the DPM are (A) Sacramento River at Fremont Weir (head of Yolo Bypass), (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 (Figure I.1-1, Table I.1-1).

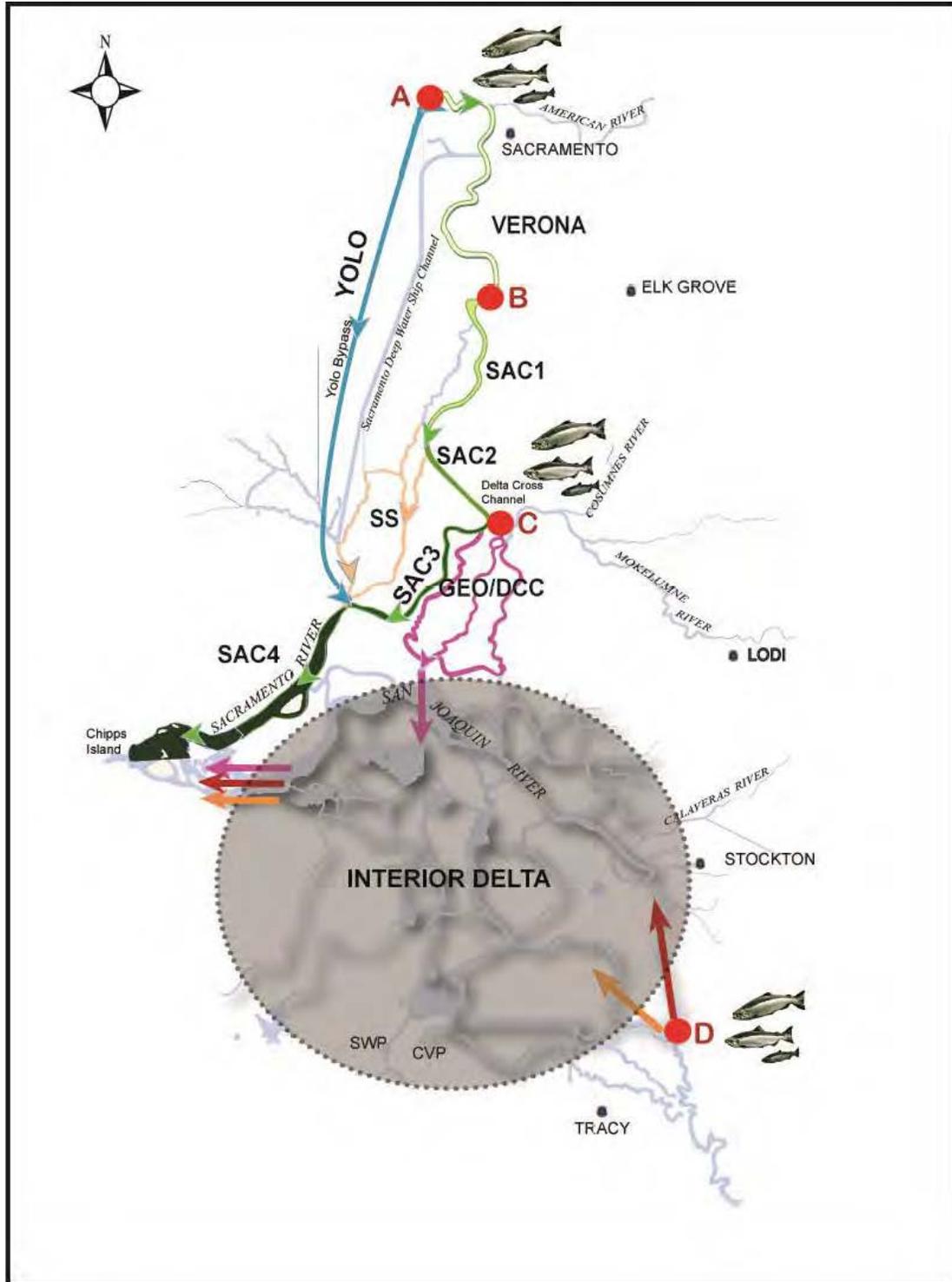
Table I.1-1. Description of Modeled Reaches and Junctions in the Delta Passage Model

Reach/Junction	Description Reach Length (km)	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
Yolo	Yolo Bypass from entrance at Fremont Weir to Rio Vista, California	NA ^a
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 ^b
A	Junction of the Yolo Bypass ^c and the Sacramento River	NA
B	Combined junction of Sutter Slough and Steamboat Slough with the Sacramento River	NA
C	Combined junction of the Delta Cross Channel and Georgiana Slough with the Sacramento River	NA
D	Junction of the Old River with the San Joaquin River	NA

^a Reach length for Yolo Bypass is undefined because reach length currently is not used to calculate Yolo Bypass speed and ultimate travel time.

^b 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.

^c Flow into the Yolo Bypass is primarily via the Fremont Weir but flow via Sacramento Weir is also included



Bold headings label modeled reaches, and red circles indicate model junctions. Salmonid icons indicate locations where smolts enter the Delta in the DPM. Smolts enter the Interior Delta from the Geo/DCC reach or from Junction D via Old River or from the San Joaquin River. 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 but survival varies within the Interior Delta depending upon whether fish enter from the Sacramento River, Mokelumne River, the San Joaquin River, or Old River.

Figure I.1-1. Map of the Sacramento–San Joaquin River Delta Showing the Modeled Reaches and Junctions of the Delta Applied in the Delta Passage Model.

I.1.4 Flow Input Data

Water movement through the Delta as input to the DPM is derived from daily (tidally averaged) flow output produced by the hydrology module of the Delta Simulation Model II (DSM2- HYDRO; <<http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/>>) or from CALSIM-II.

The nodes in the DSM2-HYDRO and CALSIM II models that were used to provide flow for specific reaches in the DPM are shown in Table I.1-2.

Table I.1-2 Delta Passage Model Reaches and Associated Output Locations from DSM2-HYDRO and CALSIM II Models

DPM Reach or Model Component	DSM2 Output Locations	CALSIM Node
Sac1	rsac155	
Sac2	rsac128	
Sac3	rsac123	
Sac4	rsac101	
Yolo		d160a+d166aa
Verona		C160a
SS	slsbt011	
Geo/DCC	dcc+georg_sl	
South Delta Export Flow	Clifton Court Forebay + Delta Mendota Canal	
Sacramento River flow at Fremont Weir		C129a

I.1.4.1 Model Functions

I.1.4.1.1 Delta Entry Timing

Recent sampling data on Delta entry timing of emigrating juvenile smolts for six Central Valley Chinook salmon runs were used to inform the daily proportion of juveniles entering the Delta for each run (Table I.1-3). 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 DPM for each run (Figure I.1-2). 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 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. A sensitivity analysis of this assumption was undertaken and showed that patterns in results would be expected to be similar for a range of entry distribution assumptions.

Table I.1-3. 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
Sacramento River Late Fall Run	Trawls at Sacramento	USFWS	1995–2005
Mokelumne River Fall Run	Rotary Screw Trap at Woodbridge	EBMUD	2001–2007
San Joaquin River Fall Run	Kodiak Trawl at Mossdale	CDFW	1996–2009

Agencies that conducted sampling are listed: USFWS = U.S. Fish and Wildlife Service, EBMUD = East Bay Municipal District, and CDFW = California Department of Fish and Wildlife.

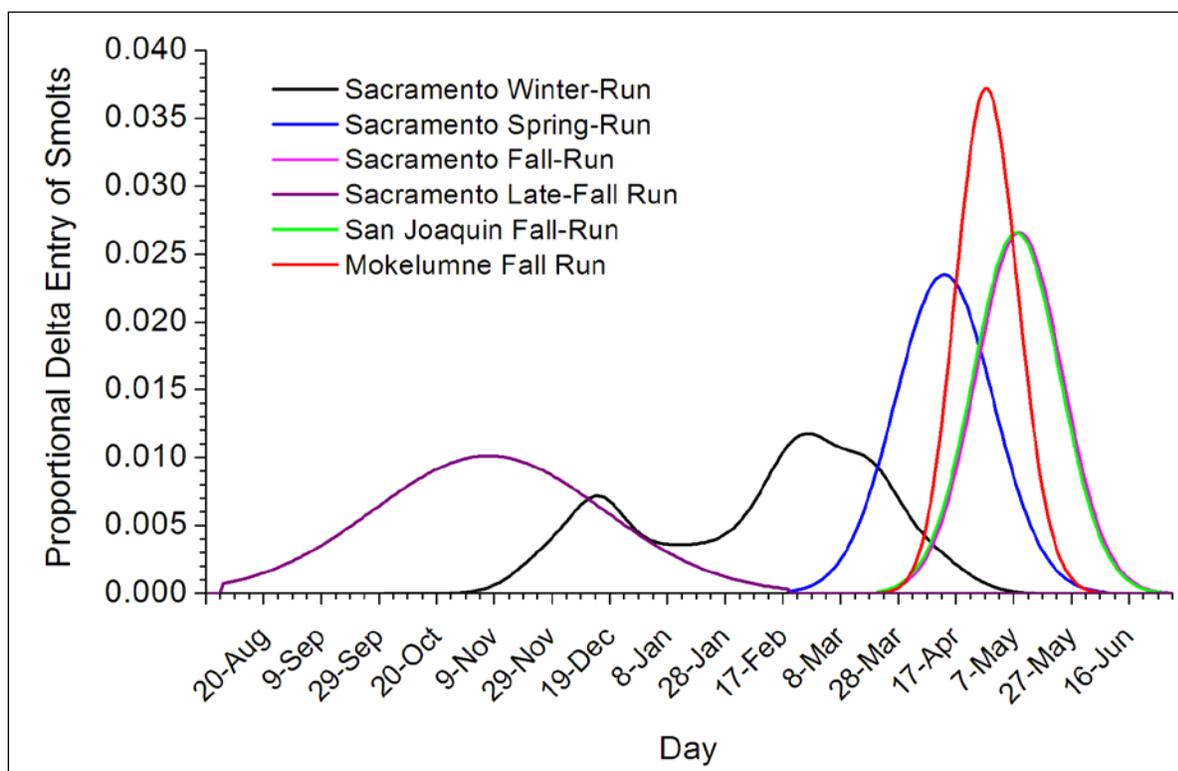


Figure I.1-2. Delta Entry Distributions for Chinook Salmon Smolts Applied in the Delta Passage Model for Sacramento River Winter-Run, Sacramento River Spring-Run, Sacramento River Fall-Run, Sacramento River Late Fall-Run, San Joaquin River Fall-Run, and Mokelumne River Fall-Run Chinook Salmon.

I.1.4.1.2 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 Yolo Bypass and 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 I.1-4) 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 I.1-4). Flow data was queried from the DWR's California Data Exchange website (<<http://cdec.water.ca.gov/>>).

Table I.1-4. 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
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.

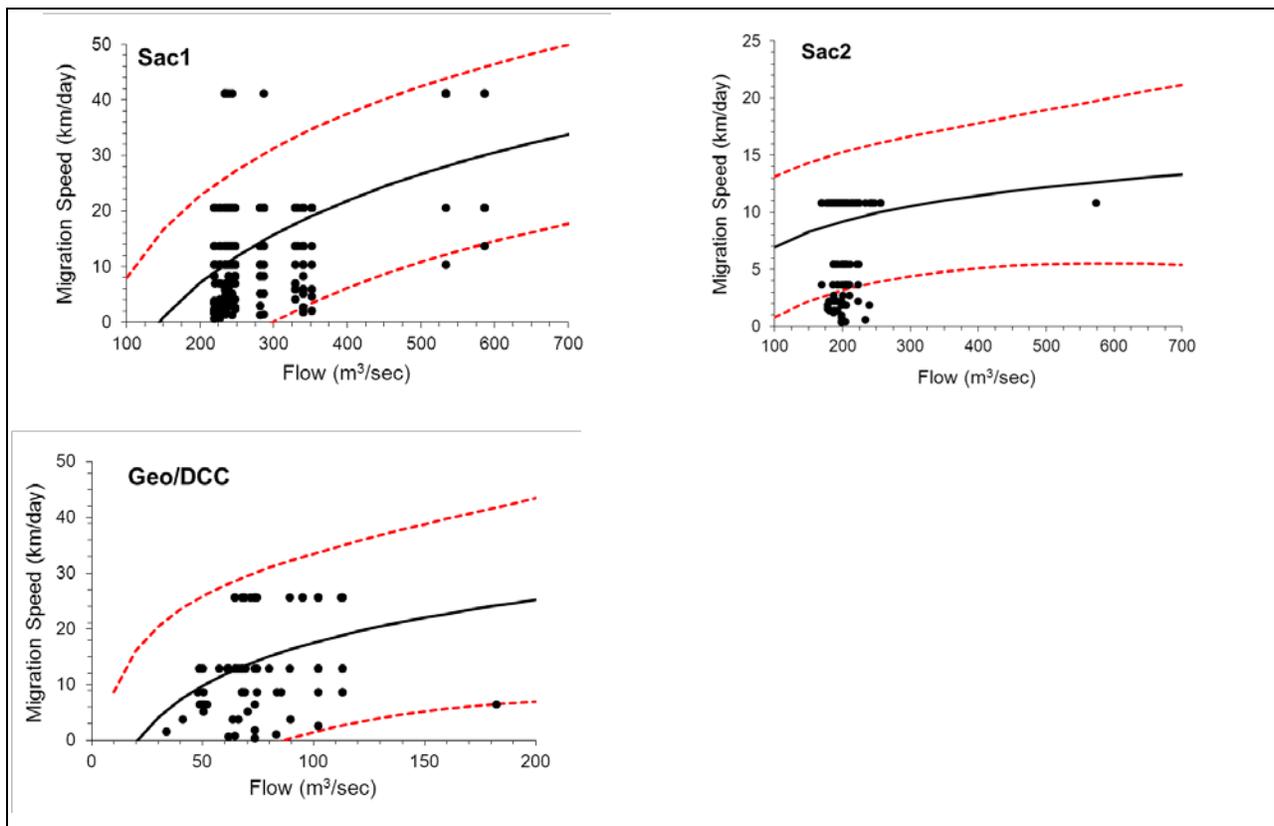
^b SS flow is calculated by subtracting Sac2 flow (SDC) from Sac1 flow (FPT).

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 (Table I.1-5, Figure I.1-3). Therefore, for reaches Sac1, Sac2, and

Geo/DCC, the regression coefficients shown in Table I.1-5 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 I.1-4). The flow-migration rate relationship that was used for Sac1 also was applied for the Verona reach.

Table I.1-5. 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)



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.

Figure I.1-3. Reach-Specific Migration Speed (km/day) as a Function of Flow (m³/sec) Applied in Reaches Sac1, Sac2, and Geo/DCC.

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 I.1-4) 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 I.1-4).

Yolo Bypass travel time data from Sommer et al. (2005) for acoustic-tagged, fry-sized (mean size = 57 mm fork length [FL]) Chinook salmon were used to inform travel time through the Yolo Bypass in the DPM. Because the DPM models the migration and survival of smolt-sized juveniles, the range of the shortest travel times observed across all three years (1998–2000) by Sommer et al. (2005) was used to inform the bounds of a uniform distribution of travel times (range = 4–28 days), on the assumption that smolts would spend less time rearing, and would travel faster than fry. On the day smolts enter the Yolo Bypass, their travel time through the reach is calculated by sampling from this uniform distribution of travel times.

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.

I.1.4.1.3 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 A (entry into the Yolo Bypass at Fremont Weir), the following relationships were used.

- Proportion of smolts entering Yolo Bypass = Fremont Weir spill / (Fremont Weir spill + Sacramento River at Verona flows).

As noted above in *Flow Input Data*, the flow data informing Yolo Bypass entry were obtained by disaggregating CALSIM estimates using historical daily patterns of variability because DSM2 does not provide daily flow data for these locations.

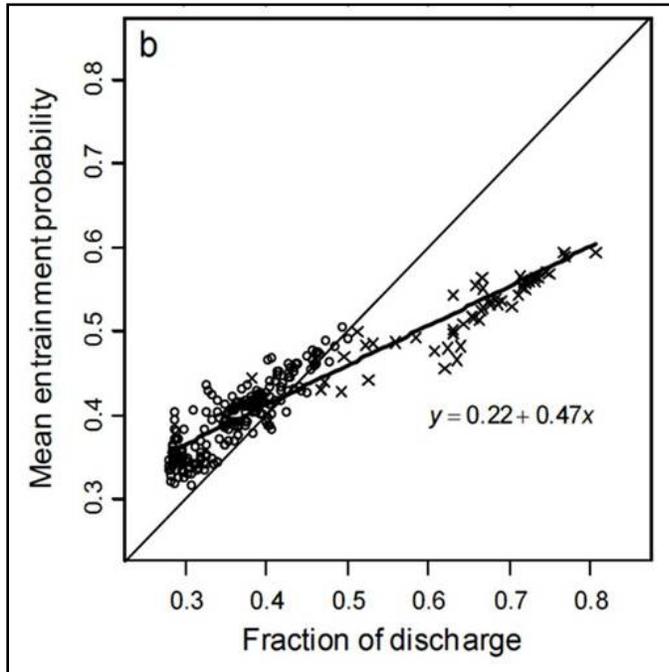
For Junction B (Sacramento River-Sutter/Steamboat Sloughs), Perry et al. (2010) found that smolts consistently entered downstream reaches in proportion to the flow being diverted. Therefore, smolts arriving at Junction B in the model move proportionally with flow. Similarly, with data lacking to inform the nature of the relationship, a proportional relationship between flow and fish movement for Junction D (San Joaquin River–Old River) also was applied. Note that the operation of the Head of Old River gate proposed under the PA is accounted for in the DSM2 flow input data (i.e., with a closed gate, relatively more flow [and therefore smolts] remains in the San Joaquin River).

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 I.1-4).

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.



Circles Depict DCC Gates Closed, Crosses Depict DCC Gates Open.

Figure I.1-4. 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).

I.1.4.1.4 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 I.1-6). For all other reaches (Geo/DCC and Yolo), reach survival is assumed to be unaffected by Delta conditions and is informed by means and standard deviations of survival from acoustic-tagging studies.

Table I.1-6. 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 ^a	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
Yolo	All Sacramento runs	Various	This section
Sac4 via Yolo ^b	All Sacramento runs	0.698 (0.153)	This section
SS and Sac4 combined	All Sacramento runs	Function of flow	Flow-Dependent Survival
Geo/DCC	Mokelumne fall-run	0.407 (0.209)	This section
	All Sacramento runs	0.65 (0.126)	This section
Interior Delta	All Sacramento runs	Function of exports	Export-Dependent Survival
	San Joaquin fall-run via Old River	Function of flow	Flow-Dependent Survival
	San Joaquin fall-run via San Joaquin River	Function of flow	Flow-Dependent Survival

^a For routes where survival is uninfluenced by Delta conditions, mean survival and associated standard deviation (in parentheses) observed during acoustic-tagging studies (Michel 2010; Perry 2010) are used to define a normal probability distribution that is sampled from the day smolts enter a reach to calculate reach survival.

^b Although flow influences survival of fish migrating through the combined routes of SS–Sac4 and Sac3–Sac4, flow does not influence Sac4 survival for fish arriving from Yolo.

For reaches Geo/DCC, Yolo, and Sac4 via Yolo, 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 I.1-7).

Mean reach survival and associated standard deviation for Geo/DCC are informed by survival data from smolt acoustic-tagging studies from Perry (2010). Separate acoustic-study survival data are applied for smolts migrating through Geo/DCC via the Sacramento River (Sacramento River runs) or Mokelumne River (Mokelumne River fall-run) (Table I.1-7). 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. For Mokelumne River fall-run, only the DCC route group survivals are used to inform Geo/DCC survival because Mokelumne River fish are not exposed to Georgiana Slough.

Smolt survival data for the Yolo Bypass were obtained from the UC Davis Biotelemetry Laboratory (M. Johnston pers. comm.). These data included survival estimates for five reaches from release near the head of the bypass to the base of the bypass. The means (and standard errors) of these estimates defined normal probability distributions from which daily value for the DPM were drawn, and were as follows: reach 1 (release site): 1.00; reach 2 (release site to I-80): 0.96 (SE = 0.059); reach 3 (I-80 to screw trap): 0.96 (0.064); reach 4 (screw trap to base of Toe Drain): 0.94 (0.107); reach 5 (base of Toe Drain to base of Bypass): 0.88 (0.064). Fish leaving the Yolo reach in the model then entered Sac4 and were subject to survival at the rate shown in Table I.1-7.

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 I.1-7. 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 Mokelumne River	0.648	12/05/06	$S_{C1} * S_{C2}$	0.407	0.209
	0.286	12/04/07–12/06/07	S_{C1}		
	0.286	11/31/08–12/06/08	S_{C1}		
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}		
Sac4 via Yolo	0.286	11/31/08–12/06/08	S_{C1}	0.698	0.153
	0.714	12/5/2006	$S_{A6} * S_{A7}$		
	0.858	1/17/2007	$S_{A6} * S_{A7}$		
	0.548	12/4/07–12/6/07	$S_{A7} * S_{A8}$		
	0.488	1/15/08–1/17/08	$S_{A7} * S_{A8}$		
	0.731	11/31/08–12/06/08	$S_{A7} * S_{A8}$		
0.851	1/13/09–1/19/09	$S_{A7} * S_{A8}$			

Source: Perry 2010.

I.1.4.1.5 Flow-Dependent Survival

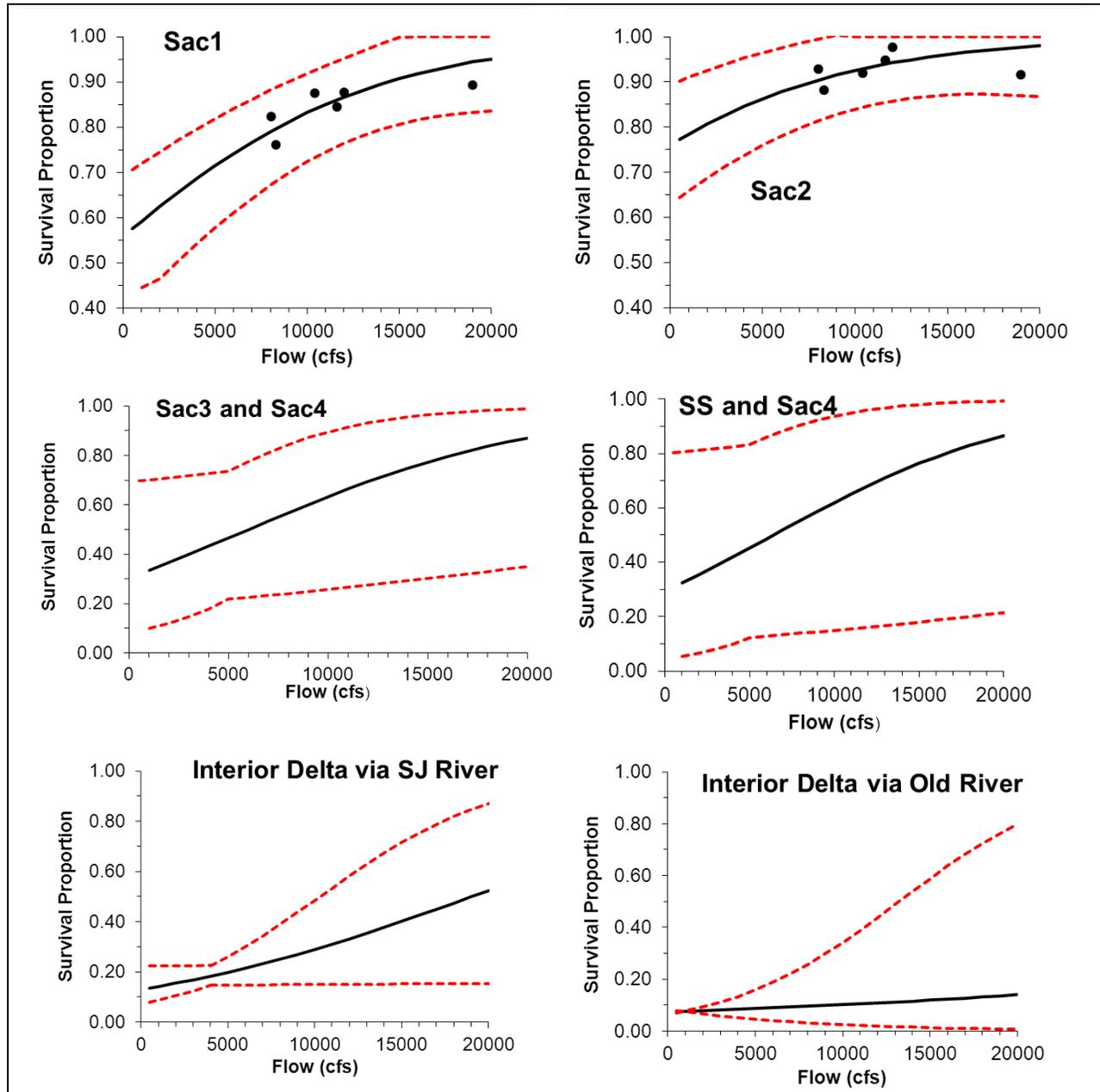
For reaches Sac1, Sac2, Sac3 and Sac4 combined, SS and Sac4 combined, Interior Delta via San Joaquin River, and Interior Delta via Old River, flow values on the day of route entry are used to predict route survival (Figure I.1-5). Perry (2010) evaluated the relationship between survival among acoustically-tagged 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 I.1-5; Table I.1-8). 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.



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.

Figure I.1-5. 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.

Table I.1-8. 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}

For smolts originating in the San Joaquin River that migrate through the Interior Delta via San Joaquin River or Old River, survival is modeled as a function of flow and exports as modeled by Newman (2010).

$$S_{SJ,OR} = \frac{e^{(\beta_0 + \beta_1 \text{flow} + \beta_2 \text{exports})}}{1 + e^{(\beta_0 + \beta_1 \text{flow} + \beta_2 \text{exports})}}$$

Where SSJ , OR is survival through the Interior Delta via the San Joaquin River or Old River, flow is average San Joaquin River flow downstream of the head of Old River or flow in Old River during the coded-wire tagging study standardized to a mean of 0 and standard deviation of 1, and exports is the combined export flow from the state and federal facilities in the south Delta during the study.

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 (Table I.1-9; Figure I.1-5). 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.

Table I.1-9. Model Averaged Parameter Estimates and Standard Deviations Used to Describe Survival through the Interior Delta via the San Joaquin River and Old River Routes

Parameter	San Joaquin Route	Old River Route
Intercept	-1.577 (0.275)	-2.297 (0.537)
Flow	0.376 (0.289)	0.166 (0.524)
Exports	0.291 (0.290)	0.279 (0.363)

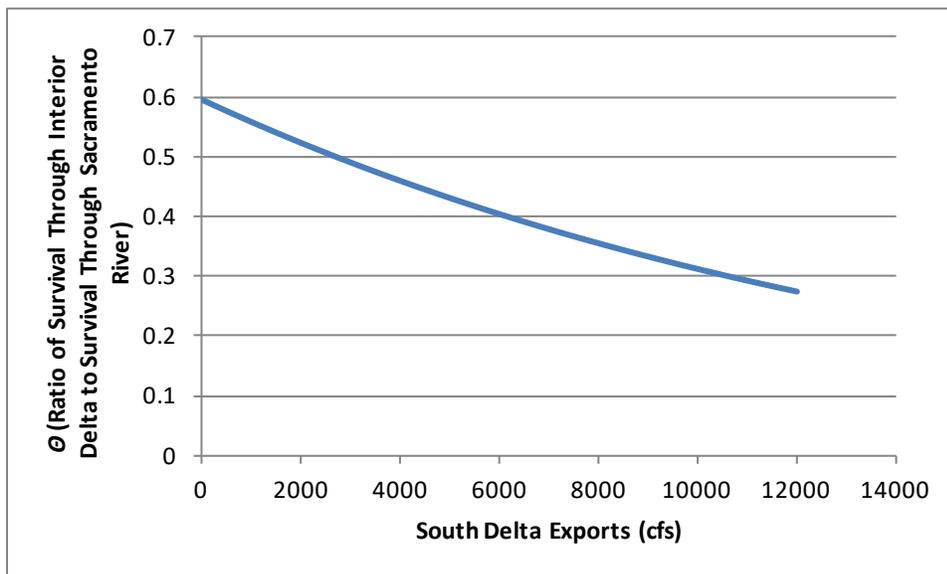
I.1.4.1.6 Export-Dependent Survival

As migratory juvenile salmon enter the Interior Delta from Geo/DCC for Sacramento races or Mokelumne River fall-run Chinook salmon, 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 I.1-6).



Source: Newman and Brandes 2010

Figure I.1-6. Relationship between θ (Ratio of Survival through the Interior Delta to Survival through Sacramento River) and South Delta Export Flows.

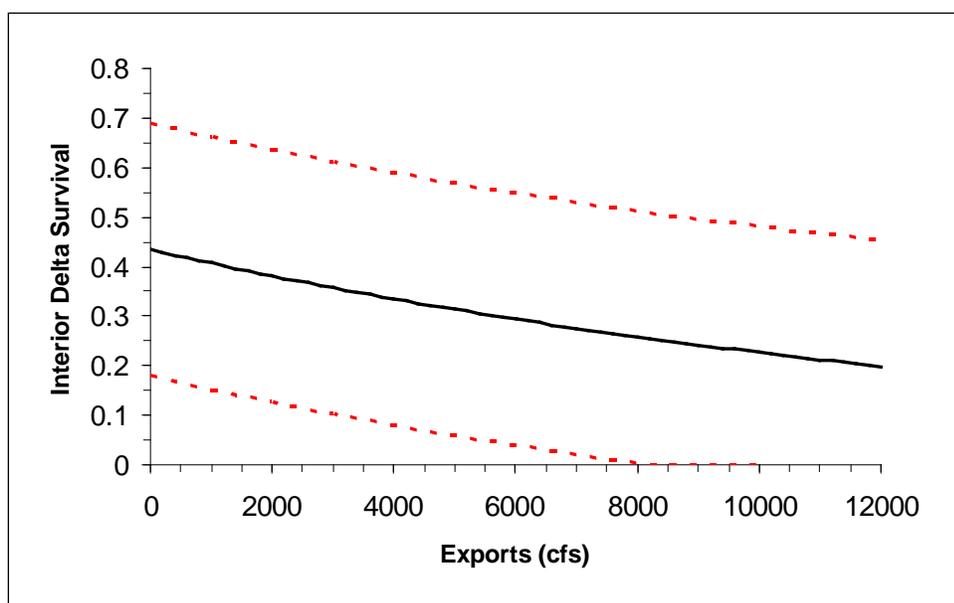
θ was converted from a ratio into a value of survival through the Interior Delta using the equation:

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

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 I.1-7)¹.

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 .

The export-dependent survival relationship for San Joaquin-origin fish was described above in the section on *Flow-Dependent Survival*.



Survival 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.

Figure I.1-7. 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/DCC.

¹ Note that the Mokelumne River fall-run does not occur in the Sacramento River but daily survival values in Sac3/Sac4 are calculated in order to inform interior Delta survival for this run according to the equation above; the Sac3/Sac4 daily survival values for this run are used solely for this purpose. Although daily survivals in Sac3/Sac4 are used to calculate Sacramento River survival for Sacramento River runs (winter-run, spring-run, Sacramento fall-run, and late fall-run), the combined Sac3/Sac4 survival used to calculate Sacramento River survival would be slightly different than that used to calculate interior Delta survival because of the travel time required for smolts to reach the interior Delta via Geo/DCC.

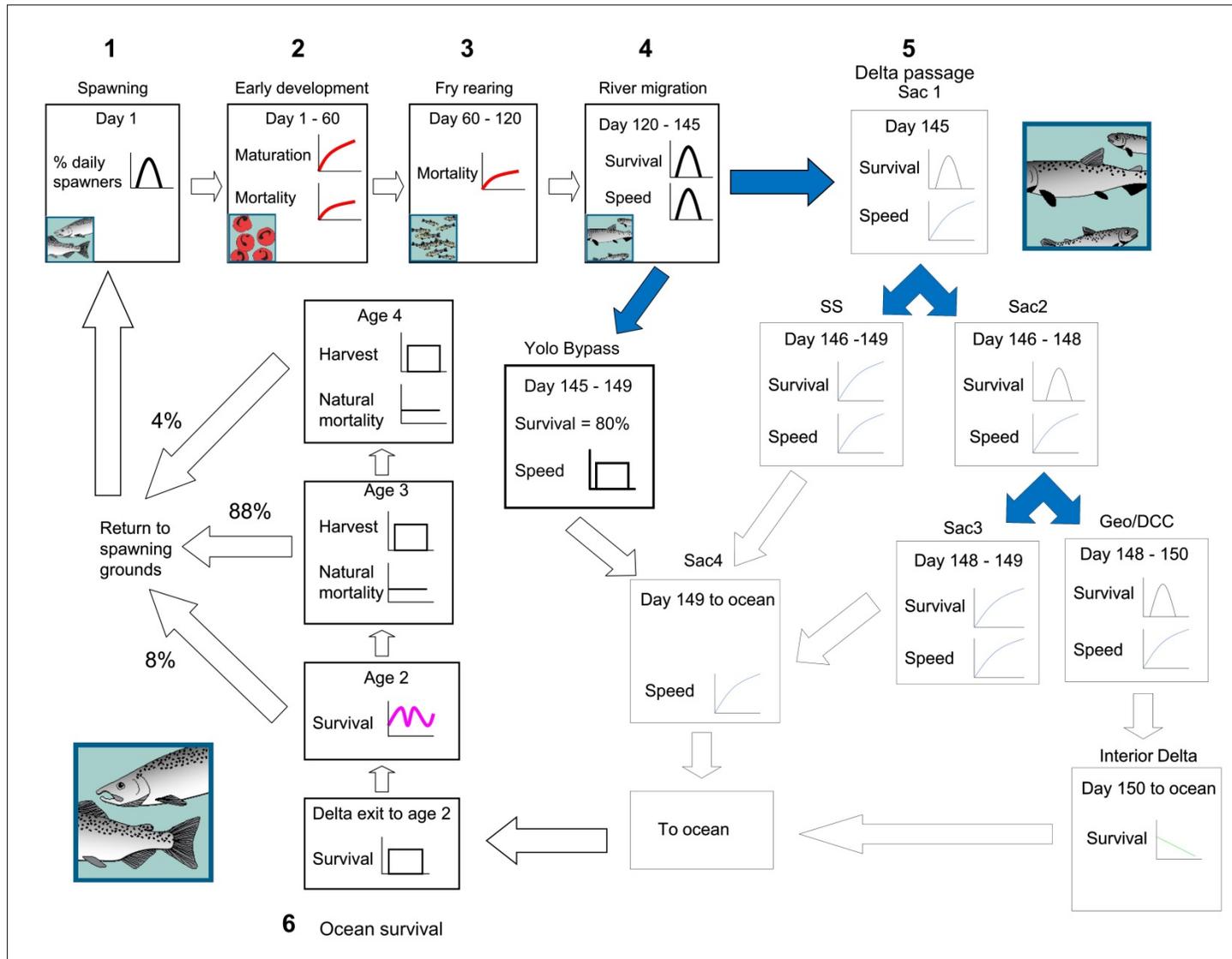
I.2 IOS Model Documentation

I.2.1 Model Structure

The Interactive Object-Oriented Simulation (IOS) Model is composed of six model stages defined by a specific spatiotemporal context and are arranged sequentially to account for the entire life cycle of winter-run Chinook salmon, from eggs to returning spawners (Figure I.2-1). In sequential order, the IOS Model stages are listed below.

1. *Spawning*, which models the number and temporal distribution of eggs deposited in the gravel at the spawning grounds in the upper Sacramento River between Red Bluff Diversion Dam and Keswick Dam.
2. *Early Development*, which models the effect of temperature on maturation timing and mortality of eggs at the spawning grounds.
3. *Fry Rearing*, which models the relationship between temperature and mortality of fry during the river rearing period in the upper Sacramento River between Red Bluff Diversion Dam and Keswick Dam.
4. *River Migration*, which estimates mortality of migrating smolts in the Sacramento River between the spawning and rearing grounds and the Delta.
5. *Delta Passage*, which models the effect of flow, route selection, and water exports on the survival of smolts migrating through the Delta to San Francisco Bay.
6. *Ocean Survival*, which estimates the effect of natural mortality and ocean harvest to predict survival and spawning returns by age.

A detailed description of each model stage follows.



Note: Red = temperature, blue = flow, green = water exports, pink = ocean productivity.

Figure I.2-1. Conceptual Diagram of the IOS Model Stages and Environmental Influences on Survival and Development of Winter-Run Chinook Salmon at Each Stage.

1.2.1.1 Spawning

For the first four simulation years of the 82-year CALSIM simulation period, the model is seeded with 5,000 spawners, of which 3,087.5 are female based on the wild male to female ratio of spawners. In each subsequent simulation year, the number of female spawners is determined by the model's probabilistic simulation of survival to this life stage. To ensure that developing fish experience the correct environmental conditions during each year, spawn timing mimics the observed arrival of salmon on the spawning grounds as determined by 8 years of carcass surveys (2002–2009) conducted by the U.S. Fish and Wildlife Service (USFWS). Eggs deposited on a particular date are treated as cohorts that experience temperature and flow on a daily time step during the early development stage. The daily number of female spawners is calculated by multiplying the daily proportion of the total carcasses observed during the USFWS surveys by the total Jolly-Seber estimate of female spawners (Poytress and Carillo 2010).

$$\text{(Equation 1)} \quad Sd = CdSJS$$

where, Sd is the daily number of female spawners, Cd is the daily proportion of total carcasses and SJS is the total Jolly-Seber estimate of female spawners.

To account for the time difference between egg deposition and carcass observations, the date of egg deposition is assumed to be 14 days prior to carcass observations (Niemela pers. comm.).

To obtain estimates of juvenile production, a Ricker stock-recruitment curve (Ricker 1975) was fit between the number of emergent fry produced each year (estimated by rotary screw-trap sampling at Red Bluff Diversion Dam) and the number of female spawners (from USFWS carcass surveys) for years 1996–1999 and 2002–2007:

$$\text{(Equation 2)} \quad R = \alpha Se^{-\beta S} + \varepsilon$$

where α is a parameter that describes recruitment rate, and β is a parameter that measures the level of density dependence.

The density-dependent parameter (β) did not differ significantly from 0 (95% CI = -6.3×10^{-6} – 5.5×10^{-6}), indicating that the relationships between emergent fry and female spawners was linear (density-independent). Therefore, β was removed from the equation and a linear version of the stock-recruitment relationship was estimated. The number of female spawners explained 86% of the variation in fry production ($F_{1,9} = 268$, $p < 0.001$) in the data, so the value of α was taken from the regression:

$$\text{(Equation 3)} \quad R = 1043 * S$$

In the IOS Model, this linear relationship is used to predict values for mean fry production along with the confidence intervals for the predicted values. These values are then used to define a normal probability distribution, which is randomly sampled to determine the annual fry production. Although the Ricker model accounts for mortality during egg incubation, the data used to fit the Ricker model were from a limited time period (1996–1999, 2002–2007) when water temperatures during egg incubation were too cool ($< 14^\circ\text{C}$) to cause temperature-related egg mortality (U.S. Fish and Wildlife Service 1999). Thus, additional mortality was imposed at higher temperatures not experienced during the years used to construct the Ricker model.

I.2.1.2 **Early Development**

Data from three laboratory studies were used to estimate the relationship between temperature, egg mortality, and development time (Murray and McPhail 1988; Beacham and Murray 1989; U.S. Fish and Wildlife Service 1999). Using data from these experiments, a relationship was constructed between maturation time and water temperature. First *maturation time* (days) was converted to a *daily maturation rate* (1/day):

$$\text{(Equation 4)} \quad \text{daily maturation rate} = \text{maturation time}^{-1}$$

A significant linear relationship between maturation rate and water temperature was detected using linear regression. Daily water temperature explained 99% of the variation in *daily maturation rate* ($F = 2188$; $df = 1, 15$; $p < 0.001$):

$$\text{(Equation 5)} \quad \text{daily maturation rate} = 0.00058 * \text{Temp} - 0.018$$

In the IOS Model, the daily mean maturation rate of the incubating eggs is predicted from daily water temperatures using a linear function; the predicted mean maturation rate, along with the confidence intervals of the predicted values, is used to define a normal probability distribution, which then is randomly sampled to determine the daily maturation rate. A cohort of eggs accumulates a percentage of total maturation each day from the above equation until 100% maturation is reached.

Data from experimental work (U.S. Fish and Wildlife Service 1999) was used to parameterize the relationship between temperature and mortality of developing winter-run Chinook salmon eggs. Predicted proportional mortality over the entire incubation period was converted to a daily mortality rate to apply these temperature effects in the IOS Model. This conversion was used to calculate daily mortality using the methods described by Bartholow and Heasley (2006):

$$\text{(Equation 6)} \quad \text{mortality} = 1 - (1 - \text{total mortality}) / (\text{development time})$$

where *total mortality* is the predicted mortality over the entire incubation period observed for a particular water temperature and *development time* was the time to develop from fertilization to emergence.

Limited sample size ($n = 3$) in the USFWS study (1999) did not allow a statistically valid test for effects of temperature on mortality (e.g., a general additive model) to be performed. However, the following exponential relationship was fitted between observed *daily mortality* and observed water temperatures (U.S. Fish and Wildlife Service 1999) to provide the required values for the IOS Model:

$$\text{(Equation 7)} \quad \text{daily mortality} = 1.38 * 10^{-15} e^{(0.503 * \text{Temp})}$$

Equation 7 yields the following graphic (Figure I.2-2), which indicates that proportional daily egg mortality increases rapidly with only small changes in water temperature. For example, within the predominant water temperature range found in model scenarios (55°F to 60°F), proportional daily mortality increases over ten-fold (~0.001 at 55°F to ~0.018 at 60°F).

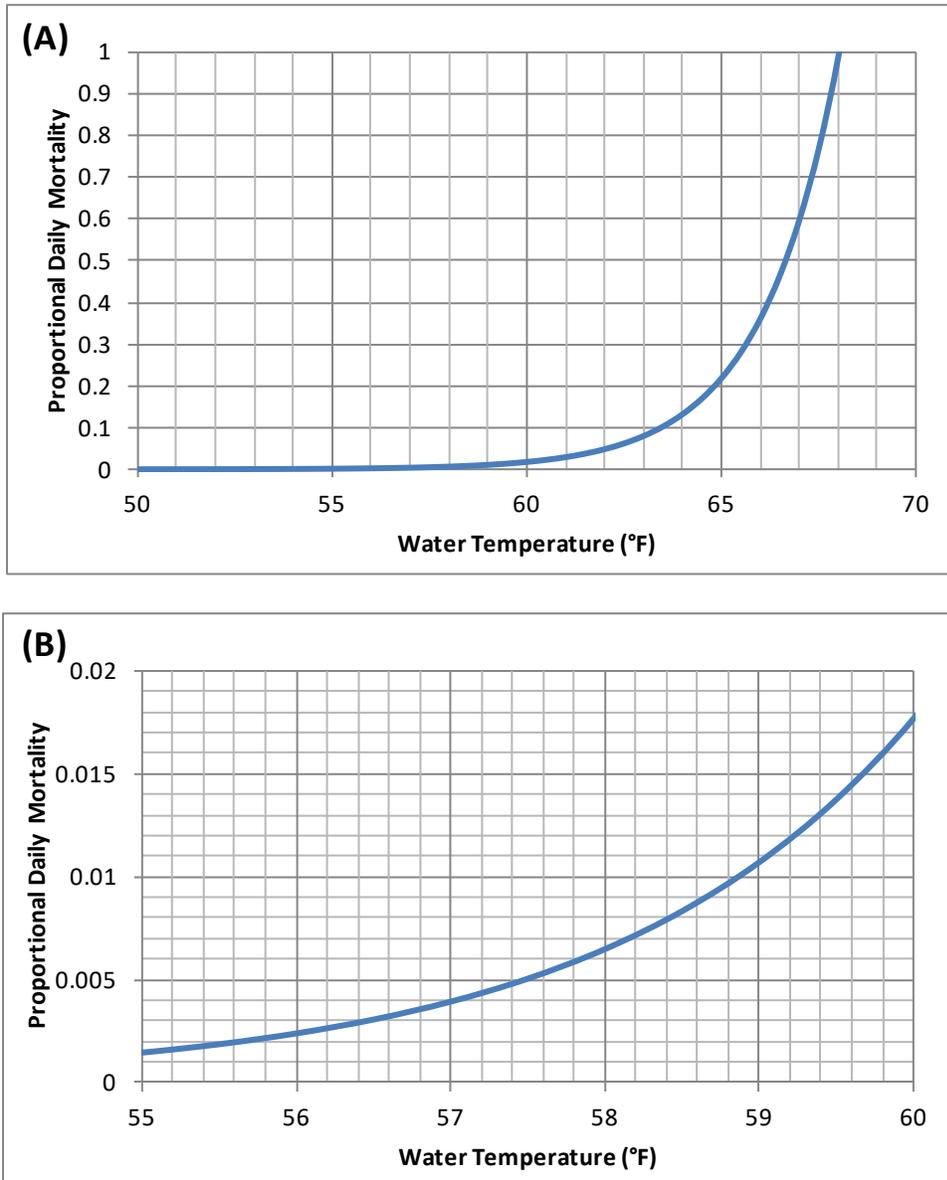


Figure I.2-2. Relationship between Proportional Daily Mortality of Winter-Run Chinook Salmon Eggs and Water Temperature (Equation 7) for (A) the Entire Temperature Range, and (B) the Predominant Range Found in Model Scenarios.

In the IOS Model, mean daily mortality rates of the incubating eggs are predicted from daily water temperatures measured at Bend Bridge on the Sacramento River using the exponential function above. The predicted mean mortality rate, along with the confidence intervals of the predicted values, is used to define a normal probability distribution, which then is randomly sampled to determine the daily egg mortality rate.

I.2.1.3 Fry Rearing

Data from USFWS (1999) was used to model fry mortality during rearing as a function of water temperature. Again, because of a limited sample size from the study by USFWS, statistical analyses to test for the effects of water temperature on rearing mortality could not be run. However, to acquire

predicted values for the model, the following exponential relationship was fitted between observed daily mortality and observed water temperatures (U.S. Fish and Wildlife Service 1999):

(Equation 8) $daily\ mortality = 3.92 \cdot 10^{-12} e^{(0.349 \cdot Temp)}$

Equation 8 yields the following graphic (Figure I.2-3), which indicates that proportional daily fry mortality increases rapidly with only small changes in water temperature. For example, within the predominant water temperature range found in model scenarios (55°F to 60°F), proportional daily mortality increases over five-fold (~0.001 at 55°F to ~0.005 at 60°F). This indicates that, although fry mortality is highly sensitive to changes in water temperature, this sensitivity is not as great as that of egg mortality within the predominant range observed in the model scenarios in focus.

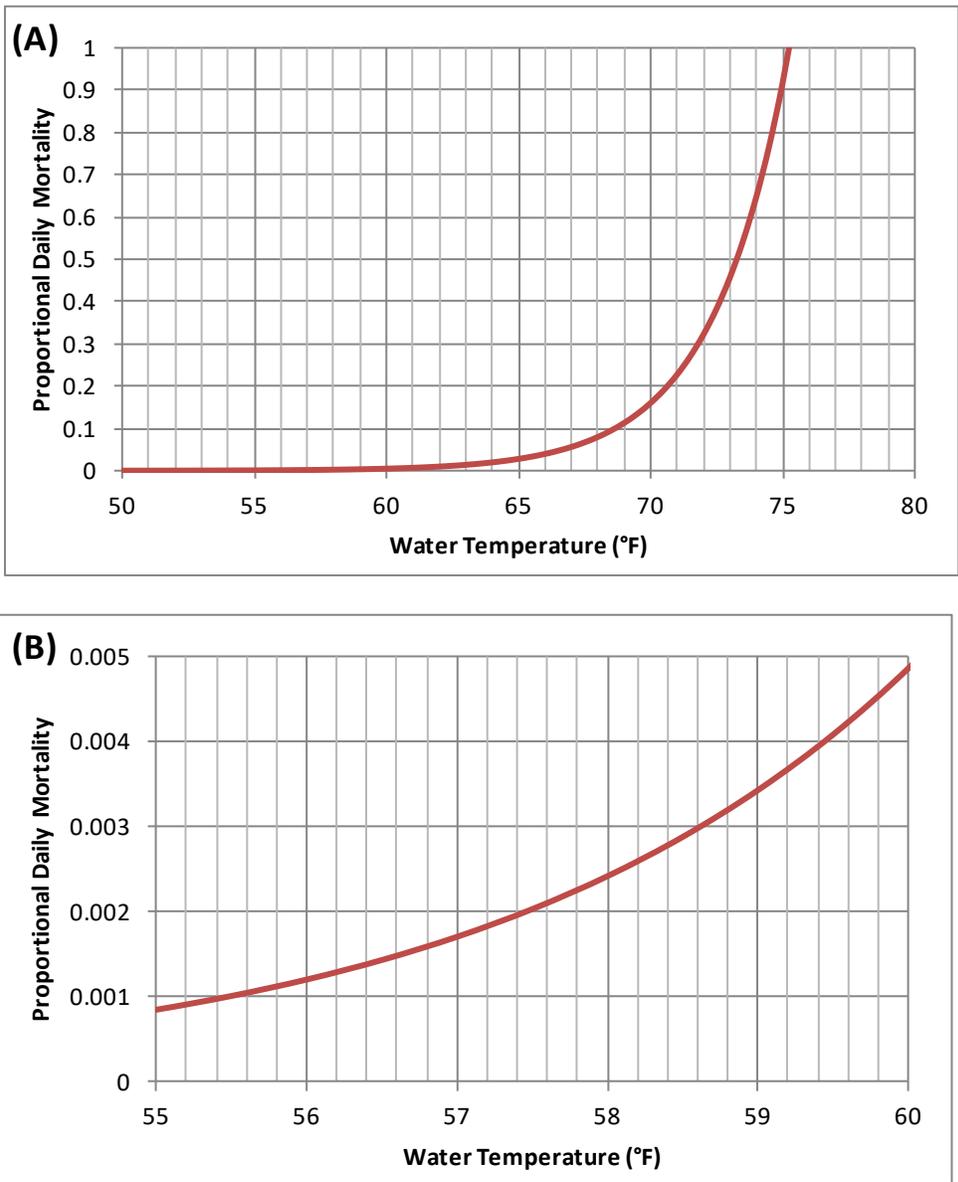


Figure I.2-3. Relationship between Proportional Daily Mortality of Winter-Run Chinook Salmon Fry and Water Temperature (Equation 8) for (A) the Entire Temperature Range, and (B) the Predominant Range Found in Model Scenarios.

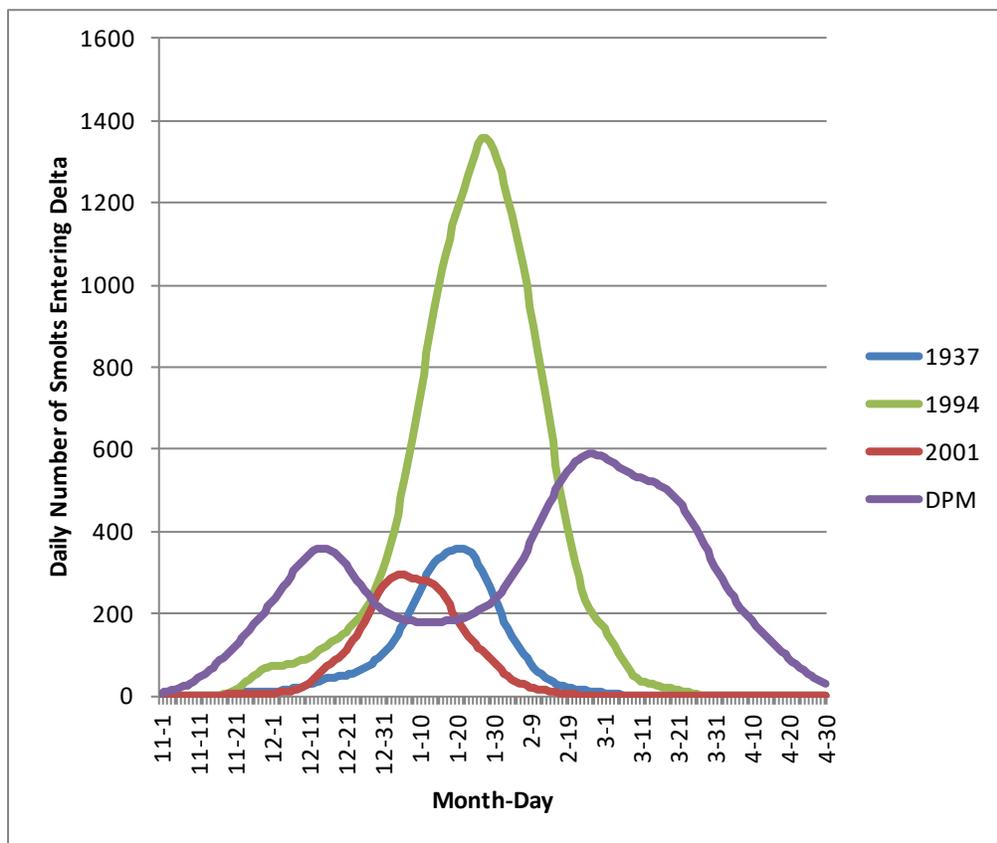
Each day the mean proportional mortality of the rearing fish is predicted from the daily water temperature using the above exponential relationship; the predicted mean mortality, along with the confidence intervals of the predicted values, is used to define a normal probability distribution, which then is randomly sampled to determine the daily mortality of the rearing fish. Temperature mortality is applied to rearing fry for 60 days, which is the approximate time required for fry to transition into smolts (U.S. Fish and Wildlife Service 1999) and enter the *River Migration* stage. All fish migrating through the Delta are assumed to be smolts.

I.2.1.4 *River Migration*

Survival of smolts from the spawning and rearing grounds to the Delta (city of Freeport on the Sacramento River) is a normally distributed random variable with a mean of 23.5% and a standard error of 1.7%. Mortality in this stage is applied only once in the model and occurs on the same day that a cohort of smolts enters the model stage because there were no data to support a relationship with flow or water temperature. Smolts are delayed from entering the next model stage to account for travel time. Mean travel time (20 days) is used along with the standard error (3.6 days) to define a normal probability distribution, which is randomly sampled to provide estimates of the total travel time of migrating smolts. Survival and travel time means and standard deviations were acquired from a study of late-fall run Chinook salmon smolt migration in the Sacramento River that employed acoustic tags and several monitoring stations (including Freeport) between Coleman National Fish Hatchery (Battle Creek) and the Golden Gate Bridge (Michel 2010).

I.2.1.5 *Delta Passage*

Winter-run Chinook salmon passage through the Delta within IOS is modeled with the DPM, which is described fully above. Note that there is one difference between the implementation of the DPM in IOS and the standalone DPM. The timing of winter-run entry into the Delta is a function of upstream fry/egg rearing and so timing changes annually, in contrast to the fixed nature of Delta entry for the standalone DPM. Also, the IOS entry distribution is a unimodal term that tends to peak between the bimodal peaks of the standalone DPM entry distribution (Figure I.2-4). As each cohort of smolts exits the final reaches of the Delta (Sac4 and the interior Delta), the cohorts accumulate until all cohorts from that year have exited the Delta. After all cohorts have arrived, they all enter the *Ocean Survival* model as a single cohort and the model begins applying mortality on an annual time step.



DPM: purple line, fixed bimodal distribution.
 IOS in 1937: blue line, an average peak of January 21.
 IOS in 1994: green line, a late peak of January 28.
 IOS in 2001: red line, an early peak of January 4.

Figure I.2-4. Winter-Run Chinook Salmon Smolt Delta Entry Distributions Assumed under the Delta Passage Model Compared with Entry Distributions for IOS in 1937, 1994, and 2001.

I.2.1.6 Ocean Survival

As described by Zeug et al. (2012), this model stage uses a set of equations for smolt-to-age-2 mortality, winter mortality, ocean harvest, and spawning returns to predict yearly survival and escapement numbers (i.e., individuals exiting the ocean to spawn). Certain values during the ocean survival life stage were fixed constant among model scenarios. Ocean survival model-stage elements are listed in Table I.2-1 and discussed below.

Table I.2-1. Functions and Environmental Variables Used in the Ocean Survival Stage of the IOS Model

Model Element	Environmental Variable	Value
Smolt-age 2 mortality	None	Uniform random variable between 94% and 98%
Age 2 ocean survival	Wells' Index of Ocean productivity	Equation 13
Age 3 ocean survival	None	Equation 14
Age 4 ocean survival	None	Equation 15
Age 3 harvest	None	Fixed at 17.5%
Age 4 harvest	None	Fixed at 45%

Relying on ocean harvest, mortality, and returning spawner data from Grover et al. (2004), a uniformly distributed random variable between 94% and 98% mortality was applied for winter-run Chinook salmon from ocean entry to age 2 and functional relationships were developed to predict ocean survival and returning spawners for age 2 (8%), age 3 (88%), and age 4 (4%), assuming that 100% of individuals that survive to age 4 return for spawning. In the IOS Model, ocean survival to age 2 is given by:

$$\text{(Equation 13)} \quad A_2 = A_i(1-M_2)(1-M_w)(1-H_2)(1-S_{r2}) * W$$

Survival to age 3 is given by:

$$\text{(Equation 14)} \quad A_3 = A_2(1-M_w)(1-H_3)(1-S_{r3})$$

And survival to age 4 is given by:

$$\text{(Equation 15)} \quad A_4 = A_3(1-M_w)(1-H_4)$$

where A_i is initial abundance at ocean entry (from the DPM stage), $A_{2,3,4}$ are abundances at ages 2–4, $H_{2,3,4}$ are harvest percentages at ages 3–4 represented by uniform distributions bounded by historical harvest levels, M_2 is smolt-to-age-2 mortality, M_w is winter mortality for ages 2–4, and $S_{r2,r3}$ are returning spawner percentages at age 2 and age 3.

Harvest mortality is represented by a uniform distribution that is bounded by historical levels of harvest. Age 2 survival is multiplied by a scalar W that corresponds to the value of Wells Index of ocean productivity. This metric was shown to significantly influence over-winter survival of age 2 fish (Wells et al. 2007). The value of Wells Index is a normally distributed random variable that is resampled each year of the simulation. In the analysis, the following values from Grover et al. (2004) were used: $H_2 = 0\%$, $H_3 = 0-39\%$, $H_4 = 0-74\%$, $M_2 = 94-98\%$, $M_w = 20\%$, $S_{r2} = 8\%$, and $S_{r3} = 96\%$.

Adult fish designated for return to the spawning grounds are assumed to be 65% female and are assigned a pre-spawn mortality of 5% to determine the final number of female returning spawners (Snider et al. 2001).

I.2.1.6.1 Time Step

The IOS Model operates on a daily time step, advancing the age of each cohort/life stage and thus tracking their numerical fate throughout the different stages of the life cycle. Some variables (e.g., annual mortality estimates) are randomly sampled from a distribution of values and are applied once per year. Although a daily time step is implemented for the Delta Passage component of IOS, for the ocean phase of the life cycle, the model operates on an annual time step by applying annual survival estimates to each ocean cohort.

I.2.1.6.2 Model Inputs

Delta flows and export flow into SWP and CVP pumping plants were modeled using monthly flow output from DSM2 CALSIM II, as described above in the DPM description. Temperature data for the Sacramento River at Keswick and Balls Ferry was obtained from the SRWQM developed by the Bureau of Reclamation (Reclamation).

I.2.1.6.3 Model Outputs

Four model outputs are used to determine differences among model scenarios.

1. Egg survival: The Sacramento River between Keswick Dam and the Red Bluff Diversion Dam provides egg incubation habitat for winter-run Chinook salmon. Water temperature has a large effect on the survival of Chinook salmon during the egg incubation period by controlling mortality as well as development rate. Temperatures in this reach are partially controlled by releases of cold water from Shasta Reservoir and ambient weather conditions.
2. Fry survival: The Sacramento River between Keswick Dam and Red Bluff Diversion Dam provides rearing habitat for juvenile winter-run Chinook salmon. Water temperature can have a large effect on the survival of Chinook salmon during the fry rearing stage by controlling mortality and development rate. Temperatures in this reach are partially controlled by releases of cold water from Shasta Reservoir and ambient weather conditions.
3. Through-Delta survival: The Delta between the Fremont Weir on the Sacramento River and Chipps Island is a migration route for juvenile winter-run Chinook salmon. Flow magnitude in different reaches of the Delta influences survival and travel time through the Delta and entrainment into alternative migration routes. Fish entering the interior Delta via the Geo/DCC reach are potentially exposed to mortality from water exports in the interior Delta.
4. Escapement: Each year of the IOS Model simulation, escapement is calculated as the combined number of 2-, 3-, and 4-year-old fish that leave the ocean and migrate back into the Sacramento River to spawn between Keswick Dam and the Red Bluff Diversion Dam. These numbers are influenced by the combination of all previous life stages and the functional relationships between environmental variables and survival rates. Only the 1926–2002 water years were considered because the first four years of the CALSIM modeling (1922–1925) were used to seed the model and had fixed numbers of spawners assumed, as described above.

I.2.2 Model Limitations and Assumptions

The following model limitations and assumptions should be recognized when interpreting results.

- Other important ecological relationships likely exist but quantitative relationships are not available for integration into IOS (e.g., the interaction among flow, turbidity, and predation). To the extent that these unrepresented relationships are important and alter IOS outcomes, each alternative considered is assumed to be affected in the same way.
- For relationships that are represented in IOS, the operational alternatives considered are not assumed to alter those underlying functional relationships.
- There is a specific range of environmental conditions (temperature, flow, exports, and ocean productivity) under which functional relationships were derived. These functional relationships are assumed to hold true for the environmental conditions in the scenarios considered.
- Differential growth because of different environmental conditions (e.g., river temperature) and subsequent potential differences in survival and other factors are not directly included in the

model. Differences in survival related to growth are indirectly included to an unknown extent in flow-survival, temperature-survival, and ocean productivity-survival relationships.

- Survival and travel time during Stages 4 (River Migration) and 5 (Delta Passage) are based on studies of yearling late fall–run Chinook salmon (c. 150–170-mm fork length) (Stage 4: Michel 2010; Stage 5: Perry et al. 2010), which are appreciably larger than downstream-migrating winter-run Chinook salmon (c. 70–100-mm fork length during the peak downstream migration) (Williams 2006:101); however, differences between model scenarios do not occur during stage 4 because survival and travel time during River Migration are independent of flow.
- Juvenile winter-run Chinook salmon migrating through the Delta all are assumed to be smolts that are not rearing in the Delta.
- Between Stage 5 (Delta Passage) and Stage 1 (Spawning), the only differences in survival between model scenarios comes from random differences based on probability distributions, although some functions have been fixed at constant values to minimize these random differences. There are no modeled flow effects on adult upstream migration (e.g., attraction flows) because there are no data available for such effects to be modeled.

I.2.3 Model Sensitivity and Influence of Environmental Variables

Zeug et al. (2012) examined the sensitivity of the IOS model estimates of escapement to its input parameter values, input parameters being the functional relationships between environmental inputs and biological outputs. Although revisions have been undertaken to IOS since that time, the main points from their analysis are still likely to be valid.

Zeug et al. (2012) found that escapement of different age classes was sensitive to different input parameters (Table I.2-2). Escapement of age-2 fish (which compose 8% of the total returning fish in a given cohort) was most sensitive to smolt-to-age-2-survival and water year when considering either independent or interactive effects of these parameters, and there was also sensitivity to river migration survival when considering interactive effects of this parameter with other parameters. Escapement of age-3 fish (which compose 88% of the total returning fish in a given cohort) was sensitive to several input parameters when considering the independent effects of these parameters but was sensitive to through-Delta survival alone when considering first-order interactions between parameters. Escapement of age-4 fish (which compose 4% of the total returning fish in a given cohort) was sensitive to nearly all input parameters when considering the independent effects of these parameters, but was not sensitive to any of the parameters when considering first-order interactions between parameters (Zeug et al. 2012).

Zeug et al. (2012) also explored how uncertainty in model parameter estimates influences model output by increasing by 10–50% the variation around the mean of selected parameters that could be addressed by management actions (egg survival, fry-to-smolt survival, river migration survival, Delta survival, age-3 harvest, and age-4 harvest). They found that model output was robust to parameter uncertainty and that age-3 and age-4 harvest had the greatest coefficients of variation as a result of the uniform distribution of these parameters. Zeug et al. (2012) noted that there are limitations in the data used to inform certain parameters in the model that may be ecologically relevant but that are not sensitive in the current IOS configuration: river survival is a good example because it is based on a three-year field study of relatively low-flow conditions that does not cover the range of potential conditions that may be experienced by downstream-migrating juvenile Chinook salmon.

To understand the influence of environmental parameter inputs on escapement estimates from IOS, Zeug et al. (2012) performed three sets of simulations of a baseline condition and either a 10% increase or a 10% decrease in river flow, exports, water temperature (on the Sacramento River at Bend Bridge; see

above), and ocean productivity (i.e., Wells Index; see above). They found that only 10% changes in temperature produced a statistically significant change in escapement; a 10% increase in temperature produced a far greater reduction in escapement (>95%) than a 10% decrease in temperature gave an increase in escapement (>10%). Zeug et al. (2012) suggested that the lack of significant changes in escapement with 10% changes of flow, exports, and ocean productivity may reflect the fact that these variables' relationships within the model were based on observational studies with large error estimates associated with the responses. In contrast, temperature functions were parameterized with data from controlled experiments with small error estimates. Also, Zeug et al. (2012) noted that water temperatures within the winter-run Chinook salmon spawning and rearing area are close to the upper tolerance limit for the species; therefore, even small changes have the potential to significantly affect the population.

Table I.2-2. Sobol' Sensitivity Indices (Standard Deviation in Parentheses) for Each Age Class of Returning Spawners Based on 1,000 Monte Carlo Iterations, Conducted to Test Sensitivity of IOS Input Parameters by Zeug et al. (2012)

Input Parameter	Age 2		Age 3		Age 4	
	Main Index (Effect Independent of Other Input Parameters)	Total Index (Effect Accounting for First-Order Interactions with Other Input Parameters)	Main Index (Effect Independent of Other Input Parameters)	Total Index (Effect Accounting for First-Order Interactions with Other Input Parameters)	Main Index (Effect Independent of Other Input Parameters)	Total Index (Effect Accounting for First-Order Interactions with Other Input Parameters)
Water year	0.300 ^a (0.083)	0.306 ^a (0.079)	0.181 ^a (0.091)	0.150 (0.091)	0.073 (0.067)	0.012 (0.065)
Egg survival	0.030 (0.016)	-0.006 (0.016)	0.222 ^a (0.081)	-0.021 (0.081)	0.102 ^a (0.044)	-0.072 (0.044)
Fry-to-smolt survival	0.039 (0.020)	-0.009 (0.020)	0.166 (0.090)	0.091 (0.092)	0.079 ^a (0.017)	-0.071 (0.017)
River migration survival	0.007 (0.034)	0.135 ^a (0.034)	0.164 (0.084)	0.062 (0.085)	0.079 (0.018)	-0.07 (0.018)
Delta survival	0.010 ^a (0.002)	-0.009 (0.002)	0.404 ^a (0.180)	0.643 ^a (0.177)	0.313 ^a (0.134)	-0.009 (0.132)
Smolt to age 2 survival	0.734 ^a (0.118)	0.454 ^a (0.113)	0.015 (0.016)	-0.006 (0.016)	0.057 ^a (0.017)	-0.052 (0.017)
Ocean productivity	0.003 (0.009)	0.009 (0.009)	0.034 ^a (0.015)	-0.034 (0.015)	0.061 ^a (0.030)	-0.048 (0.029)
Age 3 harvest	N/A	N/A	0.029 ^a (0.001)	-0.028 (0.001)	1.48 ^a (0.306)	0.188 (0.293)
Age 4 harvest	N/A	N/A	N/A	N/A	0.055 ^a (0.003)	-0.054 (0.003)

Source: Zeug et al. 2012.

^a Index value was statistically significant at $\alpha=0.05$.

I.3 Methods for the Science Integration Team (SIT) Model Floodplain Inundation Habitat Analyses for the Rivers and Bypasses

I.3.1 Sacramento River

The entire area of potential juvenile Chinook salmon rearing habitat, including the 253.3 miles of Sacramento River channel and its floodplain, was modeled using the Central Valley Floodplain Evaluation and Delineation (CVFED) HEC-RAS hydraulic model, refined for use in the NOAA-NMFS Winter Run Chinook Salmon life cycle model. The surface area of the active river channel was subtracted from total inundated area to estimate the inundated floodplain area. Using CalSim II estimates of Sacramento River flow, the CVFED model maps the area inundated at each flow and provides fine-scale, spatially explicit estimates of flow velocity, depth and roughness for the entire inundated area. The model sums the surface areas of all locations (cells) possessing high quality velocity and depth conditions for rearing Chinook salmon juveniles, as defined in Table I.3-1.

Table I.3-1. Habitat Variables Influencing Capacity for Each Habitat Type

Habitat type	Variable	Habitat* quality*	Variable range
Mainstem	Velocity	High	≤ 0.15 m/s
		Low	> 0.15 m/s
	Depth	High	> 0.2 m, ≤ 1 m
		Low	≤ 0.2 m, > 1 m
	Roughness	High	> 0.04
		Low	≤ 0.04

* Ranges of high and low habitat quality were based on published studies of habitat use by Chinook salmon fry across their range.

The rearing habitat surface areas were estimated for the four major CVPIA reaches of the Sacramento River, described as follows (the CalSim II node used to model flow for the reach is given in parentheses):

- Upper Sacramento River (CalSim Node = C104). Keswick Dam to Red Bluff, 59.3 miles.
- Upper-mid Sacramento River (CalSim Node = C115). Red Bluff to Wilkins Slough, 122.3 miles.
- Lower-mid Sacramento River (CalSim Node = C134 and Node C160). Wilkins Slough to the American River confluence, 58.0 miles.
- Lower Sacramento River (CalSim Node = C166). American River confluence to Freeport, 13.7 miles.

Note that these reaches are different than those that were used for the Sacramento River CVFED modeling, which are: Keswick Dam to Battle Creek (28.9 miles), Battle Creek to the Feather River confluence (186.5 miles), and the Feather River confluence to Freeport (33.9 miles). The rearing habitat surface area results from the modeling for these three reaches were scaled using the proportional overlap (in river miles) between them and the CVPIA reaches. For example, the results for the first CVPIA reach, Keswick Dam to Red Bluff (59.3 miles), were computed as the sum of the results from the first modeling reach, Keswick Dam to Battle Creek (28.9 miles), and 0.163 times the results from the second modeling reach, Battle Creek to the Feather River confluence (186.5 miles). The results for the Battle Creek to the Feather River confluence are multiplied by 0.163 because 0.163 is the channel

distance from Keswick to Red Bluff minus the channel from Keswick to Battle Creek (59.3-28.9 = 30.4) divided by the distance from Battle Creek to the Feather River confluence, 186.5.

I.3.2 American River

The entire area of potential juvenile Chinook salmon rearing habitat, including the 22.81 miles of the lower American River channel and its floodplain, was modeled using the CVFED HEC-RAS hydraulic model. The active channel surface area of 670.2 acres, estimated through remote sensing analysis, was subtracted from total inundated area to estimate the inundated floodplain area. Juvenile Chinook salmon rearing habitat quality was not determined for the modeled area, so the surface area of high quality habitat was assumed to be 27 percent of the total inundated area, based on results from the San Joaquin River, reported in SJRRP (2012).

I.3.3 Stanislaus River

The entire area of potential juvenile Chinook salmon rearing habitat, including the 60.31 miles of lower Stanislaus River channel and its floodplain, was modeled using the SRH-2D hydraulic model. The active channel area of 409.1 acres, estimated through remote sensing analysis, was subtracted from total inundated area to estimate the inundated floodplain area. Juvenile Chinook salmon rearing habitat quality was not determined for the modeled area, so the surface area of high quality habitat was assumed to be 27 percent of the total inundated area, based on results from the San Joaquin River, reported in SJRRP (2012).

I.3.4 San Joaquin River

The entire area of potential juvenile Chinook salmon rearing habitat in the San Joaquin River, including the 45.68 miles of river channel and its floodplain, was modeled using Central Valley Floodplain Evaluation and Delineation (CVFED) HEC-RAS hydraulic model (for Combined Upper and Lower San Joaquin River). The active channel area of 534.2 acres, estimated through remote sensing analysis, was subtracted from total inundated area to estimate inundated floodplain area. Juvenile Chinook salmon rearing habitat quality was not determined for the modeled area, so the surface area of high quality habitat was assumed to be 27 percent of the total inundated area, based on results from a San Joaquin River Restoration Program study SJRRP (2012).

I.3.5 Yolo Bypass

The entire area of potential juvenile Chinook salmon rearing habitat within the Yolo Bypass; including stream channels, ponds, canals, and ditches, and the floodplain; was modeled using the Central Valley Floodplain Evaluation and Delineation (CVFED) HEC-RAS hydraulic model, refined for use in the NOAA-NMFS Winter Run Chinook Salmon life cycle model. The surface areas of the stream channels, ponds, canals and ditches was subtracted from total inundated area to estimate the inundated floodplain area. Using CalSim II estimates of Yolo Bypass flow, the CVFED model maps the area inundated at each flow and provides fine-scale, spatially explicit estimates of flow velocity, depth and roughness for the entire inundated area. The model sums the surface areas of all locations (cells) possessing high quality velocity and depth conditions for rearing Chinook salmon juveniles, as defined in Table I.3-1.

The rearing habitat surface areas were estimated for two major reaches of the Yolo Bypass: Fremont Weir to the Sacramento Weir, and the Yolo Bypass downstream of the Sacramento Weir. The CalSim II nodes used to represent flow in these two reaches are D160 and C157, respectively.

I.3.6 Sutter Bypass

The entire area of potential juvenile Chinook salmon rearing habitat within the Sutter Bypass; including stream channels, basins, ponds, canals, and ditches, and the floodplain; was modeled using the Central Valley Floodplain Evaluation and Delineation (CVFED) HEC-RAS hydraulic model, refined for use in the NOAA-NMFS Winter Run Chinook Salmon life cycle model. The surface areas of the stream channels, basins, ponds, canals and ditches was subtracted from total inundated area to estimate the inundated floodplain area. Using CalSim II estimates of Sutter Bypass flow, the CVFED model maps the area inundated at each flow and provides fine-scale, spatially explicit estimates of flow velocity, depth and roughness for the entire inundated area. The model sums the surface areas of all locations (cells) possessing high quality velocity and depth conditions for rearing Chinook salmon juveniles, as defined in Table I.3-1.

The rearing habitat surface areas were estimated for four major reaches of the Sutter Bypass: upstream of Moulton Weir, Moulton Weir to Colusa Weir, Colusa Weir to Tisdale Weir, and downstream of Tisdale Weir. The CalSim II nodes used to represent flow in these four reaches are D117, C135, C136A, and C137, respectively.

I.4 Weighted Usable Area Modeling

I.4.1 Spawning Habitat Weighted Usable Area

The weighted usable area (WUA) is an index of the surface area of physical habitat available, weighted by the suitability of that habitat. WUA curves are normally developed as part of instream flow incremental methodology (IFIM) studies. The WUA curves used for Chinook salmon and CCV steelhead spawning habitat in the Sacramento River were obtained from two U.S. Fish and Wildlife Service (USFWS) reports (U.S. Fish and Wildlife Service 2003a, 2006). As noted above, WUA is computed as the surface area of physical habitat available weighted by its suitability. Modeling assumptions used to derive WUA curves include that the suitability of physical habitat for salmon and steelhead spawning is largely a function of substrate particle size, water depth, and flow velocity. The race- or species-specific suitability of the habitat with respect to these variables is determined by observing the fish and is used to develop habitat suitability criteria (HSC) for each race or species of fish. Hydraulic modeling is then used to estimate the amount of habitat available for different HSC levels at different river flows, and the results are used to develop spawning habitat WUA curves (Bovee et al. 1998). The WUA curves and tables are used to look up the amount of spawning WUA available at different flows.

USFWS 2003a provides WUA curves and tables for spawning winter-run, fall-run, and late fall-run Chinook salmon and CCV steelhead for three segments of the Sacramento River encompassing the reach from Keswick Dam to Battle Creek (Figure I.4-1). The WUA tables were updated in USFWS 2006. No WUA curves were developed for spring-run Chinook salmon, but, as discussed later, the fall-run curves were used to quantify spring-run spawning habitat.

Figure I.4-2 through Figure I.4-5 show the flow versus spawning WUA results for winter-run, fall-run, and late fall-run Chinook salmon and CCV steelhead in the three river segments (Segment 6 = Keswick to Anderson-Cottonwood Irrigation District [ACID] Dam, Segment 5 = ACID Dam to Cow Creek, and Segment 4 = Cow Creek to Battle Creek) as provided in USFWS 2006 (Figure 5.D-86). Note that for Segment 6, separate WUA curves were developed for periods when the ACID Dam boards were installed (April through October) and for when the boards were out because installation of the boards affects water depths and velocities for some of the sampling transects used to develop the curves.

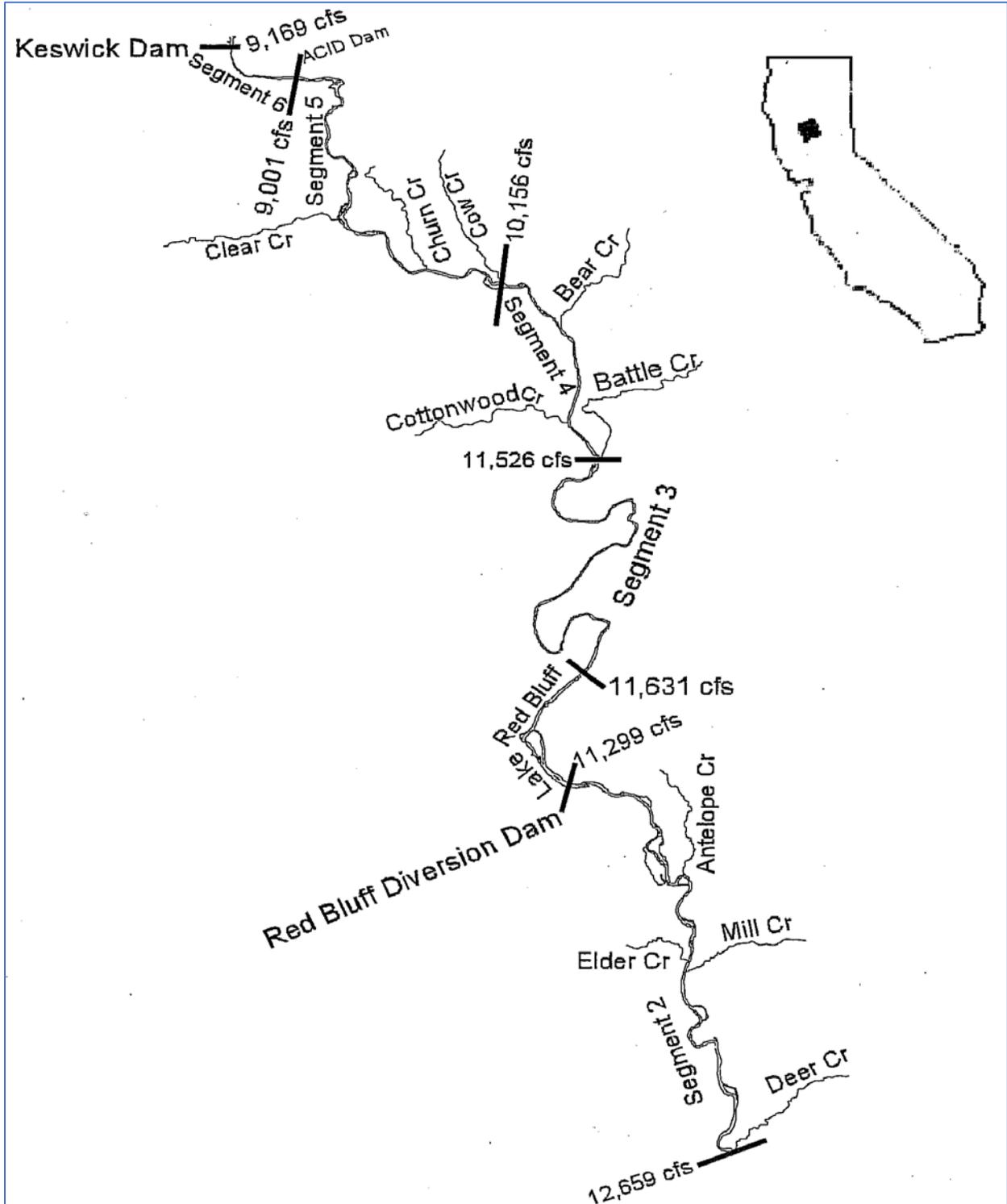


Figure I.4-1. Segments 2–6 of the Sacramento River Used in USFWS Studies to Determine Spawning Weighted Usable Area (WUA) (flows in the figure are the average flows at the upstream boundary of each segment for October 1974 to September 1993). Source: USFWS 2003a.

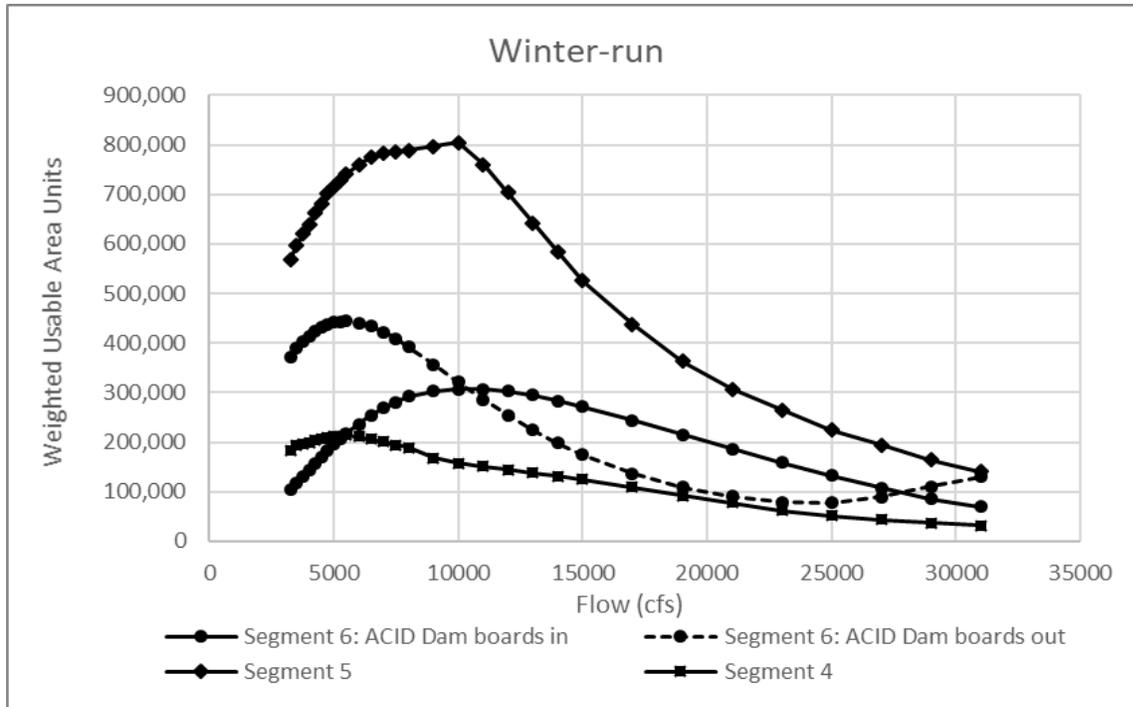


Figure I.4-2. Spawning WUA Curves for Winter-Run Chinook Salmon in the Sacramento River, Segments 4 to 6. ACID = Anderson-Cottonwood Irrigation District.

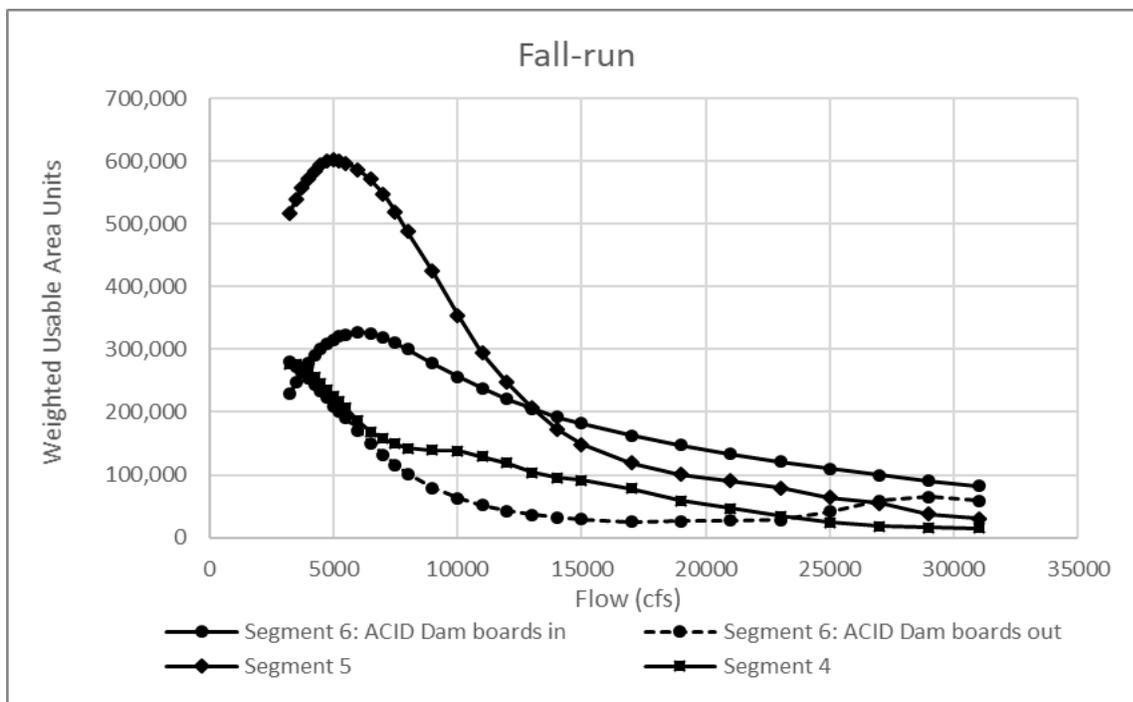


Figure I.4-3. Spawning WUA Curves for Fall-Run Chinook Salmon in the Sacramento River, Segments 4 to 6. The fall-run curves were also used to quantify spring-run Chinook salmon WUA, as discussed in the text. ACID = Anderson-Cottonwood Irrigation District.

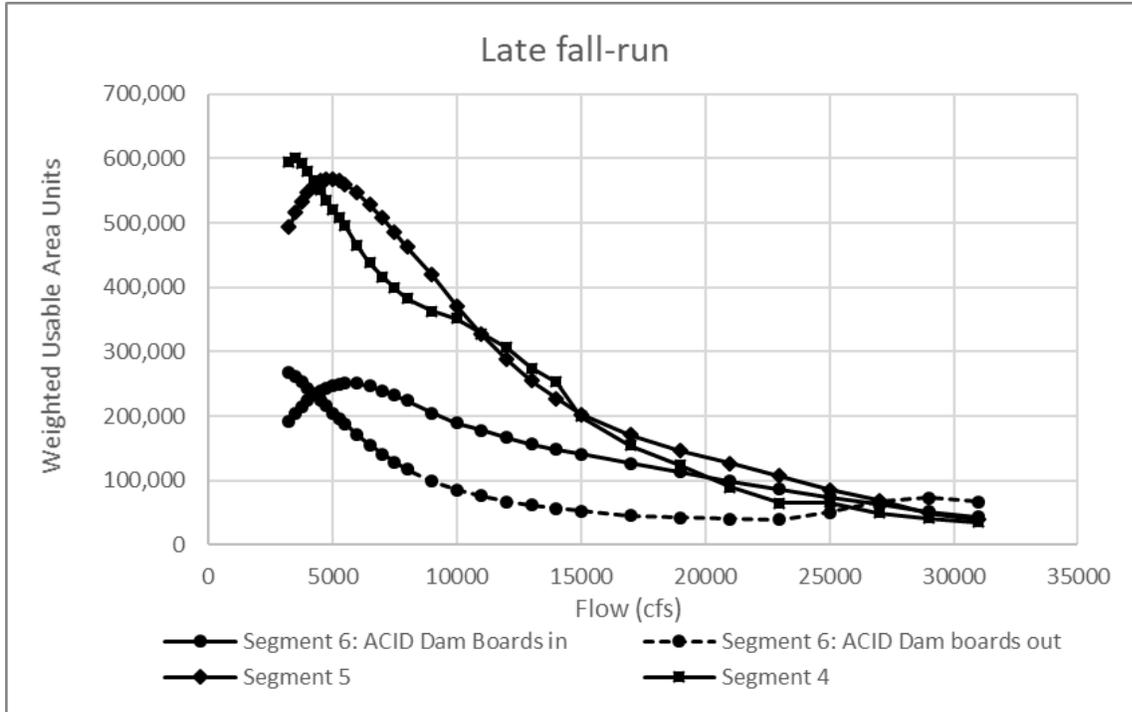


Figure I.4-4. Spawning WUA Curves for Late Fall-Run Chinook Salmon in the Sacramento River, Segments 4 to 6. ACID = Anderson-Cottonwood Irrigation District.

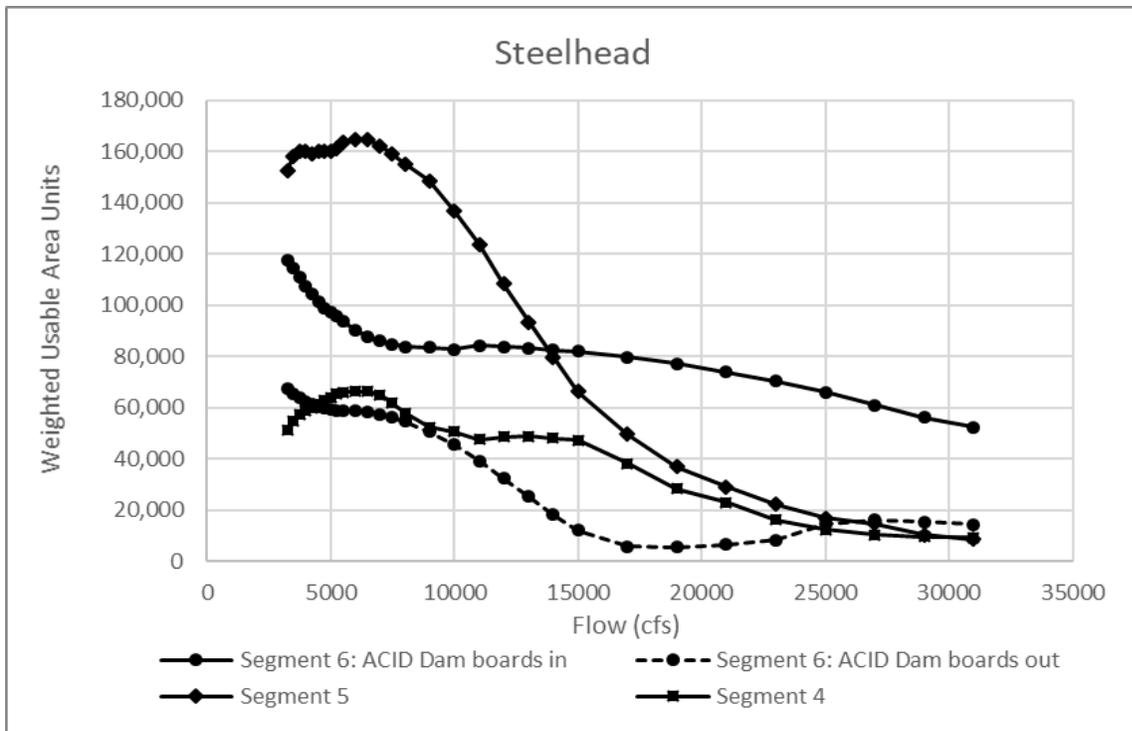


Figure I.4-5. Spawning WUA Curves for California Central Valley Steelhead in the Sacramento River, Segments 4 to 6. ACID = Anderson-Cottonwood Irrigation District.

To estimate WUA, the segment flows were estimated using Sacramento River CALSIM II flows at Keswick Dam under the project scenarios. For Segment 6, the WUA curves for the months when the ACID Dam boards are installed (April through October) were used with CALSIM II flows for those months and the WUA curves for the months when the ACID Dam boards are out were used with the flows for the rest of the year.

Although fall-run spawning WUA curves were used as surrogates for spring-run spawning, CALSIM II flows for the months of spring-run spawning, not those of fall-run spawning, were used to compute the spring-run WUA results.

Because there are no spring-run Chinook salmon WUA curves in the USFWS documentation, previous practice, as described below, has been to use fall-run Chinook salmon WUA curves to model spring-run habitat. Two models that currently produce spawning WUA outputs for spring-run Chinook salmon, SALMOD and SacEFT, derive the spring-run WUA results using the fall-run Chinook salmon spawning WUA curves as surrogates (Bartholow 2004; ESSA 2011). Mark Gard, who led the USFWS studies that produced the Sacramento River WUA curves, has endorsed this practice (Gard pers. comm.). However, this practice introduces uncertainty to the spring-run Chinook salmon results.

A potential limitation of the WUA curves presented above, as of all IFIM studies, is that they assume the channel characteristics of the river during the time of field data collection by USFWS (1995–1999), such as proportions of mesohabitat types, have remained in dynamic equilibrium to the present time and will continue to do so through the end of the project in question. If the channel characteristics substantially change, the shape of the curve may no longer be applicable.

A further limitation of the WUA curves for CCV steelhead is that the HSC used in developing the curves was obtained from previous studies of steelhead in the American River (USFWS 2003b). HSC data were not collected by USFWS for steelhead in the Sacramento River because very few steelhead redds were observed and because the steelhead redds could not be distinguished from those of resident rainbow trout. The validity of this substitution could not be tested and is uncertain (USFWS 2003a).

I.4.2 Rearing Habitat Weighted Usable Area Analysis

The rearing habitat weighted usable area (WUA) curves used for Chinook salmon rearing habitat in the Sacramento River were obtained from a U.S. Fish and Wildlife Service (USFWS) report (U.S. Fish and Wildlife Service 2005b). As noted above for spawning habitat, WUA is computed as the surface area of physical habitat available weighted by its suitability. Modeling assumptions used to derive rearing WUA curves include that the suitability of physical habitat for salmon and steelhead rearing is largely a function of water depth, flow velocity, and the availability and type of cover. The race- or species-specific suitability of the habitat with respect to these variables is determined by observing the fish and is used to develop habitat suitability criteria (HSC) for each race or species. Hydraulic modeling is then used to estimate the amount of rearing habitat available for different HSC levels at different river flows, and the results are used to develop rearing habitat WUA curves and tables (Leclerc et al. 1995; Bovee et al. 1998). These curves and tables are used to look up the amount of WUA available at different flows.

USFWS (2005b) provides WUA curves and tables for rearing winter-run, fall-run, and late fall-run Chinook salmon for three segments of the Sacramento River described above that encompass the reach from Keswick Dam to Battle Creek (Figure I.4-1). Separate curves were developed for fry and juveniles, with fry defined as fish less than 60 millimeters and juveniles defined as greater than 60 millimeters. No WUA curves were developed for spring-run Chinook salmon or CCV steelhead, but, as discussed later, the fall-run curves were used to quantify spring-run rearing habitat and the late fall-run curves were used for steelhead. Figures I.4-6 through I.4-11 show the flow versus rearing WUA results for fry and juvenile

winter-run, fall-run, and late fall-run Chinook salmon as provided in USFWS 2006. Note that for Segment 6, separate WUA curves were developed for periods when the ACID Dam boards are installed (April through October) and for when the boards are out because installation of the boards affects water depths and velocities for some of the sampling transects used to develop the curves. All rearing WUA analyses were limited to juveniles less than a year old.

To estimate WUA, the segment flows were estimated using Sacramento River CALSIM II flows at Keswick Dam under the project scenarios. For Segment 6, the WUA curves for the months when the ACID Dam boards are installed (April through October) were used with CALSIM II flows for those months and the WUA curves for the months when the ACID Dam boards are out were used with the flows for the rest of the year.

Although fall-run rearing WUA curves were used as surrogates for spring-run rearing, CALSIM flows for the months of spring-run rearing, not those of fall-run rearing, were used to compute the spring-run WUA results. This caveat applies as well to the use of the late fall-run rearing WUA curves to compute CCV steelhead WUA results.

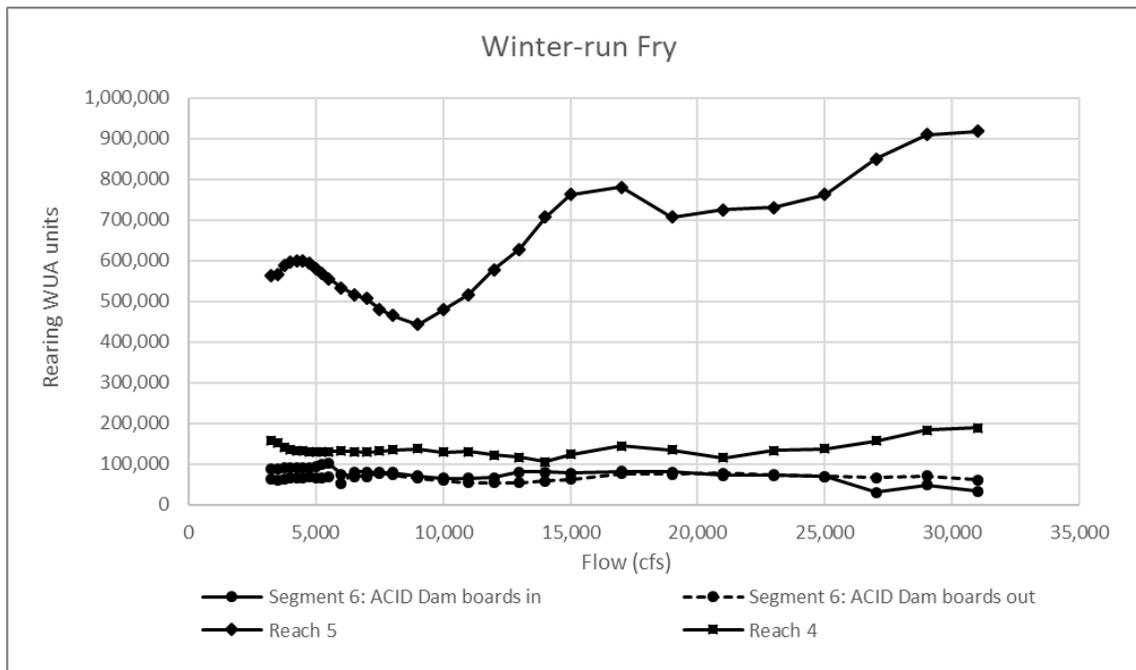


Figure I.4-6. Rearing WUA Curves for Winter-Run Chinook Salmon Fry in the Sacramento River, Segments 4 to 6. ACID = Anderson-Cottonwood Irrigation District.

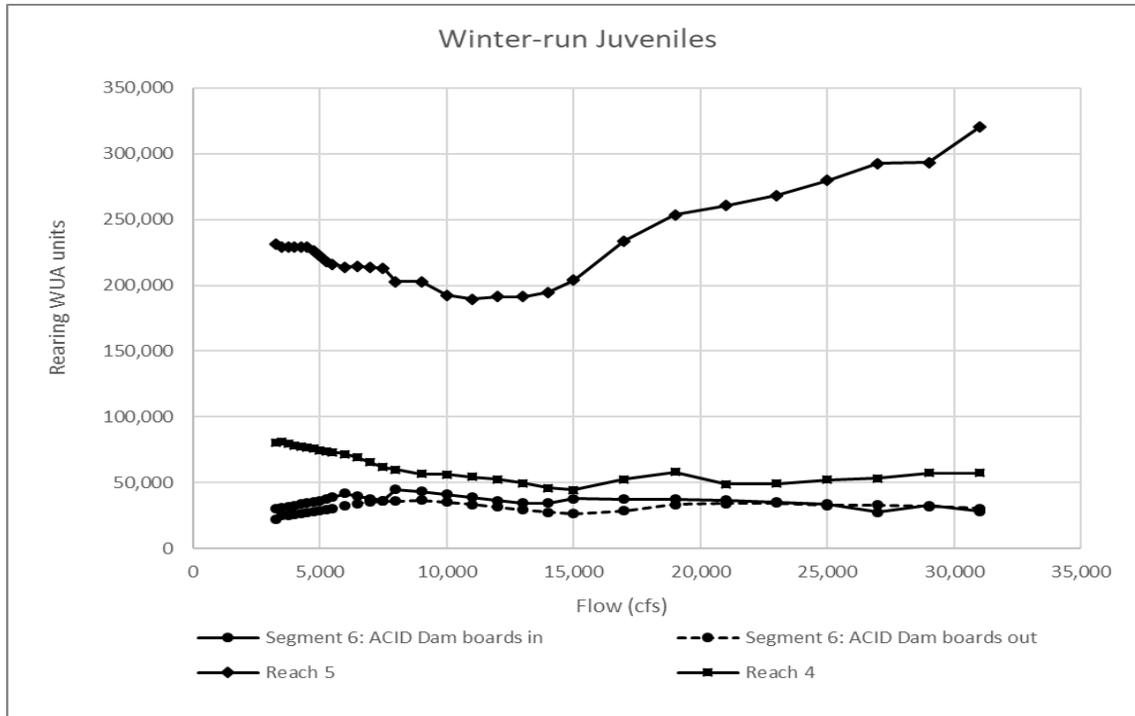


Figure I.4-7. Rearing WUA Curves for Winter-Run Chinook Salmon Juveniles in the Sacramento River, Segments 4 to 6. ACID = Anderson-Cottonwood Irrigation District.

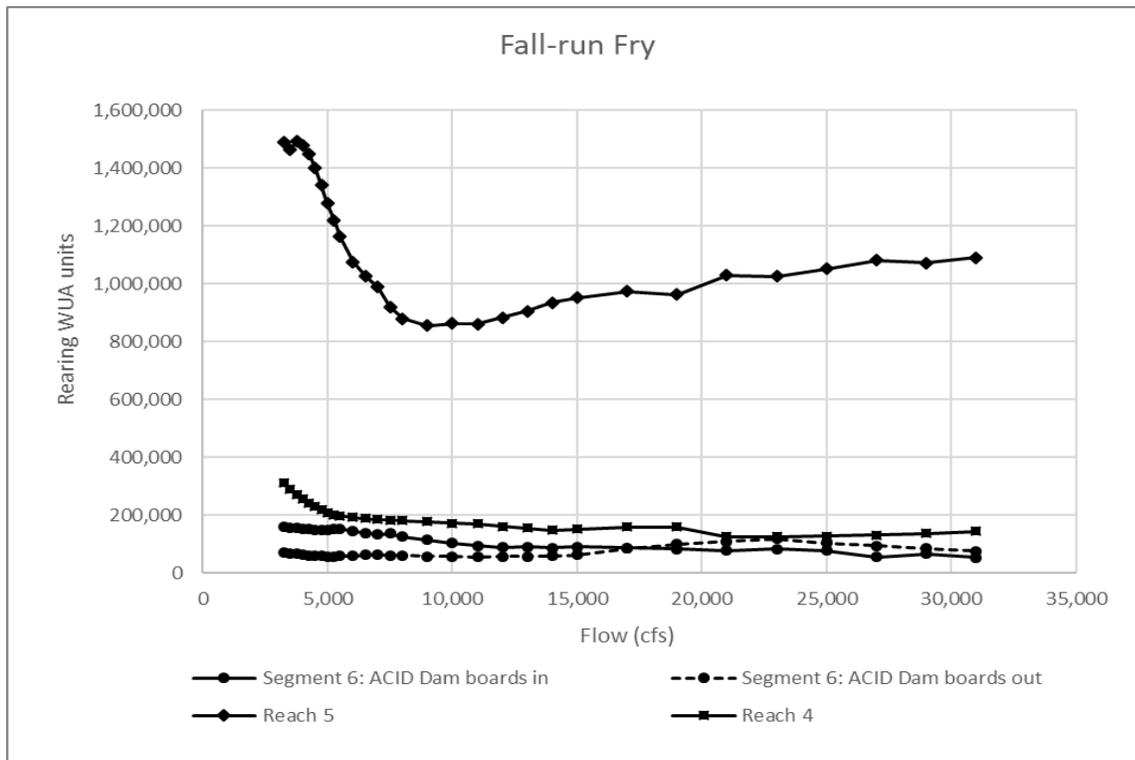


Figure I.4-8. Rearing WUA Curves for Fall-Run Chinook Salmon Fry in the Sacramento River, Segments 4 to 6. (The fall-run curves were used to quantify spring-run Chinook salmon WUA, as discussed in the text.) ACID = Anderson-Cottonwood Irrigation District.

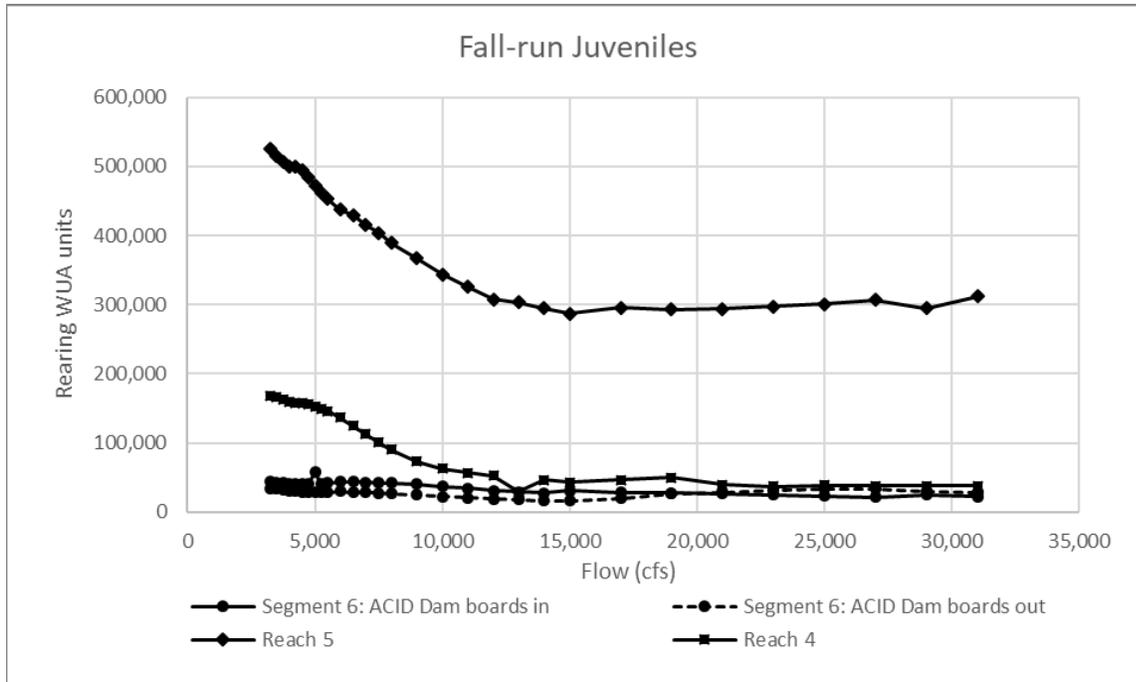


Figure I.4-9. Rearing WUA Curves for Fall-Run Chinook Salmon Juveniles in the Sacramento River, Segments 4 to 6. (The fall-run curves were used to quantify spring-run Chinook salmon WUA, as discussed in the text.) ACID = Anderson-Cottonwood Irrigation District.

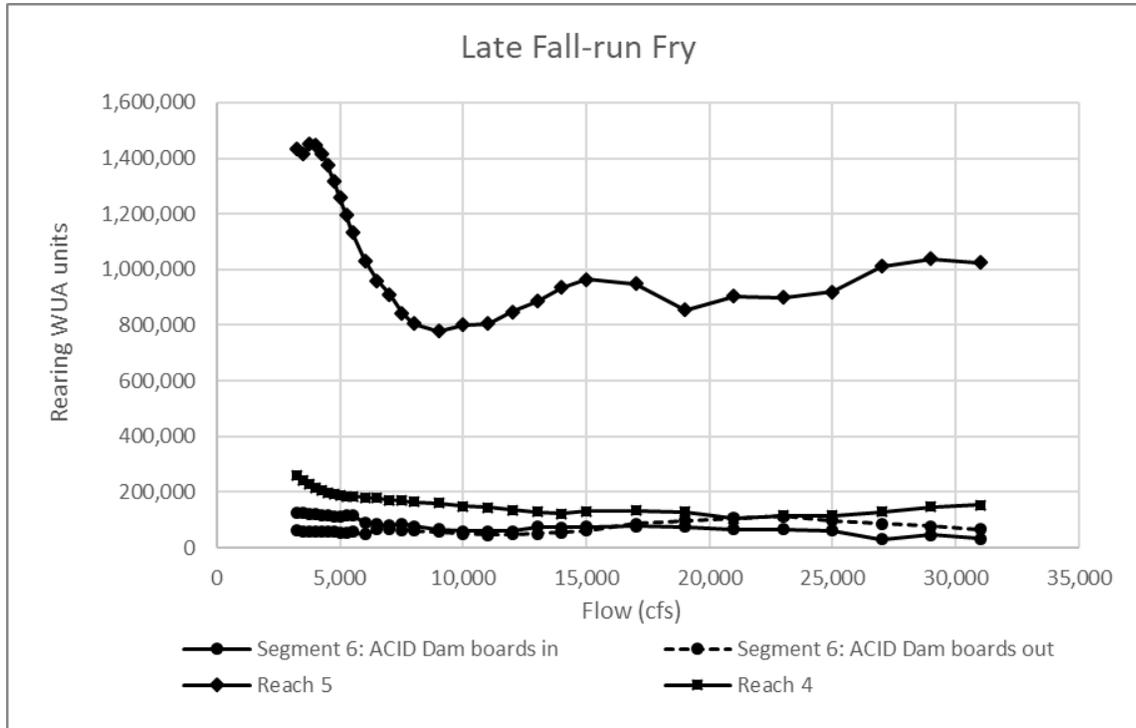


Figure I.4-10. Rearing WUA Curves for Late Fall-Run Chinook Salmon Fry in the Sacramento River, Segments 4 to 6. (The late fall-run curves were used to quantify CCV steelhead rearing WUA, as discussed in the text.) ACID = Anderson-Cottonwood Irrigation District.

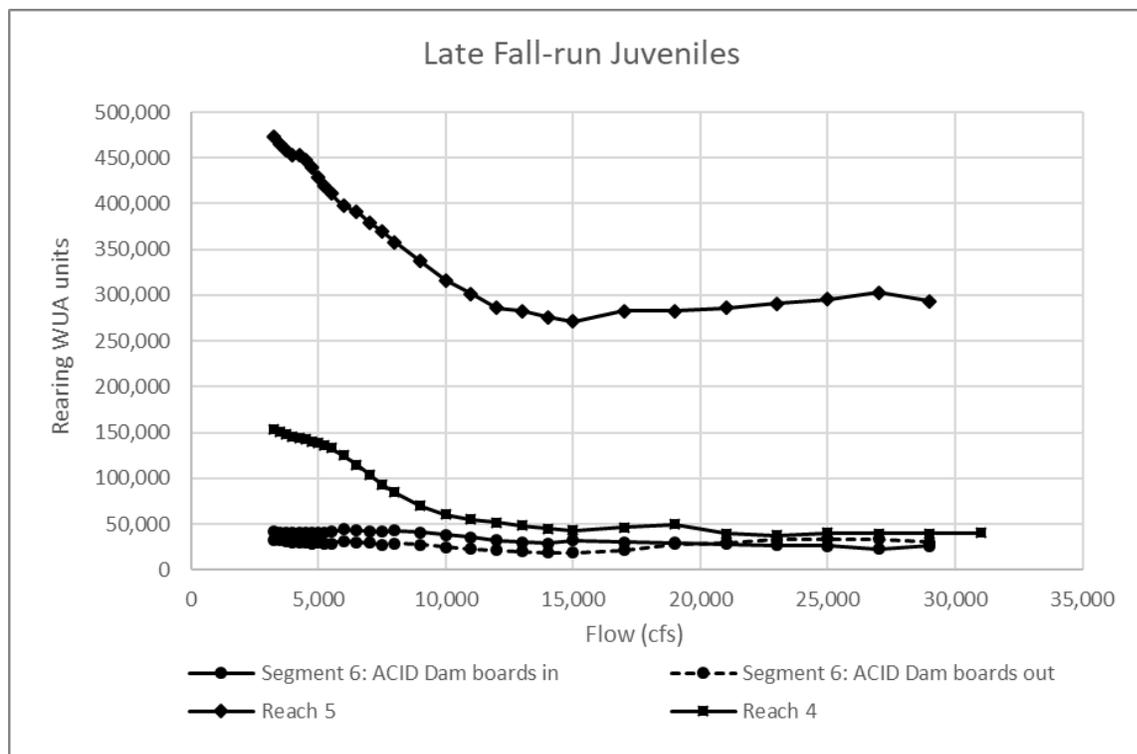


Figure I.4-11. Rearing WUA Curves for Late Fall-Run Chinook Salmon Juveniles in the Sacramento River, Segments 4 to 6. (The late fall-run curves were used to quantify CCV steelhead rearing WUA, as discussed in the text.) ACID = Anderson-Cottonwood Irrigation District.

As noted above, there are no spring-run Chinook salmon or CCV steelhead rearing WUA curves in the USFWS documentation, so the fall-run and late fall-run Chinook salmon rearing WUA curves were used as surrogates to model rearing habitat for spring-run and steelhead, respectively. These substitutions follow previous practice. For instance, the SacEFT model, which produces spawning and rearing WUA outputs for spring-run Chinook salmon and CCV steelhead, derives the spring-run WUA results using the fall-run Chinook salmon WUA curves as surrogates and the CCV steelhead WUA results using the late fall-run Chinook salmon WUA curves as surrogates (ESSA 2011; Robinson pers. comm.). Mark Gard, who led the USFWS studies that produced the Sacramento River WUA curves, has endorsed this practice for both spring-run Chinook salmon and CCV steelhead (Gard pers. comm.). It should be noted that this practice introduces additional uncertainty to the spring-run Chinook salmon and CCV steelhead results.

A potential limitation of the WUA curves presented above, as of all IFIM studies, is that they assume the channel characteristics of the river during the time of field data collection by USFWS (1995–1999), such as proportions of mesohabitat types, have remained in dynamic equilibrium to the present time and will continue to do so through the end of the project in question. If the channel characteristics substantially change, the shape of the curves may no longer be applicable. A further limitation is that the curves were developed for the Sacramento River upstream of Battle Creek, but all races of Chinook salmon and CCV steelhead spend time rearing downstream of this part of the river.

I.5 Salvage-Density Method

The salvage-density method relies on salvage data and was used to estimate changes in entrainment at the SWP/CVP export facilities. The same basic method has been used in recent effects analyses (e.g., the DMC/California Aqueduct Intertie [Bureau of Reclamation 2009]), with refinements as necessary for the present analysis. *Note that the method essentially functions as a description of changes in export flows weighted by seasonal changes in salvage density of covered species; although it generates estimates of numbers of fish lost, these estimates should only be used to compare one operational scenario to another (i.e., proposed action [PA] vs. no action alternative [NAA]) in order to get a sense of how south Delta exports differ during the period of Delta occurrence of NMFS-managed fishes².*

I.5.1 Preprocessing of Input Data

Historical monthly export data (acre-feet) for water years 1995–2009 were obtained from Reclamation’s Central Valley Operations Total Tracy Pumping web page (http://www.usbr.gov/mp/cvo/vungvari/tracy_pump.pdf) and California Department of Water Resources’ (DWR’s) State Water Project Annual Reports of Operations (<http://www.water.ca.gov/swp/operationscontrol/annual.cfm>). Historical monthly salvage data for the water years 1995–2009 were provided by Sheila Greene (DWR) for all species (S. Greene pers. comm.). (Water year 2009 was excluded for some species because the data were not complete.) These data are expanded salvage data, i.e., the extrapolated estimates of the total number of fish salvaged based on a subsample that was actually identified, counted, and measured. These data provided the basic estimates of fish density (number of fish salvaged per volume of water exported) that were subsequently multiplied by simulated export data for the CALSIM modeling period (1922–2003) to assess differences between NAA and scenarios, as described in Appendix 5.B, *DSM Methods and Results*. It is acknowledged that expanded salvage estimates have inherent statistical error associated with the expansion of subsamples (Jahn 2011) but, consistent with typical analyses employing these data (e.g., Grimaldo et al. 2009), this statistical error has not been accounted for in the current salvage-density method. The salvage-density method does not account for spatial distribution of the fish populations, which could differ between NAA and PA because of other operational factors (e.g., north Delta diversions), and assumes a linear relationship between entrainment and export flows. The assumption of a linear relationship is made because of the lack of information on how salvage would increase with increasing flows. One study that examined entrainment in relation to export rate was that of Kimmerer (2008), who showed for hatchery-released Chinook salmon that percentage salvage or percentage entrainment loss was roughly linear up to total south Delta export flows of around 250–275 cubic meters/sec (approximately 8,800–9,700 cfs), depending on assumptions regarding prescreen losses (Kimmerer 2008: his Figures 9 and 10). For perspective on the current effects analysis modeling, the percentage of CALSIM-simulated months during the main entrainment period for Chinook salmon and other covered species (December–June) in which average total south Delta exports were below 8,800 cfs and 9,700 cfs were as follows.

- NAA: 83% < 8,800 cfs, 86% < 9,700 cfs.
- PA: 95% < 8,800 cfs, 98% < 9,700 cfs.

The majority of months were below export flows at which Kimmerer’s (2008) study of Chinook salmon suggested considerable nonlinear percentage salvage or entrainment loss would occur. Kimmerer’s (2008)

² For this reason, various complex methodological refinements suggested by a scientific panel reviewing the method as part of the phase III review of the public draft Bay Delta Conservation Plan have not been implemented, as these would not be justified given the fairly coarse intent of the analysis.

study does not provide an indication of export flow rates at which nonlinearity may occur for the other species included in this analysis.

Juvenile Chinook salmon were divided into races based on fork length on the date of salvage, according to the Delta model of length at date (Brown et al. 1996). It should be noted that these divisions are not without considerable overlap between races, especially for juvenile spring-run and fall-run Chinook salmon; extrapolations of numbers of fish salvaged by race should be regarded cautiously, particularly given the relative abundance of the adult stocks from which the juveniles originate (e.g., fall-run are considerably more abundant than spring-run, and therefore the relative proportions salvaged should reflect such differences but may not when based on length criteria). Techniques such as such rapid, real-time DNA analysis are under development and may allow better classification of race in the future (Harvey et al. 2014). Data for juvenile Chinook salmon salvage were extrapolated into total entrainment losses to reflect prescreen losses (75% at SWP and 15% at CVP), louver efficiency (size-specific equations based on primary water velocity through the intake screens [California Department of Water Resources and California Department of Fish and Game 1986: Appendix A]), and losses during transport to the release site (2% for younger fish, 0% for larger fish [California Department of Water Resources and California Department of Fish and Game 1986: Appendix A]). In similar fashion, steelhead also had various entrainment losses applied: prescreen losses of 75% at SWP and 15% at CVP, and louver losses of 50%.

I.5.2 Normalization to Population Size

Winter-run Chinook salmon salvage and loss data for analysis were normalized, by measures of annual juvenile population abundance in the year of entrainment. This step aimed to adjust the salvage and loss to account for the abundance of the population (e.g., a relatively high number of fish would be expected to be entrained in a year of relatively high abundance). Normalization was undertaken by multiplying the raw monthly salvage or loss in a given month by a factor to account for the relative size of the population in that year compared to the average population size over the years from which salvage or loss data were available. The factor was the average population size in the years from which salvage data were available (1996–2009) divided by the juvenile population size appropriate to the year of salvage. Winter-run Chinook salmon estimates were normalized by the juvenile production estimate (National Marine Fisheries Service 2009). No normalization was undertaken for spring-run Chinook salmon, fall-/late fall-run Chinook salmon, steelhead, or green sturgeon because there are no suitable indices of juvenile annual abundance for these species.

I.5.3 Entrainment Index Calculation

For each species in each month at each facility, density (fish per thousand acre-foot [taf]) as entrainment loss or expanded salvage was simply calculated as the total loss or expanded salvage for the facility divided by the total volume of water exported in that month. It is acknowledged that the assumption of a linear relationship between entrainment and flow may be an oversimplification given the evidence for nonlinear relationships (e.g., Kimmerer 2008; see discussion above) and so, as previously described, ***the method essentially functions as a description of changes in export flows weighted by seasonal changes in salvage density of covered species.*** The mean entrainment index in each month of each water-year type was calculated as follows: the salvage or loss density for a given month in a given water-year type was multiplied by the CALSIM-modeled export volume for the same month for all of the water years of that water-year type. For example, there were 5 wet years (1996–1999, 2006) in the data used to calculate salvage or loss densities and there were 26 wet years in the CALSIM modeling of 1922–2003. Using the month of January as an example, there were five unique wet January salvage or loss densities calculated.

Each of these was then multiplied by each of the 26 wet January export volumes from CALSIM, giving a sample size of 130 from which to calculate means.

Although the salvage-density method does give estimates of entrainment loss or salvage in numbers of fish and there are a number of factors included in the calculations such as multipliers applied for prescreen loss and normalization to population size, ***it is most appropriate to view the results comparatively, i.e., to compare relative differences between scenarios as opposed to examining the estimates of total number of fish lost to entrainment or salvaged.*** In essence, and as noted previously, the salvage-density method provides an entrainment index that reflects export pumping weighted by each covered species' seasonal pattern of abundance in the Delta, as reflected by historical salvage data.

I.6 Reclamation Salmon Mortality Model

The Reclamation Salmon Mortality Model simulates the early life stage mortality of Chinook Salmon along reaches of the Sacramento (below Keswick Dam to Princeton), American (below Nimbus Dam to the Sacramento River confluence), and Stanislaus Rivers (below Goodwin Dam to Riverbank). The model sets an initial spawning distribution along the different river reaches (as a percentage) and uses water temperature data to simulate egg development and mortality based on temperature relationships specified in the model. Daily water temperature results come from the HEC5Q models. The final output from the Reclamation Salmon Mortality Model used in this analysis is the resulting annual percent mortality. Operations Criteria and Plan (OCAP) Biological Assessment (BA) Appendix L (Reclamation 2008a) provides detailed description of the Reclamation Salmon Mortality model structure, assumptions, and processes.

I.7 SALMOD

The SALMOD model simulates the life-stage dynamics of fall-run, late fall-run, spring-run, and winter-run Chinook Salmon populations within the Sacramento River, from below Keswick Dam to the Red Bluff Diversion Dam. The model uses daily flow and temperature data from the Sacramento River HEC5Q model to simulate the annual growth, movement, and mortality of the various riverine life stages of the four Chinook Salmon populations based on an initial annual adult population that resets each biological year. The dynamics simulated are based on assumptions and relations specified in the model. The final output from SALMOD used in this analysis is annual production (number of surviving members of each life-stage) and annual mortality based on a variety of factors, including temperature and habitat (flow) based mortality. The 2008 Operations Criteria and Plan (OCAP) Biological Assessment (BA), Appendix P provides detailed description of the SALMOD model structure, assumptions, and processes (Reclamation 2008b).

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I.8.1 Personal Communications

Gard, M. 2015. Personal communication by email. July 5, 2015—Email.

Robinson D. June 16, 2015—Email from Don Robinson, ESSA Technologies to Clint Alexander, ESSA Technologies about the use of surrogate species in the SacEFT model.